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Drag reduction induced by void waves propagating in turbulent boundary layers

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ABSTRACT

Bubble injection into turbulent boundary layers causes a reduction of wall frictional drag. The technology of bubble drag reduction (BDR) is utilized for ship energy saving. This thesis investigates a novel method of BDR, repetitive bubble injection (RBI), to improve the efficiency of drag reduction. RBI controls the air flow rate to be periodically fluctuated to give the flow a spatiotemporal fluctuation of local void fraction, termed void wave. It is in contrast to bubble injection at constant air flow rates in the conventional method, namely continuous bubble injection (CBI). Prior studies reported the enhancement of drag reduction by the use of void waves. However, the experimental condition was far from the actual ship scale. Thus, the expansion of the application scale is examined in the former part of the thesis through experiments using different scale facilities. The latter part gives further considerations of void-wave drag reduction. This thesis comprises 9 chapters including the introduction (Chapter 1) and the concluding remarks (Chapter 9).

In the first half of the thesis, four experimental studies are performed to prove the superiority of RBI over CBI in full-scale conditions. Chapter 2 investigates the streamwise development of void waves in turbulent boundary layers beneath a 4-m-long flat-bottom model ship. An evaluation employing a one-dimensional advection-diffusion equation results in the tens of meters persistence of void waves. This infers the feasibility of promotion of drag reduction by RBI on long hulls. Chapter 3 examines RBI in turbulent channel flows at bulk water speed of 5.0–7.0 m/s, corresponding channel Reynolds number $Re_m > 10^5$. The drag reduction becomes largest at the repetition frequency of 2.0 Hz. The maximum drag-reduction ratio of RBI reaches almost twice that of the CBI at the same bulk void fraction, indicating twice the efficiency per air volume. This result demonstrates the drag-reduction promotion by RBI in high-speed conditions equivalent to ships. The experiment using a 36-m-long model ship towed at 8.0 m/s in Chapter 4 is performed to obtain reference data of CBI at the same condition of Chapter 5. Chapter 5 finally conducts the quasi-full-scale test of RBI. RBI reduces the frictional drag of the bottom plate of the model ship by 24%, which was 5% higher than that of CBI. The streamwise decay of the drag-reduction effect is commonly observed at CBI and RBI. However, an evaluation based on the experimentally proposed formula indicates that the downstream persistence of the drag-reduction effect of RBI becomes more than 100 m in contrast to the persistence of 8 m of CBI.

The later half of the thesis composes one estimation study and two experimental studies. Chapter 6 estimate the net power saving on ships considering the power for blowing air using the experimental results of the quasi-full-scale test (Chapter 4 and 5). The result suggests the improvement of net performance by the use of RBI relative to CBI on a full-scale ship. Chapter 7 focuses on the temporal variation of local wall shear stress under RBI based on the data obtained in the quasi-full-scale experiment in Chapter 5. This founds the drastic change of drag reduction within the passage of a single bubble swarm. The later part of the bubble swarm produces the most drag reduction in a period. Chapter 8 aims to reveal the temporal response of turbulent flow structure to the sudden decrease in local void fraction. A significant modification is observed at the passage of the tail of

the bubble swarm. At the moment, the turbulent intensity and the Reynolds shear stress decrease by 40% and 90%, respectively, in comparison with the single-phase flow.

Chapter 9 presents a summary of all the studies. In addition, based on the findings of the present studies, ideas that can be used as a springboard for solving important problems in the future development of void-wave drag reduction are presented.

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Tanaka, T., Oishi, Y., Park, H.J., Tasaka, Y., Murai, Y., Kawakita, C., “Frictional drag reduction caused by bubble injection in a turbulent boundary layer beneath a 36-m-long flat-bottom model ship”, *Ocean Engineering*, Vol. 252, 111224 (2022), DOI: <https://doi.org/10.1016/j.oceaneng.2022.111224>.

Tanaka, T., Oishi, Y., Park, H.J., Tasaka, Y., Murai, Y., Kawakita, C., “Downstream persistence of frictional drag reduction with repetitive bubble injection”, *Ocean Engineering*, Vol. 272, 113807 (2023), DOI: <https://doi.org/10.1016/j.oceaneng.2023.113807>.

Review article

Murai, Y., Tanaka, T., Horimoto, Y., Park, H.J., Tasaka, Y., “Air lubrication technology for reducing frictional resistance of marine vessels”, *Journal of Japanese Society of Tribologists*, Vol. 67, No. 8, pp. 547–554 (2022), DOI: https://doi.org/10.18914/tribologist.67.08_547 (in Japanese).

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CHAPTER 1

Introduction

1.1 Background

The Sustainable Development Goals set up in 2015 by the United Nations share the future global development framework (Fig. 1.1). Goal 13: Climate action addresses taking urgent action against climate change caused by global warming and regulating greenhouse gas (GHG) emissions [2]. According to the latest report by the International Maritime Organization (IMO) [3], the share of shipping emissions in global anthropogenic emissions was 2.89% in 2018. The IMO adopted the strategy on reduction of GHG emissions by at least 50% by 2050 compared with the level in 2008 [4].

There are 5 main categories of measures for reducing ship GHG emissions: hull design, power and propulsion system, alternative fuels, alternative energy sources, and operation. In the review of around 150 studies by Bouman *et al.* [5], the CO₂ emission reduction potential was presented as shown in Fig. 1.2. Ship engineers agree that the alternative fuel is the direct solution to emission reduction. Ongoing projects plan to develop integrated designs of other measures for future ships.

The development of hull design has been a major effort in the long history of ship engineering because the hydrodynamic resistance mainly determines the performance. The hull design remains a core technology even in the future when shipping fuel is completely replaced with a carbon-free



Figure 1.1: The 17 Sustainable Development Goals [1]

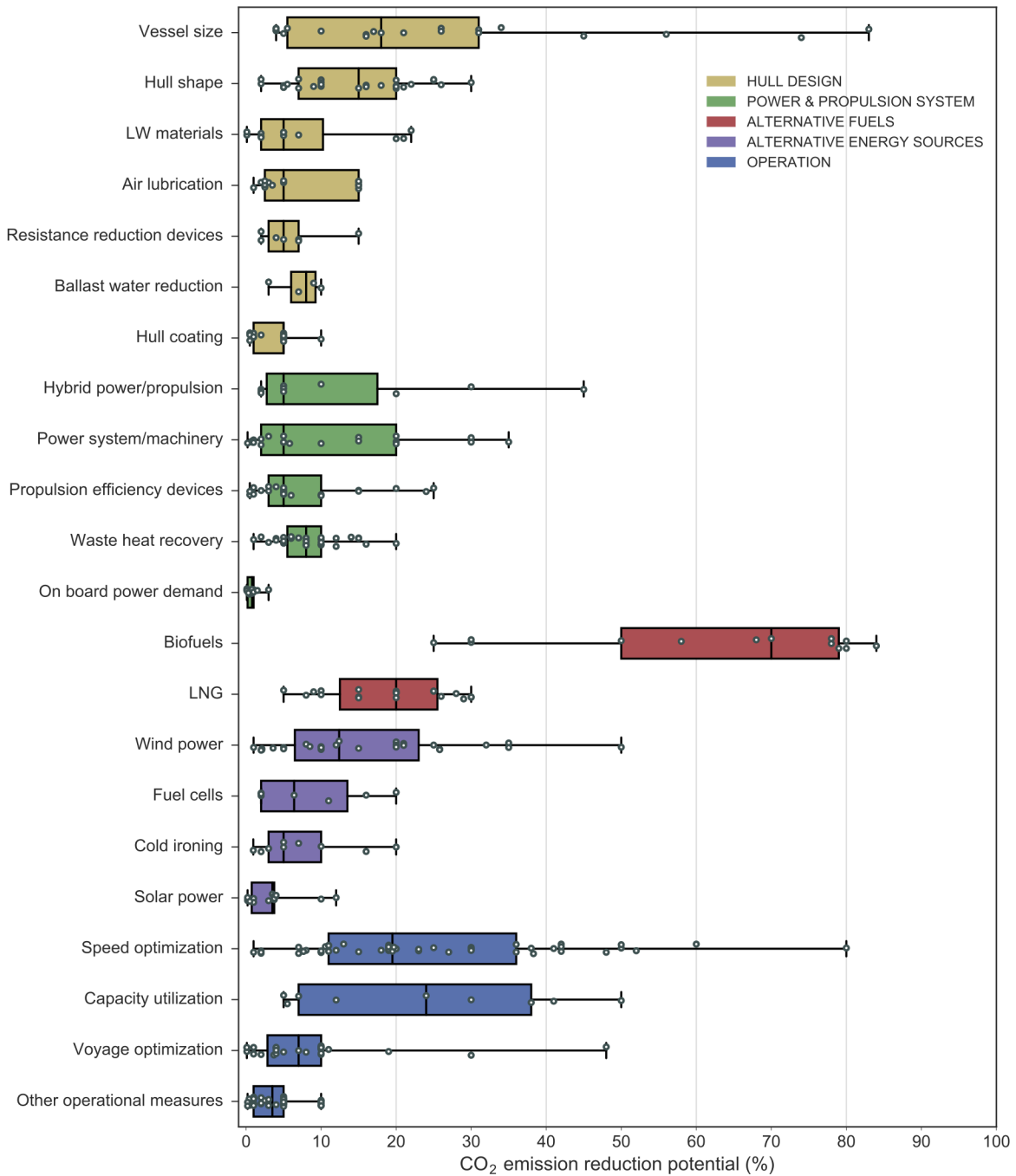


Figure 1.2: CO₂ emission reduction potential from individual measures, classified in 5 main categories of measures (Bouman *et al.* [5])

Table 1.1: Full-scale sea trials of air lubrication released by works including academic research and company reports (Mizokami and Kuroiwa [10], American Bureau of Shipping [11], and Pavlov *et al.* [12])

Year	Ship	Net power saving
2002	Seiun-Maru	2%
2004	Misaki	6%
2007	ACS Demonstrator	Small
2008	Pacific seagull	5%
2008	Filia Ariea	10%
2009	Olivia Maersk	None
2009	Kraichgau I	15%
2009	Till Deymann	20% (drag reduction)
2010	Yamatai, Yamato	10%
2012	Soyo	3%
2012	Naminoue	5%
2014	SHI HCC	8.8%
2015	SHI LNG Carrier	4.5%
2015	MT Amalienborg	4%
2019	Naminoue	3.7%

one. Air lubrication is a relatively new research area since the first experimental study by McCormick and Bhattacharyya [6] in 1973. Air bubbles are injected into the turbulent boundary layer to reduce the frictional resistance of the ship. These days more than 20 ships apply air lubrication, and 15 of them open the performance data as listed in Table 1.1. Multiple full-scale sea trials of academic research demonstrated the improvement of hull performance (Kodama *et al.* [7], Mizokami *et al.* [8], Kumagai *et al.* [9], and Mizokami and Kuroiwa [10]). The advantage of air lubrication in today's green shipping is its availability to various conditions of ship sizes, ship shapes, hull materials, ship speeds, weather, and so on. That is air lubrication is easy to combine with other measures for reducing GHG emissions and apply to existing ships. Moreover, air lubrication has no risk of environmental pollution because it simply involves blowing air into the sea.

The net power saving of air lubrication, namely the hydrodynamic resistance reduction exceeding the additional power consumption for blowing air, in the previous studies was 5% for a 120-m-long ship (Kodama *et al.* [7]), 12% for a 162-m-long ship (Mizokami *et al.* [8]), and 3.7% for a 145-m-long ship (Mizokami and Kuroiwa [10]) using blowers to inject bubbles. To reduce the energy spent in blowing air, Kumagai *et al.* [9] developed a hydrofoil bubble generator. Sea trials on an 85-m-long ship installing this device resulted in a net power saving of approximately 10%. A recent study on the device demonstrated its effectiveness for longships under high-speed conditions (Murai *et al.* [13]). The maximum net power saving of air lubrication to date is 15% in the sea trials, and Bouman *et al.* [5] estimated the emission reduction potential of air lubrication to be less than 20% (Fig. 1.1). However, new findings expected to advance the performance are accumulated in the front of the investigation of air lubrication (Murai [14]).

1.2 Air lubrication to reduce frictional resistance of ships

The reduction of frictional resistance of ships by air lubrication results from the reduction of wall frictional drag of hulls. The wall frictional drag is given by

$$D = \frac{1}{2} C_f \rho U^2 A, \quad (1.1)$$

where ρ , C_f , U , and A are respectively fluid density, friction drag coefficient, the relative speed between the wall to main fluid flow, and contact area of the wall and the fluid. The performance of air lubrication is evaluated by the reduction ratio to the frictional drag in liquid-single-phase flow, D_0 :

$$DR = 1 - \frac{D}{D_0}. \quad (1.2)$$

Hereafter, “drag reduction” refers to the reduction of frictional drag unless otherwise noted. In a streamwise uniform flow like a channel flow, the drag-reduction ratio can be defined using local wall shear stress as

$$\tau = \frac{1}{2} c_f \rho U^2 \left(= \frac{D}{A} \right), \quad (1.3)$$

$$DR = 1 - \frac{\tau}{\tau_0}. \quad (1.4)$$

Here, c_f and τ_0 are respectively local friction coefficient and the local wall shear stress in liquid-single-phase flow. The ratio of DR to the void fraction α of the flow is also an important index denoting drag reduction per unit air volume, known as gain factor,

$$G = \frac{DR}{\alpha}. \quad (1.5)$$

As reviewed by Murai [14], the range of DR and G varies depending on the bubble size and the flow speed (Fig. 1.3).

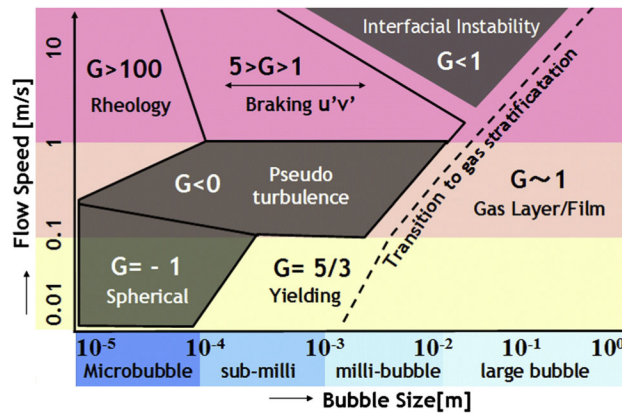


Figure 1.3: Transition diagram of the drag reduction mechanism in the air lubrication (Murai [14])

Air lubrication causes drag reduction by affecting ρ and C_f in Eq. (1.1) (or c_f in Eq. (1.3)). The hydrodynamic mechanism to reduce frictional drag depends on the bubble size and is classified into three regimes: air-layer/partial-cavity drag reduction (ALDR/PCDR), bubble drag reduction (BDR), and microbubble drag reduction (μ BDR).

Air-layer/partial-cavity drag reduction

Blowing air replaces the fluid near the wall from the water to the large bubble to decrease ρ . This effect is also interpreted as insulation of the water flow from the wall decreasing A . ALDR generates air films by blowing air at high flow rates (e.g., Elbing *et al.* [15] and Mäkiharju and Ceccio [16]), whereas PCDR stabilizes a large air cavity in a special concavity of the hull (e.g., Gokcay *et al.* [17] and Wang *et al.* [18]). ALDR/PCDR provide $G \sim 1$ because both DR and α become close to 100% as listed in Table 1.2.

Bubble drag reduction

Submillimeter-to-centimeter-sized bubbles cause drag reduction by decreasing both ρ and C_f (c_f). The existence of bubbles in the water flow immediately leads to a decrease in the mixture density at the magnitude of α . BDR generally results in $G > 1$ with several tens of percent DR at relatively low α (Table 1.3) because bubbles also cause relaxation of the Reynolds shear stress in the turbulent flow (Murai *et al.* [19]). The turbulence suppression is caused by bubble deformation (Kitagawa *et al.* [20]).

Microbubble drag reduction

The first demonstration of air lubrication by McCormick and Bhattacharyya [6] used microbubbles generated by water electrolysis around an axisymmetric body. Later detailed studies of μ BDR achieved high efficiency, namely $G > 100$, as shown in Table 1.4. A large decrease in C_f (c_f) is induced by modification of turbulent coherent structures with a small volume of bubbles (e.g., Hara *et al.* [21] and Zhang *et al.* [22]).

Table 1.2: Previous studies of ALDR/PCDR

Investigators	Configuration	DR	G
Fukuda <i>et al.</i> [23]	Model ship	80%	-
Gokcay <i>et al.</i> [17]	Model ship	20%	-
Matveev [24]	Model ship	-	-
Elbing <i>et al.</i> [25]	Flat plate	20–100%	1
Ceccio [26]	Review article		
Lay <i>et al.</i> [27]	Flat plat	-	-
Amromin <i>et al.</i> [28]	Model ship	20%	-
Elbing <i>et al.</i> [15]	Flat plate	90%	1
Jang <i>et al.</i> [29]	Flat plate	95%	1
Butterworth <i>et al.</i> [30]	Model ship	15%	-
Amromin [31]	Model ship	100%	-
Mäkiharju <i>et al.</i> [32]	Flat plate	-	-
Cucinotta <i>et al.</i> [33]	Model ship	14%	-
Mäkiharju and Ceccio [16]	Model ship	-	-
Wu and Ou [34]	Flat plate	-	-
Fang <i>et al.</i> [35]	Model ship (CFD)	-	-
Wang <i>et al.</i> [18]	Flat plate	75%	-
Zhao and Zong [36]	Model ship	15%	-

Table 1.3: Previous studies of BDR

Investigators	Configuration	DR	G
Guin <i>et al.</i> [37]	Horizontal channel	18%	2
Watanabe <i>et al.</i> [38]	Model ship	20%	-
Kato <i>et al.</i> [39]	Horizontal channel	60%	12
Gabillet <i>et al.</i> [40]	Horizontal channel	-	-
Moriguchi and Kato [41]	Horizontal channel	7%	2
Takahashi <i>et al.</i> [42]	Model ship	20%	-
Kitagawa <i>et al.</i> [20]	Horizontal channel	7%	4
van den Berg <i>et al.</i> [43]	Taylor-Couette flow	12%	3
Shen <i>et al.</i> [44]	Horizontal channel	23%	1
Murai <i>et al.</i> [19]	Horizontal channel	-	-
Sanders <i>et al.</i> [45]	Flat plate	6%	-
Murai <i>et al.</i> [46]	Horizontal channel	55%	2
van den Berg <i>et al.</i> [47]	Taylor-Couette flow	27%	3
Elbing <i>et al.</i> [25]	Flat plate	20–100%	1
Murai <i>et al.</i> [48]	Taylor-Couette flow	35%	8
Wu <i>et al.</i> [49]	Horizontal channel	22%	5
Huang <i>et al.</i> [50]	Horizontal channel	-	-
Mizokami <i>et al.</i> [8]	Ship	17%	-
van Gils <i>et al.</i> [51]	Taylor-Couette flow	40%	10
Murai [14]	Review article		
Oishi and Murai [52]	Horizontal channel	-	-
Park <i>et al.</i> [53]	Horizontal channel	-	-
Kumagai <i>et al.</i> [9]	Ship	> 15%	-
Park <i>et al.</i> [54]	Horizontal channel	22%	20
Park <i>et al.</i> [55]	Model ship	28%	6
Qin <i>et al.</i> [56]	Flat plate	23%	23
Park <i>et al.</i> [57]	Model ship	25%	6
Jha <i>et al.</i> [58]	Horizontal channel	23%	5
Oishi <i>et al.</i> [59]	Horizontal channel	9%	5
Kim <i>et al.</i> [60]	Horizontal channel	$\pm 10\%$	-
Hazuku <i>et al.</i> [61]	Horizontal channel	60%	1

Table 1.4: Previous experimental studies of μ BDR

Investigators	Configuration	DR	G
McCormick and Bhattacharyya [6]	Submerged body	35%	-
Ferrante and Elghobashi [62]	Flat plate (DNS)	20%	10
Hassan <i>et al.</i> [63]	Horizontal channel	38%	8
Zhen and Hassan [64]	Horizontal channel	38%	8
Wu <i>et al.</i> [65]	Submerged body	20%	1
Sugiyama <i>et al.</i> [66]	Taylor-Couette flow (DNS)	19%	150
Jacob <i>et al.</i> [67]	Tunnel wall	9%	2
Hara <i>et al.</i> [21]	Tunnel wall	30%	1100
Watanabe <i>et al.</i> [68]	Taylor-Couette flow	-	-
Park <i>et al.</i> [69]	Flat plate	-	-
Zhang <i>et al.</i> [22]	Tunnel wall	35%	1200

1.3 Continuous bubble injection (CBI) and repetitive bubble injection (RBI)

BDR has higher applicability on ships relative to other methods since it simply blows air through holes or slits arranged on the hull. The implementation of ALDR needs a huge capacity for blowing air at a high flow rate, and PCDR requires special concave-formed hulls. Generation of a sufficient quantity of bubbles for μ BDR consumes much power in high-speed flows around large ships. These requirements in ALDR/PCDR and μ BDR limit the expected net power saving and their feasibility on commercial ships. The main target of the present study is the BDR regime.

To find the optimal operation of BDR, the dependence of drag reduction on the bubble size has been investigated in many studies (e.g., Kato *et al.* [39], Moriguchi and Kato [41], and Shen *et al.* [44]). Previous studies revealed that the turbulent flow structure is affected differently by

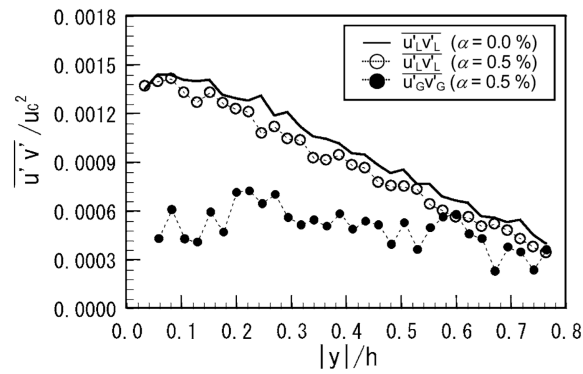


Figure 1.4: Profiles of Reynolds shear stress of the liquid phase and correlation of bubble fluctuation velocities (Kitagawa *et al.* [20])

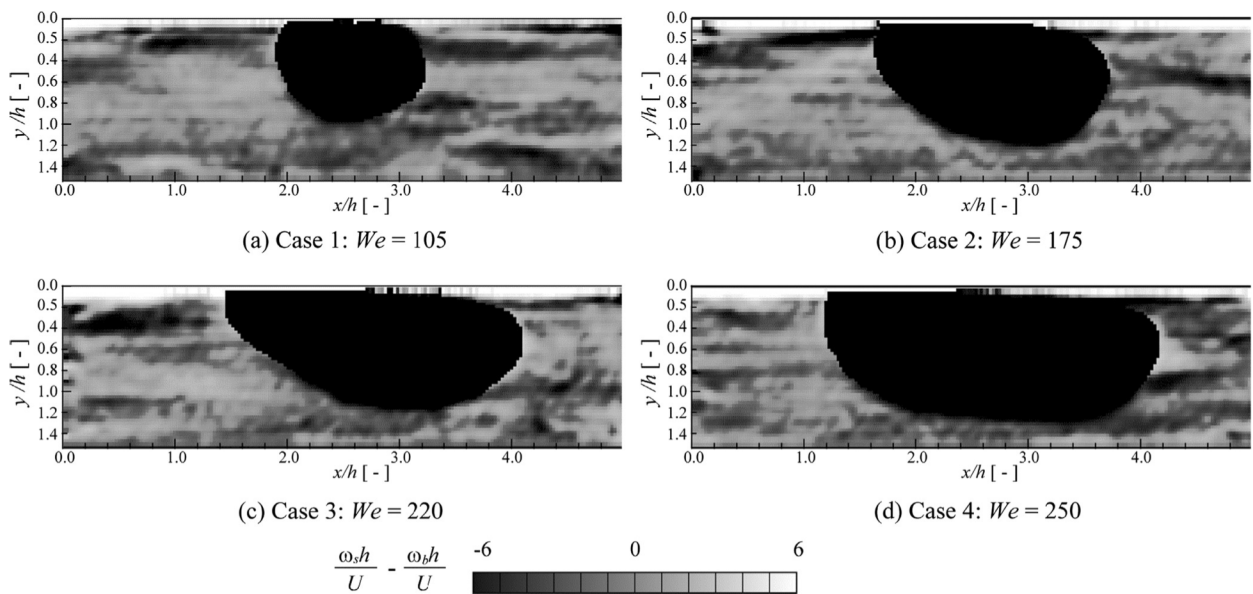


Figure 1.5: Differential vorticity relative to single-phase flow around bubbles in a turbulent channel flow (Oishi and Murai [52])

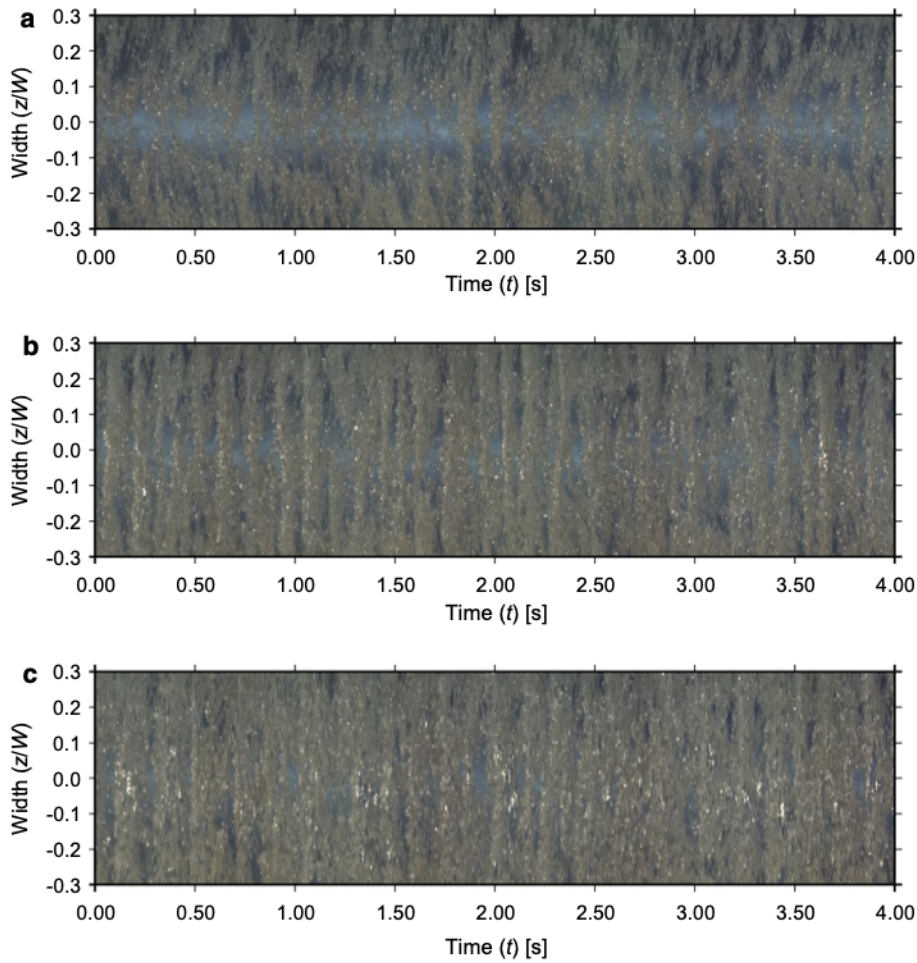


Figure 1.6: Spontaneously emerged bubble clusters beneath a flat-bottom model ship towed at 3.0 m/s. The air flow rate of the bubble injection increases from top to bottom (Park *et al.* [55])

bubbles smaller than the turbulent boundary layer thickness and larger bubbles. The small bubbles are dispersed within the turbulent boundary layer and modify the local distribution of the Reynolds shear stress (Kitagawa *et al.* [20] and Lu *et al.* [70]) as shown in Fig. 1.4. The large bubbles induce vortices owing to their velocity relative to the liquid phase (Murai *et al.* [46], Oishi and Murai [52], and Kim *et al.* [60]) as shown in Fig. 1.5. The optimization of the bubble size in the practical BDR of ships is however difficult because the size is naturally determined by the wettability of the wall surface (Kitagawa *et al.* [71]) and the balance between the turbulent shear stress and surface tension of the gas–liquid interface (Kitagawa *et al.* [20], Wu and Ou [34], and Sanders *et al.* [45]). Though the investigation of the bubble size dependence has brought a detailed understanding of bubble–liquid interaction to pull the development of BDR, new controllability needs to be explored for further improvement.

The establishment of a practically useful BDR on ships imposes the research treating the highly-complex phenomena as it is: *huge numbers of dispersed-sized deformable* bubbles migrate *long distances* in a *high-speed, spatially developing, and thin turbulent* boundary layer with repeating *breakup* and *coalescence* under *strong shear*. In this context, a notable feature of BDR was reported

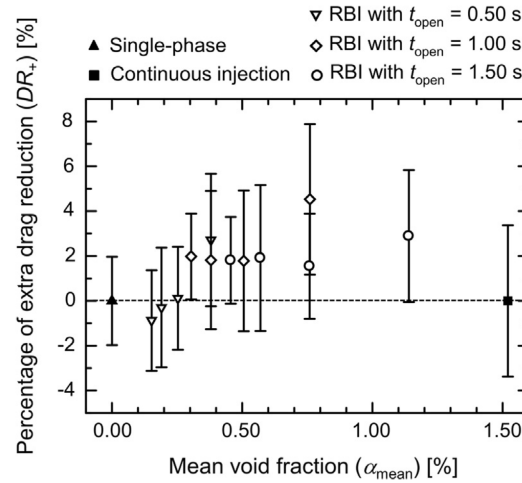


Figure 1.7: Increase of drag-reduction ratio by RBI, DR_+ , relative to CBI in a horizontal turbulent channel flow (Park *et al.* [54])

in an experiment. Park *et al.* [55] observed a spontaneous emergence of spatiotemporal fluctuation of local void fraction, termed void wave, in bubbly turbulent boundary layers that developed along a 4-m-long flat-bottom model ship towed at 2.0–3.0 m/s (Fig. 1.6). This observation was theoretically supported with the derivation of a void-wave equation from two-fluid model equations. Importantly, drag reduction was largely enhanced with the emergence of void waves (Park *et al.* [57]). The emergence of void waves originates the clustering of dispersed bubbles during their migration. This is analogous to the initiation of bubble-to-slug flow transition observed in vertical pipe flows (Lammers and Biesheuvel [72]). The difference in the horizontal system from the vertical one is the contribution of the buoyancy that always attracts bubbles to the upper wall. The growth of void waves in a horizontal boundary layer is an intrinsic process caused by the bubble buoyancy (Murai *et al.* [19]), sliding-bubble behaviors (Oishi *et al.* [73]), and the wettability of the wall surface (Kitagawa *et al.* [71]). The wave frequency is, therefore, naturally given and cannot be controlled in the conventional BDR.

Utilization of artificially generated void waves was inspired by the promotion of drag reduction caused by the spontaneous void waves. In a horizontal channel flow, Park *et al.* [54] performed repetitive bubble injection (RBI) which controls the air flow rate of the bubble injection to periodically fluctuate. RBI provided higher drag reduction in time average relative to the conventional BDR injecting bubbles at constant air flow rates, i.e., continuous bubble injection (CBI) as shown in Fig. 1.7.

1.4 Objectives

The previous study by Park *et al.* [54] demonstrated the enhancement of drag reduction by the use of artificial void waves. However, the experimental condition was far from the actual ship scale. To clarify the feasibility of RBI on ships, three topics below should be investigated. The key factor is the repetition frequency of RBI as a control parameter.

Downstream persistence

Dispersion of bubbles in the turbulent flow causes diffusion of artificial void waves during their downstream advection. This is accompanied by decrease of drag-reduction promotion due to variation of local void fraction. The diffusion proceeds earlier for void waves at a higher frequency, namely, shorter wavelength. On the other hand, the spontaneous emergence of void waves (Park *et al.* [55], [57]) implies existence of a process to accumulate bubbles in the gas–liquid two-phase turbulent boundary layer. The competition of bubble dispersion and accumulation is thought to provide the optimal frequency for void waves to persist the longest downstream.

Local drag reduction

The experiment by Park *et al.* [54] discovered that generation of void waves changes drag reduction. This indicates the time-averaged drag reduction depends not only on the time-averaged void fraction but the fluctuation of local void fraction. Additionally, the artificial void waves at the frequency of the limit of zero and infinite are thought to behave like uniformly distributed bubbles at CBI. The understandings suggest that there is the optimal frequency for void waves to produce the most efficient local drag reduction.

Total drag reduction

The optimal frequencies for the downstream persistence and the local performance can differ. The long persistent but locally ineffective void waves provide a small gain total. Likewise, the short persistence of local performance falls to weak total performance. Thus, the total drag reduction on the hull needs to be separately examined as the integral of local drag reduction along the streamwise direction. There can be the optimal frequency to give the most effective total drag reduction.

In the discussion of the spatial development of the two-phase flow, we need to consider the transition of bubble size in addition to the diffusion of void waves. In the region immediately downstream from the bubble injector, the size tends to become large, especially at high air flow rates. Then, bubbles approach the equilibrium size determined by the balance of the surface tension and the shear in the flow during their migration. The transition of bubble size provides a streamwise variation of drag reduction. Moreover, the background single-phase turbulent boundary layer originally develops streamwise. The two-phase flow with the bubble injection inevitably

has a streamwise variation in the profiles of fluid velocity and shear stress. Consequently, the optimal frequency of each topic, i.e., the downstream persistence, the local efficiency, and the total efficiency, is dependent on the downstream distance.

As a basic concept of the present thesis, we avoid resizing experimental scales using the non-dimensional parameter though it is the usual approach in the research of fluid mechanics. The scaling often compromises the essence of the phenomenon since air lubrication involves many parameters related to bubble dynamics, turbulent boundary layers, two-phase flows, and ship engineering. The transitional development of void waves and bubble size are also factors hindering the resizing. To assess the performance of RBI on full-scale ships as a fundamental result of academic research, we perform multiple experiments using different scale facilities.

1.5 Outline

The present thesis investigates drag reduction using artificial void waves generated by RBI. This thesis comprises 9 chapters including the introduction (Chapter 1) and the concluding remarks (Chapter 9).

In Chapter 2–5, the experimental scale of RBI is gradually expanded. Chapter 2 used a 4-m-long model ship towed at 1.5–3.0 m/s. It is a higher speed condition relative to the previous study of RBI (Park *et al.* [54]). The local drag reduction and the streamwise development of artificial void waves in turbulent boundary layers are investigated for various repetition frequencies. The experiment in Chapter 3 was conducted on a turbulent horizontal channel available for a water velocity of 5–7 m/s, which was equivalent to the ship speed. The optimal frequency of RBI for the local drag reduction is explored by changing the water velocity and the void fraction. Chapter 4 obtained reference data of CBI in a quasi-full-scale condition realized by a 36-m-long model ship towed at 8 m/s in a large water tank. This result is compared with RBI in Chapter 5, which used the same experimental facility. The total resistance of the model ship and the distribution of local wall shear stress was measured simultaneously. These experiments consistently demonstrate the superiority of RBI to CBI for drag reduction.

After the expansion of experimental scale, further considerations of void-wave drag reduction are provided in Chapter 6–8. Chapter 6 estimates the net power saving considering power saving by drag reduction and power consumption for blowing air based on the experimental results. The result indicates the improvement of the net performance by applying RBI relative to CBI. Chapter 7 analyses the temporal fluctuation of local wall shear stress in the quasi-full-scale experiment. This extracts the feature of drag reduction and its streamwise transition, which are related to the flow state. Chapter 8 conducted a detailed measurement of the flow field during a sudden decrease in local void fraction. It is a simulation of a characteristic moment in RBI found in the former experiment.

Chapter 9 summarizes all the studies and describes future problems to develop the void-wave drag reduction, invented from the new findings in the present thesis.

CHAPTER 2

Propagation of artificial void waves in turbulent boundary layers

Preface

This chapter focuses on the downstream persistence of artificial void waves generated by repetitive bubble injection (RBI) in turbulent boundary layers. Bubbly flow beneath a 4-m-long flat bottom model ship is optically visualized, and the streamwise development of the void waves is discussed using the projection void fraction obtained from the bubble image. The persistence is evaluated by a one-dimensional advection-diffusion equation model through the diffusion coefficient. The result infers the potential persistence of tens of meters. This work was published in Tanaka *et al.*, Ocean Eng. (2020).

2.1 Introduction

Since the first demonstration of BDR by McCormick and Bhattacharyya [6] for a submerged hull, the fluid dynamics mechanism of BDR has been widely investigated. The research until 2014 was summarized in a review by Murai [14], in which more than 190 reports were compared. After the review, a noticeable feature was discovered. The BDR effect is enhanced as void waves, quasiperiodic fluctuations of local void fraction, emerge in the two-phase turbulent boundary layer (Park *et al.* [55]). The void waves emerge spontaneously for multiple reasons. It begins with the clustering and coalescence of dispersed bubbles during their migration. The phenomenon is analogous to the initiation of bubble-to-slug flow transition observed in vertical pipe flows (Lammers and Biesheuvel [72]). The difference in the horizontal two-phase flow from the vertical system is the contribution of the bubble buoyancy that always attracts bubbles to the wall surface. Hence, the growth of void waves is an intrinsic process because of the bubble buoyancy (Murai *et al.* [46]), sliding-bubble behaviors (Oishi *et al.* [73]), and the wettability of the wall surface (Kitagawa *et al.* [71]).

Evolving from the drag reduction by spontaneous void waves, the use of artificially generated void waves was examined by Park *et al.* [53], [54] for horizontal turbulent channel flows. The artificial void waves were generated by injecting bubbles with periodically fluctuated air flow rates. This method provided higher time-averaged drag reduction ratios compared with the bubble injection at constant air flow rates. The enhancement of BDR was confirmed in these channel flows, especially at low time-averaged bulk void fractions. Park *et al.* [55] derived a void wave equation from a two-fluid model to explain mathematically the experimental results. They found that local wall shear stress and the local void fraction are dynamically coupled to produce significant persistence of the void waves in a long downstream distance. This indicates the usefulness of artificial void waves for ship drag reduction. However, artificial void waves in an external flow are supposed to diffuse easily with the weak confinement of the flow. The feasibility depends on how the artificial void waves are sustainable over a long downstream distance.

In the present chapter, the persistence of artificially generated void waves in turbulent boundary layers beneath a 4-m-long flat-bottom model ship was investigated experimentally. The bottom plate of the model ship is fully transparent, and bubbles migrating beneath its bottom surface can be optically visualized. Park *et al.* [57] conducted an experiment using the same model ship and confirmed that spontaneous void waves emerged when a constant air flow rate was supplied. They attributed the spontaneity to Tollemien–Schlichting, Kelvin–Helmholtz, and Richardson waves in the two-phase turbulent boundary layer. This work reports the downstream persistence of artificial void waves, giving new physical insights in the study of BDR, as well as a new degree of freedom in the design of BDR for practical applications.

2.2 Experimental setup and conditions

2.2.1 Towing test facility and model ship

A model ship, shown in Fig. 2.1(a), made of transparent acrylic resin was installed in the towing test facility at Hiroshima University, Japan. The facility has been certified as a standard institute for ship performance examination (ISO 9001). The water tank, shown in Fig. 2.1(b), in the facility is 100 m long, 8.0 m wide, and 3.5 m deep. The towing train of the facility runs at a speed up to 3.00 m/s when hanging the model ship, as shown in Fig. 2.1(c). The train achieves a period with a constant speed between the acceleration and deceleration processes. The period changes depending on the train speed, and it becomes approximately 7 s for the maximum speed of the train, corresponding to 21 m of displacement in the water tank.

The model ship with a 50-mm draft is 4.0 m long, 0.6 m wide, and 0.5 m high, as shown in Fig. 2.2. Beneath the bottom plate of the model ship, 20-mm-high side walls are equipped to prevent the entrance of hydraulic waves to the flat bottom plate, as in Fig. 2.2(b). The side walls preserve the two-dimensional spatial development of the turbulent boundary layer on the bottom plate. A tripping wire is fixed on the bow of the model ship to perturb the inflow onto the plate, as shown in Fig. 2.2(c). The wire is necessary to guarantee the reproducible spatial development of the turbulent boundary layer because of a smooth flat plate employed as the BDR target plane. The model ship includes a buffer chamber located 0.7 m from the bow. A part of the bottom plate in the chamber is replaced with a porous plastic plate to inject bubbles. Air stored in the chamber is regulated at a constant pressure and then injected into the flow through the porous plate, as shown in Fig. 2.2(d). Size of bubbles during their advection downstream beneath the flat plate is not significantly influenced by the hole size of the porous bubble injector. It is naturally determined by

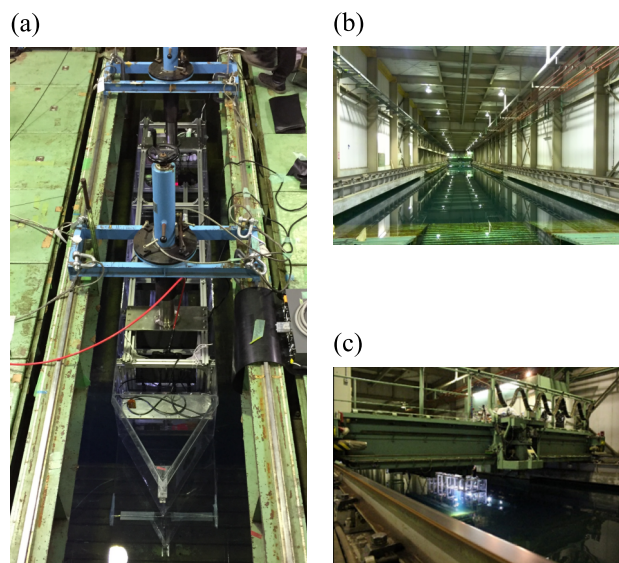


Figure 2.1: Photographs of the towing test facility: (a) model ship, (b) water tank and (c) towing train

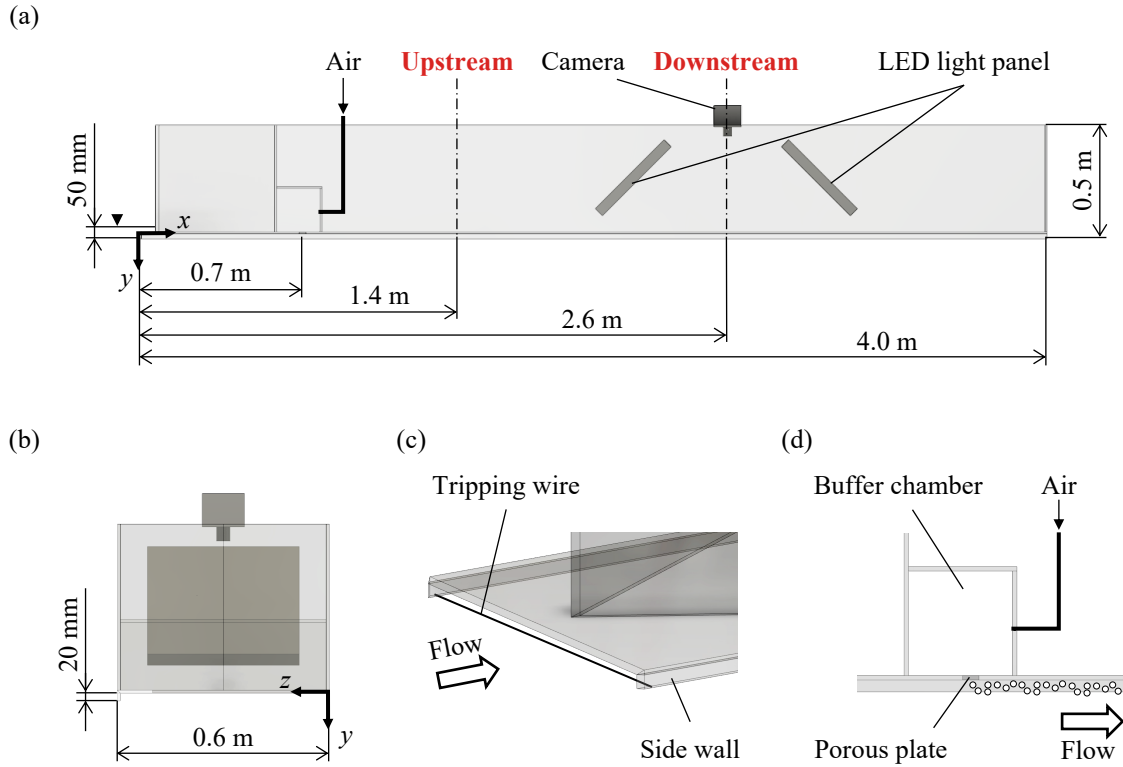


Figure 2.2: Schematic diagram of model ship: (a) side view, (b) front view, (c) detail of leading edge and (d) detail of air injector. x , y and z coordinates denote the streamwise distance from the bow of model ship, the vertical distance from the bottom plate of model ship and the spanwise direction of model ship, respectively.

the balance between fragmentation and coalescence in turbulent boundary layers (e.g., Sanders *et al.* [45]). This was also confirmed by Park *et al.* [57] using the same model ship as the present one.

2.2.2 Flow condition

As shown in Fig. 2.3, two compressors supplied air to the buffer chamber through individual air tanks, an isothermal chamber, and a air flow control system. The air control system was designed to generate an arbitrary waveform of the air volume flow rate, learned from a device developed by Tokyo Gas Corporation (Takeuchi and Kagawa [74]). The control system consists of an electromagnetic valve, a gas flow meter, and two gas pressure meters. In the case of a constant air flow rate, the control system can regulate the temporal fluctuations of the air flow rate so that they are negligible and no specific peak in the frequency spectra emerges (Park *et al.* [55]). Therefore, clear fluctuations of the void fraction observed downstream must be attributed to the spontaneous emergence of void waves during propagation in the turbulent boundary layer. The control system can also make a periodically fluctuated air flow rate of more than 20 Hz in repetition frequency. In this experiment, the variation of the air flow rate was controlled to be a sinusoidal wave. With the fluctuating air flow rate, artificial void waves were generated at the air injection point as the upstream condition of the BDR.

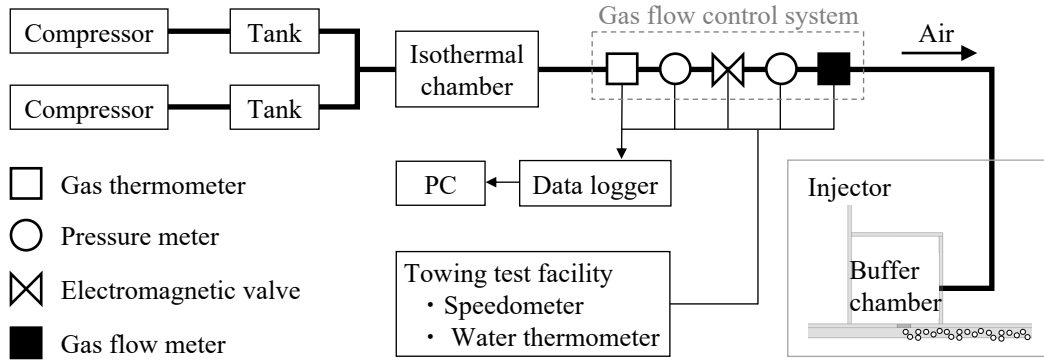


Figure 2.3: Block diagram of an air injection and measurement system. Two compressors supplied air to the buffer chamber of model ship through individual air tanks, an isothermal chamber and a air flow control system. All information from the air flow control system and measurement instruments on the towing test facility was recorded simultaneously.

The measurement instruments on the towing test facility — a speedometer for the towing train and a water thermometer in the water tank — were synchronized with the air flow control system to record all data in a multichannel data logger. The temperature was kept at approximately 33°C during the experiment, at which the corresponding density, ρ_1 , and kinematic viscosity, ν_1 , of the water were approximately 995 kg/m³ and 0.758×10^{-6} m²/s, respectively. In the series of experiments, the time-averaged air flow rate, Q_a , was varied from 0.25×10^{-3} to 1.00×10^{-3} m³/s. Past researchers used as an intuitive parameter the nominal air-layer thickness, t_a , defined as

$$t_a = \frac{Q_a}{UB}, \quad (2.1)$$

where U is the towing speed of the model ship, and B ($= 0.40$ m) is the width of the bubble injector. In the case of bubble injection with a sinusoidally fluctuated air flow rate, the instantaneous minimum air flow rate could not be set to zero perfectly, but a little emission was allowed at 0.08×10^{-3} m³/s. This is because the control system cannot close the valve completely. The repetition frequency of the fluctuation of bubble injection, f , was varied from 2 Hz to 16 Hz, as listed in Table 2.1. Here, bubble injection with a constant air flow rate is expressed as a condition of $f = 0$.

The towing speed of the model ship was set at 1.50, 2.25, and 3.00 m/s. Here, the Reynolds number is defined as

$$Re_x = \frac{xU}{\nu_1}, \quad (2.2)$$

where x denotes the streamwise distance from the bow of the model ship. Using Re_x , thickness of the boundary layer is obtained:

$$\delta = 0.56xRe_x^{-\frac{1}{5}}. \quad (2.3)$$

Table 2.1: Experimental conditions: towing speed, U ; nominal air-layer thickness, t_a ; repetition frequency of bubble injection, f ; Reynolds number, Re_x ; thickness of the boundary layer, δ ; and void fraction in the boundary layer, α_δ . Re_x , δ , and α_δ are acquired for each examined combination of U and t_a denoted as #1–7 and change from the upstream measurement region to the downstream one.

Performed f at each U and t_a conditions			
	$U = 1.50$ m/s	$U = 2.25$ m/s	$U = 3.00$ m/s
$t_a = 0.21$ mm	-	-	0–8 Hz (#5)
$t_a = 0.42$ mm	0–8 Hz (#1)	-	0–16 Hz (#6)
$t_a = 0.56$ mm	-	0–12 Hz (#3)	-
$t_a = 0.83$ mm	0–8 Hz (#2)	0–8 Hz (#4)	0–16 Hz (#7)
Conditions of boundary layers			
	$Re_x [\times 10^6]$	δ [mm]	α_δ [-]
#1	2.8–5.2	27.4–44.9	1.16–0.71%
#2	2.8–5.2	27.4–44.9	2.32–1.41%
#3	4.2–7.7	25.2–41.4	1.68–1.02%
#4	4.2–7.7	25.2–41.4	2.52–1.53%
#5	5.5–10.3	23.8–39.1	0.67–0.41%
#6	5.5–10.3	23.8–39.1	1.33–0.81%
#7	5.5–10.3	23.8–39.1	2.67–1.62%

For estimating the void fraction in two-phase turbulent boundary layers, Sanders *et al.* [45] introduced the volumetric fraction of air in the boundary layer,

$$\alpha_\delta = \frac{Q_a}{Q_a + UW\delta'}, \delta' = 0.324xRe_x^{-\frac{1}{5}}. \quad (2.4)$$

These characteristics of the turbulent boundary layer beneath the model ship are summarized in Table 2.1,

In a trial experiment using the same model ship (details of the setup are the same as Park *et al.* [57]), we tested artificial void wave generation with $U = 3.00$ m/s and $t_a = 0.46$ mm, and shear stress acting on the bottom plate was measured by a shear stress sensor installed at $x = 2.3$ m. Drag reduction ratio increased up to 15% with $f = 1$ –4 Hz from $f = 0$ as shown in Fig. 2.4. This result shows that void waves have potential to improve the drag reduction. In the present experiment, we focused on behavior of void waves and observed it at two measurement regions placed at $x = 1.4$ and 2.6 m on the bottom plate of the model ship. Here, these measurement regions are called “upstream” and “downstream” measurement regions, respectively. The observations at the two regions were conducted independently in every run of the ship.

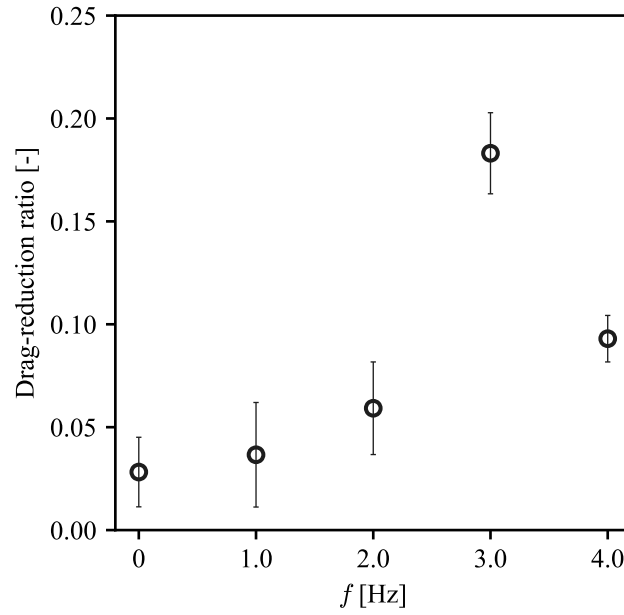


Figure 2.4: Time-averaged drag reduction ratio according with bubble injection frequency, f , at $x = 2.3$ m measured in a trial experiment (towing speed $U = 3.00$ m/s and nominal air-layer thickness $t_a = 0.69$ mm). Error bars indicate the standard deviation of the temporal fluctuation.

Table 2.2: Specification of the high-speed video camera

Frame size	1024 × 624 pixel
Resolution	0.17 mm/pixel
Recording time	6.00 s
Frame rate	2000 fps
Shutter speed	1/40000 s

2.2.3 Visualization of bubble and void wave

A high-speed video camera (FASTCAM Mini AX50, Photron Ltd.) installed in the model ship took a top view of bubbles advecting beneath the bottom plate. Two light-emitting diode (LED) panels inclined at 45° were mounted on both sides of the camera to light up the measurement region, as shown in Fig. 2.2(a). As listed in Table 2.2, the spatial resolution and the frame rate of the camera were set at 0.17 mm/pixel and 2000 fps, respectively. These camera settings ensured sufficiently high spatial and temporal resolutions to analyze the frequency characteristics of the void waves.

Figure 2.5 shows snapshots of bubbles at each towing speed keeping the nominal air-layer thickness constant, $t_a = 0.83$ mm. The gas–liquid interfaces of bubbles reflected the light from the LED panels, so that the fringe of bubbles was recognized in the snapshots. In the cases of $f = 0$, the equivalent diameters, d_{eq} , of the 50 sample bubbles in the images were manually obtained by the calculation from the projection areas of the bubbles. It was confirmed from the images that bubbles were smaller than 20 mm and bubbles were attracted to the bottom plate due to the buoyancy at the present speed. The probability density functions of d_{eq} shown in Fig. 2.6 indicate that d_{eq} were distributed around 10.0 mm ($U = 1.50$ m/s), 5.0 mm ($U = 2.25$ m/s), and 2.5 mm ($U = 3.00$ m/s).

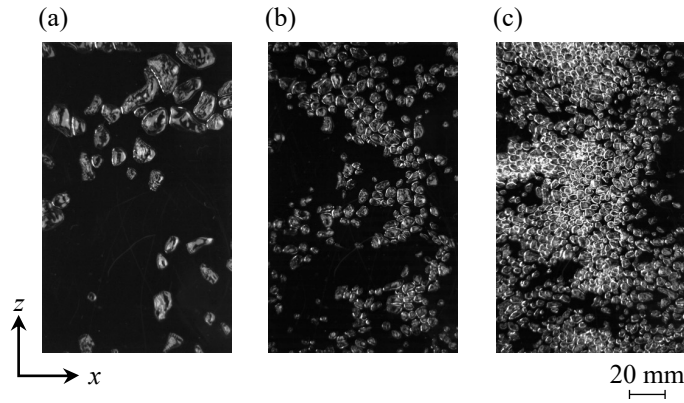


Figure 2.5: Snapshots of bubbles beneath the bottom plate of model ship captured at the downstream measurement region (repetition frequency $f = 0$ and nominal air-layer thickness $t_a = 0.83$ mm): towing speed (a) $U = 1.50$ m/s, (b) $U = 2.25$ m/s, and (c) $U = 3.00$ m/s

It was confirmed that the bubble size becomes larger from the upstream measurement region to the downstream one. The coalescence of bubbles during the advection is considered a cause of the increase in mean bubble diameter. Bubbles with these diameters are supposed to migrate in the wall proximity due to dominance of buoyancy relative to the turbulent diffusion at the flow speed tested. Installment of the side walls on the bottom plate keep bubbles stay inside the boundary layer. Thus, all the bubbles advect from the injector to the stern of model ship.

Original images taken by the camera were processed to detect the gas phase by the following procedure. The fringes of the bubbles were extracted by thresholding. Then, the areas enclosed by the fringes (including the fringes themselves) were regarded as gas phase. The ratio of the gas phase in one z -directional line of pixels was acquired as a local projection void fraction, β ($0 \leq \beta \leq 1$). Temporal variations of β were treated as void waves. The observed area was $pm85$ mm from the z -directional center of the model ship. This is narrower than half the width of the model ship. The time integral of β generally decreases from the upstream measurement region to the downstream one. The decrease of projection area can be attributed to the bubble coalescence during their advection.

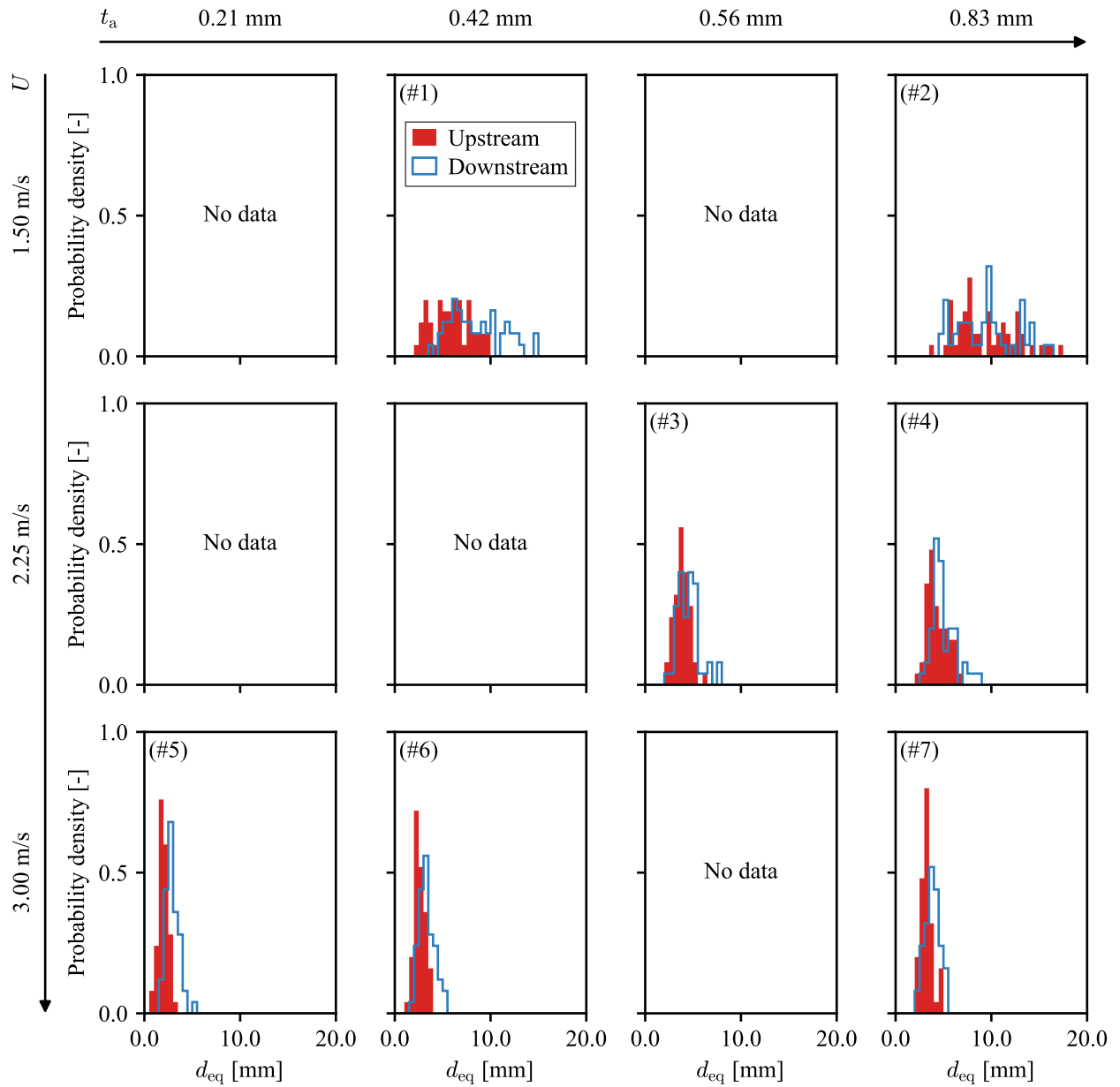


Figure 2.6: Probability density functions of equivalent diameters of bubbles, d_{eq} (repetition frequency $f = 0$) at each combination of towing speed, U , and nominal air-layer thickness, t_a . The numbers (#1–7) at the upper left of each plot correspond to that listed in Table 2.1.

2.3 Frequency characteristics of void waves

2.3.1 Spontaneous void wave

Figure 2.7 shows visualized bubbles in a timeline where spontaneous emergence of void waves were observed at $f = 0$. To obtain the frequency characteristics of the void waves, a wavelet transform was applied using the Morlet mother wavelet (Torrence and Compo [75]). The spectra obtained by the wavelet transform for the upstream region are shown in Fig. 2.8. Strong components distribute around 10 Hz at $U = 2.25$ and 3.00 m/s for all conditions of t_a . In comparison, at $U = 1.50$ m/s, strong components are found around 6 Hz at $t_a = 0.83$ mm and not found at $t_a = 0.42$ mm. The same set of results measured at the downstream measurement region is shown in Fig. 2.9. The frequencies of standing void waves are 4–8 Hz at every towing speed. The frequencies slightly decrease from the upstream measurement region to the downstream one at $U = 2.25$ and 3.00 m/s. The observed frequency matches the frequency band of past data (Park *et al.* [55], [57]). Bubble velocity was also measured beneath the same flat-bottom model ship, and the velocity had a tendency of decreasing along the streamwise direction for the cases of $U \geq 2.0$ m/s. The decrease in frequencies observed in the present experiment is attributed to the decrease in the bubble velocity. This implies that the wavelength of void waves is almost constant during their propagation.

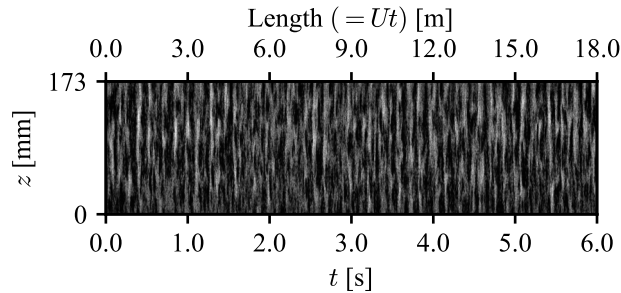


Figure 2.7: Timeline image at the downstream measurement region (towing speed $U = 3.00$ m/s, nominal air-layer thickness $t_a = 0.83$ mm and repetition frequency $f = 0$). The upper abscissa is a converted length scale as a product of time, t , and U . The z coordinate denotes the spanwise direction of model ship.

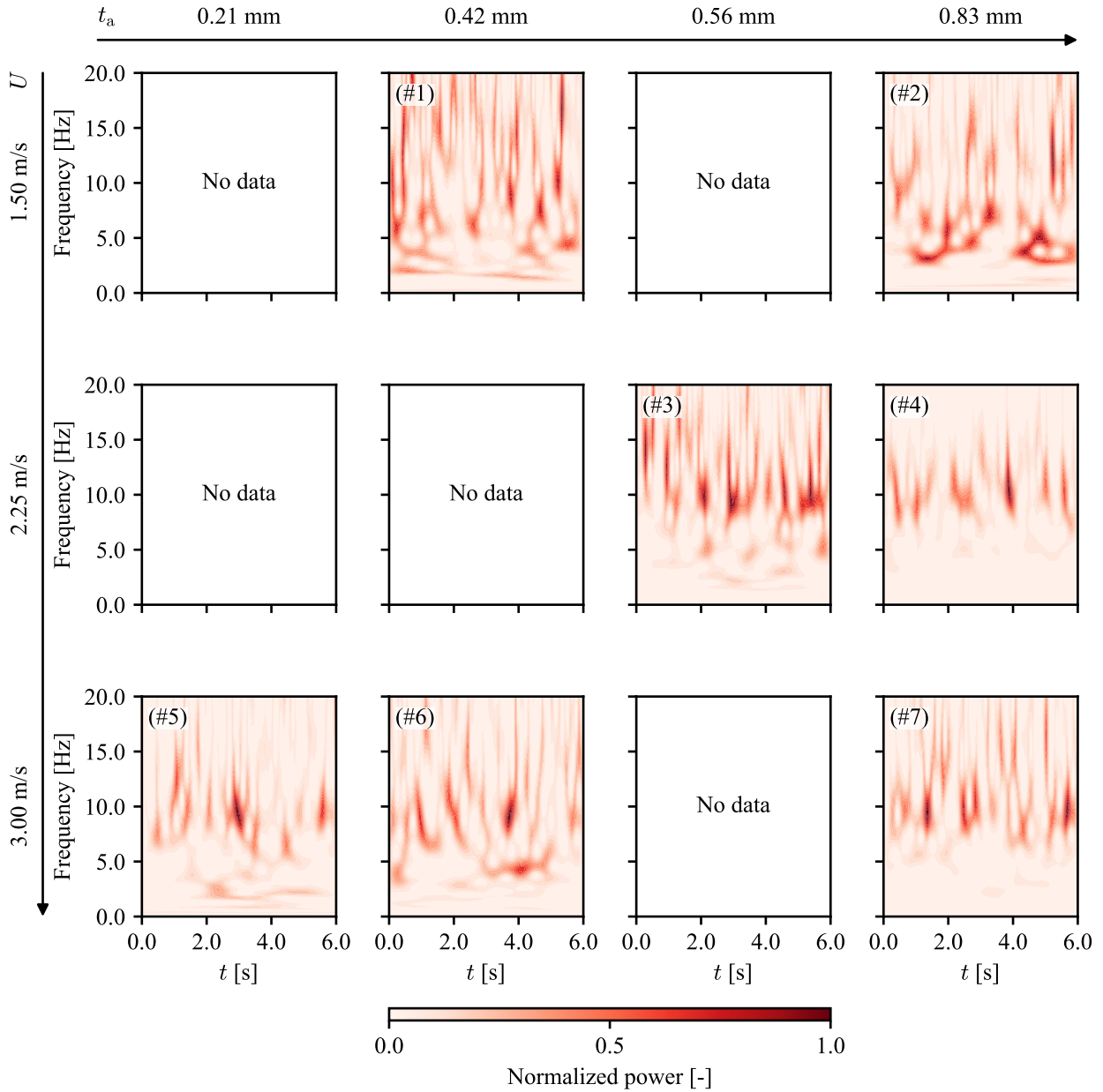


Figure 2.8: Wavelet power spectra of fluctuations of projection void fraction using the Morlet mother wavelet at the upstream measurement region (repetition frequency $f = 0$) at each combination of towing speed, U , and nominal air-layer thickness, t_a . The abscissa and ordinate indicate the time, t , and the frequency of the wavelet, respectively. Each spectrum is normalized by the value of the largest component in itself. The numbers (#1–7) at the upper left of each plot correspond to that listed in Table 2.1.

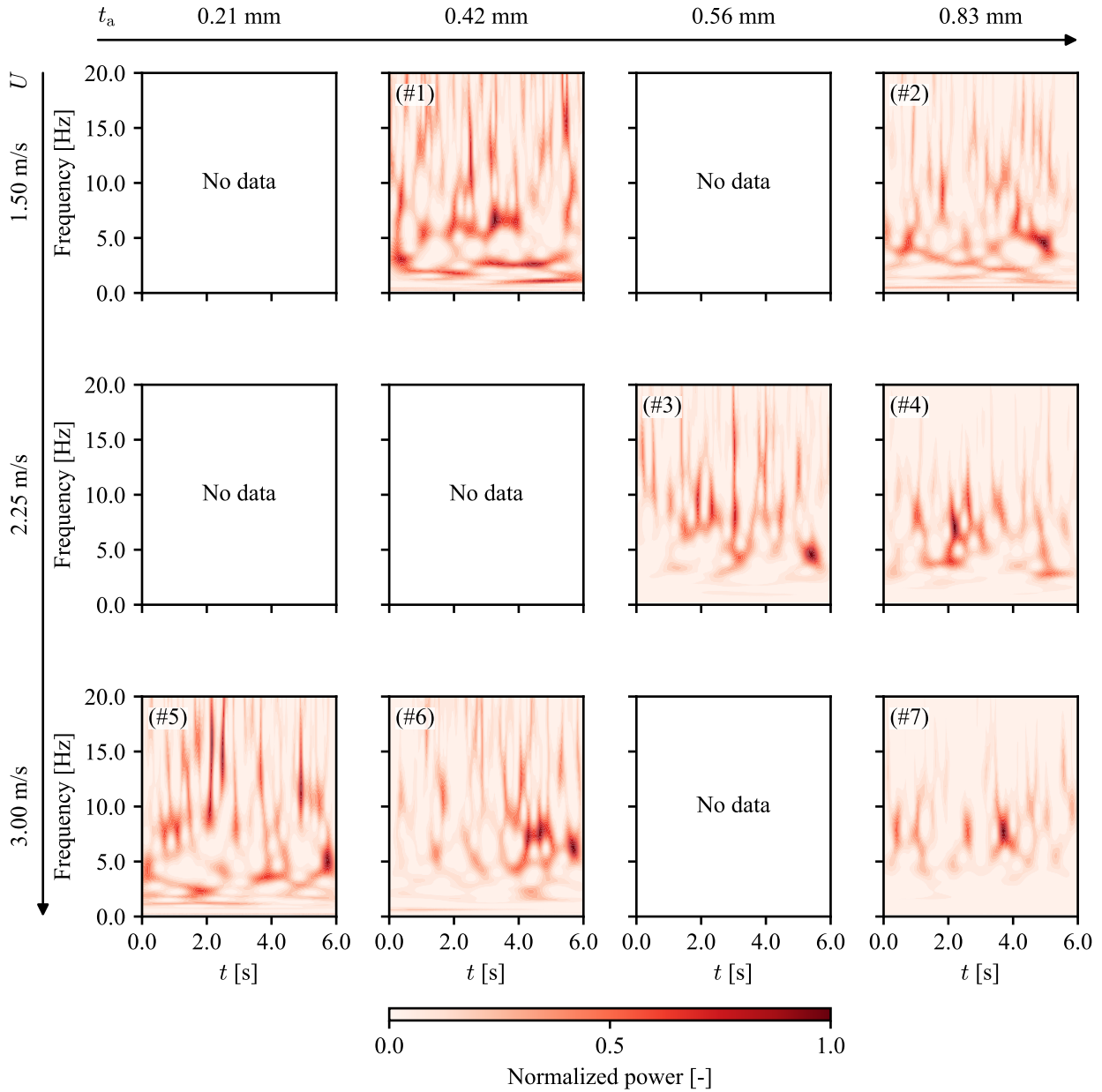


Figure 2.9: Wavelet power spectra of fluctuations of projection void fraction using the Morlet mother wavelet at the downstream measurement region (repetition frequency $f = 0$) at each combination of towing speed, U , and nominal air-layer thickness, t_a . The abscissa and ordinate indicate the time, t , and the frequency of the wavelet, respectively. Each spectrum is normalized by the value of the largest component in itself. The numbers (#1–7) at the upper left of each plot correspond to that listed in Table 2.1.

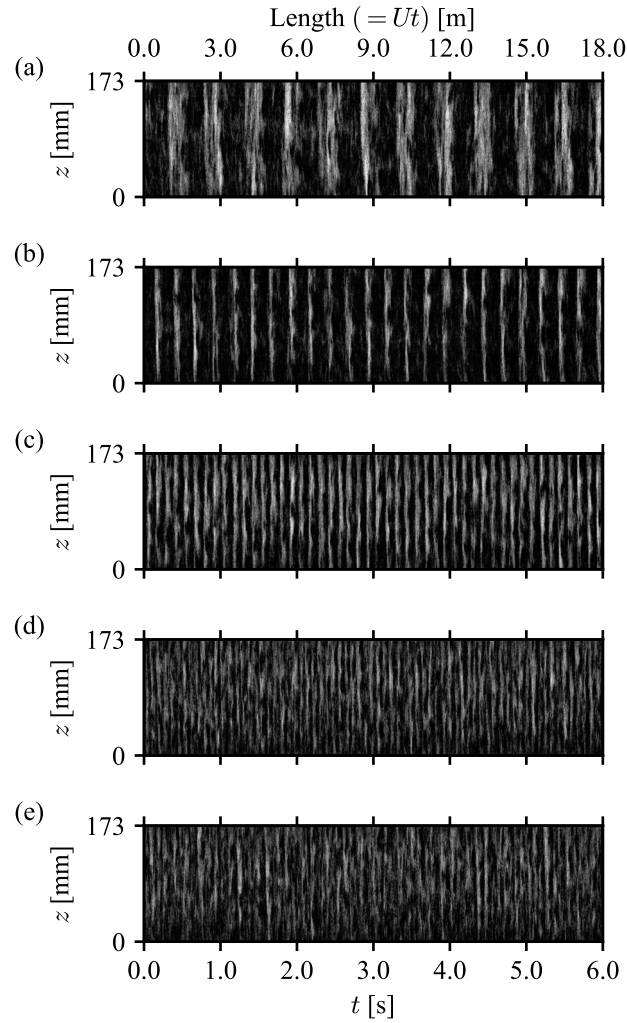


Figure 2.10: Timeline images taken at the downstream measurement region (towing speed $U = 3.00$ m/s and nominal air-layer thickness $t_a = 0.83$ mm): repetition frequency (a) $f = 2$ Hz, (b) $f = 4$ Hz, (c) $f = 8$ Hz, (d) $f = 12$ Hz and (e) $f = 16$ Hz. The upper abscissa is a converted length scale as a product of time, t , and U . The z coordinate denotes the spanwise direction of model ship.

2.3.2 Artificially generated void wave

Figures 2.10(a)–(c) depict the periodic passage of bubble swarms for $f = 2$ –8 Hz. A further increase in the frequency to more than 12 Hz makes the periodic patterns of bubbles unclear, as shown in Figs. 2.10(d) and (e). This is because bubble swarms of short intervals easily combine with each other. Linear spectra obtained by Fourier transform of fluctuations of the projection void fraction at the x -directional center of the sequential images are shown in Fig. 2.11. All the spectra are normalized by the same value. The intensity of a frequency component in the spectra corresponds to the component's amplitude in waveforms of β ($0 \leq \beta \leq 1$). For $f \leq 8$ Hz, as in Figs. 2.11(a)–(f), the largest peaks stand out at the exact same frequencies of f . In the cases of $f = 12$ and 16 Hz, as shown in Figs. 2.11(g)–(i), the peak frequencies are found at 11.8 and 15.8 Hz, respectively. The slight change of the frequency is attributed to some delays in the air flow control system. No clear peak is found in Fig. 2.11(j), which means that bubble swarms are almost dispersed in that

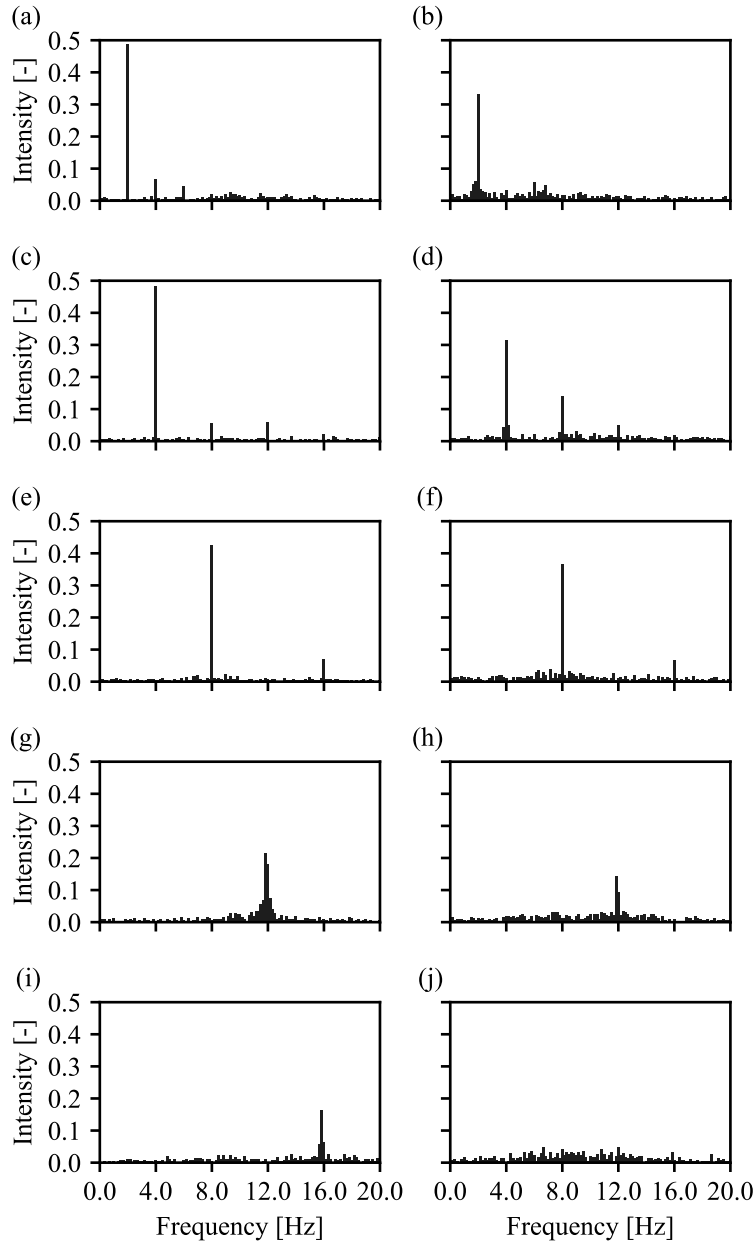


Figure 2.11: Linear spectra of projection void fraction at (left-hand side) the upstream measurement region and (right-hand side) the downstream one (towing speed $U = 3.00$ m/s and nominal air-layer thickness $t_a = 0.83$ mm): repetition frequency (a, b) $f = 2$ Hz, (c, d) $f = 4$ Hz, (e, f) $f = 8$ Hz, (g, h) $f = 12$ Hz and (i, j) $f = 16$ Hz. All the spectra are normalized by the same value; intensity of a frequency component in the spectra corresponds the component's amplitude in waveforms of projection void fraction, β ($0 \leq \beta \leq 1$).

condition. Here, the frequency of the main component of void waves, f_{main} , is read from the linear spectra: $f_{\text{main}} = f$ at $f \leq 8$ Hz, $f_{\text{main}} = 11.8$ Hz at $f = 12$ Hz, and $f_{\text{main}} = 15.8$ Hz at $f = 16$ Hz.

The intensity of the components at f_{main} in the linear spectra is plotted in Fig. 2.12. Multiple trials were performed under each experimental condition to evaluate the reproducibility of the result. In Fig. 2.12, the reproducibility is expressed as error bars that denote standard deviations. At the same towing speed and injection frequency, an increase of t_a , i.e., increase of the air flow rate, leads to a high intensity. With a high air flow rate, bubble swarms occupy a large area of the

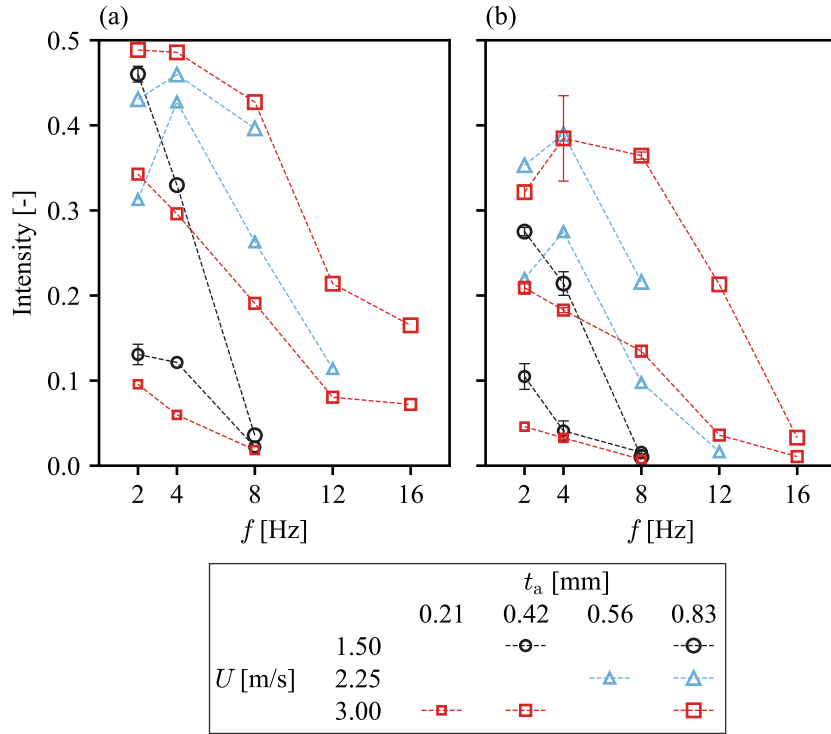


Figure 2.12: Intensity of the void wave's main component at each combination of towing speed, U , and nominal air-layer thickness, t_a , found from the linear spectrum of projection void fraction at (a) the upstream measurement region and (b) the downstream one. The intensity is normalized by the same value and corresponds the component's amplitude in waveforms of projection void fraction, β ($0 \leq \beta \leq 1$). Error bars indicate standard deviation calculated from multiple trials with the same experimental conditions.

bottom plate. Thus, the intensity evaluated from the projection void fraction depends on the air flow rate. A comparison between Figs. 2.12(a) and (b) confirmed that the intensity decreases along the streamwise direction. This is interpreted as meaning there are (1) attenuation of the void fraction fluctuations resulting from the dispersion of the void waves and (2) growth of other frequency components resulting from deformation of the void waves.

In the upstream measurement region, the intensity has a decreasing trend with the increase in the injection frequency, as shown in Fig. 2.12(a). In two cases, (1) $U = 2.25$ m/s, $t_a = 0.56$ mm and (2) $U = 3.00$ m/s, $t_a = 0.83$ mm, the intensity is nearly constant for $f \leq 8$ Hz, whereas it clearly decreases for $f \geq 12$ Hz. As shown in Fig. 2.8, the frequency of spontaneously standing void waves is approximately 10 Hz at $U = 2.25$ and 3.00 m/s in the upstream measurement region. It is deduced that artificially generated void waves easily decay at the injection frequencies higher than the frequency of spontaneously standing void waves. In the downstream measurement region, the intensity does not monotonically decrease. In several cases of U and t_a , maximum values are found at $f = 4$ Hz, as shown in Fig. 2.12(b).

Comparison of Figs. 2.12(a) and (b) indicates that the intensity has a different tendency in the upstream measurement region from that in the downstream one as the injection frequency increases.

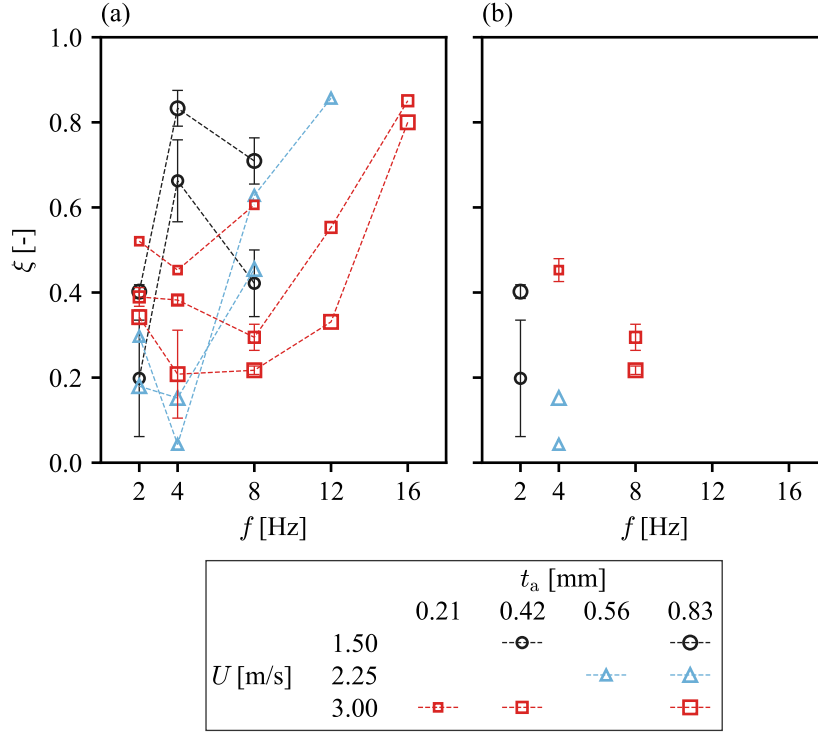


Figure 2.13: Attenuation rate, ξ , of the void wave's main component in the linear spectrum of projection void fraction from the upstream measurement region to the downstream one at each combination of towing speed, U , and nominal air-layer thickness, t_a : (a) all experimental conditions and (b) conditions corresponding to the minimum attenuation rates among the same U and t_a . Error bars indicate standard deviation calculated from multiple trials with the same experimental conditions.

Figure 2.13(a) is a summary of the attenuation rates, which are evaluated as

$$\xi = 1 - \frac{I_{\text{down}}}{I_{\text{up}}}, \quad (2.5)$$

where I_{up} and I_{down} are the intensities of f_{main} components in the upstream and downstream measurement regions, respectively. A small attenuation rate means long void wave persistence. At the same towing speed and nominal air-layer thickness, the attenuation rate takes the minimum value at $f = 2$ Hz ($U = 1.50$ m/s), $f = 4$ Hz ($U = 2.25$ m/s), and $f = 4$ or 8 Hz ($U = 3.00$ m/s), as shown in Fig. 2.13(b). Thus, the injection frequency that realizes the minimum attenuation of intensity varies depending on the towing speed.

2.4 Propagation characteristics of the void waves

As discussed in the previous section, the attenuation rate of void waves depends on the injection frequency. The attenuation rate data can be applied for estimating the persistence of void waves over long distances. In contrast, there is a wave-causing physics that must be considered in a bubbly two-phase flow system. Biesheuvel and Wijngaarden [76] derived a wave equation in liquid with dilute bubble dispersion. In the experiment reported here, bubbles are arranged closely and cause coalescence inside the bubble swarm. A good reference is the mathematical work by Lammers and Biesheuvel [72], who utilized a modified Burgers' equation to describe the periodicity of bubbly two-phase flows in a vertical pipe flow. Toward establishment of a theoretical model of the void wave propagation in horizontal turbulent boundary layers, the waveform of the void wave is evaluated in this section.

Several samples of the phase-averaged waveform of the void waves are shown in Fig. 2.14. The samples are chosen from the conditions of $U = 3.00$ m/s and $t_a = 0.83$ mm. The phase is defined by Fourier transform on the original waveforms. At least 12 cycles of void waves are averaged. As a general trend, the amplitude of the waves becomes small as the wave migrates downstream. This decay is remarkable for the higher injection frequencies. The amplitudes at $f = 4$ and 8 Hz are kept larger than those at other injection frequencies. In these two cases, a sharp and asymmetric waveform can be identified in the phase-averaged waveform. This suggests a physics that resists the decay at these particular frequencies.

The propagation velocity, u_p , and apparent diffusion coefficient, D_β , of the void wave are evaluated based on the following one-dimensional advection–diffusion equation using the data of phase-averaged waveforms,

$$\frac{\partial \beta(t, x)}{\partial t} + u_p \frac{\partial \beta(t, x)}{\partial x} = D_\beta \frac{\partial^2 \beta(t, x)}{\partial x^2}. \quad (2.6)$$

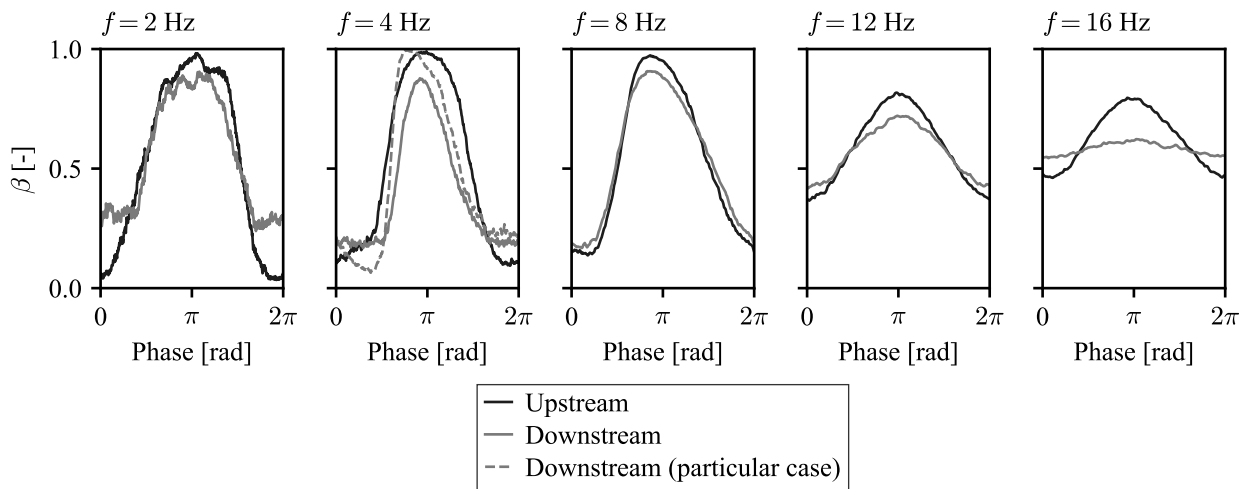


Figure 2.14: Waveforms of projection void fraction, β , evaluated by phase average with the frequency of the main component of void waves, f_{main} (towing speed $U = 3.00$ m/s and nominal air-layer thickness $t_a = 0.83$ mm). The phase is defined by Fourier transform for original waveforms.

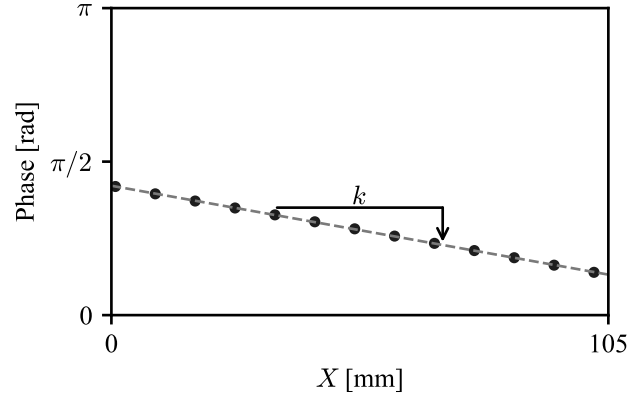


Figure 2.15: An example of phase variation of the void wave's main component in the streamwise direction, where the dashed line is linear fitting to the plots (towing speed $U = 3.00$ m/s, nominal air-layer thickness $t_a = 0.83$ mm and repetition frequency $f = 2$ Hz). X is the streamwise coordinate of the image.

The diffusion of void waves originates from the velocity difference of each bubble in a swarm. The apparent diffusion coefficient D_β represents the consequent decay and amplification of void waves according to the complicated relative motion of bubbles.

2.4.1 Propagation velocity

As reported by Park *et al.* [55], the advection velocity of individual bubbles beneath a flat plate is approximately half the towing speed. However, the propagation velocity of a void wave cannot be given by averaging of individual bubble velocities. We obtained the propagation velocity using a complex Fourier transform of the fluctuations of the projection void fraction as shown in Fig. 2.15. The transform produces the phase of the wave for a given f_{main} components. The phase changes in the streamwise direction inside the sequential images taken by a high-speed camera (see Fig. 2.5). Since the variation of the phase is linear function, the slope k is determined from the data as the wavenumber. Consequently, the propagation velocity was obtained for each measurement regions:

$$u_{\text{p, up/down}} = \frac{2\pi f_{\text{main}}}{k}. \quad (2.7)$$

The obtained velocity for all the cases examined is summarized in Fig. 2.16. It ranged from 0.47 to 0.53 in normalized scale with U , with roughly half the towing speed as a general understanding. This indicates bubble swarms being remained inside the boundary layer because the propagation velocity should be close to the towing speed if they were ejected to the outer flow region. Other than this, it was found that the velocity decreases because of bubble migration along the downstream direction for the same flow conditions. This trend is understandable with the feature of a spatially developing boundary layer where the liquid velocity in a near region to the wall gradually decreases along a streamwise direction.

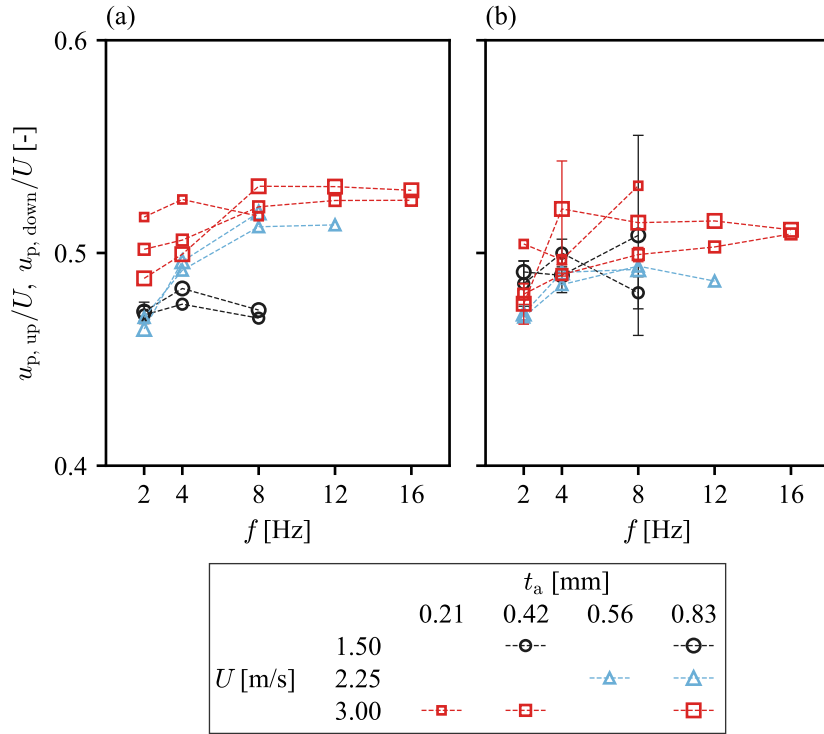


Figure 2.16: Propagation velocity of the void wave's main component at each combination of towing speed, U , and nominal air-layer thickness, t_a : (a) the upstream measurement region and (b) the downstream one. The propagation velocity is normalized by U . Error bars indicate standard deviation calculated from multiple trials with the same experimental conditions.

2.4.2 Apparent diffusion coefficient

Using Eq. (2.6), the apparent diffusion coefficient is estimated in this section. The propagation velocity from the upstream to the downstream measurement regions is obtained by the average of the values at each region:

$$u_p = \frac{u_{p, up} + u_{p, down}}{2}. \quad (2.8)$$

Substituting $x' = x - ut$ into Eq. (2.6), a one-dimensional diffusion equation,

$$\frac{\partial \beta(t, x')}{\partial t} = D_\beta \frac{\partial^2 \beta(t, x')}{\partial x'^2}, \quad (2.9)$$

is derived. Discretization of Eq. (2.9) in second-order accuracy with the Crank–Nicolson scheme yields

$$\frac{\beta_j^{i+1} - \beta_j^i}{\Delta t} = \frac{D_\beta}{2} \left(\frac{\beta_{j+1}^{i+1} - 2\beta_j^{i+1} + \beta_{j-1}^{i+1}}{\Delta x'^2} + \frac{\beta_{j+1}^i - 2\beta_j^i + \beta_{j-1}^i}{\Delta x'^2} \right), \quad (2.10)$$

where Δt and $\Delta x'$ are given by the temporal and the spatial resolutions of the present measurement. The subscripts i and j indicate the integer time step and the spatial grid coordinate, respectively. As the initial condition, the phase-averaged waveform at the upstream region is used. Equation (2.10) is numerically solved to predict the waveform in the downstream region with an arbitrary value of

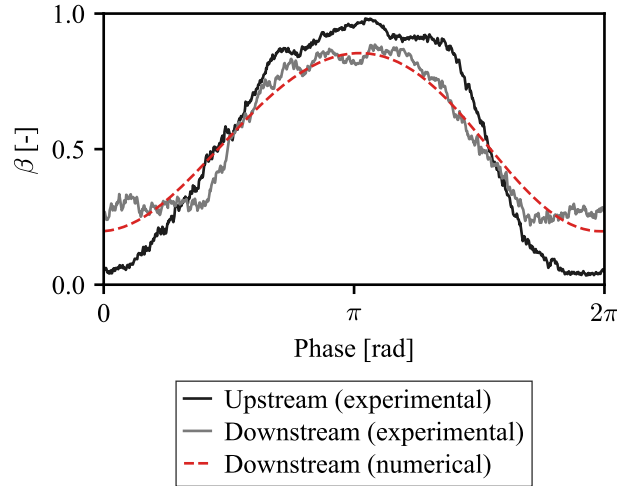


Figure 2.17: A comparison between experimentally measured waveforms and a numerically predicted waveform using Eq. (2.10) (towing speed $U = 3.00$ m/s, nominal air-layer thickness $t_a = 0.83$ mm and repetition frequency $f = 2$ Hz)

D_β . Changing D_β for a possible range iteratively, the most matched value of D_β is searched so that the downstream waveform takes the minimum difference between the measured result and the predicted result. Figure 2.17 shows a sample comparison between the measured waveform and the numerically predicted waveform that was judged as the best matching condition. Of course, a small difference remains in the matching condition because of a certain irregularity of the wave motion departing from the one-dimensional diffusion process. However, the amplitude and the width of the void wave can be well reproduced, supporting the validity of approximation by the apparent diffusion coefficient as a primary parameter in representing the void wave characteristics.

The apparent diffusion coefficients estimated from all the examined cases are plotted in Fig. 2.18. For conditions performed multiple times, diffusion coefficients were estimated for every combination of the waveforms in the upstream measurement region and in the downstream one. Positive and negative values were obtained, as indicated by the circle and square symbols, respectively.

The scattering of the positive coefficients was widely dependent on f . They ranged approximately from 10^{-4} to 10^{-1} m²/s except for a condition $(U, t_a, f) = (1.50$ m/s, 0.42 mm, 8 Hz), at which void waves almost decayed before reaching the upstream measurement region. The variance of coefficients is independent from the initial bubble sizes just after the bubble injector. Mean bubble size in the measurement regions is similar among each f at the same U and t_a . The minimum value of the coefficients appeared at $f = 2$ or 4 Hz ($U = 1.50$ m/s), $f = 4$ Hz ($U = 2.25$ m/s), and $f = 8$ Hz ($U = 3.00$ m/s). Under these conditions, the local attenuation rate of the void wave also had low values, as shown in Fig. 2.13(b).

To understand the estimated values of the apparent diffusion coefficient, we compare them with turbulent boundary layer theories to seek an analogy to void waves. Local friction coefficient, c_f ,

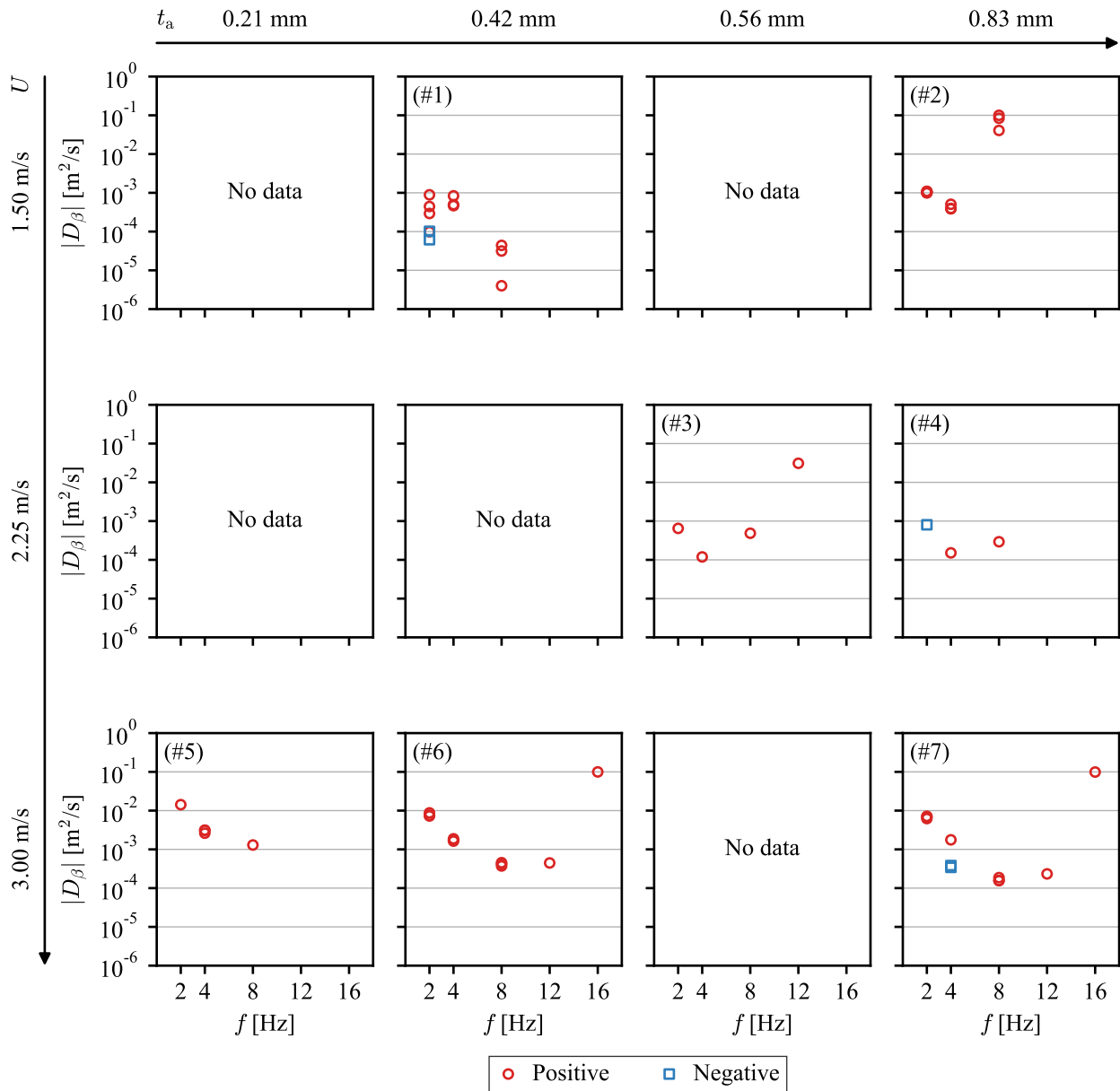


Figure 2.18: Apparent diffusion coefficients of void waves at each combination of towing speed, U , and nominal air-layer thickness, t_a . For conditions performed multiple times, diffusion coefficients are estimated for every combination of the waveforms in the upstream measurement region and in the downstream one. The numbers (#1–7) at the upper left of each plot correspond to that listed in Table 2.1.

of the boundary layer on the flat plate is given by (Schlichting [77])

$$c_{f,p} = \begin{cases} \frac{0.664}{\sqrt{Re_x}} & (\text{laminar}) \\ (2 \log_{10} Re_x - 0.65)^{-2.3} & (\text{turbulent}) \end{cases} \quad (2.11)$$

Within the range of Re_x in the present experiment (see Table 2.1), the friction coefficient of turbulent flow is approximately 10 times larger than that of laminar flow. This ratio corresponds to the ratio of turbulent kinematic viscosity (or eddy viscosity divided by fluid density), ν_t , to the laminar kinematic viscosity. In this theory, ν_t is on the order of $10^{-5} \text{ m}^2/\text{s}$ in the present range of Re_x . Because D_β is several tens of times larger than this value, void waves are regarded to have an intrinsic propagation process independent from the liquid velocity fluctuation inside the boundary layer. Additionally, the velocity gradient in turbulent boundary layers can induce the stretch of void waves in the streamwise direction. This is not a diffusion but should be regarded as the effect of differential advection. However, if this stretching effect were treated as the diffusion coefficient D'_β , the order would be estimated as

$$D'_\beta = (\gamma\delta)^2 T = (\gamma\delta)^2 \frac{L}{u_p} \approx \left(\frac{U}{\delta} \cdot \delta \right)^2 \frac{L}{u_p} = \frac{U^2}{u_p} L \approx 2UL, \quad (2.12)$$

where γ and T are the mean shear rate of the boundary layer and the time spent for bubbles migrating from the upstream to the downstream measurement regions, respectively. Here, L ($= 1.2 \text{ m}$) is the distance between the two regions. For a typical condition of $U = 3.00 \text{ m/s}$, Eq. (2.12) estimates $D'_\beta = 7.2 \text{ m}^2/\text{s}$. This is one to four digits larger than the measured diffusion coefficient D_β . Hence, void waves are unaffected by the shear, and they rather have a self-organizing mechanism in the boundary layer.

2.4.3 Downstream persistence of void waves

Using the apparent diffusion coefficient estimated from the present series of towing experiments, it is possible to predict the downstream persistence of the void waves. A sinusoidal void wave defined by

$$\beta(0, X) = C_1 + C_2 \sin \left(\frac{2\pi}{\lambda_v} X \right), \quad (2.13)$$

$$\lambda_v = \frac{u_p}{f_{\text{main}}}, \quad (2.14)$$

is considered as an initial condition of Eq. (2.9), where C_1 and C_2 are constants, and λ is the wavelength of the void wave. Adoption of a periodic boundary condition yields an analytical solution:

$$\beta(t, X) = C_1 + C_2 \sin \left(\frac{2\pi}{\lambda_v} X \right) \exp \left[-4\pi^2 \frac{D_\beta}{\lambda_v^2} t \right]. \quad (2.15)$$

This solution indicates that the amplitude of void waves attenuates exponentially during advection. For instance, in the case of $(U, t_a, f) = (3.00 \text{ m/s}, 0.83 \text{ mm}, 8 \text{ Hz})$, the corresponding diffusion coefficient measured as $D_\beta \approx 1.0 \times 10^{-4} \text{ m}^2/\text{s}$ gives the persistence of the void wave as 93% at 1-m, 69% at 5-m, 47% at 10-m, and 22% at 20-m downstream positions. Thus, void waves have the potential to persist for 10 m or longer when the optimal frequency of bubble injection is applied. In real hull configurations, the persistence of void waves may be reduced due to the secondary spanwise flow interacts with the boundary layer. This is another item to study in future considering 3D streamlines on each hull surface. On a flat bottom plane of large carriers, the streamline is kept almost parallel to the main flow direction (Fureby *et al.* [78]). Use of void waves is expected to promote drag reduction for such a hull form.

Finally, it is necessary to address to the measured fact that a negative diffusion coefficient was obtained in several conditions, as indicated by the square symbols in Fig. 2.18. The conditions are the combinations of $(U, t_a, f) = (1.50 \text{ m/s}, 0.42 \text{ mm}, 2 \text{ Hz})$, $(2.25 \text{ m/s}, 0.83 \text{ mm}, 2 \text{ Hz})$, and $(3.00 \text{ m/s}, 0.83 \text{ mm}, 4 \text{ Hz})$. In the first two conditions, phase-averaged waves showed almost no change during streamwise migration. For the third condition, the amplitude was rather intensified, as shown in Fig. 2.14. In these particular conditions, the downstream persistence of the void waves might be dramatically improved. From a mathematical perspective, a negative diffusion coefficient implied the existence of other terms in the diffusion equation, inducing the concentration of void fraction. The spontaneous development of void waves at continuous bubble injection seems to be analogous to this concentration. The frequency of spontaneous void waves is 6–10 Hz (see Fig. 2.8 and 2.9), and the negative diffusion at repetitive bubble injection is found at the repetition frequency of less than half of that. The mechanism of the spontaneous development and the determinant of the frequency were discussed in previous studies of CBI. Park *et al.* [57] attributed to macroscopic two-phase flow instability coupled with Tollemien–Schlichting wave, Kelvin–Helmholtz wave and Richardson wave since their characteristic frequencies covered the measured void wave frequencies. Oishi *et al.* [73] found contribution of poly-dispersed bubbles in spontaneous generation of the void waves, i.e. velocity difference among different sized bubbles always accumulate bubbles in shear flow environment. In case of repetitive bubble injection, a unique flow pattern is possibly induced by the spatially periodic interaction between bubble swarms and surrounding liquid flow. We need further studies to comprehensively explain this phenomenon. In this work, the possible range of the void wave behavior was demonstrated in a wide parametric study, which is expected to help the design of void-wave-laden air lubrication ships.

2.5 Conclusions

The development of void waves was examined in bubbly two-phase turbulent boundary layers beneath the flat bottom of a 4-m-long model ship. Advecting bubbles were optically visualized at two regions of the model ship during towing tests in a 100-m-long water tank. The spontaneous emergence of void waves was confirmed downstream from the bubble injector when a constant air flow rate was supplied. The frequencies of the spontaneous void waves were detected by wavelet transform and were 4–10 Hz. This range corresponded to the results of previous works using the same model ship (Park *et al.* [55], [57]). In the present study, we applied artificial generation of void waves for the model ship. It was performed by repetitive bubble injection fluctuating air flow rates periodically, using an original gas pulsar device.

From the Fourier analysis for the projection void fraction, it was confirmed that the artificially generated void waves were gradually attenuated along the streamwise direction. The attenuation was minimized at an injection frequency set smaller than the frequency of spontaneously standing void waves. Thus, the use of a longer wavelength makes the void wave persist downstream. To summarize the results quantitatively, an apparent diffusion coefficient was measured based on a one-dimensional advection diffusion equation model. It took the range of 10^{-4} – 10^{-1} m²/s in most cases, being at least one order larger than the turbulent eddy viscosity of liquid inside the turbulent boundary layer. Based on the measured diffusion coefficient, the downstream persistence of the void waves was estimated. It was longer than 10 m before decaying 40% in initial wave intensity. A very low diffusion coefficient or even negative values were also found in several particular combinations of towing speed and repetition frequency. Although this demonstrated the necessity of further study, application to large ships would be promoted by utilizing such facts of two-phase flow dynamics.

CHAPTER 3

RBI in high-speed turbulent channel flows

Preface

This chapter examines the drag reduction by repetitive bubble injection (RBI) in a high-speed flow using a turbulent horizontal channel facility. The dependence of the drag-reduction ratio was explored with varying flow speed, void fraction, and the repetition frequency of RBI. This work was published in Tanaka *et al.*, Ocean Eng. (2021).

3.1 Introduction

For a turbulent channel flow at a flow speed lower than 2 m/s, Park *et al.* [54] confirmed that the time-averaged drag-reduction ratio obtained by repetitive bubble injection (RBI) was higher than that obtained with continuous bubble injection (CBI). The advantage of RBI, however, has only been confirmed in turbulent flows of relatively low velocity whereas the practical speed of marine vessels is 5–8 m/s (10–15 knots). This doubling of speed results in quadruple shear stress and half the buoyancy effect on bubbles. In the dimensionless parameter space (Murai [14]), these differences greatly affect the Reynolds, Froude and Weber numbers simultaneously in addition to the Strouhal number of RBI; the flow condition enters the unknown domain in these parameters.

In the present study, the drag reduction due to RBI was experimentally investigated at flow speeds of 5–7 m/s in a horizontal turbulent channel flow. It should be noted that the turbulent channel flows have differences between the turbulent boundary layers beneath ships; e.g., the absence of streamwise flow development, a thinner boundary layer, and a stronger shear stress along the wall surface. With understanding these differences, bubble drag reduction (BDR) has been experimentally investigated using horizontal channel flow facilities to date (e.g., Kitagawa *et al.* [20], Guin *et al.* [37], Kato *et al.* [39], Moriguchi and Kato [41], and Kodama *et al.* [79]). The drag reduction in such bubbly channel flows can be interpreted as a local equilibrium state giving hints to understand the phenomena observed in spatially developing boundary layers (e.g., Elbing *et al.* [25], Sanders *et al.* [45], and Qin *et al.* [56]). In the present experiment, a shear-stress sensor directly measured the local wall shear stress acting on the top wall of the channel. Additionally, an optical visualization was carried out using a high-speed line-scanning camera to obtain the distribution of bubbles. A series of repetition frequencies of the RBI were examined, offering new insight into turbulent boundary layer control using the periodic fluctuation of the local void fraction.

3.2 Experimental setup

3.2.1 Experimental apparatus

Experiments were conducted in a facility (Fig. 3.1(a)) of the National Maritime Research Institute, Tokyo, Japan. The facility could achieve a mean flow speed up to 12 m/s in its test section of a horizontal channel made of fully transparent acrylic resin. The inner dimensions of the channel were a streamwise length of 3.0 m, height of 20 mm and width of 100 mm. The x , y and z coordinates in Fig. 3.1 respectively denote the streamwise distance from the inlet of the channel, vertical distance from the top wall and spanwise direction. A pump circulated tap water as the test fluid in the channel. A flow rate meter, pressure meter and thermometer were installed after the pump for measurement of the water.

Bubbles were injected at $x = 1.1$ m through a metal plate with 315 holes of 0.5 mm in diameter (Fig. 3.1(b)). Air was supplied to a buffer chamber fixed on the metal plate from a compressor through a pressure regulator, air tank and isothermal chamber. A pulsatile air flow rate control system developed by Tokyo Gas Cooperation (Takeuchi and Kagawa [74]) was used. The control system comprised a gas thermometer, two pressure sensors, an electromagnetic valve, and a air flow meter. This system could regulate both constant air flow rates and periodically fluctuating air flow rates up to 20 Hz in repetition frequency. In the present experiments, the periodic fluctuations imposed by the system had sinusoidal waveforms as shown in Fig. 3.2. The instantaneous minimum

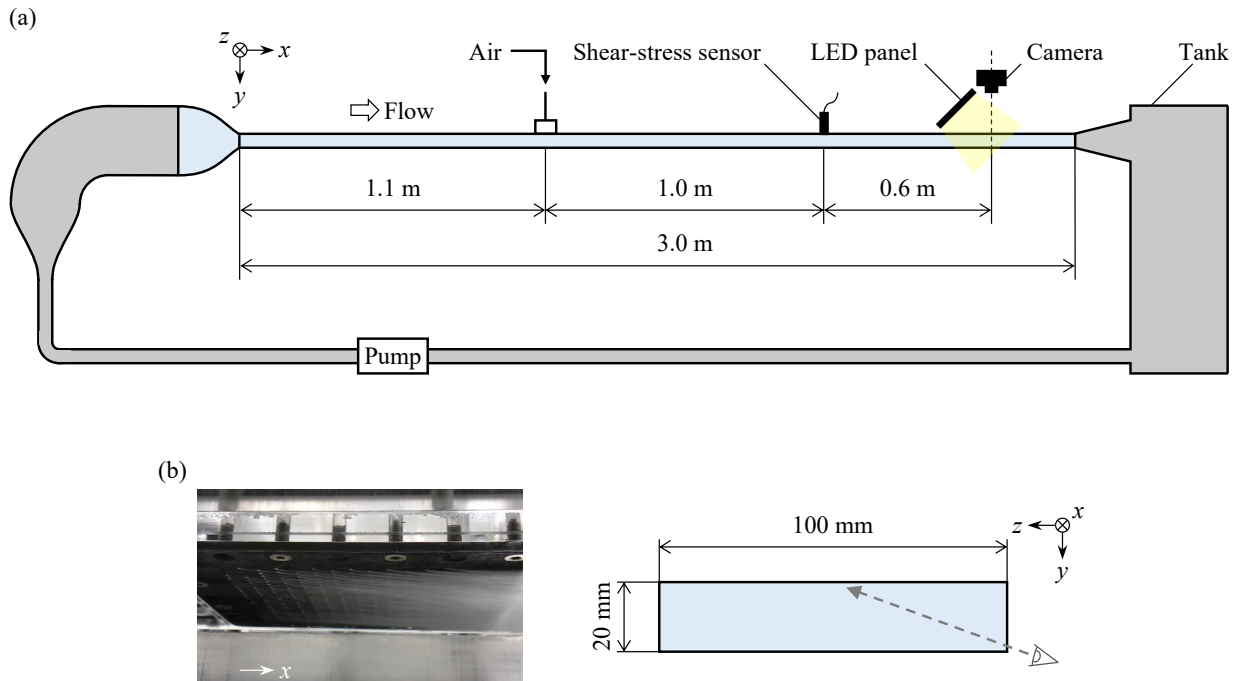


Figure 3.1: (a) Experimental setup of turbulent channel flow for bubble visualization and the measurement of wall shear stress and (b) a snapshot from the side of the channel at the bubble injection plate; x , y and z coordinates respectively denote the streamwise distance from the inlet of the channel, vertical distance from the upper wall and spanwise distance.

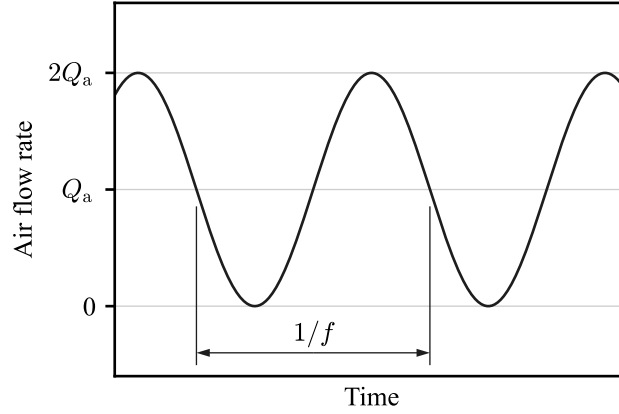


Figure 3.2: Time diagram of the air flow rate control for the RBI. The air flow rate periodically fluctuated between zero and twice the time-averaged flow rate, Q_a , following a sinusoidal waveform with a repetition frequency f .

flow rate was set to zero, and the instantaneous maximum flow rate was double the time-averaged air flow rate, Q_a . The injected bubbles were removed from the test fluid in a tank placed at the end of the test section. Although velocity profiles of the liquid phase and bubbles were not measured in the present experiments, we can refer to the results of experiments conducted by Kitagawa *et al.* [20], where CBI was examined in high-speed (5.0-m/s) turbulent flows in the same facility as used for the present experiments.

3.2.2 Experimental conditions

The side-view observation of the channel revealed that bubbles in the channel concentrated near the upper wall immediately after the position of bubble injection, $x = 1.1$ m (see Fig. 3.1(b)). The bubbles then dispersed vertically depending on liquid turbulence during their downstream migration. Snapshots of the bubbly channel flow at $x = 2.0$ m (in front of the measurement region) with various mean flow speeds are shown in Fig. 3.3. At the lowest speed (Fig. 3.3(a)), injected bubbles advected in the upper region such that the bottom border of the bubbly layer was located around the center of the channel. At mid-range speeds (Fig. 3.3(b) and (c)), the bubbly layer widened toward the bottom wall. Finally, the bubbly layer occupied the whole height of the channel at a speed higher than 8 m/s (Fig. 3.3(d)). This wholly dispersed state was not targeted in the present experiments because it is regarded as internal two-phase flow different from the geometry of BDR for ships. We thus examined three water flow rates; i.e., $Q_1 = 1.0 \times 10^{-2}$, 1.2×10^{-2} and 1.4×10^{-2} m³/s corresponding to bulk velocities of 5.0, 6.0 and 7.0 m/s, respectively.

The experiments were conducted for six conditions of Q_a for each condition of Q_1 ; the ranges of Q_a are listed in Table 3.1. The water and air flow rates determine the superficial velocity and

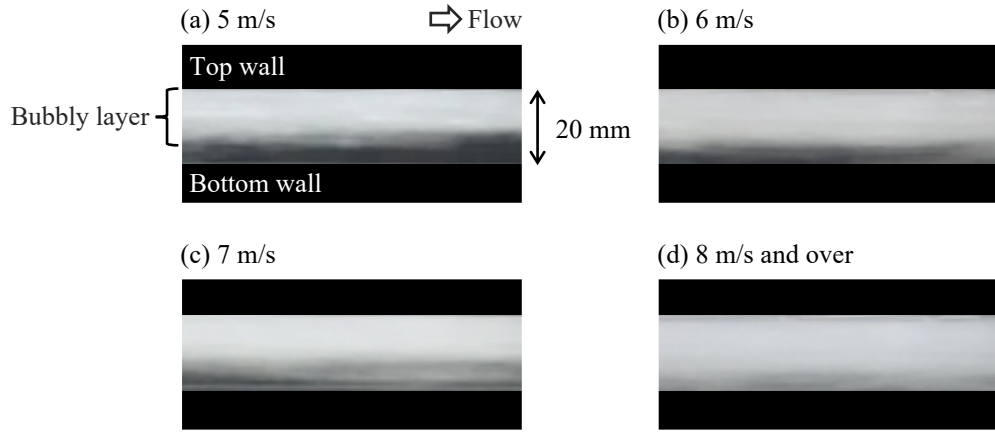


Figure 3.3: Bubble dispersion patterns inside the channel at $x = 2.0$ m with various mean flow speeds, where water flow rates are (a) 1.0×10^{-2} m³/s, (b) 1.2×10^{-2} m³/s, (c) 1.4×10^{-2} m³/s and (d) 1.6×10^{-2} m³/s and the air flow rate is constant at 1.0×10^{-3} m³/s. Exposure time was 1/30 s. The dashed lines indicate the top and bottom walls of the channel.

volumetric ratio of air to the total mixture:

$$U_m = \frac{Q_l + Q_a}{HW}, \quad (3.1)$$

$$\alpha_m = \frac{Q_a}{Q_l + Q_a}, \quad (3.2)$$

where H and W are respectively the height and width of the channel. α_m is used as the estimation of the bulk void fraction in this study because the velocities of water and bubbles are approximately the same in high-speed turbulent channel flows (Kitagawa *et al.* [20]). The water flow rate was kept constant owing to its limited controllability regardless of the variation in the air flow rate, resulting in a change in U_m of several percent with increasing α_m . The superficial velocity gives the Reynolds number according to

$$Re_m = \frac{U_m H}{\nu_l}, \quad (3.3)$$

where ν_l is the kinematic viscosity of the water at the experimental temperature, which ranged from 21.9 to 27.7°C. For each combination of Re_m and α_m , the repetition frequency, f , was set from 1.0 to 6.0 Hz. The following Strouhal number is defined as the dimensionless frequency of RBI as a reference:

$$St = \frac{fH}{U_m}, \quad (3.4)$$

which ranged from 0.3×10^{-2} to 2.3×10^{-2} . The instantaneous water flow rate, air flow rate and other quantities were simultaneously recorded by a multi-channel data logger at a sampling rate of 100 Hz. The time averages of these values were calculated for a period of 60 s; i.e., averages were taken over 6000 data points.

3.2.3 Measurement techniques

A line-scanning camera (XCM20125GIG, Nippon Electro-Sensory Devices Co., Ltd., Japan) was installed at $x = 2.7$ m to observe the bubble distribution in the channel. The camera captured images of 1×1024 pixels for 1.9 s at a frame rate of 5.2 MHz. The pixel array was set parallel to the spanwise direction of the channel and had a spatial resolution of 0.11 mm/pixel.

The local wall shear stress was directly measured using a shear-stress sensor (S10W-2S, capacity of 250 N/m^2 , SSK Co., Ltd., Japan) attached on the upper wall of the channel at $x = 2.1$ m. The sensor was a mechanical force gauge with a 10-mm-diameter sensing plate and had a temporal resolution of 20 Hz. We calibrated the shear-stress data using measurements of the water temperature and water flow rate and a formula of the wall shear stress for single-phase flow:

$$\tau_{c0} = \frac{1}{2} c_{fc0} \rho_1 U_m^2, \quad (3.5)$$

where ρ_1 and c_{fc0} are respectively the water density and local friction coefficient. The friction coefficient of a single-phase turbulent channel flow in a fully developed state was predicted using Dean's empirical law:

$$c_{fc0} = 0.073 Re_m^{-\frac{1}{4}}, \quad (3.6)$$

The time-averaged values of the measured water temperature and flow rate gave corresponding ρ_1 , U_m and Re_m . An appropriate offset of the sensor signal for the calibration was then evaluated using the difference between the raw measurement results of the shear stress and τ_{c0} calculated from Eqs. (3.5) and (3.6). In the calibration of the wall shear stress, the estimated measurement error was 11%–17% for the liquid single-phase flows. For bubbly flows, the appropriate offset was determined by the mean value of the offsets in single-phase flow measurements carried out immediately before and after each bubbly flow measurement. Using the wall shear stress after the calibration, τ , the time-averaged drag reduction ratio was defined as

$$DR = 1 - \frac{\bar{\tau}}{\tau_{c0}}, \quad (3.7)$$

where $\bar{\tau}$ is the time-averaged wall shear stress. τ_{c0} was calculated using Eqs. (3.5) and (3.6) and U_m of the bubbly flow to consider the increment of the wall shear stress due to acceleration of the liquid phase by bubble injection. Equation (3.7) thus assumes the same velocity between the liquid single-phase flow and the bubbly flow to evaluate the drag reduction. Since $\bar{\tau}$ is normalized by in Eq. (3.7), the influence of the prediction employing Eq. (3.6) is cancelled out for the evaluation of the drag reduction performance.

The wall shear stress in the single-phase flows was measured more than 50 times for individual Re_m to validate the reproducibility of the sensor signal. The standard deviation of the time-averaged shear stress after the calibration was less than 1% among the repeated trials. In the single-phase

flows, the friction Reynolds number,

$$Re_\tau = \frac{H}{2\nu_l} \sqrt{\frac{\tau_{c0}}{\rho_l}}, \quad (3.8)$$

ranged from 2.5×10^3 to 3.4×10^3 depending on the water flow rate.

Table 3.1: Experimental conditions of the RBI, where the superficial velocity U_m and Reynolds number Re_m vary several percent depending on the time-averaged air flow rate Q_a from the typical value given here for each water flow rate Q_l . The friction Reynolds number Re_τ was experimentally obtained for single-phase flows using Eq. (3.8).

Q_l [m ³ /s]	Q_a [m ³ /s]	U_m [m/s]	Re_m [-]	Re_τ [-]	α_m [%]	St [-]
1.0×10^{-2}	1.3×10^{-4} – 2.8×10^{-4}	5.1	1.1×10^5	2.5×10^3	1.3–2.8	0.4×10^{-2} – 2.3×10^{-2}
1.2×10^{-2}	3.4×10^{-4} – 4.8×10^{-4}	6.2	1.4×10^5	2.9×10^3	2.8–3.9	0.3×10^{-2} – 1.9×10^{-2}
1.4×10^{-2}	6.5×10^{-4} – 8.0×10^{-4}	7.3	1.7×10^5	3.4×10^3	4.4–5.4	0.3×10^{-2} – 1.6×10^{-2}

3.3 Measurements of CBI as reference data

Drag reduction by RBI was evaluated in comparison with CBI in the present study. In advance of the experiments on RBI, CBI (expressed as $f = 0$) with the same Re_m and α_m as for RBI was examined.

A sample of timeline images obtained in CBI is shown in Fig. 3.4(a). Bubbles appear as white areas owing to light reflection from a light-emitting diode panel mounted on the upstream side of the camera (see Fig. 3.1(a)). Figure 3.4(b) is an enlarged image of Fig. 3.4(a) around the spanwise center of the channel. The bubble shapes can be clearly recognized by their bright outlines owing to the sufficiently high temporal and spatial resolution of the camera. Because each bubble passed the scanning line of the camera in less than 0.5 ms as shown in Fig. 3.4(b), interfaces of the individual bubbles are a little blurred. As an indicator of the bubble size, the mean spanwise width of bubbles, d_z , was measured for 100 randomly selected samples in the images. The mean width was around 1.0 mm, and it slightly decreased with Re_m as shown in Fig. 3.5. Sanders *et al.* [45] proposed the maximum stable bubble size, $d_{\max}$, in a turbulent flow:

$$d_{\max} \approx \left(\frac{\sigma}{2\rho_l} \right)^{\frac{3}{5}} \left(\frac{\kappa y}{u_\tau^3} \right)^{\frac{2}{5}}, \quad (3.9)$$

where σ and κ are the interfacial tension and von Kármán constant. The good correspondence of d_z and $d_{\max}$ is shown by dashed lines in Fig. 3.5, where $y = 8.0$ mm is used in Eq. (3.9). The bubble size is seen to be naturally determined by fragmentation and coalescence in the turbulent flows.

The CBI resulted in $DR > 0$ for all conditions of Re_m and α_m as shown in Fig. 3.6. To compare the drag-reduction ratio between the present experiments and previous studies, we summarize reports of BDR using horizontal channels and flat plates in Table 3.2. Here, representative results for bubble sizes similar to those of the present bubbles were selected. The present results are confirmed to be reasonable, with some previous studies obtaining greater values of DR owing to differences in experimental conditions.

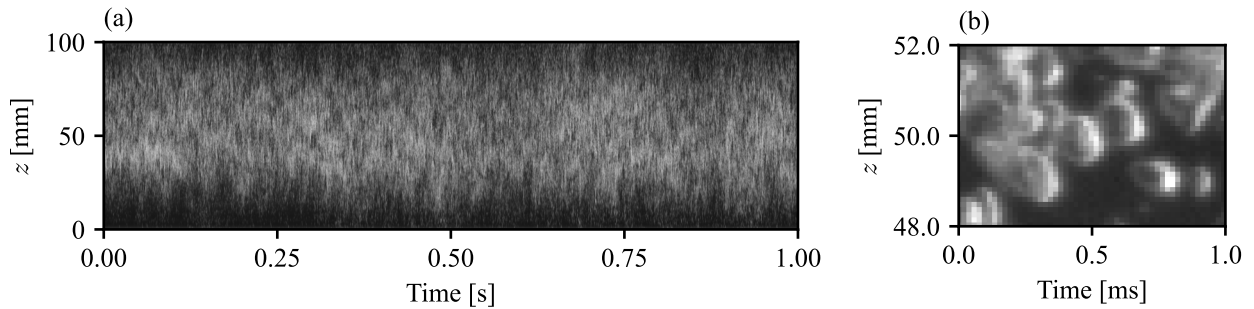


Figure 3.4: Timeline images of CBI captured by the line-scanning camera ($Re_m = 1.4 \times 10^5$; $U_m = 6.2$ m/s, $\alpha_m = 3.4\%$): (a) a full-channel-width image and (b) an enlarged image of (a) around the spanwise center of the channel. White areas correspond to bubbles.

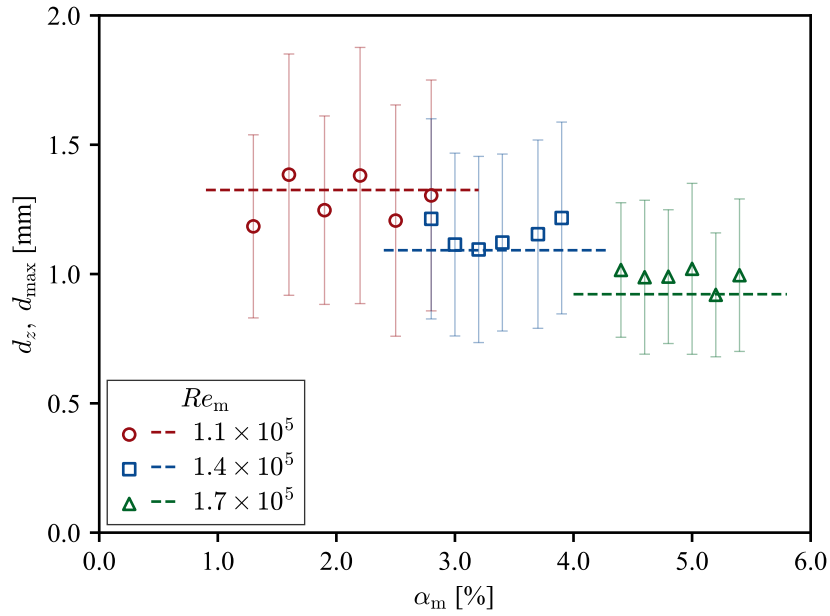


Figure 3.5: Mean spanwise bubble width, d_z , of CBI versus α_m . The error bars indicate the standard deviations for 100 sample bubbles found in timeline images. The dashed lines denote the maximum stable bubble size, $d_{\max}$, obtained by Eq. (3.9) for each Re_m at $y = 8.0$ mm.

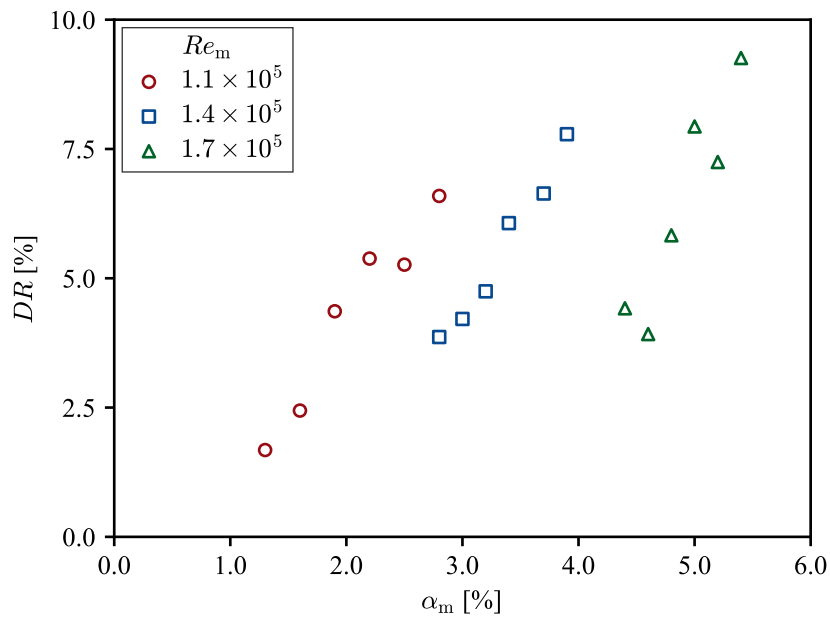


Figure 3.6: Drag-reduction ratio, DR , of CBI versus α_m

Table 3.2: Previous studies on BDR using horizontal channels and flat plates. Experimental conditions and results are extracted for bubble sizes similar to those of the present experiments.

Investigator	Configuration	Bubble size	Flow speed	Void fraction	Drag reduction
Guin <i>et al.</i> [37]	Horizontal channel	0.9 mm	4.5 m/s	11% (bulk)	18%
Kato <i>et al.</i> [39]	Horizontal channel	0.5 mm	8 m/s	5% (near wall)	60%
Moriguchi and Kato [41]	Horizontal channel	1.0 mm	4–8 m/s	3% (bulk)	7%
Kitagawa <i>et al.</i> [20]	Horizontal channel	0.5 mm	5.0 m/s	0.5% (bulk)	3%
Sanders <i>et al.</i> [45]	Flat plate	0.5 mm	12 m/s	-	6%
Shen <i>et al.</i> [44]	Horizontal channel	0.5 mm	11.1 m/s	20% (bulk)	23%
Elbing <i>et al.</i> [25]	Flat plate	0.1 mm	20.0 m/s	0.5% (near wall)	7%
Qin <i>et al.</i> [56]	Flat plate	1.0 mm	6 m/s	1% (near wall)	23%
Jha <i>et al.</i> [58]	Horizontal channel	2.7 mm	2.0 m/s	5% (bulk)	23%

3.4 Results and discussion

3.4.1 Fluctuations of the void fraction and the wall shear stress

Representative examples of timeline images captured by the high-speed line-scanning camera are shown in Fig. 3.7 for the conditions of $Re_m = 1.4 \times 10^5$ and $\alpha_m = 3.4\%$. Periodic patterns of the bubble distribution comprising several large bubble crowds are observed in the images. The images confirm that the bubble size in RBI is independent of the repetition frequency, f , and almost the same as that in CBI.

The timeline images were processed by thresholding to detect areas of the gas phase. For each instantaneous spanwise frame, we calculated the gas area ratio as the projection void fraction, β , in the central 89 pixels, which corresponds to the downstream location of the sensing plate of the sensor. Waveforms of β are shown in Fig. 3.8(a). The waveforms at $f = 1.0$ and 2.0 Hz fluctuate from zero to unity owing to the clearly separated bubble crowds (Fig. 3.7(a) and (b)). Linear spectra of β were acquired by Fourier transform of the time-series of approximately 10^5 data points using the rectangular window and shown in Fig. 3.8(b). In each spectrum, the highest peak appears at the control frequency of RBI, f , indicated by a triangular symbol. The maximum intensity at the peak, $I_{\beta, \max}$, denotes the amplitude of the original waveform at the frequency f . $I_{\beta, \max}$ is confirmed to vary depending on f . We also see the development of a harmonic component; i.e., $2f$ (see Fig. 3.8(b)).

For all RBI, $I_{\beta, \max}$ is presented in Fig. 3.9. The dependence of $I_{\beta, \max}$ on f is similar among all Re_m in that $I_{\beta, \max}$ intensifies around $f = 2.0$ Hz and becomes lowest at $f = 4.0$ Hz. We confirmed

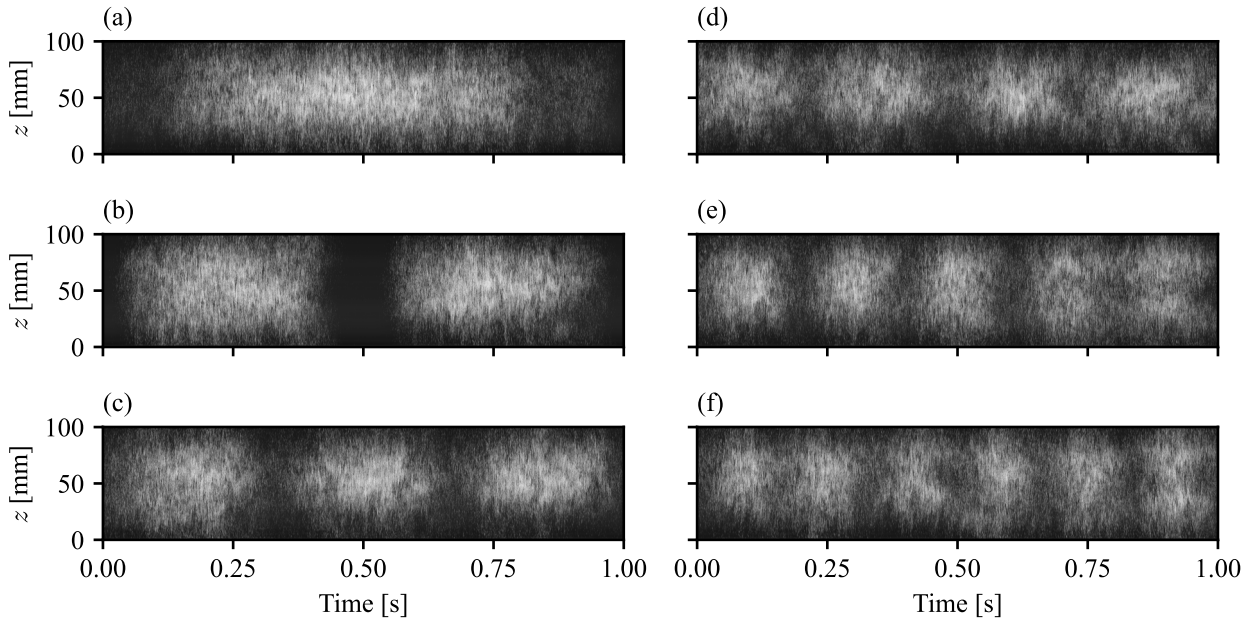


Figure 3.7: Timeline images of RBI captured by the line-scanning camera ($Re_m = 1.4 \times 10^5$: $U_m = 6.2$ m/s, $\alpha_m = 3.4\%$): (a) repetition frequency $f = 1.0$ Hz, (b) 2.0 Hz, (c) 3.0 Hz, (d) 4.0 Hz, (e) 5.0 Hz and (f) 6.0 Hz. White areas correspond to swarms of bubbles.

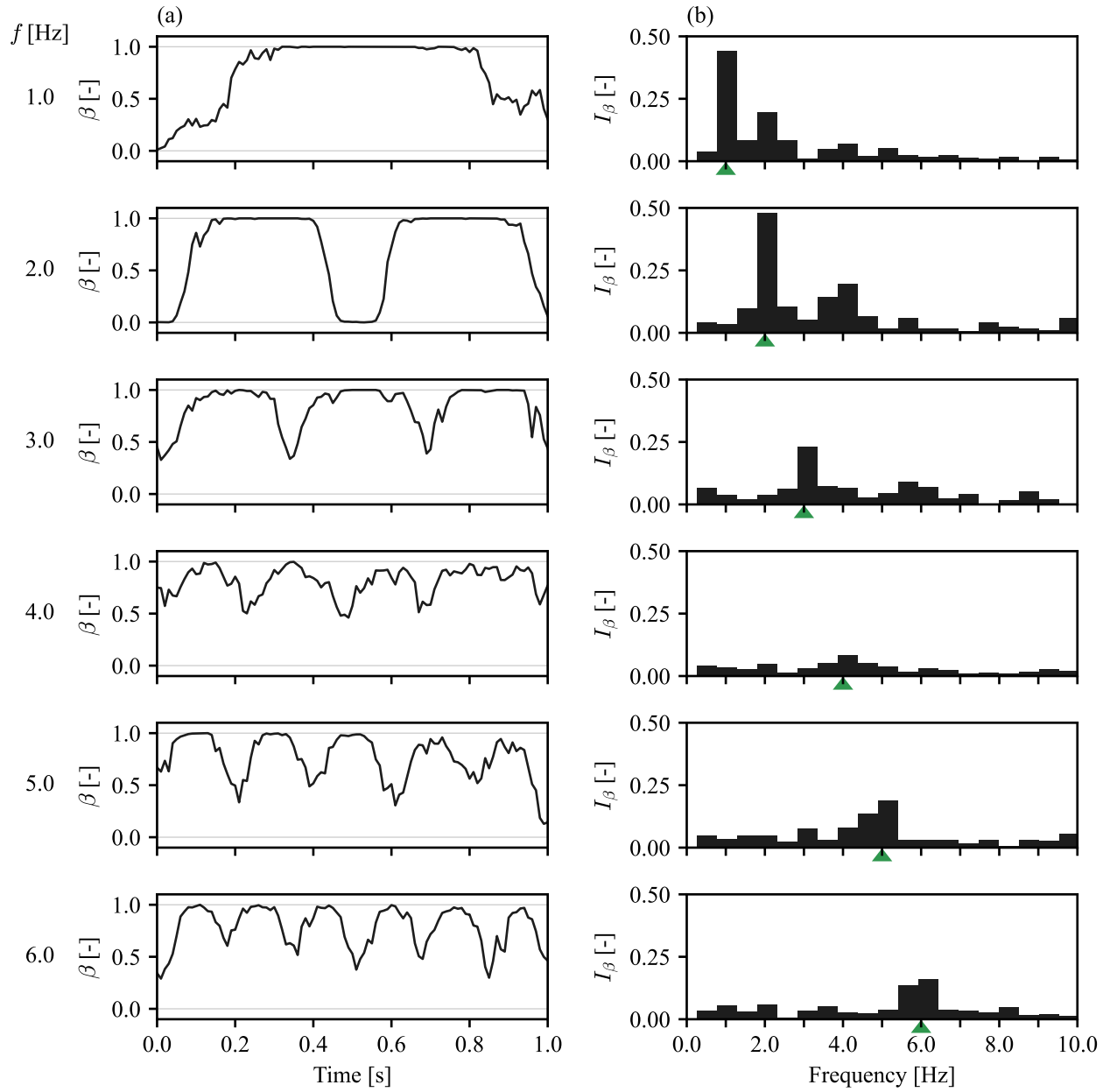


Figure 3.8: (a) Temporal waveforms of the projection void fraction, β , and (b) their linear spectra at $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and $\alpha_m = 3.4\%$. Each row of graphs corresponds to a value of $f = 1.0$ to 6.0 Hz from top to bottom. The running average of the original data with a duration of 0.10 s is presented for clarity in (a). The triangular markers below the abscissa of (b) denote the experimental condition of the repetition frequency, f .

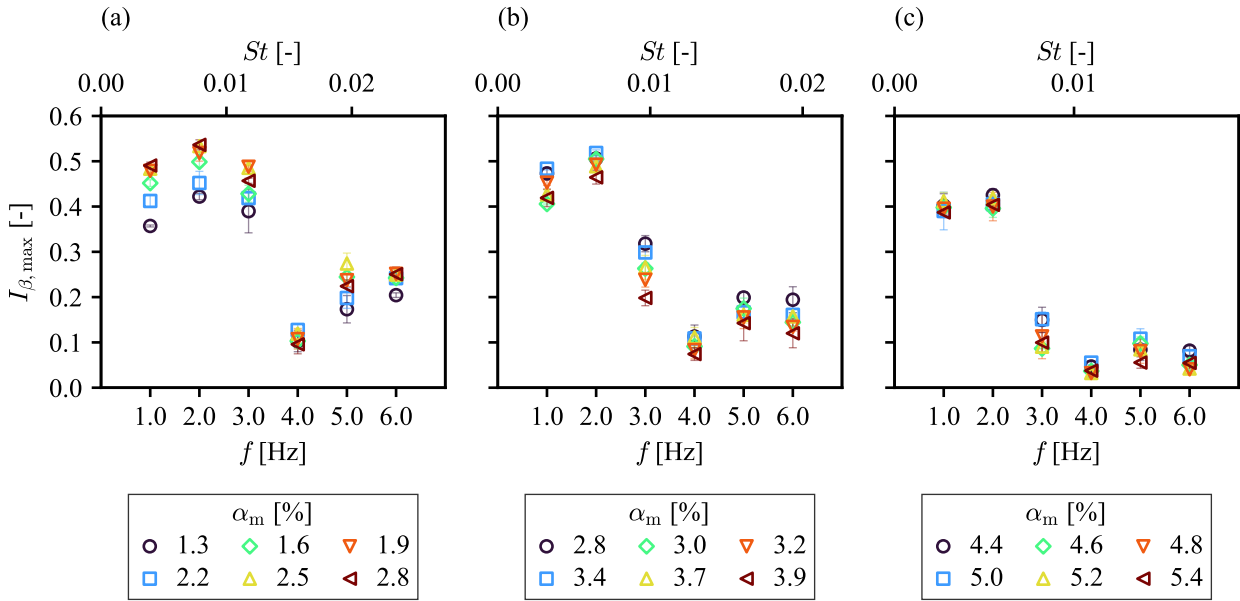


Figure 3.9: Maximum values in linear spectra of the projection void fraction, $I_{\beta, \max}$, versus the repetition frequency, f : (a) $Re_m = 1.1 \times 10^5$ ($U_m = 5.1$ m/s), (b) $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and (c) $Re_m = 1.7 \times 10^5$ ($U_m = 7.3$ m/s). The error bars indicate the standard deviations calculated for three individual timeline images under each condition. The upper abscissa gives the Strouhal number, St , corresponding to the repetition frequency.

by the same analysis of CBI that $I_{\beta, \max}$ at $f = 4.0$ Hz is equal to or a little larger than $I_{\beta, \max}$ in CBI. Conversely, even the intermediate $I_{\beta, \max}$ occurring at $f = 3.0, 5.0$ and 6.0 Hz indicates the inducement of the strong fluctuation of the void fraction by RBI. $I_{\beta, \max}$ becomes large with increasing α_m at $Re_m = 1.1 \times 10^5$, while no such tendency is found at other Re_m . At $Re_m = 1.4 \times 10^5$ and 1.7×10^5 , there is a prominent development of a harmonic component instead.

The fluctuation of the void fraction induces the fluctuation of the wall shear stress, τ , as shown in Fig. 3.10(a). The periodicity of the fluctuation holds regularly at $f = 1.0$ – 3.0 Hz, resulting in clear peaks at the frequency identical to f in the linear spectra as shown in Fig. 3.10(b). At $f = 4.0$ – 6.0 Hz, the periodicity irregularly disappears owing to the occasional abatement of fluctuation as circled in Fig. 3.10(a). In the absence of periodicity, bubble distributions are supposed to be scattered by turbulent dispersion. At a high repetition frequency, however, the linear spectra of the wall shear stress still have clear peaks at a frequency coinciding with the repetition frequency, f .

The maximum intensity in the spectra, $I_{\tau, \max}$, indicates the amplitude of the original waveform at the controlled frequency of the RBI because the largest peak appears at f . As shown in Fig. 3.11, $I_{\tau, \max}$ at the same f increases with α_m at $Re_m = 1.1 \times 10^5$ and 1.4×10^5 , while it is almost constant against α_m at $Re_m = 1.7 \times 10^5$. At $Re_m = 1.7 \times 10^5$, a harmonic component in the spectra tends to develop instead. The intensity $I_{\tau, \max}$ increases around $f = 2.0$ Hz and becomes small at $f \geq 4.0$ Hz for all Re_m as shown in Fig. 3.11, relating to a similar dependence of $I_{\beta, \max}$ on f .

The relationship between $I_{\beta, \max}$ and $I_{\tau, \max}$ for different conditions of Re_m and α_m is shown in Fig. 3.12. Figure 3.12(a) indicates $I_{\tau, \max}$ increases depending on $I_{\beta, \max}$ at $Re_m = 1.1 \times 10^5$. Oishi

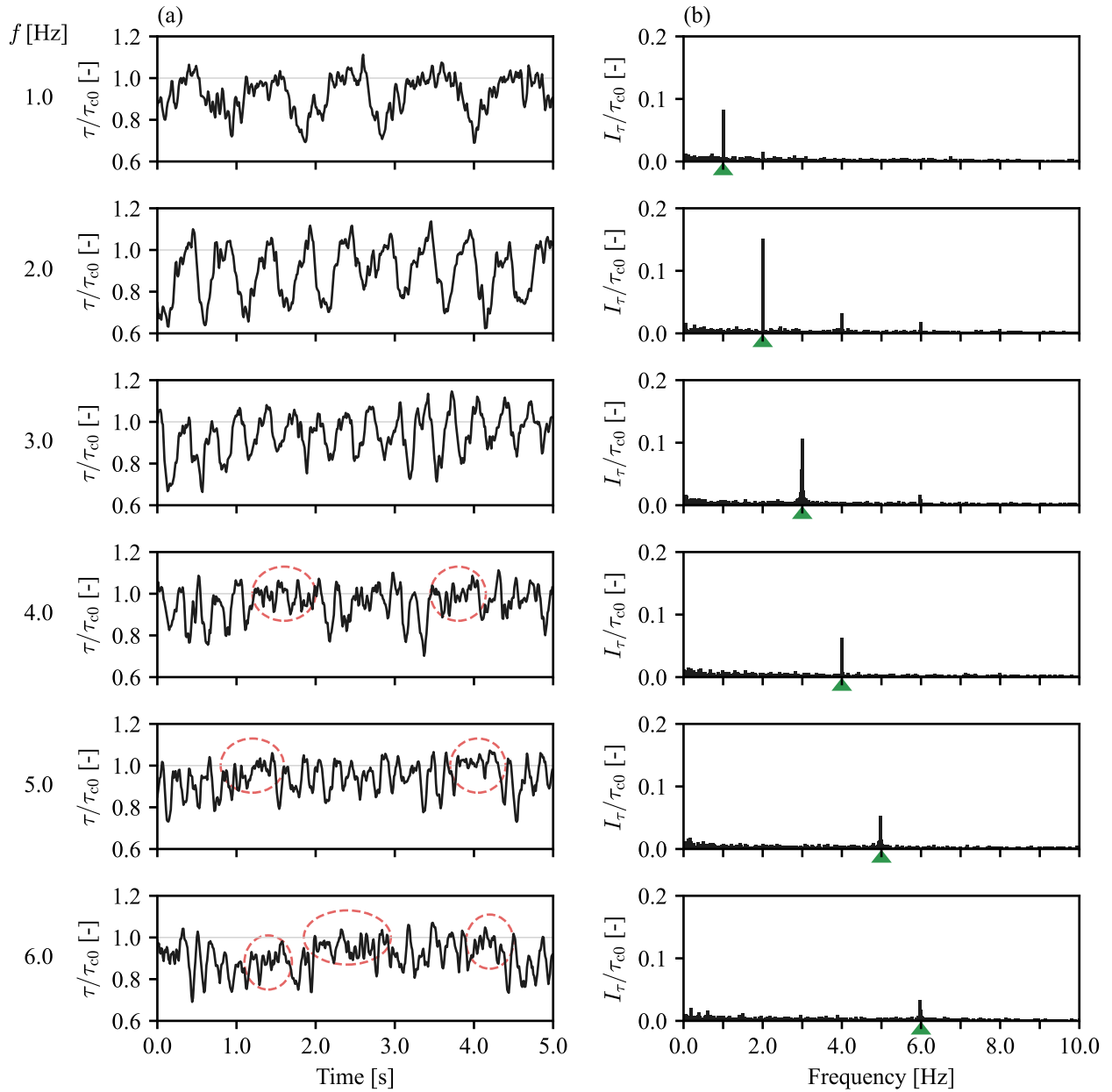


Figure 3.10: (a) Temporal waveforms of the wall shear stress, τ , and (b) their linear spectra acquired at $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and $\alpha_m = 3.4\%$. The rows of graphs correspond to $f = 1.0$ to 6.0 Hz from top to bottom. Both τ and I_τ are normalized by the wall shear stress of the liquid single-phase flow, τ_{c0} . The circles in (a) indicate the moments when periodic fluctuation disappears. The triangular markers below the abscissa of (b) denote the experimental condition of the repetition frequency, f .

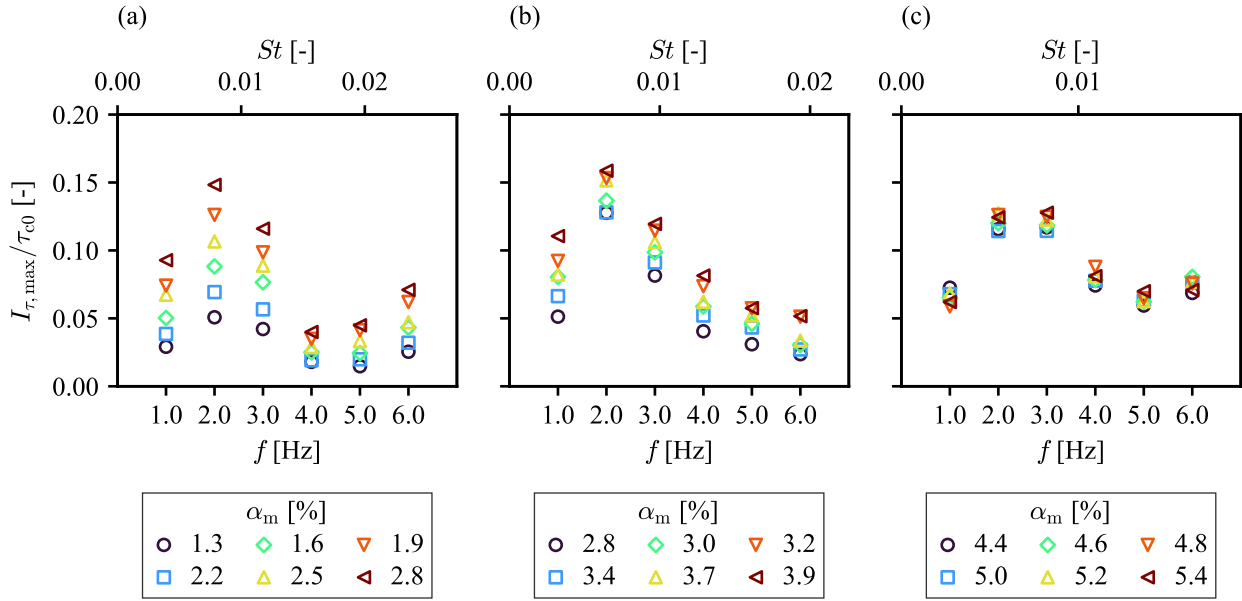


Figure 3.11: Maximum values in linear spectra of the wall shear stress, $I_{\tau, \max}$, according to the repetition frequency, f : (a) $Re_m = 1.1 \times 10^5$ ($U_m = 5.1$ m/s), (b) $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and (c) $Re_m = 1.7 \times 10^5$ ($U_m = 7.3$ m/s). $I_{\tau, \max}$ is normalized by the wall shear stress of the liquid single-phase flow, τ_{c0} . The upper abscissa gives the Strouhal number, St , corresponding to the repetition frequency.

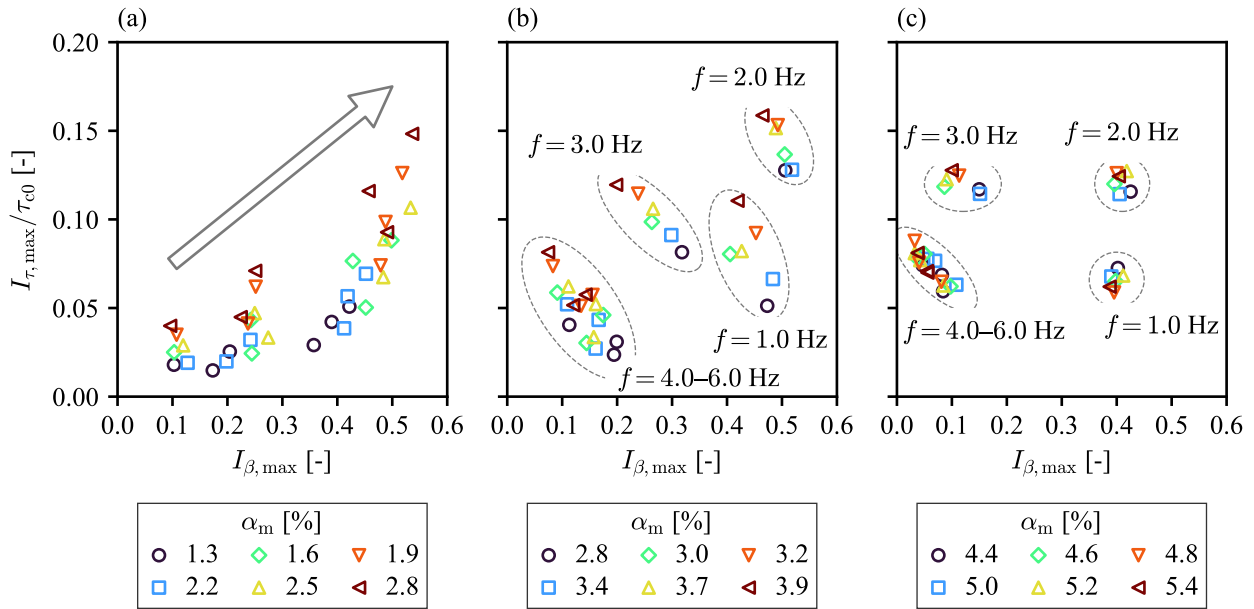


Figure 3.12: Relationship between the maximum value in the linear spectra of the projection void fraction, $I_{\beta, \max}$, and that of the wall shear stress, $I_{\tau, \max}$: (a) $Re_m = 1.1 \times 10^5$ ($U_m = 5.1$ m/s), (b) $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and (c) $Re_m = 1.7 \times 10^5$ ($U_m = 7.3$ m/s). $I_{\tau, \max}$ is normalized by the wall shear stress of the liquid single-phase flow, τ_{c0} .

et al. [59] experimentally observed temporal correlation of projection void fraction and local wall shear stress in bubbly channel flows. This knowledge supports the increase of $I_{\tau, \max}$ with $I_{\beta, \max}$ found in Fig. 3.12(a). At $Re_m = 1.4 \times 10^5$ and 1.7×10^5 , the correlation between $I_{\beta, \max}$ and $I_{\tau, \max}$ decreases at the same f as shown in Fig. 3.12(b) and (c). A comparison of conditions resulting in the lowest $I_{\beta, \max}$ and highest $I_{\beta, \max}$ (i.e., $f = 4.0$ – 6.0 Hz and $f = 2.0$ Hz, respectively) reveals that $I_{\tau, \max}$ increases with $I_{\beta, \max}$. A larger fluctuation of the wall shear stress is induced by generating larger fluctuation of the temporal void fraction in the present high-speed turbulent channel flows. As previously mentioned, either or both of $I_{\beta, \max}$ and $I_{\tau, \max}$ is constant against α_m at $Re_m = 1.4 \times 10^5$ and 1.7×10^5 owing to the prominent development of the harmonic components. The non-linear effect of gas–liquid two-phase turbulent flows can induce the development though it hardly showed simple dependence on the experimental parameters (Re_m , α_m and f). Further detailed investigation of the bubbly flow is needed to clarify the correlation between the fluctuation of the void fraction and the fluctuation of the wall shear stress.

3.4.2 Promotion of drag reduction by RBI

The time-averaged drag-reduction ratio DR of RBI under different conditions of Re_m , α_m and f is shown in Fig. 3.13. At $Re_m = 1.4 \times 10^5$ (Fig. 3.13(b)), a maximum drag reduction of 12% is obtained. The drag reduction increases with α_m as in the case of CBI (see Fig. 3.6). The dependence of DR on α_m is attributed to the reasons commonly discussed in previous studies on CBI (e.g., Murai [14] and Ceccio [26]). Moreover, the repetition frequency of RBI affects DR . The drag reduction becomes largest at $f = 2.0$ Hz and smallest at $f = 4.0$ Hz. We find that DR (Fig. 3.13(b)) and $I_{\tau, \max}$

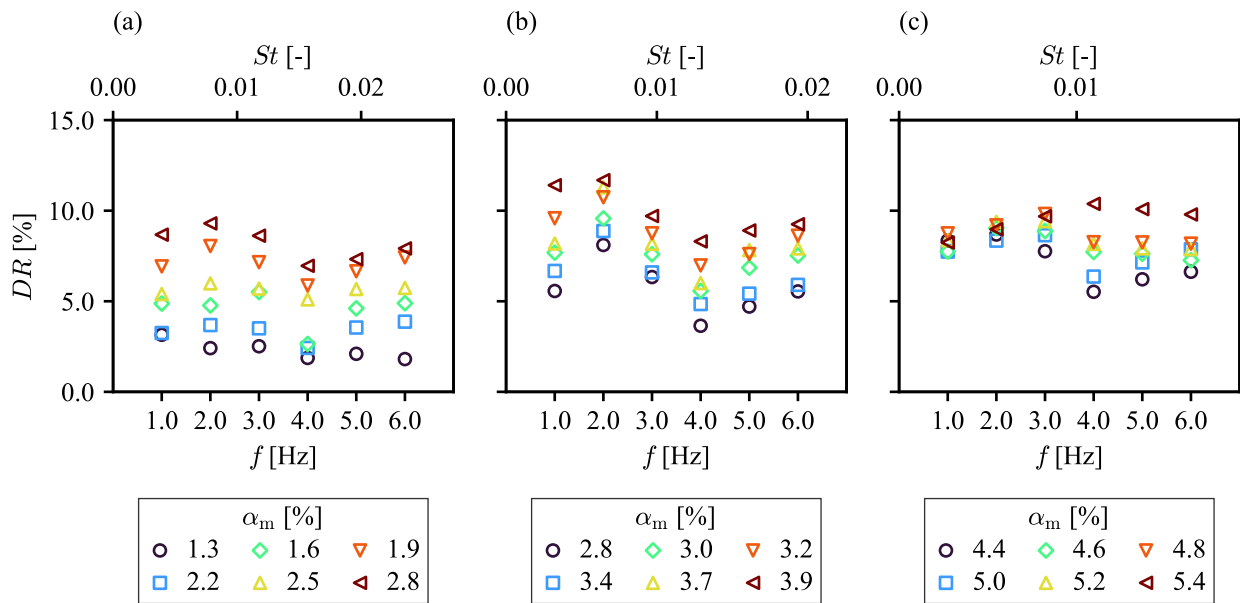


Figure 3.13: Drag-reduction ratio, DR , of RBI: (a) $Re_m = 1.1 \times 10^5$ ($U_m = 5.1$ m/s), (b) $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and (c) $Re_m = 1.7 \times 10^5$ ($U_m = 7.3$ m/s). The upper abscissa is the Strouhal number, St , corresponding to the repetition frequency.

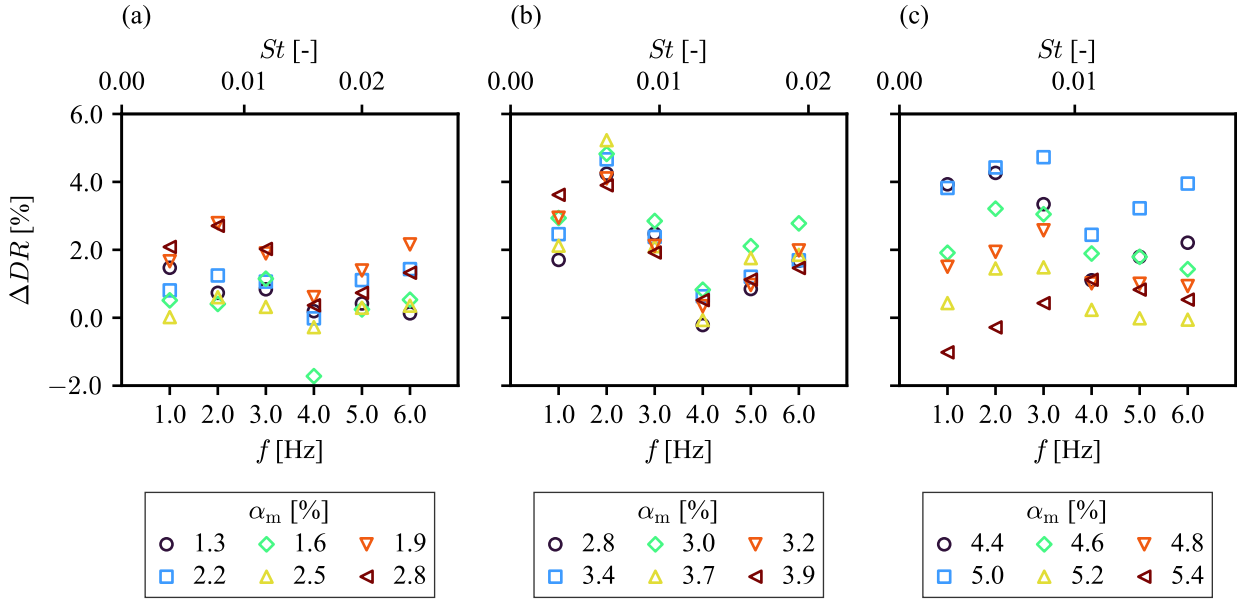


Figure 3.14: Promotion of drag reduction, ΔDR , by RBI compared with CBI at the same Re_m and α_m : (a) $Re_m = 1.1 \times 10^5$ ($U_m = 5.1$ m/s), (b) $Re_m = 1.4 \times 10^5$ ($U_m = 6.2$ m/s) and (c) $Re_m = 1.7 \times 10^5$ ($U_m = 7.3$ m/s). The upper abscissa gives the Strouhal number, St , corresponding to the repetition frequency.

(Fig. 3.11(b)) have the similar dependence on f at $f = 1.0$ –4. Hz. At $f = 5.0$ and 6.0 Hz, however, DR increases with the repetition frequency though $I_{\tau, \max}$ decreases. This implies there are multiple bands of the repetition frequency promoting drag reduction. The higher frequencies are, however, less suitable for ship drag reduction since void waves are thought to diffuse in downstream regions immediately.

At $Re_m = 1.1 \times 10^5$, the same dependence of DR on α_m and f is found as shown in Fig. 3.13(a). Although the variation in DR with f is unclear at the lowest value of α_m ($= 1.3\%$), it becomes prominent with increasing α_m . At the highest flow speed (i.e., $Re_m = 1.7 \times 10^5$), the dependence of DR on f is similar to that for the lower Re_m when $\alpha_m = 4.4\%$ –5.2%, while DR intensifies at $f = 4.0$ Hz when $\alpha_m = 5.4\%$ as shown in Fig. 3.13(c). Moreover, the increase in DR with α_m is small especially at $f = 1.0$ –3.0 Hz.

We evaluate the promotion of drag reduction due to RBI compared with CBI at the same Re_m and α_m ,

$$\Delta DR (Re_m, \alpha_m, f) = DR (Re_m, \alpha_m, f) - DR (Re_m, \alpha_m, 0), \quad (3.10)$$

as shown in Fig. 3.14. The maximum ΔDR , obtained at $(Re_m, \alpha_m, f) = (1.4 \times 10^5, 3.4\%, 2.0 \text{ Hz})$, is 5.2%. This value is comparable to the base DR due to CBI. Therefore, the drag-reduction ratio is nearly doubled by RBI under this condition. Park *et al.* [54] reported the similar superiority of RBI in terms of the drag-reduction ratio in turbulent channel flows but at lower velocities. This experiment clarified the promotion of drag reduction by periodic passage of bubbles was higher than the repetitive blowing of liquid into the channel flow. In the present experiment, ΔDR decreases with increasing α_m at $Re_m = 1.7 \times 10^5$ and it is less sensitive to α_m at $Re_m = 1.1 \times 10^5$ and 1.4×10^5 .

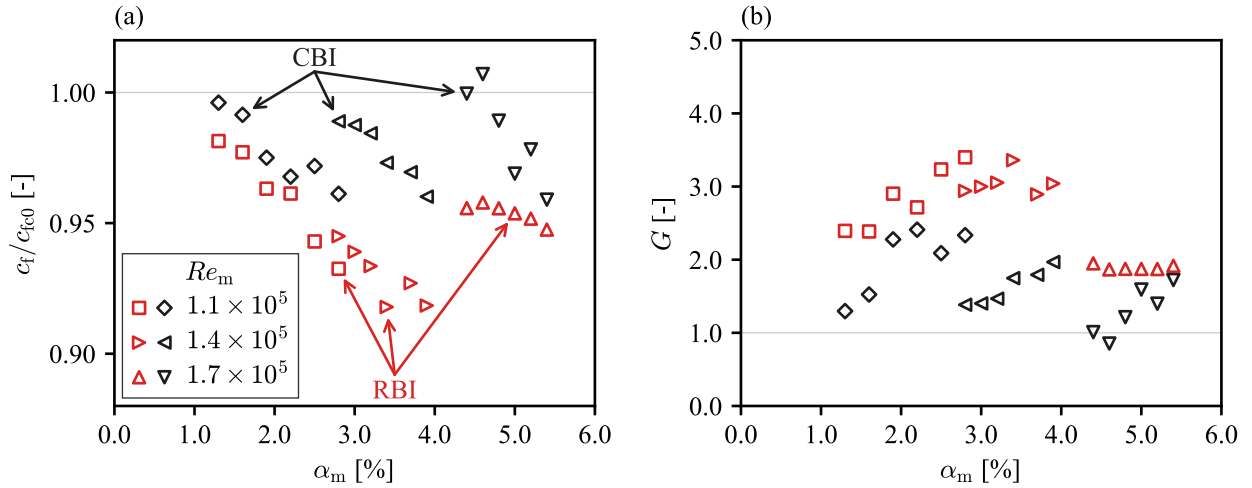


Figure 3.15: (a) Minimum local friction coefficient, c_f , and (b) maximum gain factor, G , obtained by RBI among the different conditions of f at common Re_m and α_m . The friction coefficient is normalized by that of the liquid single-phase flow, c_{f0} . The results of CBI are presented for comparison.

This indicates the disappearance of the effect that promotes drag reduction under the conditions of lower Re_m . A reason for the disappearance is the difference in the vertical bubble distribution in the channel flows. The bubbly layer of RBI periodically becomes thicker than that of the CBI (see Fig. 3.3), which is associated with the fluctuating air flow rate, and it periodically reaches the bottom wall at $Re_m = 1.7 \times 10^5$. As Xu *et al.* [80] found in their numerical study on CBI, the spatial evolution of the void fraction distribution largely contributes to the enhancement of the drag reduction. This suggests that the confinement of the wavy advecting bubbly layer by the bottom wall depresses the promotion of drag reduction by RBI.

The mechanism of BDR is explained by two factors: the modification of turbulence and the decrease in mean fluid density. α_m represents the effect of the drag reduction originating from the latter factor. To clarify the contribution of the turbulence modification by the RBI, we evaluate the local friction coefficient, c_f , expressed as

$$c_f = \frac{2\bar{\tau}}{(1 - \alpha_m) \rho_l U_m^2}. \quad (3.11)$$

The minimum values of c_f among different conditions of f at common Re_m and α_m are shown in Fig. 3.15(a) as the best result of the RBI, where c_f of CBI is also plotted for comparison. The decrease in c_f due to RBI clearly denotes the stronger depression of turbulence relative to CBI. As common results of CBI and RBI, c_f/c_{f0} linearly decreases, indicating intensification of the effect of the turbulence modification, with increasing α_m at the same Re_m . At $Re_m = 1.1 \times 10^5$ and 1.4×10^5 , the slope of c_f/c_{f0} against α_m appears similar for CBI and RBI. At $Re_m = 1.7 \times 10^5$, however, the slope is more gradual for RBI, and c_f for RBI likely becomes equivalent to that for CBI at higher α_m . The discrepancy in c_f/c_{f0} between CBI and RBI at common Re_m and α_m is largest at $Re_m = 1.4 \times 10^5$. The discrepancy is small at $Re_m = 1.1 \times 10^5$ and decreases with α_m at $Re_m = 1.7 \times 10^5$ owing to the difference in slope. The results of c_f indicate that there is a suitable Re_m at which the

effect of turbulence modification by RBI is intensified in the turbulent channel flow.

We evaluate the efficiency of the drag reduction per unit air volume using a gain factor (Murai [14]) as the sensitivity to void fraction:

$$G = \frac{DR}{\alpha_m}. \quad (3.12)$$

The largest values of G among the common Re_m and α_m conditions are shown in Fig. 3.15(b). G is obviously increased by RBI compared with CBI under all Re_m and α_m conditions. At $Re_m = 1.4 \times 10^5$, especially, G for RBI is twice that for CBI. This clearly shows the improvement in the efficiency of drag reduction when adopting RBI.

3.5 Conclusions

We investigated the drag reduction due to repetitive bubble injection (RBI) in high-speed horizontal turbulent channel flows with water velocity of 5–7 m/s, corresponding to $Re_m = 1.1 \times 10^5$ – 1.7×10^5 . The size of bubbles was approximately 1.0 mm. The bubbles were injected into the channel flow with periodically fluctuating air flow rates in RBI. The bubble distribution in the channel was visualized using a line-scanning camera. The periodicity in the temporal variation of the projection void fraction calculated from the sequential images was confirmed to coincide with the repetition frequency of the bubble injection. The wall shear stress acting on the top wall of the channel was directly measured using a shear-stress sensor. RBI induced the periodic fluctuation of the wall shear stress at a frequency identical to the repetition frequency.

The time-averaged drag-reduction ratio was increased by applying RBI compared with continuous bubble injection (CBI) at the same estimated bulk void fraction in the channel flow. We found that RBI at a repetition frequency of 2.0 Hz tended to promote the drag reduction most effectively and at most doubled the drag-reduction ratio relative to CBI. In terms of the promotion of drag reduction, the local friction coefficient was lower than that of CBI, indicating the stronger depression of turbulence. Owing to the decrease in the friction coefficient, the efficiency of the drag reduction per unit air volume improved, especially at $Re_m = 1.4 \times 10^5$. The high efficiency of drag reduction due to RBI was demonstrated in the high-speed turbulent flows.

CHAPTER 4

CBI in a turbulent boundary layer beneath a 36-m-long model ship

Preface

This chapter aims to collect reference data on the drag reduction of continuous bubble injection (CBI) to be compared with that of repetitive bubble injection (RBI) in a large-scale towing test of a model ship. Downstream decay of the drag-reduction effect is revealed by measurement of the local wall shear stress at multiple locations. A formula describing the streamwise distribution of local wall friction is proposed by a function fitting to the experimental results. This work was published in Tanaka *et al.*, Ocean Eng. (2022).

4.1 Introduction

Boundary layers are thinner and the shear stress stronger for horizontal turbulent channel flows in examining the performance of bubble drag reduction (BDR) than for the turbulent boundary layers of ship hulls cruising in open water. Additionally, the pressure loss in the channel affects the mechanism of drag reduction. The development of BDR for ships essentially requires investigation using plate boundary layers in an open-water environment. Previous studies on BDR in spatially developing turbulent boundary layers on flat surfaces are listed in Table 4.1. These studies showed an appreciable effect of BDR for different flow conditions. Other studies on BDR in external flows included experiments using axisymmetric bodies (McCormick and Bhattacharyya [6], Wu *et al.* [65], and Deutsch and Castano [81]), model ships (Wu *et al.* [65] and Lattore *et al.* [82]), and real ships (Kodama *et al.* [7], Mizokami *et al.* [8], Kumagai *et al.* [9], and Mizokami and Kuroiwa [10]). As summarized by Merkle and Deutsch [83], BDR has been investigated on flat plates up to 1 m in length at a plate-length-based Reynolds number $Re_L \lesssim 10^7$ in the several decades since the first demonstration of BDR by McCormick and Bhattacharyya [6]. Recently, experiments using a 4-m-long flat-bottom model ship was performed at a ship speed up to 3 m/s, resulting in $Re_L = O(10^7)$ (Park *et al.* [55], [57]). In these experiments, periodic patterns of bubble clusters spontaneously emerged downstream and enhanced the drag reduction.

The environment of the practical application of BDR to ships is of a larger scale in that $Re_L = O(10^8-10^9)$ and the considered downstream is more than tens of meters. Sanders *et al.* [45] and Elbing *et al.* [25] examined the air lubrication on a 13-m-long flat plate fixed in a large recirculating-water tunnel at a wide range of flow speeds, and BDR was realized at main flow velocities higher than 12 m/s. In their experiments on BDR, the strong shear in the boundary layer fragmented larger bubbles into smaller bubbles with a size of several hundred micrometers and induced a lift force that pulled the tiny bubbles away from the wall surface. The thickness of the bubbly layer, δ_{bubble} , then developed into 60% of the thickness of the single-phase boundary layer, δ (Sanders *et al.* [45]). The vertical dispersion of bubbles caused rapid decay of the drag reduction by the end of the 13-m-long plate. This finding is conceptually illustrated in Fig. 4.1. A point of discussion is whether the phenomenological similarity of such the spatial transition and downstream limit of drag reduction holds at a longer plate in a flow of moderate velocity as much as the cruising speed of commercial ships. In the present study, an experiment using a 36-m-long model ship was conducted at the towing speed of 8 m/s, which corresponds to the practical speed of ships at $Re_L = O(10^8)$. To clarify the spatial development of the drag-reduction effect in detail, the local wall shear stress was measured at 23 locations on the two-dimensional bottom plane. According to the results of previous studies using long model ships (Watanabe *et al.* [38], Takahashi *et al.* [42], and Kodama *et al.* [79]), the long downstream persistence of drag reduction is expected as shown in Fig. 4.1. Moreover, the state of the flow beneath the model ship was observed at 4 locations using four high-speed video cameras. The state of two-phase flow in the turbulent boundary layer, which was reported by Elbing *et al.* [25] for a 13-m-long plate, was covered by the present experiment.

Table 4.1: Previous studies on BDR in spatially developing turbulent boundary layers on flat surfaces. L_p , U , Re_L , and N_w are respectively the length of the plate, free-stream velocity, plate-length-based Reynolds number, and the number of locations measuring local wall shear stress. Hot-wire probes and force-gage-type shear-stress sensors were used for the shear stress measurement. The major targets of the previous studies related to the present study are presented.

Investigators	L_p [m]	U [m/s]	Re_L [-]	N_w [-]	Major target
Madavan <i>et al.</i> [84]	0.8	4.6–16.8	4×10^6 – 1×10^7	6	Streamwise decay of drag reduction
Pal <i>et al.</i> [85]	1.1	4.6, 10.7	5×10^6 – 1×10^7	3	Effect of near-wall void fraction to drag reduction
Watanabe <i>et al.</i> [38]	40.0	7.0	3×10^8	6	Drag reduction on a long flat plate
Kodama <i>et al.</i> [79]					
Kato <i>et al.</i> [39]	0.6	6.0–10.0	3×10^6 – 6×10^6	2	Velocity and turbulence intensity in the bubbly boundary layer
Takahashi <i>et al.</i> [42]	50.0	7.0	4×10^8	8	2% drag reduction downstream 40 m
Sanders <i>et al.</i> [45]	12.9	6.6–19.9	8×10^7 – 3×10^8	5	Loss of drag reduction due to lift force on bubbles
Elbing <i>et al.</i> [25]	12.9	6.7–20.3	8×10^7 – 3×10^8	6	Transition to air-layer drag reduction
Park <i>et al.</i> [55], [57]	4.0	2.0–3.0	1×10^7 – 2×10^7	3	Spontaneous emergence of void waves
Tanaka <i>et al.</i> [86]	4.0	1.5–3.0	8×10^6 – 2×10^7	1	Promotion of drag reduction by repetitive bubble injection
Zhang <i>et al.</i> [22]	0.8	2.0–8.0	2×10^6 – 6×10^6	-	Detailed measurement of bubbly turbulent boundary layers

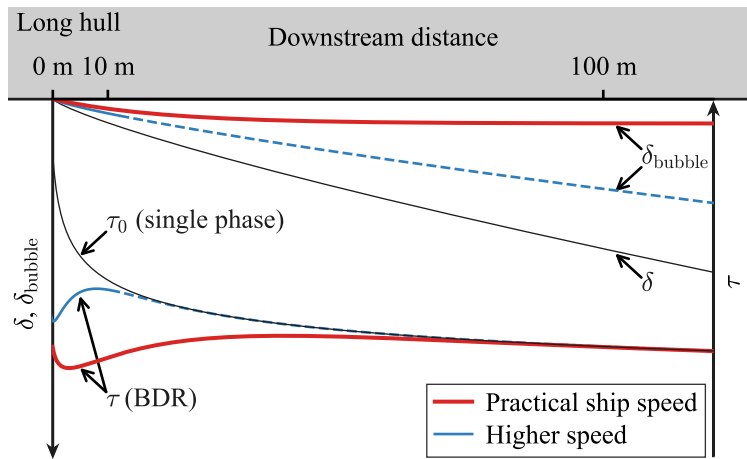


Figure 4.1: Characteristics of BDR on a long hull in terms of the thickness of the bubbly layer, δ_{bubble} , and local wall shear stress, τ : present expectation in a practical-ship-speed condition and the previous findings in the higher-speed condition. The solid and dashed lines for the higher-speed condition respectively illustrate the experimental results of Sanders *et al.* [45] and its extrapolation over the longer downstream distance. δ is the thickness of the boundary layer of the single-phase flow.

4.2 Towing test facility and model ship

The experiment was performed at the towing test facility of the National Maritime Research Institute, Tokyo, Japan. The facility has been certified as a standard institute for ship performance examination (ISO 9001). The water tank of the facility (Fig. 4.2(a)) is 400 m long, 18 m wide, and 8 m deep. The towing train, shown in Fig. 4.2(b), runs over the tank at up to 15 m/s to pull the model ship floating on the water. The model ship used in the experiment had a slender shape that was 36.0 m long and 1.0 m wide (Fig. 4.3(a)). At a position 7 m from the bow, the model ship was connected to the train by a towing rod. The bottom of the model ship was a flat plate. Protrusions fixed at the bow perturbed the inflow onto the bottom plate to guarantee the development of a turbulent boundary layer. The temperature of the water was $20.6^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ during the experiment, resulting in a density $\rho_1 \approx 1.0 \times 10^3 \text{ kg/m}^3$ and kinematic viscosity $\nu_1 \approx 0.99 \times 10^{-6} \text{ m}^2/\text{s}$.

As the bubble injector, a part of the bottom plate at a distance of 3.1 m from the bow had 41 holes that were 30 mm in diameter (Fig. 4.3(b)). Compressed air was supplied to the holes for injecting bubbles into the turbulent boundary layer. The model ship had side walls protruding downward

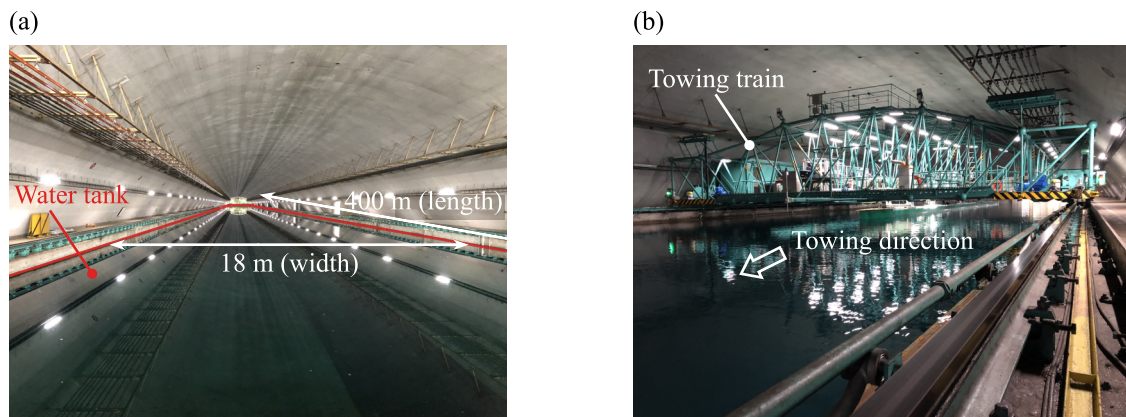


Figure 4.2: Photographs of the towing test facility: (a) water tank of 400 m in length and 18 m in width and (b) towing train viewed from the front

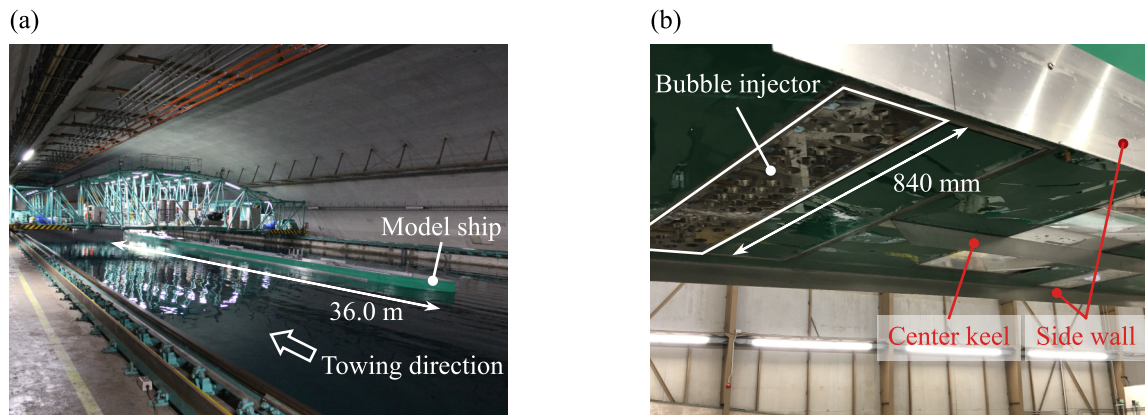


Figure 4.3: Photographs of the 36-m-long model ship: (a) overall view from behind and (b) bottom around the bubble injector. The model ship is connected to the towing train at a position 7 m from the bow. The breadth of bubble injector is 0.84 m, and the model ship has side walls and a center keel on the bottom plate.

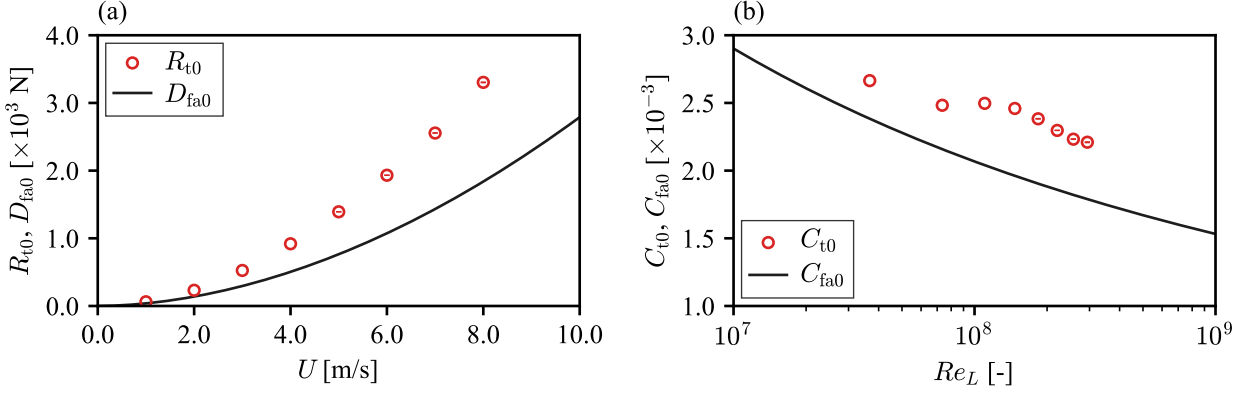


Figure 4.4: (a) Total resistance of the model ship R_{t0} and frictional drag of the air-lubricated part D_{fa0} defined by Eq. (4.19) and (b) total drag coefficient of the model ship C_{t0} and friction drag coefficient of the air-lubricated part C_{fa0} defined by Eq. (4.19). Vertical error bars plotted on circle markers indicate the maximum and minimum values in three trials at towing speed $U = 4.0\text{--}8.0$ m/s and corresponding plate-length-based Reynolds number $Re_L = 1.8 \times 10^8\text{--}2.9 \times 10^8$. The standard deviations were less than 1% of R_{t0} and C_{t0} . At the lower speed conditions, R_{t0} and C_{t0} were measured once.

from the bottom plate by 50 mm as shown in Fig. 4.3(b). The side walls confined the bubbles beneath the model ship (Kawashima *et al.* [87]) and prevented the entry of hydraulic waves to the bottom plane. In previous studies using a 40-m-long slender model ship (Watanabe *et al.* [38] and Kodama *et al.* [79]), little drag reduction was achieved at the stern because bubbles immediately escaped from the side. The design of the present model ship avoided a rapid decrease in bubble density. The center keel (Fig. 4.3(b)) on the bottom plate prevented an uneven accumulation of bubbles toward one side of the ship and maintained the balance of the model ship around the roll axis. The draft of the ship was kept at 70 mm during the experiment, and the wetted surface area of the model ship including the side walls and the center keel was 46.8 m^2 .

A load cell (TP-U-500, ORIENTEC Co., Ltd., Japan) was equipped with the towing rod for the measurement of the total resistance acting on the model ship. The total resistance without the bubble injection, R_{t0} , was measured at a towing speed $U = 1.0\text{--}8.0$ m/s. R_{t0} monotonically increased with U as shown in Fig. 4.4(a). The error bars at $U = 4.0\text{--}8.0$ m/s indicate the maximum and minimum values in three trials, and variation was less than 1% of R_{t0} at each U . The total drag coefficient of the model ship in the absence of bubbles, C_{t0} , is obtained from R_{t0} as

$$C_{t0} = \frac{2R_{t0}}{\rho_l U^2 A_w}, \quad (4.1)$$

where A_w is the wetted surface area of the model ship. Figure 4.4(b) shows that C_{t0} decreased with the plate-length-based Reynolds number Re_L defined by

$$Re_L = \frac{UL_t}{\nu_l}, \quad (4.2)$$

where L_t is the total length of the model ship. Frictional drag was reduced at the bottom plate

downstream from the bubble injector. We refer to this downstream part as the air-lubricated part. The frictional drag and the friction drag coefficient of the air-lubricated part are obtained in Section 4.4. The Froude number of the model ship,

$$Fr_L = \frac{U}{\sqrt{gL_t}}, \quad (4.3)$$

was 0.05–0.43 at $U = 1.0$ – 8.0 m/s.

4.3 Experimental setup and conditions

The total resistance of the model ship and the wall shear stress acting on the bottom plate were measured simultaneously. The shear stress was directly obtained by shear-stress sensors (S10W-2S, SSK Co., Ltd., Japan) flush-mounted with the bottom plane (Fig. 4.5(a)). Each sensor locally measured the shear stress via a 10-mm-diameter sensing plate (Fig. 4.5(b)) with temporal resolution of 40 Hz. The sensing plate is supported by a cantilever in the device and moves on the target plane two-dimensionally. The displacement of the sensing plate is converted to the voltage signal by the strain gauge incorporated in the sensor. The output signal represents the wall shear stress only in the streamwise direction because the response to the spanwise displacement is canceled out by the internal circuit of the gauge. The arrangement of 23 sensors on the model ship is shown in Fig. 4.6, where x and y coordinates respectively denote the downstream distance from the bow and the spanwise position. The sensors were aligned in the streamwise direction at 4.0 m intervals from $x = 4.5$ m except for $x = 16.5$ m and in the spanwise direction at $y = 250, 125, -125, -250$ mm. These sensors were the same type as those used in Chapter 3 and were calibrated following the same procedure. For the calibration, the local friction coefficient of a plate in the absence of bubbles was predicted using the Prandtl–Schlichting law (Schlichting [77]) expressed as

$$c_{fp0} = (2 \log_{10} Re_x - 0.65)^{-2.3}. \quad (4.4)$$

Here, the downstream-distance-based Reynolds number is defined by

$$Re_x = \frac{Ux}{\nu_1}. \quad (4.5)$$

The wall shear stress in the single-phase flow is then obtained as

$$\tau_{p0} = \frac{1}{2} c_{fp0} \rho_l U^2. \quad (4.6)$$

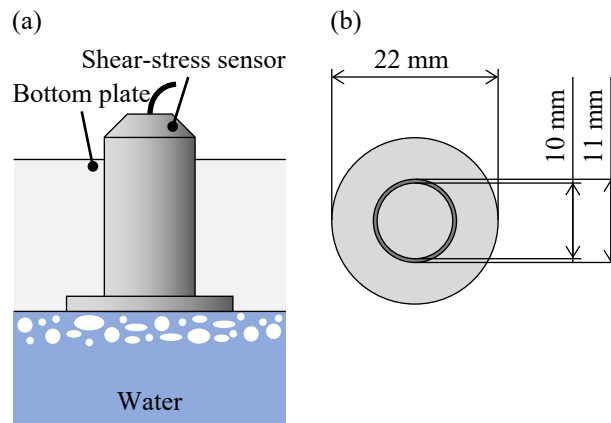


Figure 4.5: Illustration of the shear-stress sensor used to directly measure the local wall shear stress acting on the bottom plate: (a) sensor flush-mounted with the bottom plane and (b) dimensions of the sensing plane

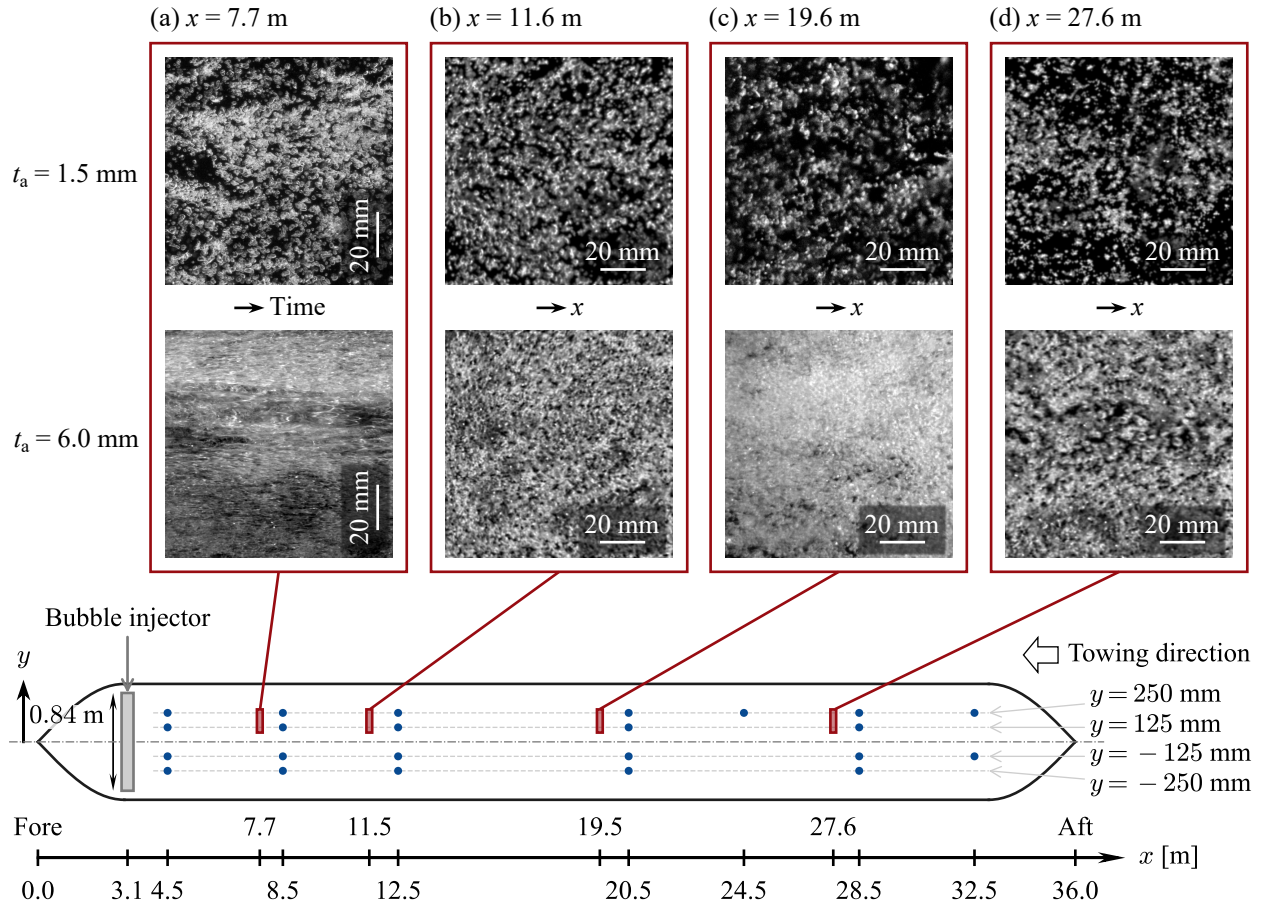


Figure 4.6: Arrangement of the 23 shear-stress sensors on the bottom plate of the model ship (lower) and snapshots of the two-phase flow taken through acrylic observation windows of the bottom plate at the highest and lowest conditions of nominal air-layer thickness t_a (upper). x and y coordinates denote the streamwise distances from the bow and the spanwise position. The bubble injector locates at 3.1 m from the bow. The snapshots were taken at four locations using (a) a high-speed line-scanning camera and (b, c, d) high-speed video cameras. Bubbles appear as white areas owing to the light reflection of the illumination from above. The snapshots of (a) are streamwise timeline images, and those of (b, c, d) are x - y plane images.

The shear-stress sensors were calibrated by the measurement of single-phase flow using the predicted τ_{p0} . The calibration in the measurement of bubbly flow referred to that of the single-phase flow. Measurements of the single-phase flow were conducted immediately before and after each series of three trials for one experimental condition of BDR. The measurement range of the sensor is ± 250 Pa. All the sensors used in the experiment were inspected in advance and had 1.92% nonlinearity, 1.26% repeatability, and 1.39% hysteresis.

BDR was examined at $U = 8.0$ m/s as a practical ship speed, resulting in $Re_L = 2.9 \times 10^8$ and $Fr_L = 0.43$. The air flow rate, Q_a , for the bubble injection was varied from 1.0×10^{-2} to 4.0×10^{-2} m³/s. Characteristics of the turbulent boundary layer beneath the model ship are summarized in Table 4.2, where Re_x and c_{fp0} were calculated at $x = 3.1$ m (the bubble injector) and $x = 36.0$ m (the end of the ship) using Eqs. (4.5) and (4.4), respectively. Using Re_x and c_{fp0} , the other quantities (i.e., the

Table 4.2: Characteristics of the single-phase turbulent boundary layer beneath the model ship at the bubble injector and the stern of the model ship: downstream-distance-based Reynolds number, Re_x ; local friction coefficient, c_{fp0} ; friction velocity, u_τ ; friction length, l_τ ; thickness of the boundary layer, δ , and volumetric fraction of air in the boundary layer, α_δ

	Bubble injector ($x = 3.1$ m)	Stern ($x = 36.0$ m)
Re_x [-]	2.5×10^7	2.9×10^8
c_{fp0} [-]	2.3×10^{-3}	1.6×10^{-3}
u_τ [m/s]	2.7×10^{-1}	2.3×10^{-1}
l_τ [m]	3.7×10^{-6}	4.3×10^{-6}
δ [m]	3.8×10^{-2} ($= \delta_b$)	2.7×10^{-1}
α_δ [-]	3.6×10^{-2} – 1.3×10^{-1}	5.3×10^{-3} – 2.1×10^{-2}

friction velocity u_τ , friction length l_τ , and thickness of the boundary layer δ) were obtained:

$$u_\tau = \sqrt{\frac{1}{2} c_{fp0} U^2}, \quad (4.7)$$

$$l_\tau = \frac{\nu_l}{u_\tau}, \quad (4.8)$$

$$\delta = 0.37x Re_x^{-\frac{1}{5}}. \quad (4.9)$$

δ at the bubble injector is used as a representative length scale of the boundary layer and is denoted δ_b in the following. The model ship was extremely long in terms of the length scale; i.e., $L \sim 1000\delta_b$. Sanders *et al.* [45] introduced the volumetric fraction of air in the boundary layer,

$$\alpha_\delta = \frac{Q_a}{Q_a + UW\delta'}, \delta' = 0.324x Re_x^{-\frac{1}{5}}. \quad (4.10)$$

As shown in Table 4.2, α_δ decreases streamwise direction due to the expansion of the boundary layer. As a control parameter of air lubrication in engineering practice, we use the nominal air-layer thickness, t_a , of the air flow rate (Pavlov *et al.* [12]) as

$$t_a = \frac{Q_a}{UB}, \quad (4.11)$$

where B_a ($= 0.84$ m) is the width of the bubble injector (see Fig. 4.3(b)). t_a was 1.5–6.0 mm and less than the boundary layer thickness δ_a as the normalized nominal air-layer thickness,

$$t_a^* = \frac{t_a}{\delta_b}, \quad (4.12)$$

was less than unity as summarized in Table 4.3. $t_a^* < 1$ indicates that the state of the two-phase flow tends to become a mixture of small bubbles and the liquid phase rather than the stably separated flow of the gas layer and liquid. The flow beneath the bottom plate was visualized by four high-speed cameras mounted on the model ship. The snapshots are shown in Fig. 4.6(a)–(d) for the lowest and highest t_a . All the flow is confirmed to be a mixture of small bubbles except for $t_a = 6.0$ mm at

Table 4.3: Experimental conditions of the air flow rate, Q_a , for the bubble injection and corresponding nominal air-layer thickness t_a . The nondimensional nominal air-layer thickness, t_a^* , is normalized by the boundary layer thickness at the bubble injector.

Q_a [m ³ /s]	t_a [mm]	t_a^* [-]
1.0×10^{-2}	1.5	3.9×10^{-2}
2.0×10^{-2}	3.0	7.8×10^{-2}
3.0×10^{-2}	4.5	1.2×10^{-1}
4.0×10^{-2}	6.0	1.6×10^{-1}

the first observation position ($x = 7.7$ m). At larger t_a , streamwise-elongated bubbles occasionally appeared in this upstream region. These large bubbles advected downstream and broke up into small bubbles during their migration. The bubble size was determined by the natural fragmentation and coalescence in the turbulent boundary layer beneath the model ship (Sanders *et al.* [45]). The size of bubbles was confirmed as being several millimeters in the downstream regions from the snapshots. We obtain the Froude number of bubbles

$$Fr_b = \frac{|u'|}{\sqrt{gd}} \sim \frac{u_\tau}{\sqrt{gd}}, \quad (4.13)$$

where u' and d are turbulent fluctuating velocity and bubble size, respectively. By approximating the magnitude of u' with u_τ and using $d = O(10^{-3})$ m, we obtain $Fr_b \sim O(1)$, indicating the inertia and buoyancy comparably act on the bubbles.

The total resistance and the local wall shear stress with bubble injection were obtained by taking the temporal average over a measurement of 4.0 s within the section 140–180 m from the end of the 400-m-long water tank. Each measurement was performed at 20-minute intervals to allow the calming down of surface waves in the water tank generated by the towing of the model ship.

4.4 Results and discussions

4.4.1 Total resistance of the model ship

The measurement result of the total resistance without bubble injection (R_{t0}) and with bubble injection (R_t) directly gives the reduction of total resistance,

$$\Delta R_t = R_{t0} - R_t. \quad (4.14)$$

For the present model ship having a length of 36 m and breadth of 1 m, the resistance of at most 500 N was decreased by BDR as shown in Fig. 4.7. The ratio of the total resistance reduction ($\Delta R_t/R_{t0}$) increases with t_a up to 15% with the same tendency as observed in the previous study using a long model ship (Watanabe *et al.* [38], Takahashi *et al.* [42], and Kodama *et al.* [79]). This result also agrees with the general tendency of BDR, namely the enhancement of the drag reduction with an increase in the air flow rate for bubble injection.

Using the experimental results of the total resistance of the model ship, we evaluate the reduction of the frictional drag at the bottom plate downstream from the bubble injector termed the air-lubricated part. We refer to the remaining upstream part as the bow part as shown in Fig. 4.8. The areas (respectively, A_b , A_a , A_t) and lengths (respectively, L_b , L_a , L_t) of the bow part, air-lubricated part, and total bottom plate are summarized in Table 4.4. The total resistance can be divided into two components of the frictional resistance, R_f , and residuary resistance, R_r , consisting of wave drag and pressure drag as

$$R_t = R_f + R_r. \quad (4.15)$$

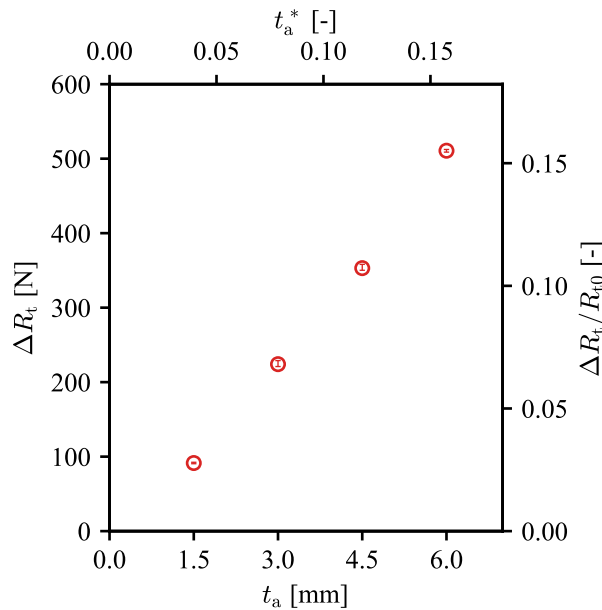


Figure 4.7: Reduction of the total resistance, ΔR_t , and the ratio of the total resistance reduction of the model ship, $\Delta R_t/R_{t0}$, where vertical error bars indicate the maximum and minimum values in three trials. The resistance reduction was obtained for the 36-m-long and 1-m-wide flat-bottom model ship.

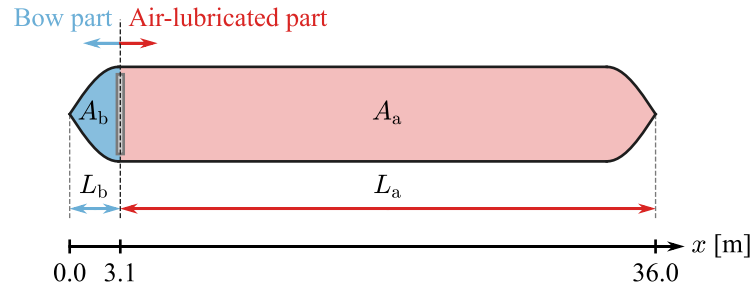


Figure 4.8: Schematic diagram denoting bow part and air-lubricated part of the bottom plate. A_b (A_a) and L_b (L_a) are the length and area of the bow part (air-lubricated part).

Table 4.4: Areas and lengths of the bow part, air-lubricated part, and whole bottom plate

Area of bow part A_b	2.1 m ²
Area of air-lubricated part A_a	32.1 m ²
Total area of bottom plate A_t	34.2 m ²
Length of bow part L_b	3.1 m
Length of air-lubricated part L_a	32.9 m
Total length of bottom plate L_t	36.0 m

Though R_f and R_r are not separately measurable in the present towing test, R_r is thought to be not modified by the bubble injection. Thus, the frictional resistance reduction, ΔR_f , is obtained as

$$\Delta R_f = \Delta R_t. \quad (4.16)$$

The frictional resistance reduction of the model ship is attributed to the frictional drag reduction of the air-lubricated part:

$$\Delta D_{fa} = \Delta R_t. \quad (4.17)$$

In the evaluation of drag-reduction ratio, the frictional drag at the air-lubricated part without bubble injection, D_{fa0} , is not directly measurable. We estimated D_{fa0} with predicting the friction drag coefficient of a plate in a single-phase turbulent boundary layer by the Prandtl–Schlichting law (Schlichting [77]) as

$$C_{fp0}(l) = \frac{0.455}{(\log_{10} Re_l)^{2.58}}, \quad (4.18)$$

where l is the length of the plate and $Re_l = Ul/\nu_1$. The friction drag coefficient of the air-lubricated part in the absence of bubbles, C_{fa0} , and then the frictional drag, D_{fa0} , are obtained by

$$C_{fa0} = \frac{1}{A_a} \{C_{fp0}(L_t) A_t - C_{fp0}(L_b) A_b\}, \quad (4.19)$$

$$D_{fa0} = \frac{1}{2} C_{fa0} \rho U^2 A_a. \quad (4.20)$$

The estimated D_{fa0} and C_{fa0} depending on the towing speed are shown in Fig. 4.4. At $U = 8.0$ m/s, D_{fa0} was approximately 60% of the measured total resistance R_{t0} .

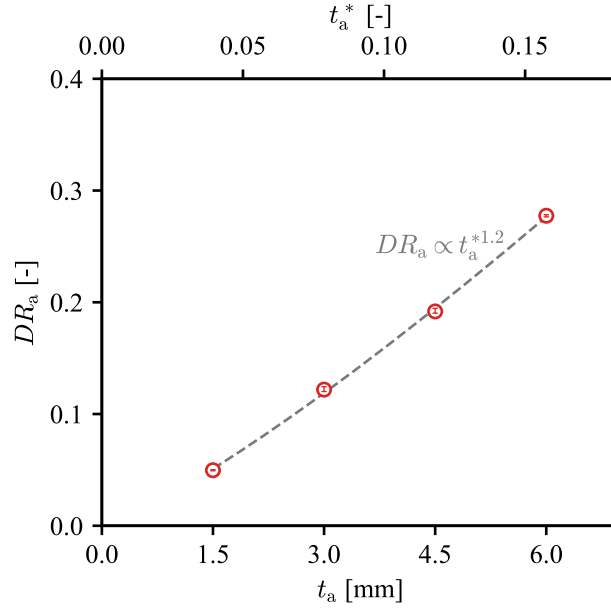


Figure 4.9: Ratio of the frictional drag reduction, DR_a , at the air-lubricated part of the model ship obtained by the measurement of total resistance. The length and area of the air-lubricated part are 32.9 m and 32.1 m², respectively. Vertical error bars indicate the maximum and minimum values in three trials. The dashed line shows the fitting of the experimental results by a power function.

The ratio of the frictional drag reduction at the air-lubricated part, DR_a , was obtained as

$$DR_a = \frac{\Delta D_{fa}}{D_{fa0}}, \quad (4.21)$$

as shown in Fig. 4.9. DR_a increased with t_a and reached 28% at $t_a = 6.0$ mm. Since the growth rate of DR_a also continues to increase as t_a , we fitted power functions to experimental results using the least-squares method and obtained a power index of 1.2 as shown by the dashed line in Fig. 4.9. This means that DR_a increases more rapidly than expected from the linear proportional relation with t_a^* (i.e., the air flow rate of bubble injection). The rapid increase in DR_a can be explained by the transition of the spatial distribution of the local drag reduction depending on the air flow rate as discussed in the following.

4.4.2 Distribution of the local friction coefficient

The local friction coefficient, c_f , was obtained from the local wall shear stress τ as

$$c_f = \frac{2\tau}{\rho_l U^2}. \quad (4.22)$$

The distribution of c_f at 23 measurement positions is shown in Fig. 4.10. At $t_a = 1.5$ – 4.5 mm, c_f is almost equivalent in the spanwise direction at each downstream distance x . At $t_a = 6.0$ mm, however, the spanwise variation appears larger especially at $x = 4.5$ – 20.5 m. In this upstream region, the ununiform spanwise distribution of bubbles is thought to emerge beneath the model ship.

The streamwise distribution of c_f is shown in Fig. 4.11, where c_f is averaged in the spanwise direction across three trials. The black solid line indicates c_{fp0} obtained using Eq. (4.4). At $t_a = 1.5$ and 3.0 mm, c_f is equal to or a little smaller than c_{fp0} at all the downstream distances and

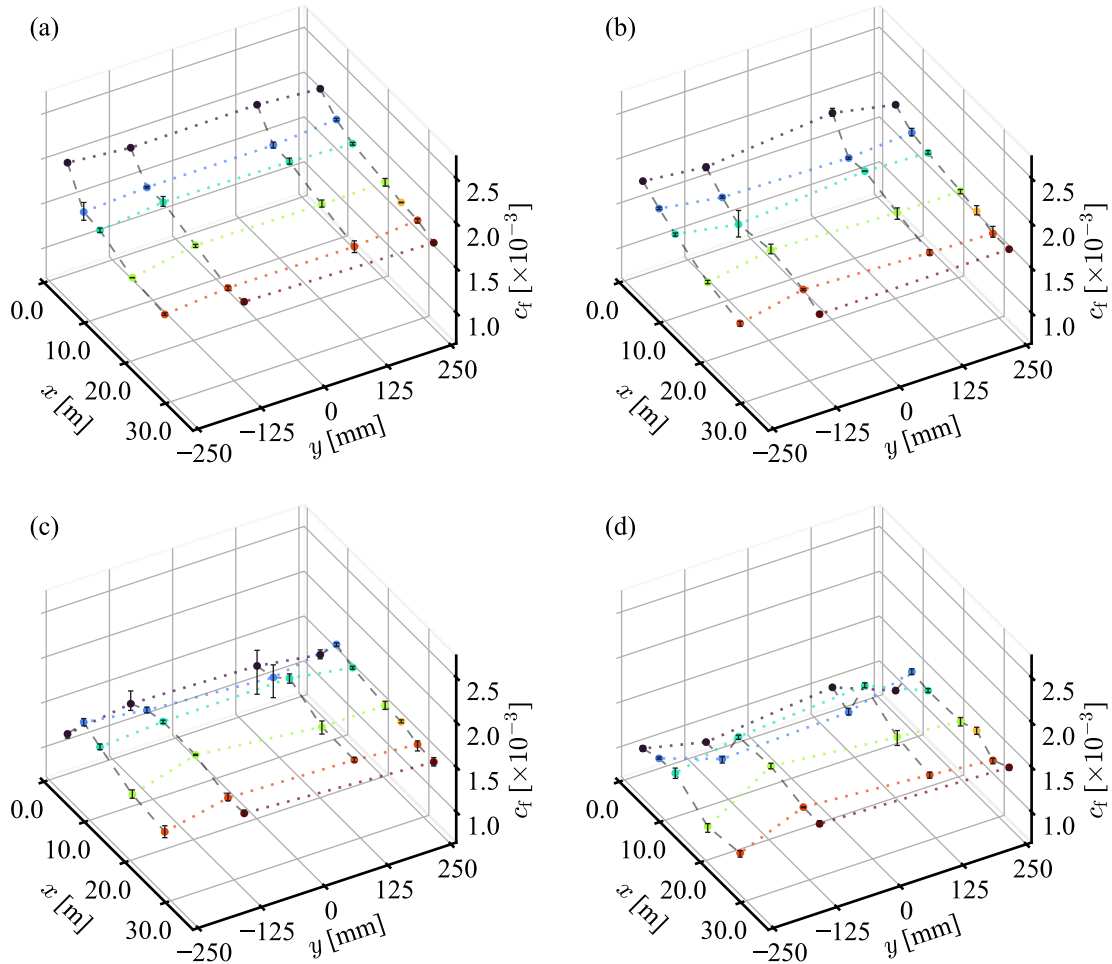


Figure 4.10: Distribution of the local friction coefficient, c_f , on the bottom plate obtained by the measurement of local wall shear stress: (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, (c) $t_a = 4.5$ mm, and (d) $t_a = 6.0$ mm. The dashed lines and the dotted lines respectively indicate the streamwise (x) and spanwise (y) row of the 23 measurement positions. Vertical error bars indicate the maximum and minimum values in three trials at each position.

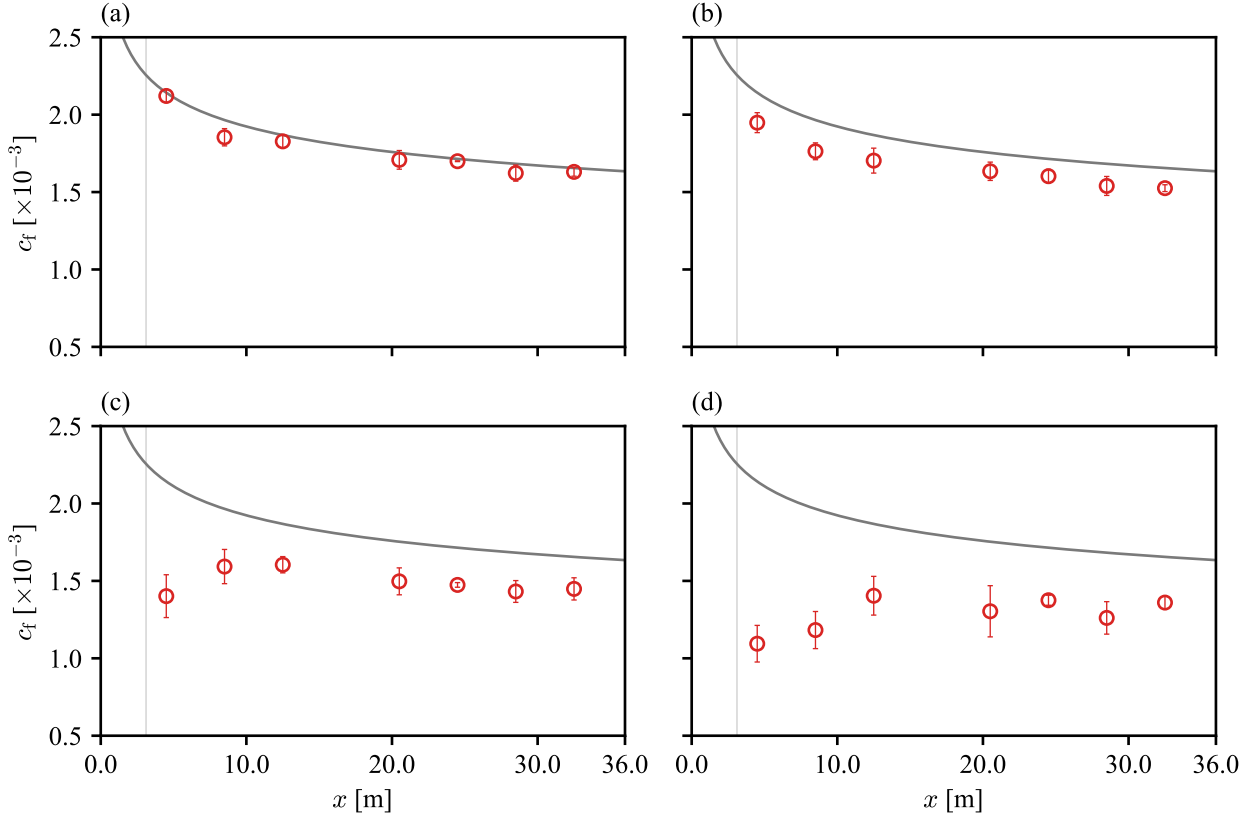


Figure 4.11: Streamwise distribution of the local friction coefficient, c_f : (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, (c) $t_a = 4.5$ mm, and (d) $t_a = 6.0$ mm. Vertical error bars indicate the standard deviation in the spanwise direction across three trials. The solid line indicates the friction coefficient in the single-phase turbulent boundary layer obtained using Eq. (4.4). The vertical dashed line at $x = 3.1$ m indicates the position of the bubble injector.

develops in the streamwise direction in a similar manner to c_{fp0} . This means the realization of weak drag reduction over the entire air-lubricated part. The friction coefficient is lower at $t_a = 4.5$ and 6.0 mm than at the lower t_a . Under these conditions, c_f in the upstream region ($x = 4.5$ – 8.5 m) tends to be smaller than that in the midstream region ($x = 12.5$ m). Such a streamwise increase in c_f does not occur in the single-phase turbulent boundary layer, and it is thus a distinctive feature of BDR observed experimentally in the present study. At $t_a = 4.5$ mm, the manner of the streamwise development of c_f is similar to that of c_{fp0} in the downstream region ($x = 12.5$ – 32.5 m). At $t_a = 6.0$ mm, however, c_f does not simply decrease like c_{fp0} in the downstream region, indicating that the effect of the drag reduction remains transient.

The streamwise variation of the void fraction in the turbulent boundary layer can cause the streamwise transition of the drag-reduction effect. The relationship between the local friction coefficient ratio c_f/c_{fp0} and α_δ is shown in Fig. 4.12. Here, c_f was averaged in the spanwise direction at the same downstream distance. The dashed lines in Fig. 4.10 were obtained by fitting a linear function to the plots and indicate the inclination of c_f/c_{fp0} to α_δ at each t_a . At $t_a = 4.5$ and 6.0 mm, c_f/c_{fp0} decreases with increasing α_δ in correspondence with the general trends of BDR on flat plates (Ceccio [26]). At $t_a = 1.5$ and 3.0 mm, however, c_f/c_{fp0} is less dependent on α_δ and roughly

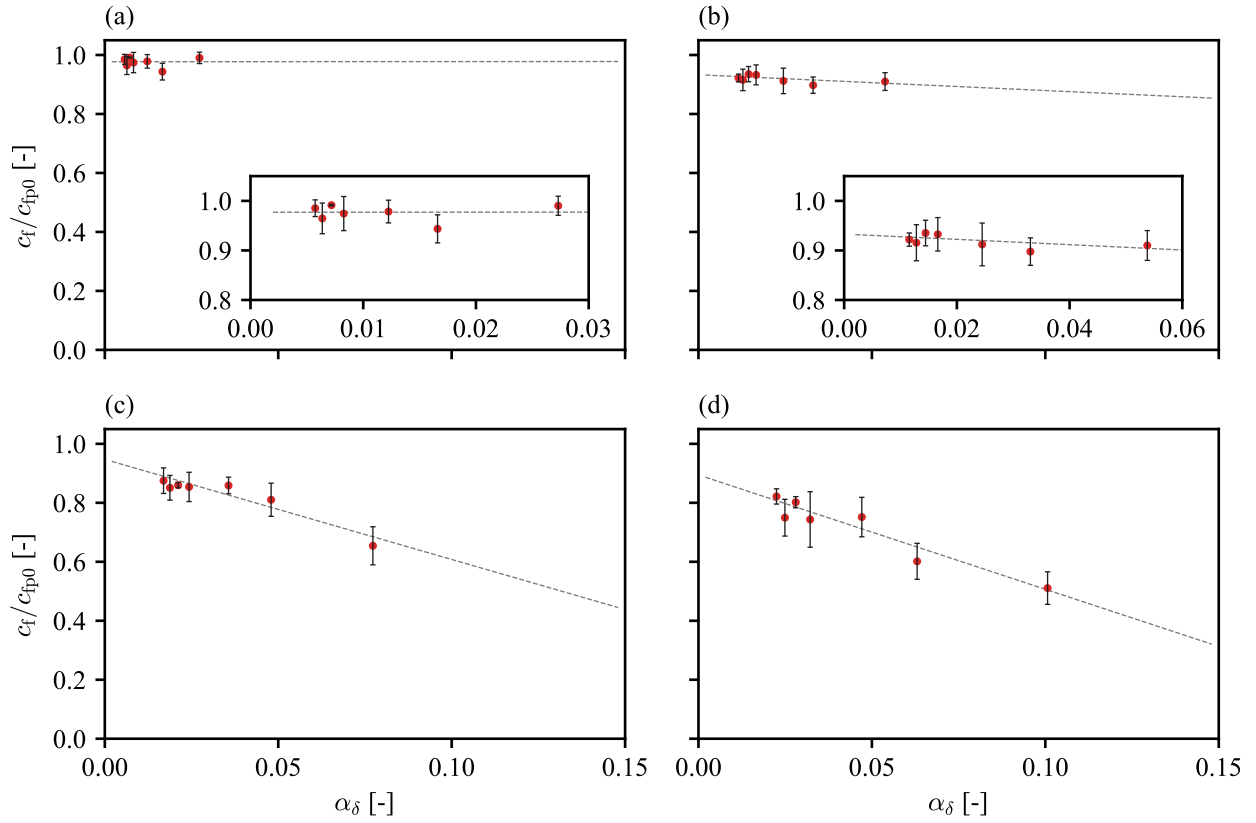


Figure 4.12: Ratio of the local friction coefficient, c_f/c_{fp0} , as a function of the volumetric fraction of air in the boundary layer, α_δ : (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, (c) $t_a = 4.5$ mm, and (d) $t_a = 6.0$ mm. Vertical error bars indicate the standard deviation in the spanwise direction across three trials. The dashed lines show the fitting of a linear function to the plots. Enlarged plots are inserted in (a) and (b).

constant against α_δ . In the turbulent boundary layer beneath the present flat plate, the scaling of c_f/c_{fp0} against α_δ fails, and characteristics of the streamwise transition of the drag-reduction effect depend on t_a .

4.4.3 Streamwise transition of the local drag reduction

The ratio of the local friction coefficient c_f/c_{fp0} is plotted against the downstream distance x in Fig. 4.13. At $t_a = 1.5$ and 3.0 mm, the variation in c_f/c_{fp0} is small. At $t_a = 4.5$ and 6.0 mm, the ratio of the drag reduction exceeds 30% at the first measurement position ($x = 4.5$ m) and decays downstream, approaching a constant value. As shown in Fig. 4.6(a), streamwise-elongated large bubbles appeared at $x = 7.7$ m and broke up during their downstream migration at larger t_a . The notable decay in the drag reduction can be attributed to the streamwise transition of the state of the two-phase flow.

The present model ship experiment was designed as a quasi-full-scale test of BDR, and the experimental conditions of U and t_a were set to equivalent to the practical conditions in the dimensional domain. To allow utilization of the present results for the prediction of performance on

full-scale ships, a model giving extrapolation of the drag-reduction effect is needed. The establishment of a model describing the spatial transition of the drag-reduction effect has been an important effort in the research of BDR. Merkle and Deutsch [83] proposed an exponential function of the local void fraction, and Kumagai *et al.* [9] and Murai *et al.* [13] developed a reciprocal function for the streamwise distance. These prior models, however, do not explicitly express the result of the present experiment, namely the streamwise decay of the drag-reduction ratio. As a new model available for the practical design of BDR, we provide a formula for the ratio of friction coefficient c_{fm} to c_{fp0} as a function of x :

$$\frac{c_{fm}}{c_{fp0}} = 1 - (I_0 - I_\infty) \exp \left[-3 \frac{x - L_b}{L_{95}} \right] - I_\infty. \quad (4.23)$$

This model has three coefficients (i.e., I_0 , I_∞ , and L_{95}) according to the characteristics of the streamwise variation of local drag reduction in the turbulent boundary layer. All the coefficients depend on t_a and U though the ship speed was examined only for $U = 8.0$ m/s in this study. I_0 denotes the initial drag-reduction effect at the bubble injector. I_0 is predicted to become large as the high t_a owing to two reasons: the high local void fraction and the appearance of large bubbles. The void fraction decreases to approach an equilibrium value determined by the distribution of bubbles beneath the two-dimensional bottom plate resulting from the balance of turbulent dispersion and the buoyancy of the bubbles. Moreover, the large bubbles breakup during their migration. These transitions cause the decay of local drag reduction to the downstream effect sufficiently far from the injector, I_∞ . The distance to decay is also thought to be dependent on t_a since the two-way interaction of the bubbles and the liquid phase causes a delay in the transition. As a factor denoting the decay length, the coefficient L_{95} is employed in Eq. (4.23). L_{95} is the 95% decay length of the drag-reduction ratio from I_0 to I_∞ because $\exp[-3(x - L_b)/L_{95}] \approx 0.05$ when $x - L_b = L_{95}$. The coefficients are determined by the curve fitting with the least-squares method using the experimental results of c_f/c_{fp0} . In the fitting, limitations are given for the range of each coefficient as $0 \leq I_0 - I_\infty \leq 1$, $0 \leq I_\infty \leq 1$, and $L_{95} \geq 1.4$ m (i.e., the distance between the bubble injector and the first measurement position). The obtained fitting curves well correspond to the experimental results at each t_a as shown in Fig. 4.13.

The ratio of drag reduction at the air-lubricated part can be calculated through the integration of the local friction coefficients of Eqs. (4.4) and (4.23):

$$DR_a' = 1 - \frac{\int_{L_b}^{L_t} c_{fm} dx}{\int_{L_b}^{L_t} c_{fp0} dx}. \quad (4.24)$$

This method provides the calculation error based on the measurement error of the ratio of local friction coefficient because the value of coefficients in Eq. (4.23) is determined by fitting to the experimental results. The measurement error was evaluated as at most 10% in the standard deviation as shown in Fig. 4.13. The drag-reduction ratio obtained by Eq. (4.24) is compared with DR_a ,

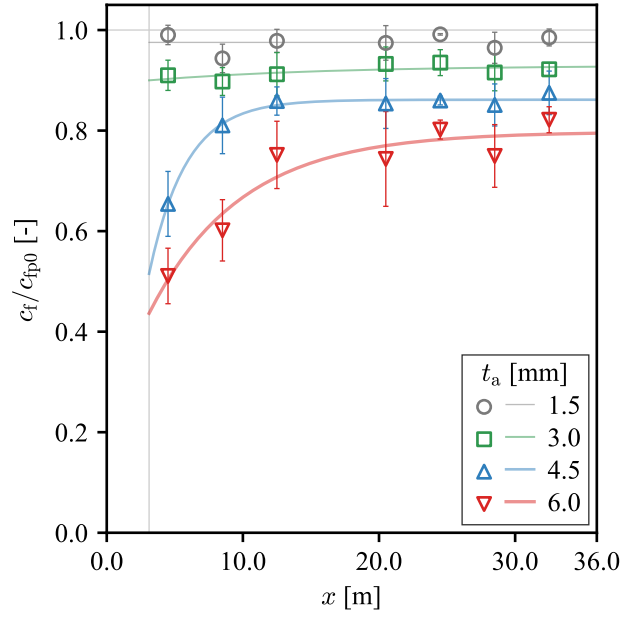


Figure 4.13: Streamwise distribution of the ratio of the local friction coefficient c_f/c_{fp0} , where vertical error bars indicate the standard deviation in the spanwise direction across three trials. The solid lines show the fitting of a curve to the experimental results using Eq. (4.23). The vertical dashed line at $x = 3.1$ m indicates the position of the bubble injector, and the horizontal dotted line denotes $c_f/c_{fp0} = 1.0$.

which is obtained from the measurement of total resistance, in Fig. 4.14. At $t_a = 4.5$ and 6.0 mm, DR_a and DR'_a show good correspondence as the plots are close to the dashed line indicating the agreement of values. It confirms the negligibly small change of the residuary resistance included in the total resistance with bubble injection assumed in Eq. (4.16). At $t_a = 1.5$ and 3.0 mm, DR'_a is definitely smaller than DR_a . Under these conditions, the strong drag reduction emerging immediately after the bubble injector possibly decays before the first measurement position of the local friction coefficient. This can result in the underestimation of the drag reduction.

Coefficients for each t_a are given in Table 4.5. Both I_0 and I_∞ increase with t_a , indicating the intensification of the drag-reduction effect at the entire air-lubricated part. Although I_∞ becomes large by degrees with t_a , I_0 suddenly increases in the range $t_a = 3.0$ to 4.5 mm. This implies that the appearance of the streamwise-elongated large bubbles (see Fig. 4.6(a)) dramatically improves the local drag-reduction effect. Another possible reason for the sudden increase in I_0 is the decay of the initial drag-reduction effect before the first measurement position in behavior similar to the loss of drag reduction a few meters downstream from the bubble injector for higher-speed flows (Elbing *et al.* [25] and Sanders *et al.* [45]). Additionally, L_{95} has two jumps from $t_a = 1.5$ to 3.0 mm and from $t_a = 4.5$ to 6.0 mm. Each means the increase of the streamwise persistence of the drag reduction in upstream regions. The decrease of L_{95} from $t_a = 3.0$ to 4.5 mm is caused by the drastic change of initial effect I_0 due to appearance of large bubbles. That is, L_{95} at the lower t_a reacts to the relatively smaller drag reduction at the upstream region, and that at higher t_a is associated with the stronger drag reduction. This switch is allowed since one combination of all the coefficients denotes the characteristics of the streamwise transition of drag reduction. The trend of increase

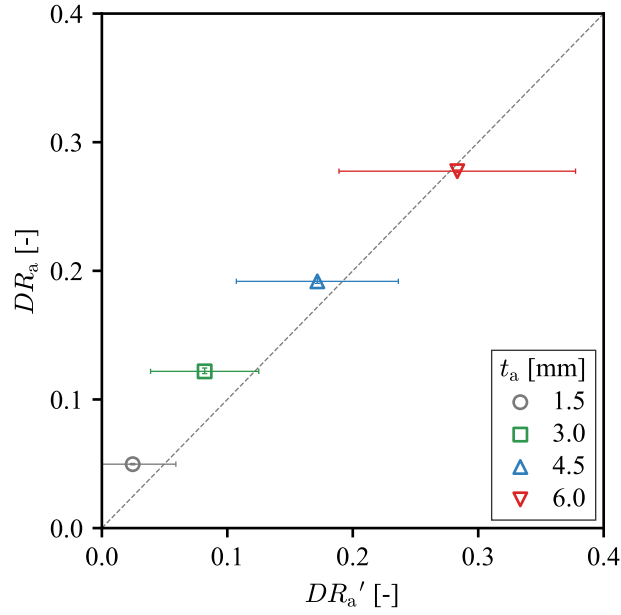


Figure 4.14: Correlation of the ratio of drag reduction obtained from the two types of measurement: the local wall shear stress (DR'_a) and the total resistance of the model ship (DR_a). Vertical error bars indicate the maximum and minimum values of DR_a in three trials identical to Fig. 4.9, and horizontal error bars show the estimated error of DR'_a at each t_a using the streamwise-maximum standard deviation of c_f/c_{fp0} in the spanwise direction across three trials shown in Fig. 4.13.

in L_{95} indicates the self-elongation of the persistence of the initial effect as the longer distance is required to recover the turbulence after the stronger drag reduction. Importantly, the present large-scale towing test and the experimental model of Eq. (4.23) quantitatively show that the drag reduction can persist for longer than 20 m in a boundary layer with a sufficiently high air flow rate. The improvement in the local drag-reduction effect at multiple points (i.e., improvements of the initial effect, downstream effect, and persistence) comprehensively raises the total drag-reduction ratio at the air-lubricated part.

Note that the model of Eq. 4.23 is proposed for engineering use to predict total drag reduction and the included coefficients are determined by the fitting to the experimental results. The coefficients shown in Table 4.5 are determined by three trials using a model ship now. In the strict view, the coefficients are available only for the ship speed of 8.0 m/s and nominal air-layer thickness conditions investigated in this study. However, the trends are expected to be applicable to conditions close to the present experiments with caution to the existence of the abrupt transition of the drag-reduction regime in air lubrication (Elbing *et al.* [25]). The accuracy and the applicability to wide parameters of these coefficients need improvement with more experimental data on long hulls like the present model ship.

4.4.4 Full-scale estimation

On the basis of Eq. (4.23) obtained from the experiment using the 36-m-long model ship, a method of estimating the drag reduction of a full-scale ship is proposed in this section. I_∞ is treated as zero

Table 4.5: Characteristics of the streamwise transition of the drag-reduction effect described by the coefficients in Eq. (4.23) at each t_a , which is obtained by the measurement of local shear stress at 23 positions on the bottom plate. These coefficients represent a drag-reduction performance at a 36-m-long flat-bottom model ship on average across three trials.

t_a [mm]	I_0 [-]	I_∞ [-]	L_{95} [m]
1.5	0.02	0.02	1.4
3.0	0.10	0.07	39.1
4.5	0.49	0.14	8.2
6.0	0.56	0.20	20.3

in the estimation because the drag reduction is thought to expire a sufficient distance downstream on a hull with a three-dimensional shape, and the local friction coefficient on ship hulls is estimated as

$$c_{fe} = c_{fp0} \left(1 - I_0 \exp \left[-3 \frac{x - x_b}{L_{95}} \right] \right). \quad (4.25)$$

Here, x_b is a position of bubble injector, and we supposed that the rest coefficients, I_0 and L_{95} , are not modified from the result of the model ship experiment. The integration of the local friction coefficients of single-phase flow (c_{fp0}) and under BDR (c_{fe}) gives the prediction of drag-reduction ratio at the air-lubricated part of the ship as

$$DR_e = 1 - \frac{\int_{x_b}^{L_{ship}} c_{fe} dx}{\int_{x_b}^{L_{ship}} c_{fp0} dx}. \quad (4.26)$$

This method provides the error of estimation attributed to the measurement error of the ratio of local friction coefficient because the value of coefficients in Eq. (4.25) is based on the experimental results. The measurement error in the present experiment was evaluated as at most 10% in the standard deviation as shown in Fig. 4.13.

As a case of expansion of Eq. (4.26) to a practically probable design of BDR for ships, we suppose the situation of bubble injection at multiple streamwise distances (i.e., n -point injections). The drag-reduction ratio, DR_n , at the air-lubricated part of the ship is calculated as

$$DR_n = 1 - \frac{\int_{x_1}^{L_{ship}} c_{fp0} (1 - \sum_{k=1}^n J_k) dx}{\int_{x_1}^{L_{ship}} c_{fp0} dx}, \quad (4.27)$$

$$J_k = \begin{cases} 0 & (x < x_k) \\ I_0 \exp \left[-3 \frac{x - x_k}{L_{95}} \right] & (x \geq x_k), \end{cases} \quad (4.28)$$

where n is the number of bubble injectors, and L_{ship} and x_1 are respectively the length of the ship and the position of the first bubble injector. The term J_k denotes the downstream drag reduction induced by the bubble injection at the k -th position, x_k . We use the experimental result of I_0 and L_{95} in Eq. (4.28) and assume that J_k can be simply summed over the multiple injections in the present equation referring to the experimental results of Watanabe *et al.* [38]. As an example of the

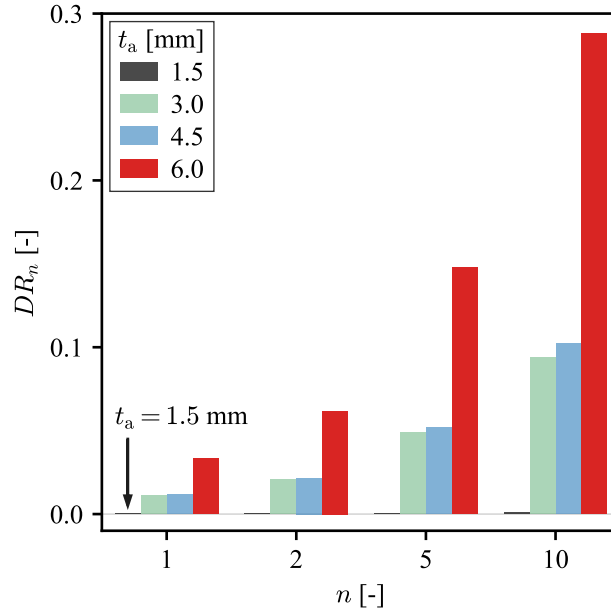


Figure 4.15: Full-scale estimation of the drag reduction using Eqs. (4.27)–(4.29) with the bubble injection at single and multiple streamwise distances. The experimentally obtained characteristics of streamwise transition of drag-reduction effect shown in Table 4.5 were used in the estimation.

estimation, a condition is given: $L_{\text{ship}} = 150$ m, $x_1 = 20$ m, and the positions of bubble injector as

$$x_k = x_1 + \frac{k-1}{n} (L_{\text{ship}} - x_1). \quad (4.29)$$

The prediction of DR_n can provide the error caused by the measurement error likewise DR_e . DR_n calculated for various n is shown in Fig. 4.15 and as a whole corresponds to the level of the drag reduction obtained in previous full-scale sea trials (Kodama *et al.* [7], Mizokami *et al.* [8], Kumagai *et al.* [9], and Mizokami and Kuroiwa [10]). In the case of $n = 1$, DR_n at $t_a = 6.0$ mm is approximately twice that at $t_a = 4.5$ mm although the drag-reduction ratio of the model ship differed less between these values of t_a (see Fig. 4.9). The contribution of the persistence of the drag-reduction effect strongly emerges in the full-scale estimation. As an increase in DR_n with the increment of n is confirmed by Fig. 4.15, Eq. (4.25) can be used to easily predict the drag reduction in support of the practical design of BDR of ships.

4.5 Conclusions

The reduction of frictional drag through bubble injection in a turbulent boundary layer was examined using a 36-m-long flat-bottom model ship towed at 8.0 m/s, for which the Reynolds number Re_L reached 2.9×10^8 . The resistance of the model ship and the distribution of the local wall shear stress on the entire bottom plate was experimentally measured for the first time. We confirmed that the ratio of the drag reduction at the air-lubricated part on the bottom plate increased with the air flow rate for the bubble injection and reached 28% on bulk average, whereas the local drag reduction was 50% behind the bubble injector. By increasing the air flow rate, the local drag reduction was enhanced at all measurement positions until the end of the ship. Additionally, the local drag reduction has a profile that decays with the downstream distance depending on the air flow rate. Considering this feature, we presented a formula (Eq. 4.23) describing the streamwise transition of the ratio of the friction coefficient by finding the most approximate but simplest mathematical functions. The evaluation using this function quantitatively characterized the drag-reduction performance in terms of the initial effect at the bubble injector, the downstream effect, and the downstream persistence of the initial drag-reduction effect. All the performances were improved by increasing the air flow rate, and the persistence reached 20 m in the best case.

Owing to the present quasi-full-scale test, the persistence of the drag reduction at several tens of meters was experimentally demonstrated. Using the experimental result for the 36-m-long model ship, we proposed a method of predicting the drag reduction for a full-scale ship. The results of the full-scale estimation again highlighted the importance of the persistence of local drag reduction for the total drag reduction of a ship. The function used in the present full-scale estimation is flexibly adaptable for the future design of the practical application of BDR to ships.

CHAPTER 5

RBI in a turbulent boundary layer beneath a 36-m-long model ship

Preface

This chapter examines the drag reduction of repetitive bubble injection (RBI) in a quasi-full-scale condition using a 36-m-long flat-bottom model ship towed at 8.0 m/s. The performance of RBI is compared with that of continuous bubble injection (CBI) in terms of the total drag reduction of the model ship and the local friction reduction. The feature of RBI is quantitatively evaluated using the formula of streamwise transition proposed in the previous chapter. This work was published in Tanaka *et al.*, Ocean Eng. (2023).

5.1 Introduction

In the context of exploring the way to maximize efficiency of bubble drag reduction (BDR) per unit air volume, repetitive bubble injection (RBI) was found to be an effective solution. In an initial study, RBI had higher drag reduction than the conventional method (i.e., continuous bubble injection, CBI) at the same void fraction in turbulent horizontal channel flow (Park *et al.* [54]). Later studies of RBI and the related researches are listed in Table 5.1. The results motivated the present study using the turbulent boundary layer beneath a 36-m-long model ship towed at 8 m/s as the quasi-full-scale test of RBI. RBI generates spatiotemporal fluctuation of the local void fraction, termed the void wave, in the flow. Even in CBI, void waves spontaneously emerge downstream in bubbly turbulent boundary layers. Drag reduction is enhanced with the appearance of spontaneous void waves (Park *et al.* [55], [57]). Park *et al.* [55] derived the void-wave equation from the two-fluid model equations, and Oishi *et al.* [59] experimentally observed the temporal correlation of the local void fraction and local wall shear stress inferred from the equation. The idea of RBI originates from the active use of artificially generated void waves in promoting drag reduction.

In this study, the results of CBI in Chapter 4 is used for comparison. The primary interest is whether drag reduction is promoted by RBI in the high-speed flow of an open system such as a ship. The total resistance of the model ship and the local wall shear stress at 23 locations on a flat-bottom plate were measured in the experiment. The downstream transition of local drag reduction is related to the state of two-phase flow in the turbulent boundary layer (Elbing *et al.* [25] and Sanders *et al.* [45]). The state beneath the model ship was visually confirmed at four locations using high-speed video cameras. The present results of the distribution of the local wall shear stress identify the downstream persistence of the drag-reduction effect. The long persistence is favorable for large ships as will be discussed for the full-scale estimation of drag-reduction performance.

Table 5.1: Previous studies on RBI and void waves promoting frictional drag reduction

Investigator	Configuration	Flow speed [m/s]	Length [m]	Findings
Park <i>et al.</i> [54]	Horizontal channel	1.1	6.0	First confirmation of drag-reduction promotion by RBI
Park <i>et al.</i> [55]	Model ship	2.0–3.0	4.0	Spontaneous emergence of void waves
Park <i>et al.</i> [57]	Model ship	3.0	4.0	Frequency of spontaneous void waves
Tanaka <i>et al.</i> [88]	Horizontal channel	1.4	6.0	Propagation of artificial void waves
Oishi <i>et al.</i> [59]	Horizontal channel	0.5–2.5	4.0	Temporal correlation between local void fraction and local wall shear stress
Park <i>et al.</i> [89]	Horizontal channel	1.5	4.0	Modeling of void-wave propagation
Chapter 2	Model ship	1.5–3.0	4.0	Downstream persistence of artificial void waves in turbulent boundary layers
Chapter 3	Horizontal channel	6.0–8.0	3.0	Promotion of drag reduction by RBI in high-speed flows

5.2 Experimental facility and setup

The experiment was conducted in a towing test facility at the National Maritime Research Institute, Tokyo, Japan, which has been certified as a standard institute for ship performance examination (ISO 9001). The dimensions of the water tank shown in Fig. 5.1(a) were 400 m in length, 18 m in width, and 8 m in depth. The temperature of the water was $20.6^\circ\text{C} \pm 0.4^\circ\text{C}$, and the density and the kinematic viscosity were $\rho_1 \approx 1.0 \times 10^3 \text{ kg/m}^3$ and $\nu_1 \approx 0.99 \times 10^{-6} \text{ m}^2/\text{s}$, respectively. The train towing the model ship moved over the water tank as shown in Fig. 5.1(b). The model ship had a slender shape with a length of 36.0 m and breadth of 1.0 m as summarized in Table 5.2. The bottom of the model ship was a flat plate. Protrusions at the bow perturbed the inflow to initiate the development of two-dimensional turbulent boundary layers beneath the bottom plate. The bottom plate of the model ship was equipped with side walls of 50 mm in height and a center keel of 20 mm in height. The side walls confined the bubbles beneath the model ship (Kawashima *et al.* [87]) and averted the entry of hydraulic waves to the bottom. The center keel prevented the uneven accumulation of bubbles toward one side of the ship to preserve the balance around the roll axis. The draft was kept at 70 mm during the experiment, and the wetted surface area including the side walls and center keel was 46.8 m^2 .

The model ship was connected to the train by a towing rod at a position 7 m from the bow. A load cell (TP-U-500, ORIENTEC Co., Ltd., Japan) was incorporated in the connecting rod for the measurement of the total resistance acting on the model ship R_t . Under the experimental condition of a towing speed $U = 8.0 \text{ m/s}$, the total resistance without bubble injection was $R_{t0} = 3.3 \times 10^3 \text{ N}$. The variation in the measured total resistance was confirmed to be less than $\pm 5 \text{ N}$ in three trials.

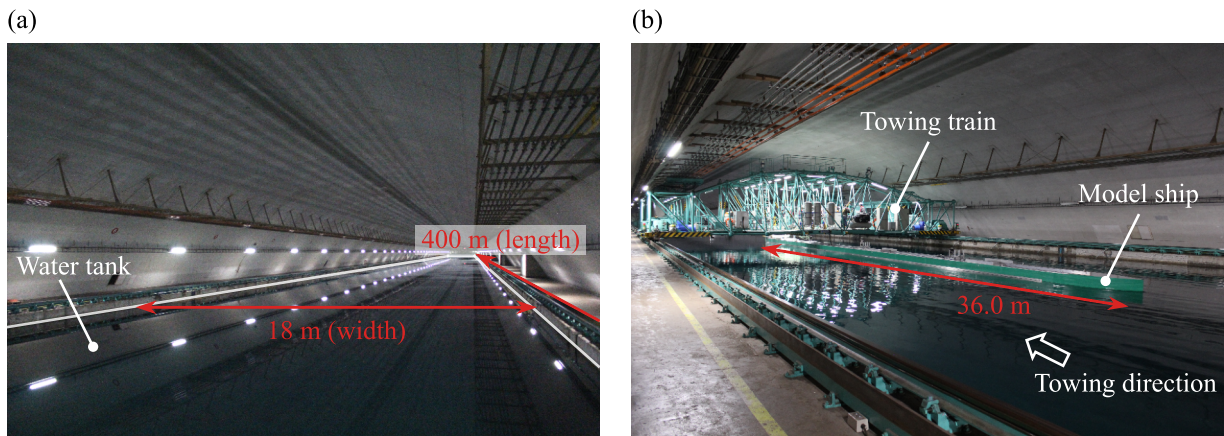


Figure 5.1: Photographs of the towing test facility: (a) 400-m-long and 18-m-wide water tank with a depth of 8 m and (b) the train towing the 36-m-long model ship as viewed from behind

Table 5.2: Principal particulars of the model ship and specifications of the bottom plate. The bow part and air-lubricated part respectively refer to the upstream and downstream sections of the bottom plate from the bubble injector.

Model ship	
Length	36.0 m
Breadth	1.0 m
Draft (d)	70 mm
Wetted surface area	46.8 m ²
Breadth of bubble injector (B)	0.84 m
Bottom plate	
Total length (L_t)	36.0 m
Total area (A_t)	34.2 m ²
Length of bow part (L_b)	3.1 m
Area of bow part (A_b)	2.1 m ²
Length of air-lubricated part	32.9 m
Area of air-lubricated part	32.1 m ²

The plate-length-based Reynolds number and Froude number are defined as

$$Re_L = \frac{UL_t}{\nu_1}, \quad (5.1)$$

$$Fr_L = \frac{U}{\sqrt{gL_t}}, \quad (5.2)$$

and they had values of $Re_L = 2.9 \times 10^8$ and $Fr_L = 0.05$. Here, L_t is the length of the bottom plate. The frictional drag was reduced by bubble injection at the bottom plate downstream from the bubble injector located 3.1 m from the bow. We refer to this downstream section as the air-lubricated part and the remaining upstream section as the bow part as shown in Fig. 5.2. The length and area of the total bottom plate, bow part, and air-lubricated part are summarized in Table 5.2. Following Chapter 4, the frictional drag of the air-lubricated part in the absence of bubbles, D_{fa0} , is estimated as follows. The friction drag coefficient of a plate in turbulent boundary layers is given by the Prandtl–Schlichting law (Schlichting [77]):

$$c_{fp0}(l) = \frac{0.455}{(\log_{10} Re_l)^{2.58}}, \quad (5.3)$$

where $Re_l = Ul/\nu_1$ and l is the length of the plate. The increment of the frictional drag from the bow part to the total bottom plate corresponds to D_{fa0} :

$$D_{fa0} = \frac{1}{2}\rho_1 U^2 \{c_{fp0}(L_t) A_t - c_{fp0}(L_b) A_b\}, \quad (5.4)$$

where L and A respectively refer to the length and area and the subscripts “t” and “b” respectively refer to the total bottom plate and bow part. The frictional drag of the air-lubricated part was estimated as $D_{fa0} = 1.8 \times 10^3$ N, which is approximately 55% of the total resistance R_{t0} .

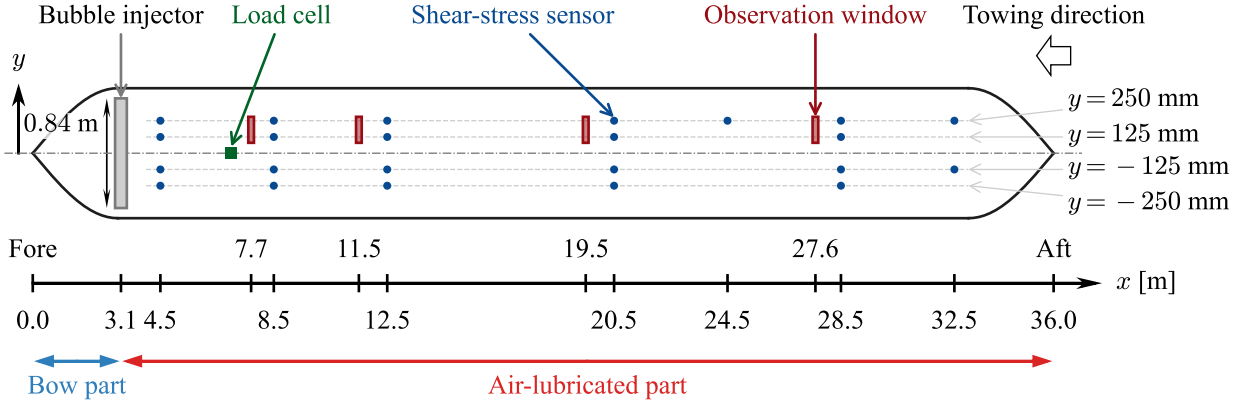


Figure 5.2: Schematic diagram of the model ship, where x and y coordinates are respectively the downstream distance from the bow and spanwise position. Bubbles were injected into the turbulent boundary layer at $x = 3.1$ m. The model ship was connected to the towing train at $x = 7$ m by a rod incorporating a load cell. The circles show the arrangement of 23 shear-stress sensors on the bottom plate. High-speed video cameras were mounted above the four observation windows at approximately 1 m upstream from rows of shear-stress sensors. The bottom plates of the upstream and downstream sections from the bubble injector are respectively referred to as the bow part and air-lubricated part.

The wall shear stress acting on the bottom plate, τ , was directly measured by shear-stress sensors (S10W-2S, SSK Co., Ltd., Japan) carefully mounted flush with the target plane. Each sensor measured the shear stress locally using a mechanical force gauge with a 10-mm-diameter sensing plate. The maximum measurable range was 40 Hz, which was adequately high to resolve the temporal fluctuation imposed by RBI in the present experiments. The arrangement of 23 sensors on the model ship is shown in Fig. 5.2, where x and y coordinates are respectively the downstream distance from the bow and the spanwise position. The sensors were aligned in the streamwise direction at 4.0-m intervals from $x = 4.5$ m except for $x = 16.5$ m and in the spanwise direction at $y = 250, 125, -125$, and -250 mm. These sensors were of the same type as those used in Chapter 4 and calibrated following the same procedure. In the calibration, the local friction coefficient in the single-phase turbulent boundary layer on a plate is given by the Prandtl–Schlichting law (Schlichting [77]),

$$c_{fp0} = (2 \log_{10} Re_x - 0.65)^{-2.3}, \quad (5.5)$$

and the local wall shear stress is obtained as

$$\tau_{p0} = \frac{1}{2} c_{fp0} \rho_l U^2. \quad (5.6)$$

Here, the downstream-distance-based Reynolds number is defined by

$$Re_x = \frac{Ux}{\nu_l}. \quad (5.7)$$

Table 5.3: Characteristics of the single-phase turbulent boundary layer beneath the bottom plate of the model ship at the bubble injector and stern: downstream-distance-based Reynolds number, Re_x ; local friction coefficient, c_{fp0} ; friction velocity, u_τ ; friction length, l_τ ; thickness of turbulent boundary layer, δ . δ at $x = 3.1$ m is used as a representative length scale of the boundary layer, δ_b .

	$x = 3.1$ m (bubble injector)	$x = 36.0$ m (stern)
Re_x [-]	2.5×10^7	2.9×10^8
c_{fp0} [-]	2.3×10^{-3}	1.6×10^{-3}
u_τ [m/s]	2.7×10^{-1}	2.3×10^{-1}
l_τ [m]	3.7×10^{-6}	4.3×10^{-6}
δ [m]	3.8×10^{-2} ($= \delta_b$)	2.7×10^{-1}

All the sensors were calibrated by a measurement of the single-phase flow using τ_{p0} . The single-phase flow was measured for calibration immediately before and after each series of three trials under individual experimental conditions of RBI. The measurement range of the sensors was ± 250 Pa. All the sensors used in the experiment were inspected in advance and had 1.92% nonlinearity, 1.26% repeatability, and 1.39% hysteresis of the rated output.

The total resistance and the local wall shear stress with bubble injection were obtained by taking the temporal average over a measurement of 4.0 s within the section 140–180 m from the end of the 400-m-long water tank. The measurement time and the test section were chosen to comply safety management of the high-speed towing test. A wait time of more than 20 minutes between trials was adopted to allow the calming of surface waves in the water tank generated by the towing of the model ship. The characteristics of the single-phase turbulent boundary layer beneath the model ship are given in Table 5.3 for $x = 3.1$ m (the bubble injector) and $x = 36.0$ m (the stern). Using Re_x and c_{fp0} respectively defined by Eqs. (5.7) and (5.5), the friction velocity u_τ , friction length l_τ , and thickness of the boundary layer δ are obtained as

$$u_\tau = \sqrt{\frac{1}{2} c_{fp0} U^2}, \quad (5.8)$$

$$l_\tau = \frac{\nu_l}{u_\tau}, \quad (5.9)$$

$$\delta = 0.37 x Re_x^{-\frac{1}{5}}. \quad (5.10)$$

The thickness of the boundary layer at the bubble injector, δ_b , is used as a representative length scale of the boundary layer hereafter.

5.3 Experimental conditions

5.3.1 Conditions of RBI

A part of the bottom plate at 3.1 m from the bow was replaced with a bubble injector with a 0.84-m-wide acrylic plate having 41 holes of 30 mm in diameter (Fig. 5.2). Compressed air was supplied to the holes for the injection of bubbles into the turbulent boundary layer. A pulsatile gas flow rate control system (Takeuchi and Kagawa [74]) was used to regulate the air flow rate. The control system comprised a gas thermometer, pressure sensors, electromagnetic valves, and gas flow rate meters. This system can periodically fluctuate the air flow rate with a repetition frequency up to 20 Hz. The periodical fluctuations were controlled to have square waveforms as shown in Fig. 5.3, where T and T' are respectively the period of one cycle and the duration of bubble injection. The experimental parameters of RBI, namely the repetition frequency, f , and duty cycle, γ , were determined by T and T' as

$$f = \frac{1}{T}, \quad (5.11)$$

$$\gamma = \frac{T'}{T}. \quad (5.12)$$

The conditions of RBI examined in the present experiment are summarized in Tabl 5.4. The time-averaged air flow rate, Q_a , was set at 1.0×10^{-2} , 2.0×10^{-2} , and 3.0×10^{-2} m³/s. In the periodic fluctuation, the instantaneous minimum air flow rate was controlled to be zero, and the instantaneous maximum air flow rate was thus $4Q_a$ at $\gamma = 0.25$ and $2Q_a$ at $\gamma = 0.50$ as shown in Fig. 5.3.

In engineering practice, the nominal air-layer thickness (Pavlov *et al.* [12]),

$$t_a = \frac{Q_a}{UB} \quad (5.13)$$

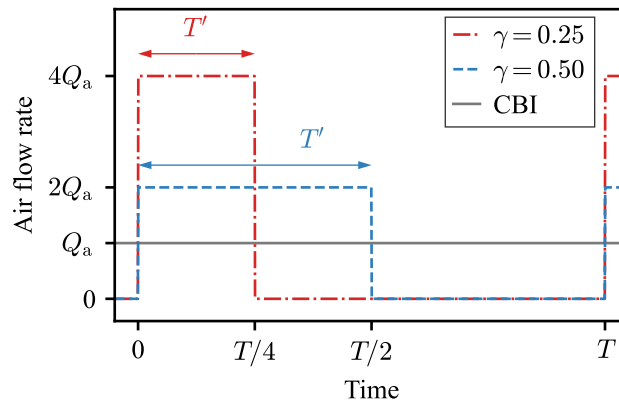


Figure 5.3: Time diagram of the air flow rate control for RBI, where T and T' are respectively the period of one cycle and the duration of bubble injection. The time-averaged air flow rate, Q_a , was the same for RBI of each duty cycle, $\gamma (= T'/T)$, as well as CBI. The air flow rate periodically fluctuated between zero and the maximum, namely $4Q_a$ at $\gamma = 0.25$ and $2Q_a$ at $\gamma = 0.50$.

Table 5.4: Experimental conditions of RBI: time-averaged air flow rate, Q_a ; repetition frequency, f ; duty cycle, γ ; nominal air-layer thickness, t_a ; non-dimensional nominal air-layer thickness, t_a^*

Q_a [m ³ /s]	f [Hz]	γ [-]	t_a [mm]	t_a^* [-]
1.0×10^{-2}	0.5, 1.0, 2.0	0.25, 0.50	1.5	3.9×10^{-2}
2.0×10^{-2}	0.5, 1.0, 2.0	0.25, 0.50	3.0	7.8×10^{-2}
3.0×10^{-2}	0.5	0.25, 0.50	4.5	1.2×10^{-1}

is used as an indicator of air flux in a flow, where B is the width of the bubble injector. t_a ranged 1.5–4.5 mm in the present experiment and was equivalent to the practical condition of BDR on ships (Mizokami *et al.* [8]). The ratio of t_a to the boundary layer thickness δ_b provides the normalized nominal air-layer thickness,

$$t_a^* = \frac{t_a}{\delta_b}. \quad (5.14)$$

Under the present condition that $t_a^* < 1$ (see Table 5.4), the bubbly flow is thought to be confined in the turbulent boundary layer, and blowing air tends to produce bubbles dispersed in the continuous liquid phase rather than stable cavities separated from the liquid flow.

5.3.2 Observation of bubbly flow produced by RBI

The state of the two-phase turbulent boundary layer beneath the bottom plate was observed at four locations, namely $x = 7.7, 11.6, 19.6$, and 27.6 m, through transparent acrylic windows illuminated by white-light sources. A high-speed line-scanning camera at $x = 7.7$ m and three high-speed video cameras at the other locations recorded the light reflected from the bubbles. The distribution of migrating bubbles is shown in Fig. 5.4 by timeline images for CBI and RBI at $t_a = 3.0$ mm. There was a periodical passage of bubble swarms corresponding to frequency f in upstream regions ($x = 7.7$ and 11.6 m). Bubble swarms elongated streamwise during their advection owing to bubble dispersion in the turbulent flow, and the periodicity became unclear in downstream regions ($x = 19.6$ and 27.6 m), especially at $f = 2.0$ Hz.

Under the present flow conditions, the bubbles approached an equilibrium size of several millimeters naturally determined by the balance of bubble fragmentation and coalescence. We calculate the Froude number of bubbles

$$Fr_b = \frac{|u'|}{\sqrt{gd}} \sim \frac{u_\tau}{\sqrt{gd}}, \quad (5.15)$$

where u' and d are turbulent fluctuating velocity and bubble size, respectively. By approximating the magnitude of u' with u_τ and using $d = O(10^{-3})$ m, we obtain $Fr_b \sim O(1)$, indicating the inertia and buoyancy comparably act on the bubbles. In Chapter 4, streamwise-elongated large bubbles were confirmed to appear in upstream regions and brake up into the small bubbles downstream with CBI at $t_a \geq 4.5$ mm. In the case of RBI, such large bubbles were generated even at $t_a = 3.0$ mm as circled in Fig. 5.4 owing to the instantaneous maximum air flow rate being much larger than CBI at the same t_a . The large bubbles broke up during their migration, and only small bubbles were

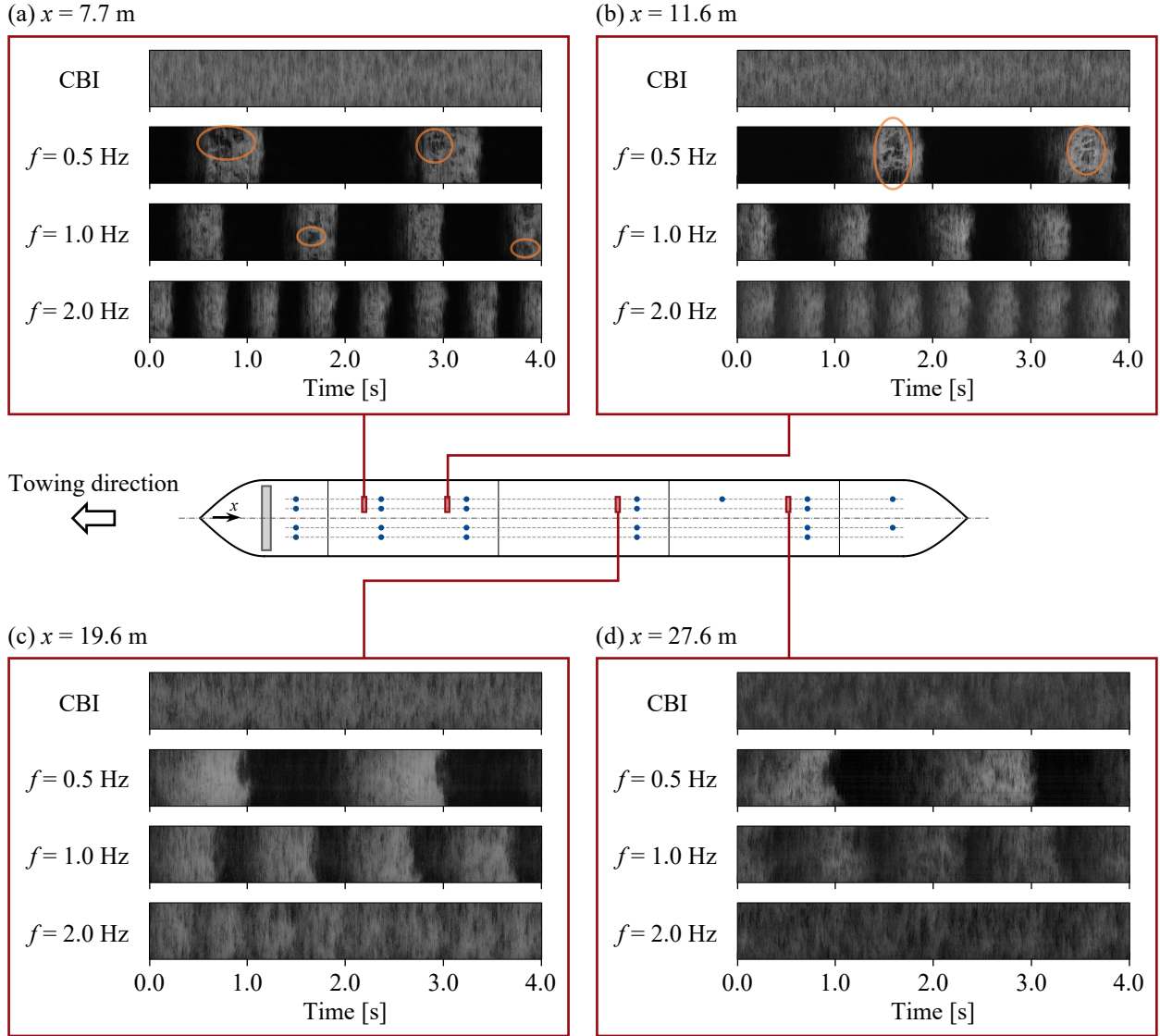


Figure 5.4: Streamwise timeline images of the bubbly flow beneath the bottom plate taken through observation windows with CBI at $t_a = 3.0$ mm and RBI at $(t_a, \gamma) = (3.0 \text{ mm}, 0.25)$. The images were obtained by (a) a high-speed line-scanning camera and (b, c, d) high-speed video cameras. Crowds of small bubbles appear as white areas owing to the reflection of the illumination from above. Circles on the images denote large bubbles surrounded by the bubble crowd. The x coordinate is the downstream distance from the bow.

observed in downstream regions. RBI is expected to provide streamwise transitions of the local drag reduction entirely different from those of CBI owing to the difference in the state of bubbly flow. At $t_a = 4.5$ mm, there can be a competition of local drag reduction between CBI and RBI in upstream regions because such large bubbles appeared for both methods.

5.4 Results and disucussion

5.4.1 Promotion of drag reduction by RBI

The reduction of total resistance, ΔR_t , is obtained as

$$\Delta R_t = R_{t0} - R_t, \quad (5.16)$$

and is shown in Fig. 5.5. ΔR_t is improved by RBI at $f = 0.5$ Hz relative to CBI at each t_a . At $f = 0.5$ Hz, $\gamma = 0.25$ results in larger ΔR_t than $\gamma = 0.50$. Although the lower γ results in higher ΔR_t , an extremely short duty cycle is not practical on ships owing to the limited regulation of a high instantaneous air flow rate. In the best case in the present experiment, RBI reduced the resistance by approximately 440 N at $(t_a, f, \gamma) = (4.5 \text{ mm}, 0.5 \text{ Hz}, 0.25)$ for the present model ship. This reduction is 80 N larger than that of CBI at the same t_a . In terms of the ratio of the total resistance reduction, $\Delta R_t/R_{t0}$, RBI at $(t_a, f, \gamma) = (4.5 \text{ mm}, 0.5 \text{ Hz}, 0.25)$ provides a 13% resistance reduction, which is 3% improvement relative to CBI.

The total resistance reduction is attributed to the reduction of frictional drag,

$$\Delta D_f = \Delta R_t, \quad (5.17)$$

because the residuary drag, which consists of wave drag and pressure drag, is thought to be not modified by the bubble injection. The ratio of the frictional drag reduction at the air-lubricated part, DR_a , is expressed as

$$DR_a = \frac{\Delta D_f}{D_{fa0}} (\propto \Delta R_t), \quad (5.18)$$

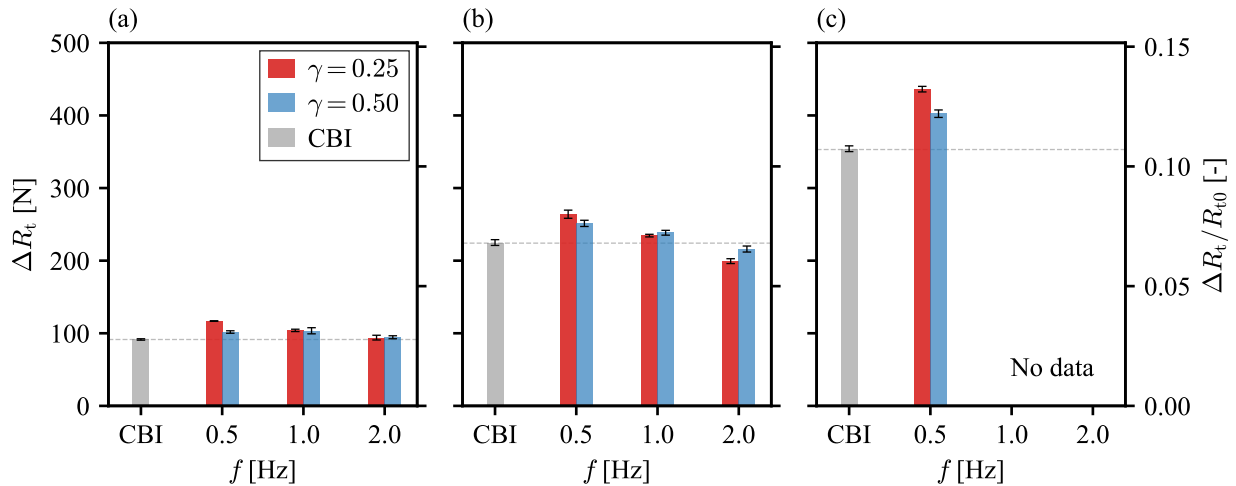


Figure 5.5: Reduction of the total resistance, ΔR_t , and the ratio of the total resistance reduction, $\Delta R_t/R_{t0}$: (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, and (c) $t_a = 4.5$ mm. Vertical error bars indicate the maximum and minimum values in three trials. The horizontal dashed line indicates the performance of CBI obtained in Chapter 4. The resistance reduction was obtained for the 36-m-long and 1-m-wide flat-bottom model ship.

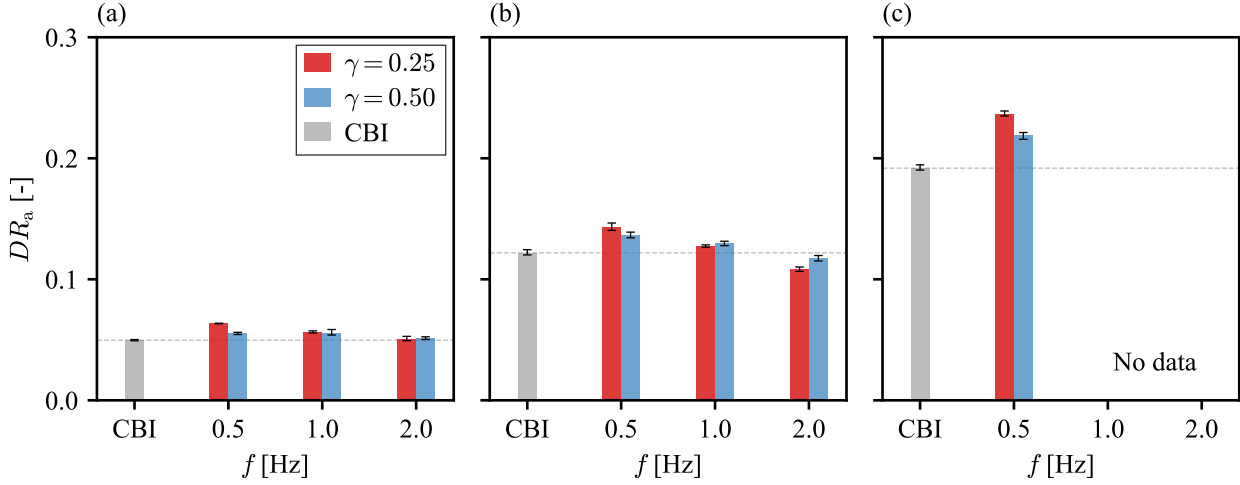


Figure 5.6: Ratio of the frictional drag reduction at the air-lubricated part of the model ship, DR_a , obtained by the measurement of total resistance: (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, and (c) $t_a = 4.5$ mm. Vertical error bars indicate the maximum and minimum values obtained in three trials. The horizontal dashed line indicates the performance of CBI obtained in Chapter 4. The length and area of the air-lubricated part are 32.9 m and 32.1 m², respectively.

and is shown in Fig. 5.6. RBI at $(f, \gamma) = (0.5 \text{ Hz}, 0.25)$ has the largest DR_a and enhances the drag reduction by 1%, 2%, and 5% relative to CBI at $t_a = 1.5, 3.0$, and 4.5 mm respectively. The maximum 24% frictional drag reduction is obtained using RBI.

The power saved by the frictional drag reduction is the product of ΔD_f and U :

$$W_s = \Delta D_f U. \quad (5.19)$$

Blowing air into the zero-pressure gradient turbulent boundary layer beneath the present flat-bottom model ship requires power corresponding to the potential energy of the ship draft, d , given by

$$W_0 = \rho g d Q_a, \quad (5.20)$$

where g is the gravitational acceleration (Kumagai *et al.* [9] and Murai *et al.* [13]) and W_0 is the minimum power consumption for bubble injection. Gross power consumption is radically dependent on individual systems for blowing air, and this is outside the scope of the present study. The power coefficient of BDR,

$$\zeta = \frac{W_s}{W_0} (\propto \Delta R_t), \quad (5.21)$$

is shown in Fig. 5.7. All the conditions result in $\zeta > 100$ with the small draft d ($= 70$ mm), namely power savings more than 100 times the power consumption. At each t_a , RBI at $(f, \gamma) = (0.5 \text{ Hz}, 0.25)$ has the largest ζ because it has the greatest ΔR_t . Importantly, ζ increases with Q_a although the increment of Q_a is considered in Eq. (5.20). This indicates that the improvement is due to the effect of turbulence modification by bubble injection rather than reduced density of the two-phase mixture. We confirmed the gain factor G (Murai [14]) using the void fraction at the bubble injector

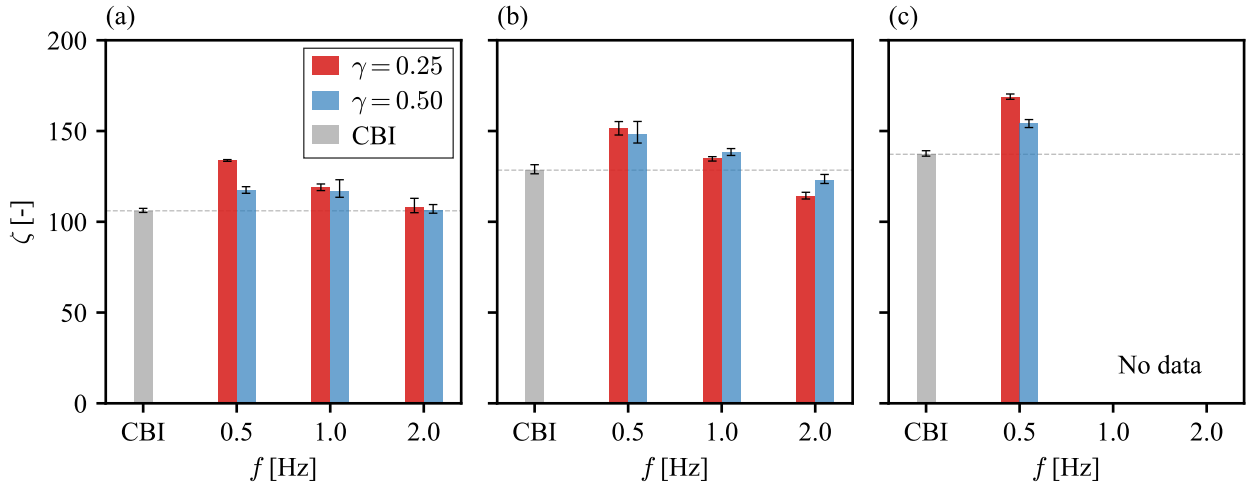


Figure 5.7: power coefficient of frictional drag reduction, η : (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, and (c) $t_a = 4.5$ mm. Vertical error bars indicate the maximum and minimum values obtained in three trials. The horizontal dashed line indicates the performance of CBI based on the results of Chapter 4. A power saving was made for the 36-m-long and 1-m-wide flat-bottom model ship.

was larger than unity. This indicated the drag-reduction mechanism realized on the model ship was basically classified into the regime of BDR.

5.4.2 Streamwise transition of the local drag reduction

Using the experimentally measured local wall shear stress τ , local friction coefficient c_f was obtained as

$$c_f = \frac{2\tau}{\rho_l U^2}. \quad (5.22)$$

The ratio of the friction coefficient relative to the single-phase flow is plotted against the downstream distance x in Fig. 5.8, where error bars indicate the standard deviation in the spanwise direction and across three trials, namely the result for 3–12 data at each x position. Generally, the drag reduction is strongest at the first measurement position ($x = 4.5$ m) and decreases downstream. The drag-reduction ratio of RBI at the first measurement position reached 31% at $(t_a, f, \gamma) = (4.5$ mm, 0.5 Hz, 0.50).

As expected from the observation of the state of bubbly flow, the relationship of the local drag reduction between CBI and RBI depends on t_a . At $t_a = 1.5$ mm (Fig. 5.8(a)–(c)), the drag reduction is promoted by RBI at $\gamma = 0.25$ in the upstream region ($x = 4.5$ – 12.5 m) although RBI at $\gamma = 0.50$ does not promote drag reduction over the entire air-lubricated part. This dependence on γ implies that there is a lower limit of the magnitude of the fluctuation of the instantaneous air flow rate for drag-reduction promotion, which is analogous to the result for the turbulent channel flow (Chapter 3). At $t_a = 3.0$ mm (Fig. 5.8(d)–(f)), RBI enhances the drag reduction in the upstream region under all the conditions of f and γ . The case that $(f, \gamma) = (0.5$ Hz, 0.25) shows an increase in drag reduction due to RBI even in the downstream region ($x = 20.5$ – 32.5 m). This result is reasonable because the periodic pattern of the bubble distribution generated by RBI tends to remain at longer

distances at a lower frequency and lower duty cycle. At $t_a = 4.5$ mm (Fig. 5.8(g)), CBI realized a higher drag reduction than RBI at the first measurement position, and RBI promoted drag reduction from the second measurement position. The state of flow changed in the downstream migration from the two-phase mixture including both large bubbles and small bubbles to that including only small bubbles. The large bubbles broke up within 10 m downstream of the bubble injector for CBI (Chapter 4) whereas they survived longer downstream for RBI (see Fig. 5.4). This difference reversed the drag-reduction performance of CBI and RBI between the first and second measurement positions.

As found from the distribution of the local drag reduction, RBI in a turbulent boundary layer has two effects that contribute to improving the total resistance reduction: (i) the promotion of local drag reduction induced by the periodical fluctuation of the local void fraction, as reported in previous studies of RBI in turbulent channel flows (Park *et al.* [54], Chapter 3), and (ii) the downstream preservation of large bubbles due to the high concentration of air. We evaluate the characteristics of the distribution of the local drag reduction using a formula describing the streamwise transition over long distances as

$$\frac{c_{fm}}{c_{fp0}} = 1 - (I_0 - I_\infty) \exp \left[-3 \frac{x - L_b}{L_{95}} \right] - I_\infty. \quad (5.23)$$

This formula was established in Chapter 4 originally for the results of local drag reduction of CBI. It is adaptable for RBI since the streamwise decay of drag reduction from the strong initial state to the weak downstream state is observed in common with CBI. This formula is established by the fit to experimental results to enhance usability in the practical design of BDR on ships. I_0 and I_∞ denote the ratio of the local friction reduction relative to the local friction of the single-phase flow, at the bubble injector and far downstream from the injector respectively. L_{95} is the 95% decay length of the drag-reduction effect from I_0 to I_∞ because $\exp[-3(x - L_b)/L_{95}] \approx 0.05$ for $x - L_b = L_{95}$. Thus, L_{95} is an indicator of the persistence of the initial effect. In the adaption of Eq. (5.23) to RBI, the coefficients reflect the effects due to void waves, i.e., the drag reduction due to fluctuation of the local void fraction and the streamwise transition of drag reduction due to the spatial development of void waves, in addition to the common factors with CBI described in Chapter 4. These three coefficients were obtained from the experimental results. Here, the drag reduction effect at $(t_a, f, \gamma) = (3.0 \text{ mm}, 0.5 \text{ Hz}, 0.25)$ and $(4.5 \text{ mm}, 0.5 \text{ Hz}, 0.25)$ does not seem to reach the far-downstream state, because c_f/c_{fp0} does not converge on a constant value at the last measurement position ($x = 32.5$ m) as shown in Fig. 5.8. The distribution of c_f/c_{fp0} under other conditions of RBI, however, shows that the drag-reduction ratio in the sufficiently downstream region is the same as that for CBI. We thus give the I_∞ of CBI in the evaluation of RBI; i.e., $I_\infty = 0.02, 0.07$, and 0.14 at $t_a = 1.5, 3.0$, and 4.5 mm, respectively. The other coefficients, I_0 and L_{95} , were determined by curve fitting adopting the least-squares method and experimental data of c_f/c_{fp0} . In the curve fitting, the coefficients were confined as $0 \leq I_0 - I_\infty \leq 1$ and $L_{95} \geq 1.4$ m (i.e., the distance between the bubble injector and first measurement position of local wall shear stress).

The obtained fitting curves well represent the experimental results as shown in Fig. 5.8. Only the plot of $(t_a, f, \gamma) = (4.5 \text{ mm}, 0.5 \text{ Hz}, 0.25)$ appeared not to follow the curve at $x = 32.5$ m, considering

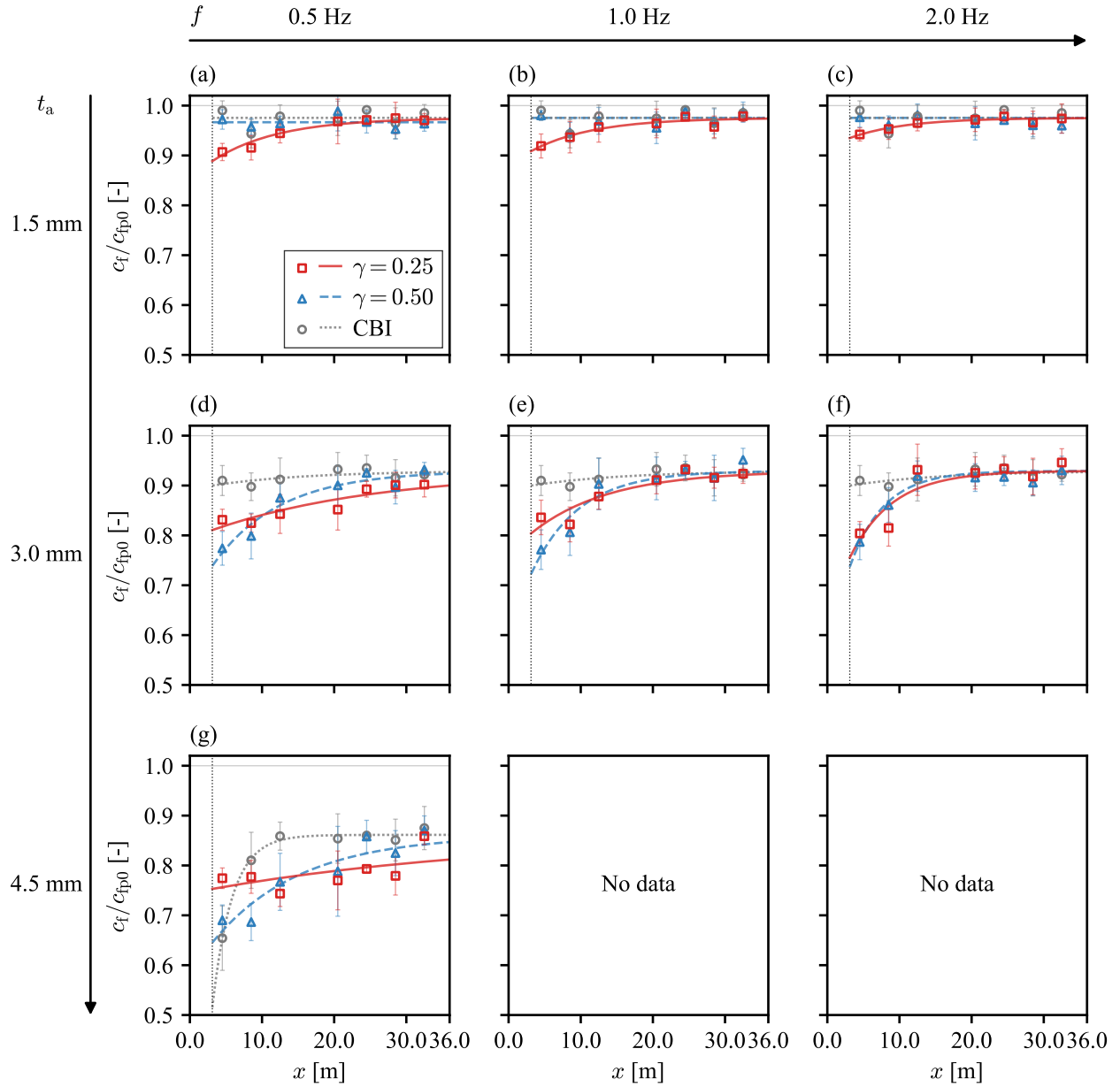


Figure 5.8: Streamwise distribution of the ratio of the local friction coefficient, c_f/c_{fp0} , where vertical error bars indicate the standard deviation in the spanwise direction across three trials. The data of CBI refer to the results of Chapter 4. The lines show the fitting of a curve to the experimental results using Eq. (5.23). The vertical gray dotted line at $x = 3.1$ m indicates the position of the bubble injector, and the horizontal solid line indicates $c_f/c_{fp0} = 1.0$.

that the error bar indicates one standard deviation. By integrating the friction coefficients under bubbly flow and single-phase flow conditions calculated respectively using Eq. (5.23) and Eq. (5.5), the ratio of drag reduction at the air-lubricated part is obtained as

$$DR'_a = 1 - \frac{\int_{L_b}^{L_t} c_{fm} dx}{\int_{L_b}^{L_t} c_{fp0} dx}. \quad (5.24)$$

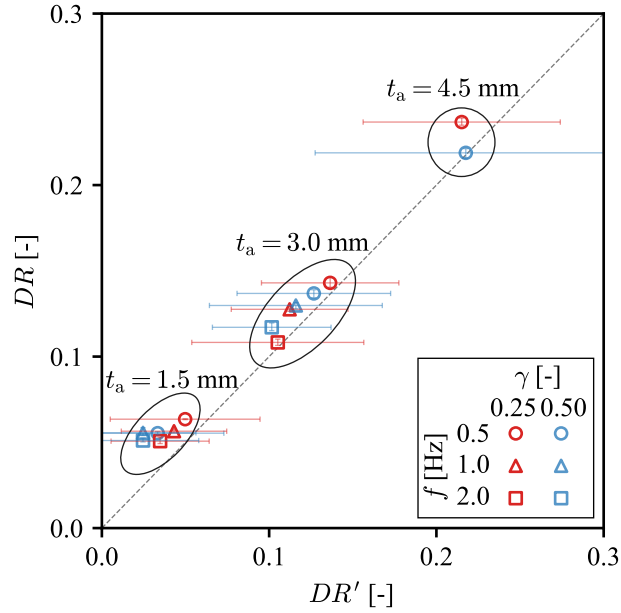


Figure 5.9: Comparison of the ratio of drag reduction in the air-lubricated part obtained from the local wall shear stress (DR'_a) and the total resistance of the model ship (DR_a). The dashed line denotes $DR_a = DR'_a$. Vertical error bars indicate the maximum and minimum values of DR_a in three trials as for Fig. 5.6. Horizontal error bars denote the estimated error of DR'_a using the streamwise-maximum standard deviation of c_f/c_{fp0} in the spanwise direction across three trials shown in Fig. 5.8.

This method provides the error in the estimation due to the error in the measurement of the ratio of the local friction coefficient because the coefficients in Eq. (5.23) are obtained from experimental results. The measurement error in the present experiment was evaluated as being at most a standard deviation of 9%. The drag-reduction ratio based on the measurement of the total resistance (DR , defined by Eq. (5.18)) and that of the local wall shear stress (DR') are compared in Fig. 5.9. DR and DR' show good agreement under all experimental conditions as the plots are close to the dashed line indicating correspondence. This confirms the good accuracy of the local wall shear stress measurements, and also means the negligibly small change of the residuary resistance included in the total resistance with bubble injection assumed in Eq. (5.17). DR tends to be larger than DR' because the contribution of frictional drag reduction on the surface of the side walls and the center keel cannot be removed in the evaluation of DR .

Coefficients of the fitting curves, I_0 and L_{95} , are respectively shown in Fig. 5.10 and Fig. 5.11. The result of I_0 quantitatively indicates the dependence of the initial drag reduction on f and γ , as shown by the distribution of the local friction coefficient in the upstream regions in Fig. 5.8. At $t_a = 1.5$ mm (Fig. 5.10(a)), RBI at $\gamma = 0.25$ induces an additional reduction of the local friction of more than 5% by comparison to CBI at all f , though RBI at $\gamma = 0.50$ results in almost the same local friction reduction as CBI. At $t_a = 3.0$ mm (Fig. 5.10(b)), I_0 for RBI is double that for CBI and $\gamma = 0.50$ results in higher local friction reduction than does $\gamma = 0.25$. At $t_a = 4.5$ mm (Fig. 5.10(c)), CBI results in higher local friction reduction at the bubble injector. However, RBI induces large local friction reduction as I_0 remains above 0.2. Additionally, L_{95} is longer for RBI than for CBI as

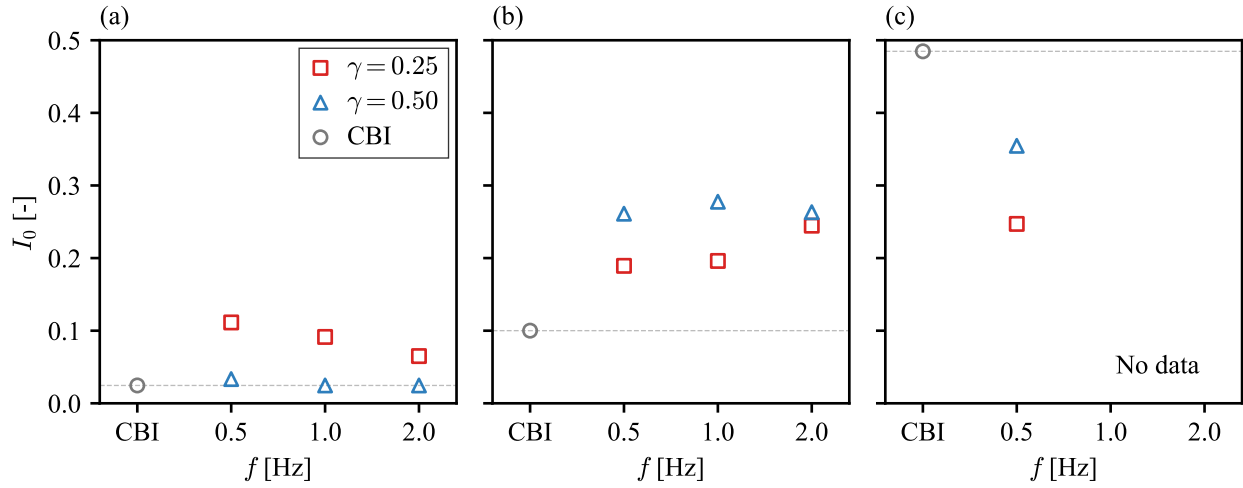


Figure 5.10: Initial effect of drag reduction at the bubble injector, I_0 , evaluated by fitting Eq. (5.23) to the measurements of local shear stress at 23 positions on the bottom plate: (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, and (c) $t_a = 4.5$ mm. The horizontal dashed line indicates the performance of CBI obtained in Chapter 4. I_0 represents the drag-reduction performance for the 36-m-long flat-bottom model ship averaged across three trials.

shown in Fig. 5.11, indicating longer downstream persistence of the drag-reduction effect. Note that the value of L_{95} for CBI at $t_a = 3.0$ mm was judged to be an outlier caused by the small difference between I_0 and I_∞ in Chapter 4. L_{95} reached 120 m at $(t_a, f, \gamma) = (4.5 \text{ mm}, 0.5 \text{ Hz}, 0.25)$ in the best case of the present experimental conditions. The present examination of RBI experimentally shows a persistence of drag reduction longer than 100 m. This result is preferable for the practical design of RBI for actual ships.

5.4.3 Full-scale estimation

This section estimates the full-scale performance by clarifying the effect of the downstream persistence of the local drag reduction on the total drag reduction for a ship's hull. We here focus on RBI at $(f, \gamma) = (0.5 \text{ Hz}, 0.25)$ and $t_a = 3.0$ and 4.5 mm, which greatly reduced drag in the model ship experiment. Because the drag-reduction effect goes to zero at a sufficient downstream distance for ships, I_∞ in Eq. (5.23) is replaced with zero in this estimation. The local friction coefficient under BDR is then given as

$$c_{fe} = c_{fp0} \left(1 - I_0 \exp \left[-3 \frac{x - x_b}{L_{95}} \right] \right), \quad (5.25)$$

where x_b is the position of the bubble injector on the ship. The drag reduction per unit breadth of the hull is estimated through the integration of the local friction coefficients of Eq. (5.5) and Eq. (5.25) as

$$\Delta D_{fe} = \frac{1}{2} \rho_l U^2 \int_{x_b}^{L_{ship}} (c_{fp0} - c_{fe}) dx, \quad (5.26)$$

where L_{ship} is the length of the ship. ΔD_{fe} is calculated for the variable L_{ship} with $x_0 = 10$ m as an example in Fig. 5.12. ΔD_{fe} increases with L_{ship} and approaches a constant value through the

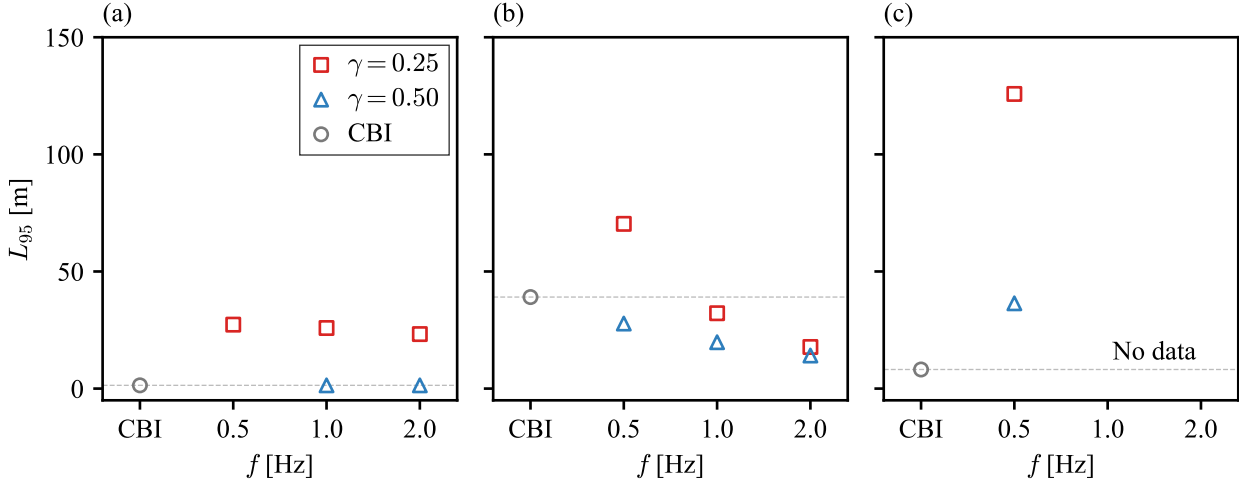


Figure 5.11: Downstream persistence of the drag reduction effect as the 95% decay length of the initial drag-reduction effect, L_{95} , evaluated by fitting Eq. (5.23) to the measurements of local shear stress at 23 positions on the bottom plate: (a) $t_a = 1.5$ mm, (b) $t_a = 3.0$ mm, and (c) $t_a = 4.5$ mm. The horizontal dashed line indicates the performance of CBI obtained in Chapter 4. L_{95} represents the drag-reduction performance for the 36-m-long flat-bottom model ship averaged across three trials.

downstream decay of the drag reduction. For RBI at $t_a = 4.5$ mm, ΔD_{fe} continues to increase the long range of L_{ship} owing to having the largest L_{95} in the experiments. At $t_a = 3.0$ mm, ΔD_{fe} of RBI is estimated to reach 3 times that of CBI at $L_{ship} = 60$ m. The improvement in ΔD_{fe} is greater at $t_a = 4.5$ mm and becomes approximately 7 times that of CBI for $L_{ship} > 130$ m.

The ratio of the frictional drag reduction at the air-lubricated part of the ship is predicted as

$$DR_e = 1 - \frac{\int_{x_b}^{L_{ship}} c_{fe} dx}{\int_{x_b}^{L_{ship}} c_{fp0} dx}. \quad (5.27)$$

DR_e approaches zero for long hulls because the frictional drag in single-phase flow continues to increase with L_{ship} . As shown in Fig. 5.13, $DR_e = 0.05$ and 0.11 are expected at $t_a = 3.0$ and 4.5 mm, respectively, for a long hull of $L_{ship} = 100$ m. At $t_a = 4.5$ mm, CBI has higher DR_e than RBI until $L_{ship} = 15$ m, namely 5-m-long air-lubricated part, owing to the larger initial drag reduction at the bubble injector. However, DR_e of CBI rapidly decreases with increasing L_{ship} , and the effect of RBI surpassed that of CBI owing to the long persistence of drag reduction. The present estimation of the full-scale performance confirms the importance of the downstream persistence of the drag-reduction effect to the efficient total resistance reduction of long ships. Additionally, the estimations indicate the superiority of RBI over CBI in drag reduction for full-scale ships.

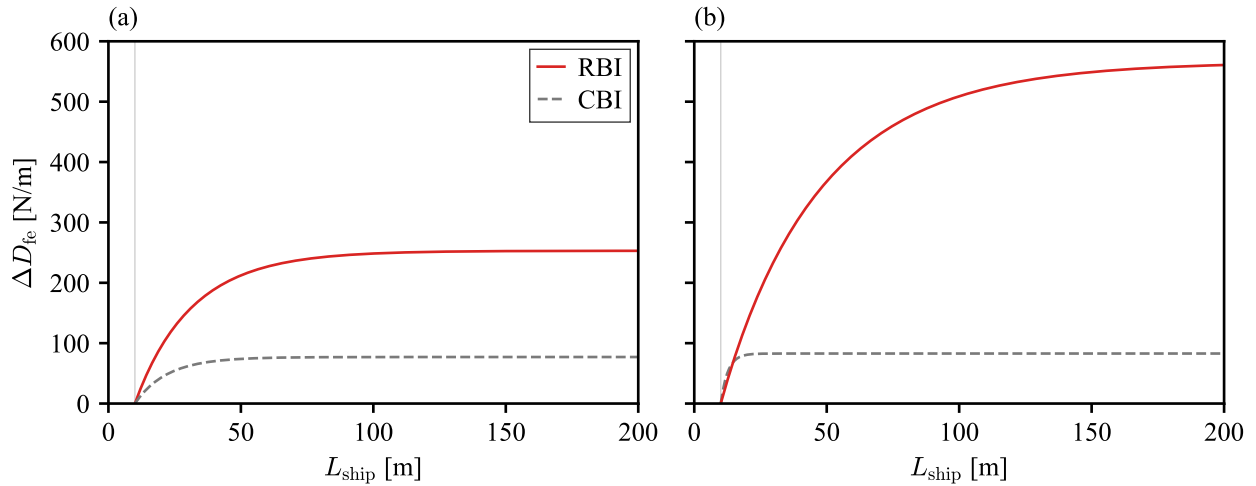


Figure 5.12: Estimation of the drag reduction per unit breadth of the hull, ΔD_{fe} , as a function of the ship length, L_{ship} , with RBI at $(f, \gamma) = (0.5 \text{ Hz}, 0.25)$ and CBI: (a) $t_a = 3.0$ mm and (b) $t_a = 4.5$ mm. The experimentally obtained characteristics of the streamwise transition of drag-reduction effect shown in Figs. 5.10 and 5.11 were used in the estimation. The position of bubble injection was set at 10 m from the bow as indicated by the vertical dotted line. The data of CBI are based on the results of Chapter 4.

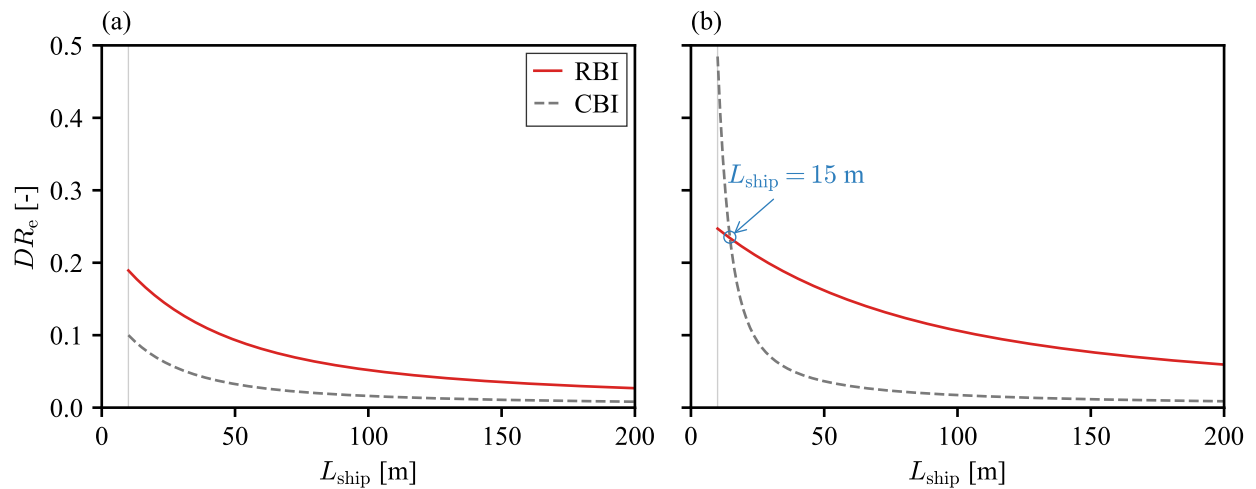


Figure 5.13: Estimation of the drag-reduction ratio at the air-lubricated part of the hull, DR_e , as a function of the ship length, L_{ship} , for RBI at $(f, \gamma) = (0.5 \text{ Hz}, 0.25)$ and CBI: (a) $t_a = 3.0$ mm and (b) $t_a = 4.5$ mm. The experimentally obtained characteristics of the streamwise transition of the drag-reduction effect shown in Figs. 5.10 and 5.11 were used in the estimation. The position of bubble injection was set at 10 m from the bow as indicated by the vertical dotted line. The data of CBI are based on the results of Chapter 4.

5.5 Conclusions

On the basis of the results of previous studies showing the promotion of drag reduction through repetitive bubble injection (RBI) at smaller-scale facilities, RBI was examined in a quasi-full-scale environment reaching a Reynolds number $Re_L = 2.9 \times 10^8$. Bubbles were injected into a turbulent boundary layer beneath a 36-m-long flat-bottom model ship towed at 8.0 m/s. RBI at a repetition frequency of 0.5 Hz and duty cycle of 0.25 reduced the total resistance of the model ship most. Under these conditions, the drag-reduction ratio in the air-lubricated part on the bottom plate was 24%, which was 5% higher than that of continuous bubble injection (CBI). The ratio of the local drag reduction behind the bubble injector was 23% for RBI and 35% for CBI at the same time-averaged air flow rate. However, the drag-reduction ratio of RBI surpassed that of CBI from 5 m downstream of the injector owing to large bubbles surviving the long downstream distance. The preservation of periodic pattern of bubble swarms induced the promotion of drag reduction by RBI to the end of model ship. The estimation of the recovery frequency of the turbulent boundary layer was confirmed to correspond well to the repetition frequency giving the largest drag reduction in the experiment, namely 0.5 Hz. This method of estimation is expected to be useful in predicting the optimal frequency in the practical design of RBI.

We applied a formula describing the streamwise transition of the drag reduction on long hulls to evaluate the characteristics of drag reduction of RBI; i.e., the initial effect at the bubble injector and the downstream persistence of the initial effect. The initial effect was enhanced by RBI at lower air flow rates, whereas CBI had an effect more than 15% stronger than that of RBI at the highest air flow rate. Meanwhile, the downstream persistence of drag reduction was improved by RBI at all air flow rates, reaching 120 m under the present experimental conditions. We predicted the ratio of the frictional drag reduction on full-scale ships from the experimental results for the model ship. The full-scale estimation indicates that RBI promotes drag reduction relative to CBI for a hull having the air-lubricated part longer than 5 m. Moreover, the predicted performance of RBI is approximately 7 times that of CBI for long hulls exceeding 130 m.

CHAPTER 6

Estimation of net power saving on ships

Preface

This chapter aims to compare the net power saving of repetitive bubble injection (RBI) with that of continuous bubble injection (CBI) on full-scale ships. An estimation method to compare the performance is presented. It uses the experimental result of the previous chapters to predict the magnitude of the contribution of drag reduction. The energy consumption for blowing air is estimated by the use of a result of a full-scale sea trial. The estimation indicates the robust superiority of RBI for hull parameters and properties of the air-blowing system.

6.1 Introduction

In ship engineering, the performance of air lubrication needs to be evaluated by net power saving. The net performance is determined as

$$\eta_{AL} = \eta_{DR} - \eta_{AB}. \quad (6.1)$$

by the power saving caused by the drag reduction, η_{DR} , and the power consumption for air-blowing, η_{AB} . The results of previous sea trials are summarized in Table 6.1. Mizokami *et al.* [8] and Mizokami and Kuroiwa [10] developed a system for keeping the pressure balance of multiple injectors. Two different ships equipped the system and achieved power savings of 12% and 4%, respectively. Kumagai *et al.* [9] designed a hydrofoil bubble generator to minimize the power needed for blowing air by utilizing the negative pressure generated behind the device. The bubble generator succeeded in bubble injection without the operation of the blower, namely $\eta_{AB} = 0\%$. The drag reduction, including additional drag attributed to the device, directly provided the net performance $\eta_{AL} = 10\%$.

Improvement of η_{DR} is a matter of fluid mechanics with kinds of viewpoints. Fluid velocity and void fraction are the most important parameters in air lubrication. In the case of a very high void fraction, stabilization of air film on the hull is the key to reduce much friction (e.g., Elbing *et al.* [15], Mäkiharju and Ceccio [16], and Jang *et al.* [29]). The transition between the air film state to the dispersed bubbly state, depending on the void fraction, leads to a large change of drag reduction (Elbing *et al.* [25] and Jha *et al.* [58]). In the bubbly state, bubble size relative to the thickness of the turbulent boundary layer affects the drag reduction as discussed by Murai [14]. The detailed measurement of bubbly flow in various flow conditions by Hazuku *et al.* [61] gives a rich database for the design of bubble drag reduction (BDR). For the design of BDR on ship hulls, Yoon *et al.* [90], [91] made a model of bubble behaviors in turbulent boundary layers on inclined walls. Additionally, the result of an experiment using a 50-m-long model ship by Watanabe *et al.* [38] gives information about the arrangement of air injectors in the longitudinal direction of the hull.

Repetitive bubble injection (RBI) provides higher drag reduction than continuous bubble injection (CBI) at the same time-averaged air flow rate as reported in Chapter 2, 3, and 5. That is the improvement of η_{DR} by RBI. However, η_{AB} is also increased by RBI because temporal control of flow rate generally causes loss in the system blowing air. The net performance η_{AL} should be discussed to prove the superiority of RBI for ship power saving. This study performs an estimation

Table 6.1: Efficiency of drag reduction η_{DR} , air-blowing η_{AB} , and net power saving η_{AL} in the previous sea trials of air lubrication

	Ship (length)	η_{DR}	η_{AB}	η_{AL}
Mizokami <i>et al.</i> [8]	YAMATAI (162 m)	15%	6%	12%
Kumagai <i>et al.</i> [9]	Filia Ariea (85 m)	10%	0%	10%
Mizokami and Kuroiwa [10]	NAMINOUE (145 m)	6%	2%	4%

of η_{AL} with changing parameters based on former experimental results of drag reduction and power needed for blowing air.

6.2 Estimation method

6.2.1 Formulation of net power saving

CBI has already succeeded in saving the net power of ships in the sea trials (Mizokami *et al.* [8], Kumagai *et al.* [9], and Mizokami and Kuroiwa [10]). In this study, the gain of power saving caused by RBI relative to CBI is discussed. The gain is determined by the change of drag reduction and that of the power consumption for air-blowing:

$$\Delta\eta_{AL} = \Delta\eta_{DR} - \Delta\eta_{AB}. \quad (6.2)$$

The performance of the hull is expressed by brake horsepower, BHP, in the practice of ship engineering in Japan. Using the expression, Eq. (6.2) is rewritten as

$$\Delta\eta_{AL} = \frac{\Delta BHP}{BHP^0} - \frac{\Delta ABP}{BHP^0}. \quad (6.3)$$

Here, ΔBHP and ΔABP are the changes of BHP and the change of air-blowing power ABP between RBI and CBI. The superscript “0” indicates the base state without bubble injection.

BHP is expressed using effective horsepower, EHP, as

$$BHP = \frac{\eta_T}{\eta} EHP, \quad (6.4)$$

where η_T and η are the transfer coefficient and the propulsion coefficient of the ship. Blowing air affects η owing to the involution of bubbles to the propeller but does not η_T . Additionally, the propulsion coefficient is thought to be common between CBI and RBI, namely $\eta^C = \eta^R$, where the superscript “C” and “R” indicate CBI and RBI. Representation of η^C and η^R by $\eta^{C,R}$ gives

$$\frac{\Delta BHP}{BHP^0} = \frac{\eta^0}{EHP^0} \frac{\Delta EHP}{\eta^{C,R}} = \Lambda_1 \frac{\Delta EHP}{EHP^0}. \quad (6.5)$$

$\Lambda_1 (= \eta^0/\eta^{C,R})$ is a parameter indicating modification of the propulsion coefficient due to bubbles. For a ship, EHP is calculated by

$$EHP = \{(1 + K)C_f + C_w + \Delta C_f\} \frac{1}{2} \rho S V^3, \quad (6.6)$$

where C_f , C_w , K , and ΔC_f are coefficients of the ship: friction drag coefficient, wave drag coefficient, form factor, and surface roughness factor, respectively. ρ , S , and V are density of seawater, wetted surface area of the ship, and ship speed. Then, Eq. (6.5) becomes

$$\frac{\Delta BHP}{BHP^0} = \Lambda_1 \frac{(1 + K)(C_f^C - C_f^R)}{(1 + K)C_f^0 + C_w^0 + \Delta C_f^0} = \frac{\Lambda_1}{1 + \Lambda_2} \frac{C_f^C - C_f^R}{C_f^0}. \quad (6.7)$$

The new parameter $\Lambda_2 (= (C_w^0 + \Delta C_f^0)/(1 + K)C_f^0)$ is the ratio of residuary drag to the frictional drag.

By employing the expression of the air-blowing power with the ratio to the BHP⁰,

$$ABP = \eta_{AB} BHP^0, \quad (6.8)$$

the second term of the right-hand side of Eq. (6.3) is rewritten as

$$\frac{\Delta ABP}{BHP^0} = \eta_{AB}^R - \eta_{AB}^C. \quad (6.9)$$

Finally, Eq. (6.2) becomes

$$\Delta \eta_{AL} = \frac{\Lambda_1}{1 + \Lambda_2} \frac{C_f^C - C_f^R}{C_f^0} - (\eta_{AB}^R - \eta_{AB}^C), \quad (6.10)$$

with

$$\Delta \eta_{DR} = \frac{\Lambda_1}{1 + \Lambda_2} \frac{C_f^C - C_f^R}{C_f^0}, \quad (6.11)$$

$$\Delta \eta_{AB} = \eta_{AB}^R - \eta_{AB}^C. \quad (6.12)$$

It is expected that $\Delta \eta_{DR} > 0$ and $\Delta \eta_{AB} > 0$.

6.2.2 Power saving owing to frictional drag reduction

Estimation of $\Delta \eta_{DR}$ comes to the acquisition of the friction drag coefficient except for the parameters Λ_1 and Λ_2 . The method provided in Chapter 4 and 5 is available for this estimation:

$$C_f = \frac{1}{L_{ship}} \int_0^{L_{ship}} c_f dx, \quad (6.13)$$

$$c_f = \begin{cases} c_f^0 & (x < x_0) \\ c_f^0 \left(I_0 \exp \left[-3 \frac{x-x_0}{L_{95}} \right] \right) & (x \geq x_0) \end{cases}, \quad (6.14)$$

where L_{ship} and x_0 are the ship length and the position of blowing air. The local friction coefficient in the absence of bubbles is estimated by Kármán–Schoenherr law (Schlichting [77]),

$$\frac{1}{\sqrt{c_f^0}} = 4.13 \ln(Re_x c_f). \quad (6.15)$$

The initial drag-reduction effect, I , and the 95% decay length of the drag-reduction effect, L_{95} , were obtained in the experiments using the 36-m-long model ship. The values are shown in Table 6.2.

Table 6.2: Coefficients used in the estimation of the friction drag coefficient: initial drag-reduction effect, I , and the 95% decay length of the drag-reduction effect, L_{95} . The values were obtained by the experiment using the 36-m-long model ship (Chapter 4 and 5). The nominal air-layer thickness, t_a , the repetition frequency of RBI, f , and the duty cycle of RBI, γ , are the control parameters of BDR.

t_a [mm]	f [Hz]	γ [-]	I_0 [-]	L_{95} [m]
3.0	CBI	-	0.10	39.1
	0.5	0.25	0.19	70.3
	0.5	0.50	0.26	27.8
	1.0	0.25	0.20	32.2
	1.0	0.50	0.28	19.8
	2.0	0.25	0.24	17.8
	2.0	0.50	0.26	14.1
4.5	CBI	-	0.48	8.2
	0.5	0.25	0.25	125.8
	0.5	0.50	0.35	36.4

The nominal air-layer thickness, t_a , the repetition frequency of RBI, f , and the duty cycle of RBI, γ , are the control parameters of BDR.

6.2.3 Power consumption for blowing air

The head loss of blowing air in a real scale system entirely depends on the design, e.g., pipe length, bends, and valves. Prediction of the loss based on theoretical formula is difficult even for CBI, which does not impose temporal fluctuation on the air flow rate like RBI. The present estimation uses the result of the sea trial shown in Fig. 6.1 (Mizokami *et al.* [8]). They measured the power consumption for blowing air in a practical system equipped on the ship. A power function defined as

$$\eta_{AB}^C(t_a) = a \left(\frac{t_a}{D} \right)^p + b \quad (6.16)$$

is fitted to the data for the use of the estimation. Here, D is the ship draft, and $D = 9.0$ m.

Two cases of fitting are performed considering the possible properties of the system. The first case (case I) supposes the system has no loss independent of the air flow rate. In this case, $b = 0$ was given before the fitting, then a and p were determined. The result is $a = 388$ and $p = 1.24$ (Fig. 6.1). The second case (case II) sets p at a value beforehand and obtains a and b , assuming the existence of constant loss in the system. The obtained curves are shown in Fig. 6.2(a). In case II, p is examined in $1.0 \leq p \leq 2.0$, and b is given the lower limitation, $b \geq 0$, indicating the positive loss. The result of a and b is shown in Fig. 6.2(b).

In RBI with the air flow rate controlled to be a square waveform (see Fig. 4.3), the air is blown at $1/\gamma$ times larger flow rate for γ times shorter time than CBI. This leads to a simple model of η_{AB} at RBI:

$$\eta_{AB}^R(t_a) = \gamma \eta_{AB}^C \left(\frac{t_a}{\gamma} \right) = \gamma \left\{ a \left(\frac{t_a}{\gamma D} \right)^p + b \right\}. \quad (6.17)$$

The coefficients in Eq. (6.17), i.e., a , b , and p , are given by the fitting result of Eq. (6.16).

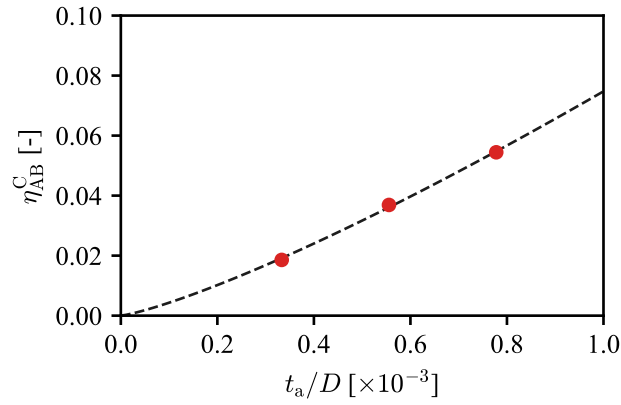


Figure 6.1: Curve fitting (case I) to the experimental result by Mizokami *et al.* [8]. The markers denote the experimental data of the power coefficient of blowing air, η_{AB}^C , as a function of the nominal air-layer thickness, t_a . The dashed line is the result of fitting using Eq. (6.16) with $b = 0$.

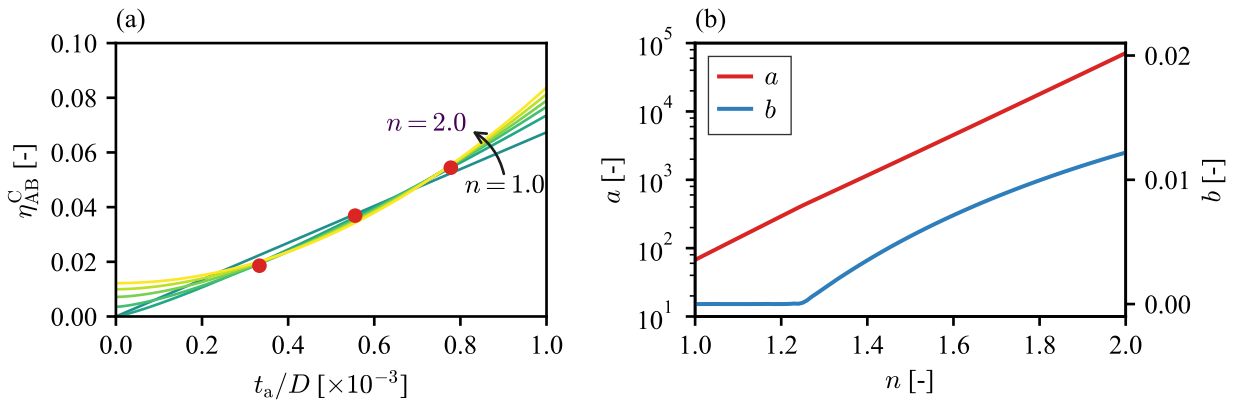


Figure 6.2: Curve fitting (case II) to the experimental result by Mizokami *et al.* [8]: (a) the data of the power coefficient of blowing air, η_{AB}^C , as a function of the nominal air-layer thickness, t_a , and the obtained curves using Eq. (6.16) with p set before the fitting, and (b) the coefficients a and b determined by the fitting

The original data is measured on a 162-m long ship cruising at 6.8 m/s (Mizokami *et al.* [8]). The longer length and the higher speed potentially cause the decrease of η_{AB} owing to the increase of BHP^0 . Similarly, η_{AB} is increased for the shorter length and the lower speed ship. Those dependencies are, however, not accounted for in the estimation because the influence depends on the design of the hull. The present estimation method aims to give a reasonable value of $\Delta\eta_{AB}$ to judge whether total performance can improve by RBI.

6.3 Estimation results

The dependence of $\Delta\eta_{AL}$ on the parameters of the estimation is discussed in this section. The effect of RBI parameters (t_a , f , and γ) and the hull parameters (Λ_1 , Λ_2 , x_0 , and L_{ship}) are shown in Section 6.3.1 and 6.3.2, respectively. These estimations use case I of the fitting function for η_{AB}^C . The dependence on the property of the air-blowing system is given in Section 6.3.3, applying case II. The estimation supposes the ship speed of 8.0 m/s though the term is not explicitly included in the formulation. This is because the coefficients describing the characteristics of drag reduction used in Eq. (6.14) was obtained at the speed in the model ship experiment (Chapter 4 and 5). Additionally, the ship draft is set to 9.0 m identical to the sea trial by Mizokami *et al.* [8] for Eq. (6.16) and (6.17).

6.3.1 Dependence on RBI parameters

The dependence of $\Delta\eta_{DR}$ on control parameters of RBI is shown in Fig. 6.3, where the typical hull parameters were given, i.e., $\Lambda_1 = 1$, $\Lambda_2 = 0.25$, $x_0 = 0$ m, and $L_{ship} = 150$ m. All the conditions of RBI result in $\Delta\eta_{DR} > 0$, namely an increase in drag reduction. At $t_a = 3.0$ mm, $\Delta\eta_{DR}$ becomes higher as the lower f and γ . The drag-reduction effect increases as t_a , and $\gamma = 0.25$ gives higher performance than $\gamma = 0.50$ at $t_a = 4.5$ mm. These trends match the result of frictional drag reduction in the model ship experiment (see Fig. 4.6). The maximum $\Delta\eta_{DR}$ obtained in the present hull parameters is 6.1% at $f = 0.5$ Hz and $\gamma = 0.25$, implying considerable enhancement of drag reduction in the comparison with the η_{DR} in the previous sea trials (Table 6.1)

The dependence of $\Delta\eta_{AB}$ on t_a and γ is shown in Fig. 6.4. The parameter f does not affect the coefficient η_{AB} in the model of Eq. (6.17). The calculation confirms $\Delta\eta_{AB} > 0$ as expected, corresponding to the general understanding of loss in the pipe. Additionally, $\Delta\eta_{AB}$ gets larger at $\gamma = 0.25$ than $\gamma = 0.50$ because the power consumption during blowing air increases as $1/\gamma$ to the power of n ($= 1.24$) and the duration of blowing decreases as the ratio of γ . $\Delta\eta_{AB}$ is at most 1.2% obtained at $t_a = 4.5$ mm and $\gamma = 0.25$.

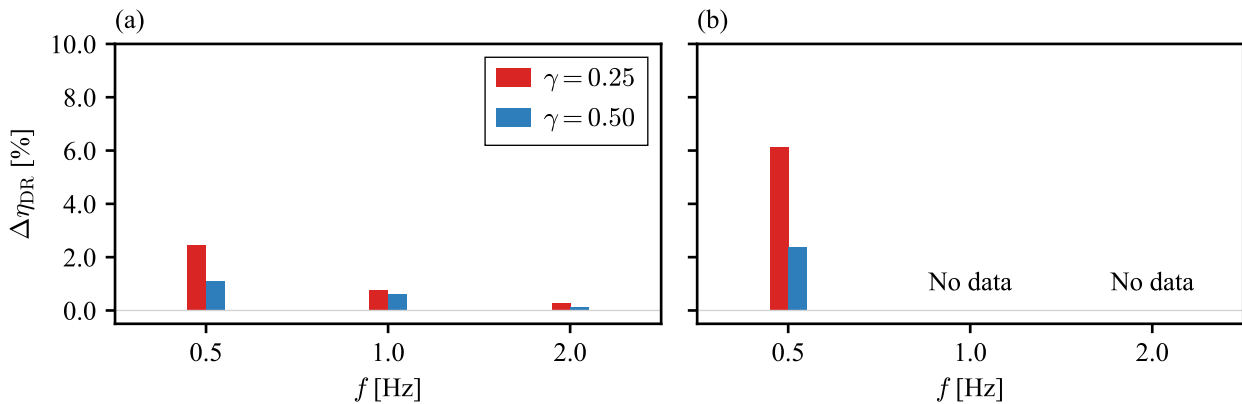


Figure 6.3: The change of drag-reduction coefficient by RBI relative to CBI: (a) $t_a = 3.0$ mm, and (a) $t_a = 4.5$ mm

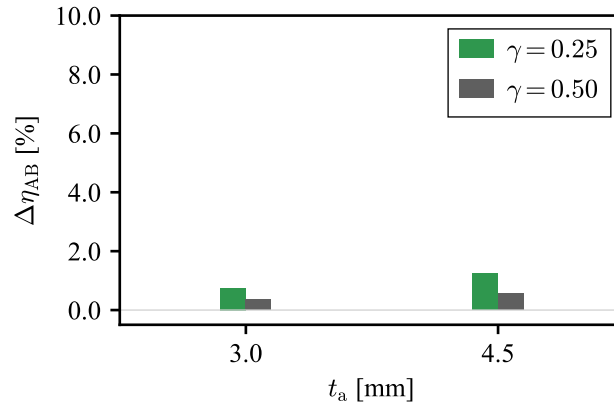


Figure 6.4: The change of air-blowing coefficient by RBI relative to CBI

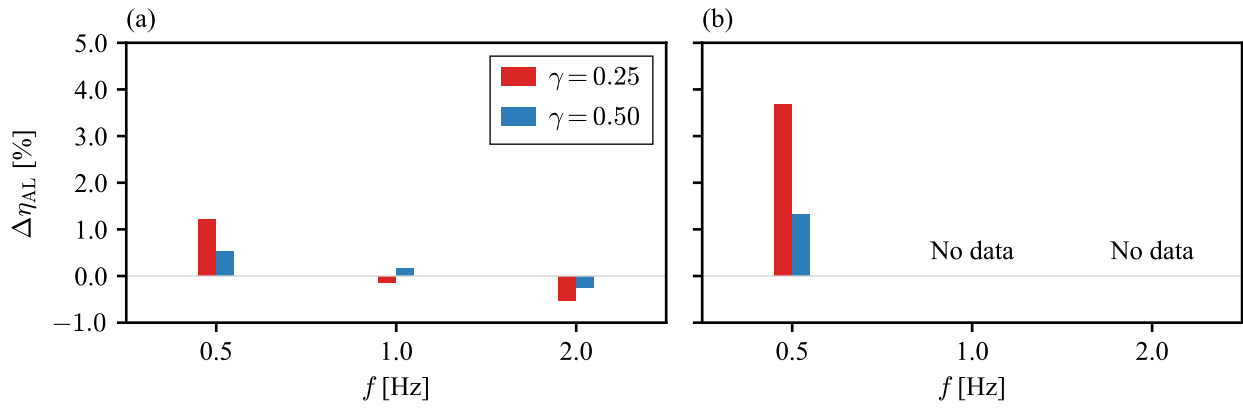


Figure 6.5: The gain of net power saving of air lubrication by RBI relative to CBI: (a) $t_a = 3.0$ mm, and (b) $t_a = 4.5$ mm

Using $\Delta\eta_{DR}$ and $\Delta\eta_{AB}$, the gain of net power saving $\Delta\eta_{AL}$ shown in Fig. 6.5 was obtained. The estimation results in positive $\Delta\eta_{AL}$ at $f = 0.5$. At the higher f , the increase in power saving is canceled due to the extra power consumption for blowing air. The result indicates that RBI can improve hull performance. The best condition $f = 0.5$ Hz and $\gamma = 0.25$ increases η_{AL} by 3.7%. Further investigation for the optimal control of RBI will contribute to the realization of more high $\Delta\eta_{AL}$ and stable $\Delta\eta_{AL} > 0$.

6.3.2 Dependence on hull parameters

In the examination of the dependence of hull parameters, the conditions of RBI were set $t_a = 4.5$ mm and $f = 0.5$ Hz, where high $\Delta\eta_{AL}$ is obtained. Both $\gamma = 0.25$ and 0.50 were given to clear the effect of change in η_{AB} . The base condition of hull parameters was the same as the former calculation except for a parameter that examined its influence on $\Delta\eta_{AL}$. The parameter Λ_1 represents a modification of the propulsion coefficient η due to bubbles. $\Lambda_1 (= \eta^0 / \eta^{C,R})$ is larger than unity because the existence of bubbles in the flow gets the propulsion performance worse. Therefore, the parameter

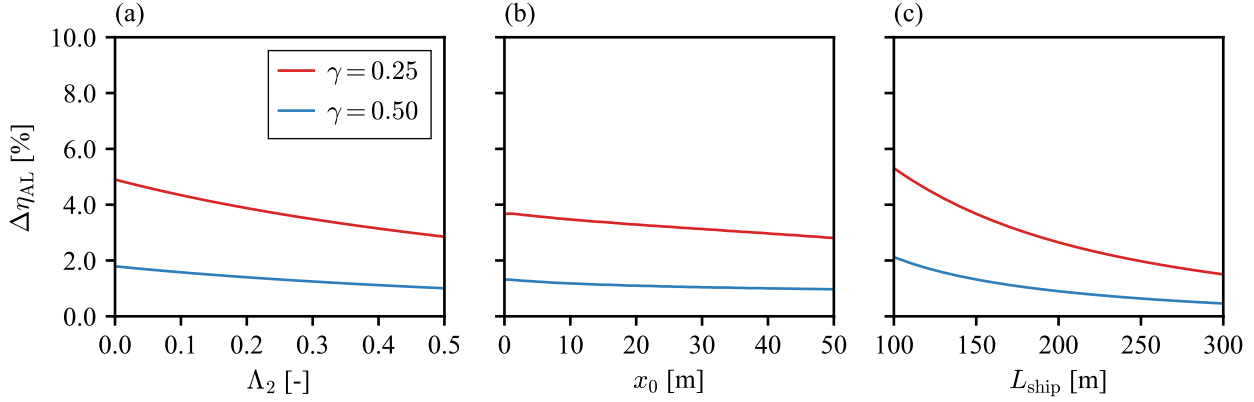


Figure 6.6: Effect of hull parameters on the gain of net power saving of air lubrication by RBI relative to CBI: (a) Λ_2 , (b) x_0 , and (c) L_{ship}

always has the effect to raise $\Delta\eta_{AL}$. Since a smaller effect on the propulsion is desirable in the design of BDR for ships, Λ_1 is set unity hereafter.

The dependence of $\Delta\eta_{AL}$ on the other parameters is shown in Fig. 6.6. The important result is $\Delta\eta_{AL} > 0$ for all the examined conditions. Λ_2 is the ratio of residuary drag to the frictional drag, and $\Lambda_2 \approx 0.25$ for large ships (Kodama *et al.* [79]). The smaller Λ_2 indicates the larger amount of frictional drag at the same BHP⁰. Thus, $\Delta\eta_{AL}$ becomes high at small Λ_2 by getting much drag reduction as shown in Fig. 6.6(a). As for the dependence on x_0 , $\Delta\eta_{AL}$ decreases as x_0 owing to lack of drag reduction on the hull in $x < x_0$ (Fig. 6.6(b)). As shown in Fig. 6.6(c), $\Delta\eta_{AL}$ gets lower for longer ships. This is because the drag-reduction ratio decays to zero in the sufficiently long downstream distance both at CBI and RBI according to the model of Eq. (6.14).

For all the hull parameter, RBI at $\gamma = 0.25$ produces higher $\Delta\eta_{AL}$ than that at $\gamma = 0.50$. Nevertheless, RBI at $\gamma = 0.50$ still gives positive $\Delta\eta_{AL}$. This indicates the principal parameter of RBI, which needs optimization first in practical use, is the repetition frequency.

6.3.3 Dependence on air-blowing property

The sensitivity of $\Delta\eta_{AL}$ to the property of the system blowing air is examined using case II of the fitting function for η_{AB}^C . The RBI parameters were $t_a = 4.5$ mm, $f = 0.5$ Hz, and $\gamma = 0.25, 0.50$, and hull parameters were set typical values. As shown in Fig. 6.7, $\Delta\eta_{AL}$ decreases as p owing to the term increasing as a function of γ^{1-n} in Eq. (6.17). The effect of p is more steep for $\gamma = 0.25$ than $\gamma = 0.50$. Thus, $\Delta\eta_{AL}$ at $\gamma = 0.25$ falls below that at $\gamma = 0.25$ for $p \approx 2.0$. However, $\Delta\eta_{AL}$ is positive even with a system having such a severe property for RBI.

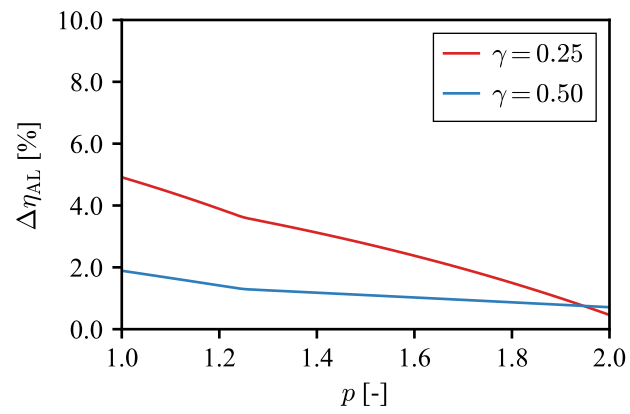


Figure 6.7: Effect of the property of air-blowing system on the gain of net power saving of air lubrication by RBI relative to CBI

6.4 Conclusions

This study presented the estimation of net performance of repetitive bubble injection (RBI) on ships and the dependence of the performance on basic parameters in the practical design. The gain of net performance contains two terms representing the power saving owing to the frictional drag reduction by the bubbles and the power consumption for blowing air into the water. The contribution of drag reduction is calculated using the model describing the streamwise distribution of the local friction coefficient provided in Chapter 4 and 5. The estimation of the power consumption is based on the experimental result of a sea trial using a ship (Mizokami *et al.* [8]).

Using this method, the gain of the net power saving by RBI relative to continuous bubble injection was examined by changing the parameters related to the control of RBI, the design of the ship, and the property of the air-blowing system. The highest gain in RBI conditions is 6.1% obtained at the nominal air-layer thickness of 4.5 mm, the repetition frequency of 0.5 Hz, and the duty cycle of 0.25. This gain is comparable to the net power saving obtained in the previous sea trials. For the best condition of RBI, the dependence of the gain on hull parameters and air-blowing properties is calculated. It confirms RBI produces the positive gain for those modifications robustly. The present study offers a prospect of RBI in terms of the net preformancer as the fundamental result for the more detailed design in practical use.

CHAPTER 7

Local friction under propagation of void waves in a turbulent boundary layer

Preface

This chapter aims to advance the understanding of the phenomena that occur to promote drag reduction using the experimental data obtained in Chapter 5. The characteristics observed in the temporal variation of local friction and its relationship to bubble distribution are discussed. The phase-averaged waveforms of local wall shear stresses reveal the process of streamwise transition of the drag-reduction effect.

7.1 Introduction

The modification of the local wall shear stress caused by the multiple bubbles is a focus in the study of the drag reduction by bubbles. Bubble clusters consisting of several bubbles cause the fluctuation of the local void fraction in the flow. Oishi *et al.* [59] measured the void fraction and the wall shear stress simultaneously in horizontal channel flows and found their temporal correlation with a time lag. The flow modulation by a single bubble is attributed to the relaxation of the Reynolds shear stress owing to deformability (Kitagawa *et al.* [20]), generation of vortices (Oishi and Murai [52]), and formation of a thin liquid film between the wall and the bubble (Murai *et al.* [46] and Kim *et al.* [60]). However, the expansion of this knowledge to the bubble clusters is unrevealed because of the involution of the bubble-bubble interaction to the phenomena.

Previous studies of the bubble drag reduction (BDR) for ships revealed spatiotemporal fluctuation of local void fraction, termed void wave, had an effect to enhance drag reduction. Park *et al.* [55] observed the downstream creation of bubble swarms consisting of huge numbers of bubbles with air injection at constant flow rates into turbulent boundary layers beneath a flat bottom of a model ship. They derived a void-wave equation that denotes the linkage of the local void fraction and the local wall shear stress. The equation indicates the potential existence of void waves during the drag reduction. The relationship between the void wave and the drag reduction was complemented by an experiment using the same model ship (Park *et al.* [57]). It concluded that the spontaneous emergence of void waves enhanced drag reduction.

Repetitive bubble injection (RBI) imposes void waves on the flow for the purpose of inducing the enhancement of drag reduction artificially relative to continuous bubble injection (CBI). Following the demonstration of the drag-reduction promotion in turbulent channel flows by Park *et al.* [54], the studies incorporated in this thesis have been developing RBI. Chapter 2 focused on the downstream persistence of the artificial void waves by performing the optical visualization of the bubbly flow beneath a flat-bottom model ship. The diffusion coefficient based on a model of one-dimensional advection-diffusion equation infers the void waves can persist tens of meters. Chapter 3 experimentally explored the optimal frequency of RBI for drag reduction in high-speed turbulent channel flows. The measurement of the local wall shear stress confirmed the match of its frequency of fluctuation to the repetition frequency of RBI. The experiment in Chapter 5 confirmed the promotion of drag reduction in a large-scale environment and found the persistence of the drag-reduction effect to the end of the 36-m-long model ship.

In the experiment using the 36-m-long model ship, the bubble distribution was optically visualized and the local wall shear stress, τ , was directly measured using a shear stress sensor. The timeline images of the bubbly flow and the waveforms of the wall shear stress are shown in Fig. 7.1. A quick look confirms the reduction of wall shear stress at the time bubble swarms pass. The present study aims to elucidate the characteristics of the periodical fluctuation of the wall shear stress induced by the void wave in the turbulent boundary layer. A detailed analysis process was built to extract reliable features from the experimental data.

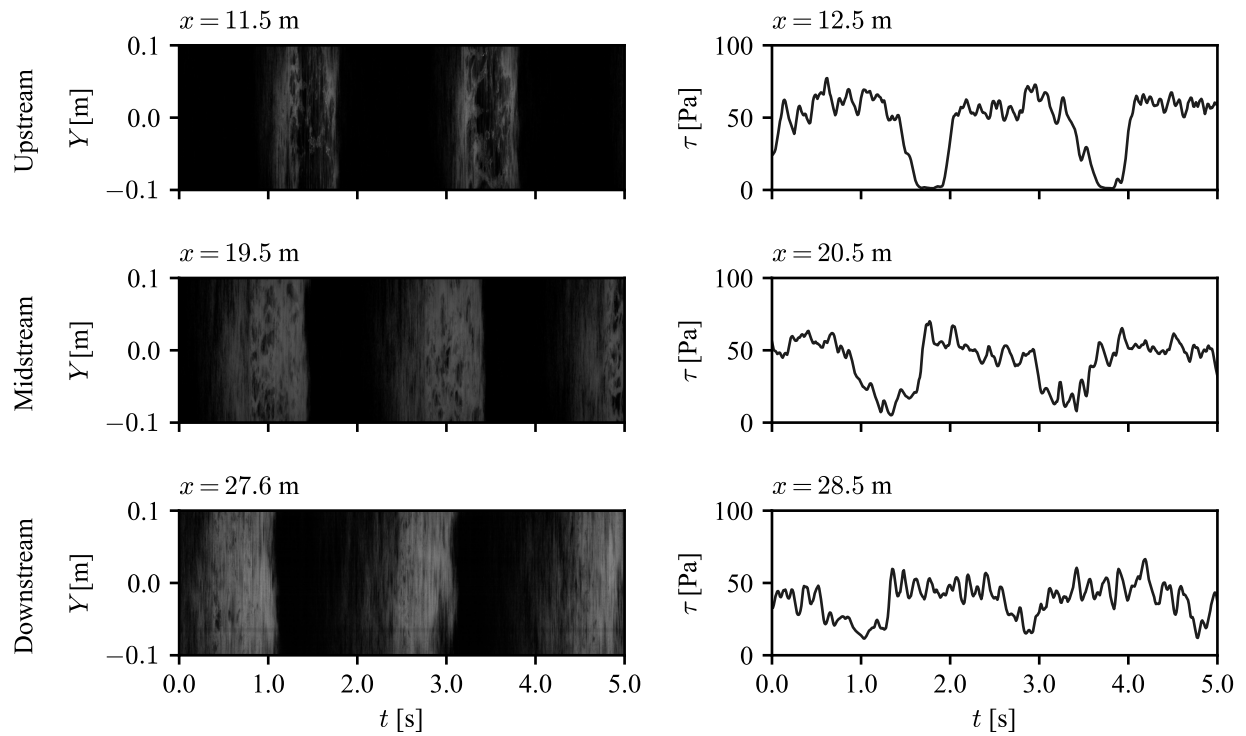


Figure 7.1: Timeline images of the flow (left) and waveforms of the wall shear stress (right) on a 36-m-long model ship during BDR (Chapter 5). The images and the waveforms were simultaneously obtained at three regions: upstream (top), midstream (middle), and downstream (bottom) of the turbulent boundary layer beneath the model ship. x is the distance from the bow, and Y is the spanwise coordinate of the origin at the center of the image. Bubble swarms appear as white areas in the image owing to the reflection of the illumination. These data were obtained at the condition giving the largest drag reduction in the experiment.

7.2 Experimental setup

The experimental setup is identical to that of Chapter 5. The experiment was conducted in a towing test facility at the National Maritime Research Institute, Tokyo, Japan, which has been certified as a standard institute for ship performance examination (ISO 9001). The dimensions of the water tank were 400 m in length, 18 m in width, and 8 m in depth. The length and width of the model ship were 36.0 m and 1.0 m. The towing speed of the model ship was set to 8.0 m/s. In this study, we focus on the experimental condition producing the large drag reduction, i.e., the nominal air-layer thickness $t_a = 4.5$ mm, the repetition frequency $f = 0.5$ Hz. The two conditions of the duty cycle, $\gamma = 0.25$ and 0.50 , were examined.

Three high-speed video cameras were mounted on the model ship at three positions, namely $x = 11.5$, 19.5 , and 27.6 m. The specifications of flow visualization at each position are summarized in Table 7.1. Three different cameras were used and individually set the recording condition. Crowds of small bubbles appear as white areas owing to the reflection of the lighting from above (Fig. 7.1). The flow contains bubbles larger than a millimeter size. The spatial resolution allows recognizing the existence of bubbles but clearly resolving the shape of the bubbles.

The local wall shear stress was measured using shear-stress sensors (S10W-2S, SSK Co., Ltd., Japan) simultaneously with the flow visualization. The sensors were carefully mounted flush with the bottom plane of the model ship and calibrated by the procedure described in Chapter 5. The sensor measured the shear stress locally using a mechanical force gauge with a 10-mm-diameter plate. The maximum measurable range was 40 Hz, which was adequately high to resolve the temporal fluctuation imposed by RBI in the present experiments. The sensors were placed downstream of the cameras, i.e., $x = 12.5$, 20.5 , and 28.5 m, and aligned in the four spanwise positions of $y = 250$, 125 , -125 , and -250 mm.

The flow visualization and the shear-stress measurement were conducted 5.0 s within the section 140–180 m from the end of the 400-m-long water tank. A wait time of more than 20 minutes between trials was adopted to allow the calming of surface waves in the water tank generated by the towing of the model ship. Two periods of RBI at 0.5 Hz are included in the obtained data from one trial. To improve the reliability of the result, three trials were repeated in the experiment and the analysis process specialized for the obtained data is built in the present study.

Table 7.1: Specifications of flow visualization at three downstream positions

Position (x, y)	11.5 m, 0.2 m	19.5 m, 0.2 m	27.6 m, 0.2 m
Camera	FASTCAM Mini AX200 (Photoron)	MEMRECAM HX-7S (Optronis)	FASTCAM Mini AX50 (Photoron)
Image size ($S_X \times S_Y$)	1024×1024	1080×1920	1024×1024
Spatial resolution	0.22 mm/pixel	0.11 mm/pixel	0.25 mm/pixel
Frame rate	2000 s^{-1}	2000 s^{-1}	2000 s^{-1}
Lighting	LED panel	Metal halide lamp	Metal halide lamp

7.3 Modification of wall friction depending on flow states

As seen from the timeline image (Fig. 7.1), the flow periodically experiences two distinct states: a state with dense bubbles and another state with few bubbles. We refer to the former one as the “bubbly flow state” and the latter one as the “liquid-dominant flow state” hereafter. Because a certain number of bubbles coming out from the swarms can exist, the liquid-dominant flow appearing in RBI should be distinguished from the liquid-single-phase flow at the condition without bubble injection.

To discuss the characteristics of the wall friction in the two states separately, the flow state is identified using the bubble image by the process shown in Fig. 7.2. The average brightness of a snapshot was calculated by

$$\bar{B}(t) = \frac{1}{S_X S_Y} \sum_{X,Y} B(X, Y, t), \quad (7.1)$$

where X and Y are coordinates of the image in the streamwise and the spanwise direction. S_X and S_Y indicate the image size in the respective direction. The brightness was calculated for 4.0 s from the beginning of the recording, corresponding to the time of two-cycle of RBI. The obtained $\bar{B}$ was normalized as

$$\bar{B}'(t) = \frac{\bar{B}(t) - \min(\bar{B}(t))}{B_{\max} - \min(\bar{B}(t))}, \quad (7.2)$$

where the maximum brightness $B_{\max} = 255$. The normalized average brightness $\bar{B}'$ is almost zero for a snapshot of bubbles not seen and becomes relatively higher during the passage of bubble swarms (Fig. 7.2(a)). The flow is decided to be bubbly flow state for $\bar{B}' > \epsilon_B$, where ϵ_B is the threshold. The result for different ϵ_B is shown in Fig. 7.2(b). $\epsilon_B = 1\%$ was judged to be suitable by the comparison of the result and the timeline image.

The utilization of the flow state to the waveform of the wall shear stress needs adjustment of

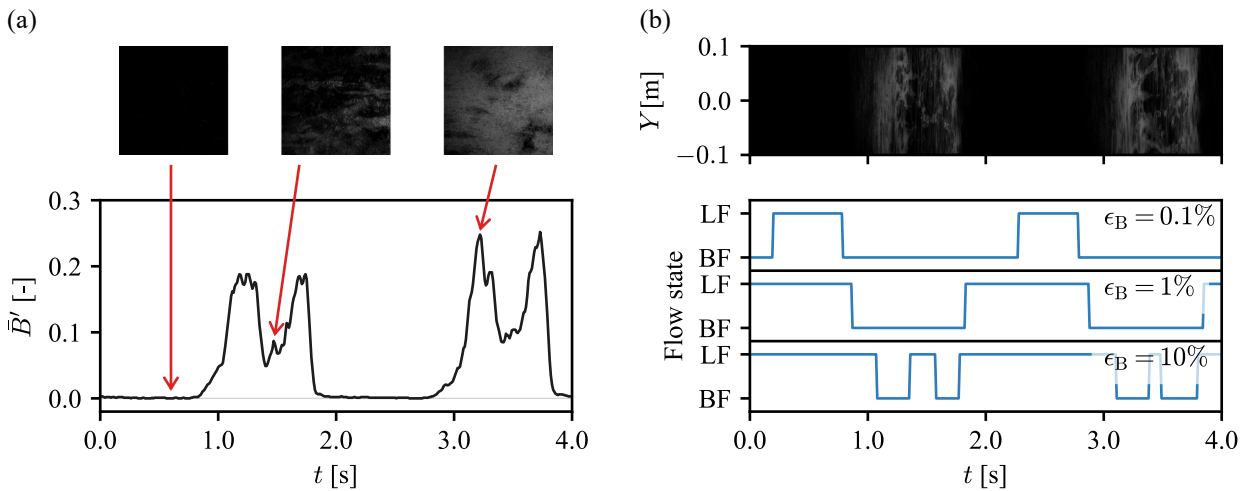


Figure 7.2: Method to identify the flow state: (a) acquisition of normalized average brightness of a snapshot, $\bar{B}'$, and (b) threshold for $\bar{B}'$ to judge the flow state at ϵ_B . The abbreviations, BF and LF, respectively represent bubbly flow state and liquid-dominant flow state.

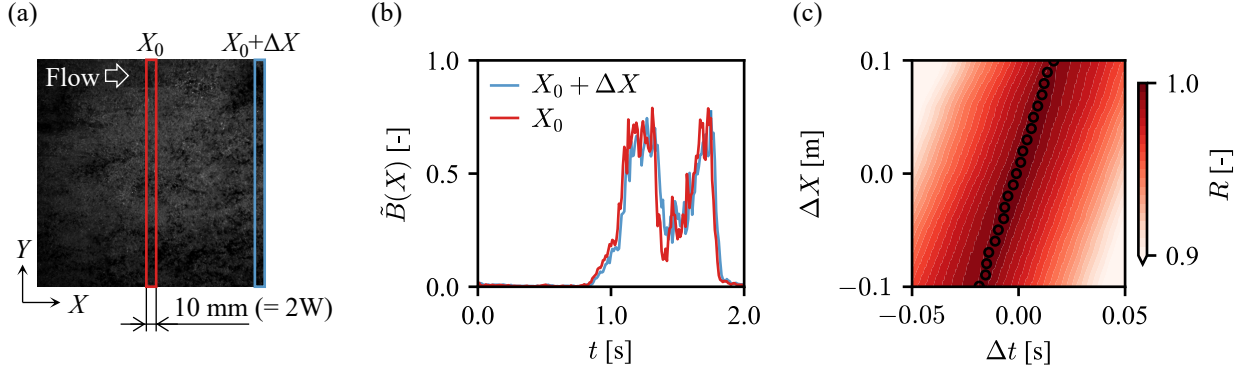


Figure 7.3: Method to obtain the advection velocity of void wave: (a) rectangular windows for calculating local average brightness $\tilde{B}$, (b) the waveforms of $\tilde{B}$ at the center, X_0 , and a displaced position, $X_0 + \Delta X$, and (c) the cross-correlation coefficient of the waveforms for the time lag Δt . Circle markers in (c) denote the time difference giving the maximum R at each ΔX .

the time difference in the observation positions. In a local rectangle window around the streamwise center of the image, X_0 , shown in Fig. 7.3(a), the average brightness is calculated by

$$\tilde{B}(X_0, t) = \frac{1}{2WS_Y} \sum_{X_- \leq X < X_+, Z} B(X, Z, t), \quad X_{\pm} = X_0 \pm W. \quad (7.3)$$

The window size $2W$ was set to 10 mm to be larger than the size of the bubbles. In the same way, the local average brightness $\tilde{B}(X, t)$ is calculated at $X = X_0 + \Delta X$ for the displacement ΔX with $2W$ intervals. $\tilde{B}(X, t)$ at different ΔX have similar waveforms but exhibit time lag as shown in Fig. 7.3(b). The cross-correlation coefficient of the waveforms at the center $\tilde{B}(X_0, t)$ and at the displaced position $\tilde{B}(X_0 + \Delta X, t)$ is calculated for the time lag Δt as

$$R(\Delta X, \Delta t) = \frac{\sum_t \tilde{B}(X_0, t) \tilde{B}(X_0 + \Delta X, t + \Delta t)}{\sqrt{\sum_t \tilde{B}(X_0, t)^2} \sqrt{\sum_t \tilde{B}(X_0 + \Delta X, t + \Delta t)^2}}. \quad (7.4)$$

The distribution of R is shown in Fig. 7.3(c) in Δt - ΔX plane, where the time difference giving the maximum R at each ΔX is marked. The fitting of a linear function to the data gives the advection velocity of the void wave, V . The result varies in 5.7–6.1 m/s exhibiting little explicit dependence on γ and x .

The time lag between the observation of the flow and the measurement of the wall shear stress was adjusted using V . Consequently, the flow state judged from the bubble image is applicable to the waveform of the wall shear stress (Fig. 7.4). In the following analysis of the wall shear stress, the data only where the flow state is identified is used, and the available maximum phase is referred to $\theta_{\max}$. As seen in Fig. 7.4, the wall shear stress is equivalent to that in the liquid-dominant flow state at the beginning of the bubbly flow state, and then it largely drops.

Probability density distribution of the wall shear stress in each flow state is shown in Fig. 7.5 for $\gamma = 0.25$. At $x = 12.5$ m, the distribution of the bubbly flow state has double peaks at $\tau/\tau_{p0} \approx 0$ and $\tau/\tau_{p0} \approx 1$, where τ_{p0} is the wall shear stress in the single-phase flow without bubble injection

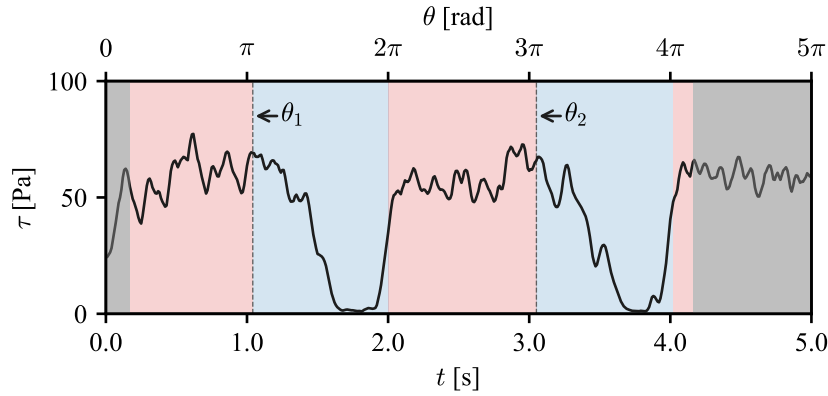


Figure 7.4: Distinguishment of flow state overlaid to the waveform of the wall shear stress. The blue and red areas respectively denote the bubbly flow state and the liquid-dominant flow state. The data of the wall shear stress in the gray area is not used in the following analysis owing to the not identified flow state. The top abscissa indicates the phase converted from the time with the repetition frequency of RBI.

predicted using the Prandtl–Schlichting law (Schlichting [77]),

$$\tau_{p0} = \frac{1}{2} c_{fp0} \rho_l U^2, \quad (7.5)$$

$$c_{fp0} = (2 \log_{10} Re_x - 0.65)^{-2.3}. \quad (7.6)$$

The peak in lower τ corresponds to the large decrease in wall shear stress caused by the film-like large bubbles appearing in upstream regions. The peak in higher τ is formed in the duration before the large drag-reduction effect emerges. The two distributions around the respective two peaks look to merge as the downstream propagation to $x = 20.5$ and 28.5 m since the large drag reduction decays owing to the breakup of bubbles. The distribution of the liquid-dominant flow state is similar to that in the single-phase flow.

The distributions for $\gamma = 0.50$ is shown in Fig. 7.6. The double peaks are more nearby in the upstream region ($x = 12.5$ m) relative to $\gamma = 0.25$. The two distributions merge in the downstream regions, and the whole distribution at $x = 28.5$ m gets to resemble that of CBI. This infers that the drag-reduction effect of RBI in the further downstream approaches that of CBI. This prospect is thought to stand for $\gamma = 0.25$ as well although the change of the distribution during the downstream migration looks weak in the observed downstream distance.

The probability distributions of the bubbly flow state clarify that there are two factors causing the streamwise transition of drag reduction: (i) the disappearance of significant drag reduction, namely $(\tau/\tau_{p0} \approx 0)$, due to the breakup of large bubbles, and (ii) longer persistent drag-reduction promotion by void waves, which diffuse as the result of dispersion of the small bubbles, investigated in Chapter 2 and 3. This finding was obtained by conducting a large-scale model ship experiment with U and t_a set equal to ship conditions. In the model of the streamwise transition of local drag reduction in Chapter 5 (Eq. (5.23)), exponential decay according to a single coefficient is used as a consequent superposition of the phenomena occurring in the two-phase turbulent boundary

layer. The separation of the multiple factors can be established by clarifying the direct relationship between the state of bubbly flow and the drag reduction including the temporal responses by further studies.

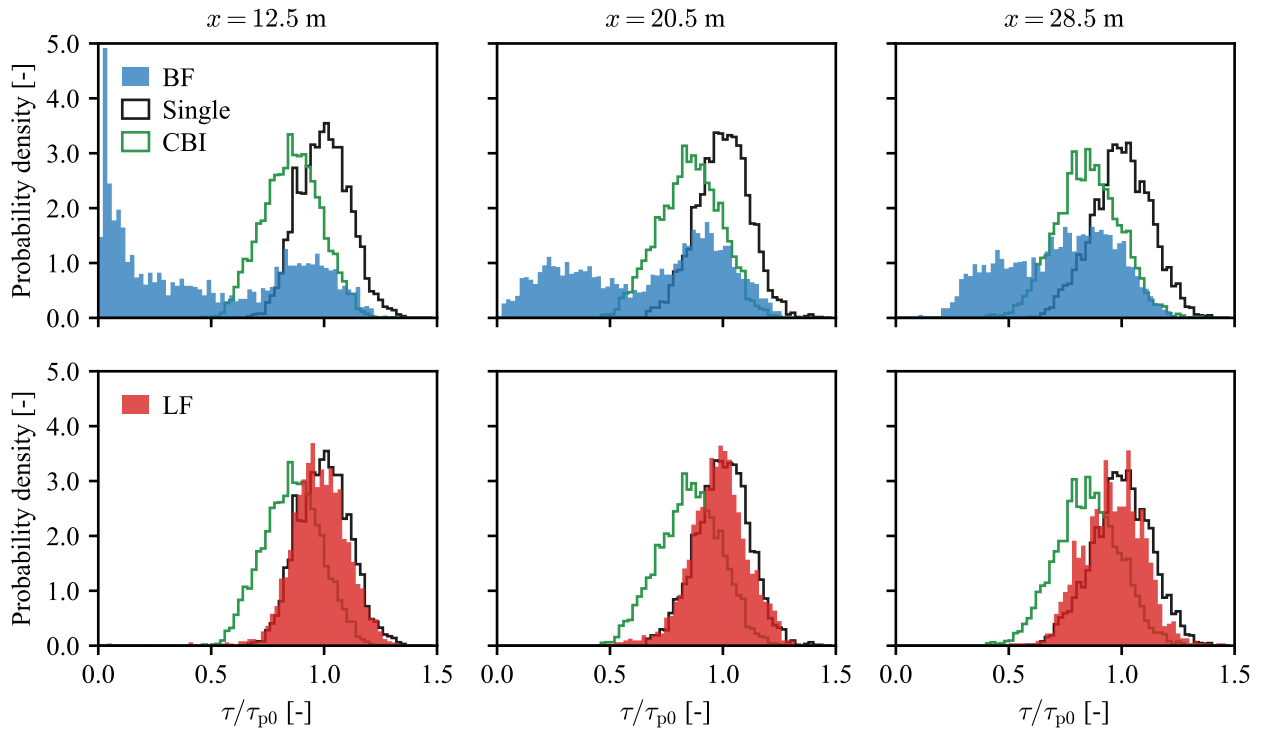


Figure 7.5: Probability density distribution of the wall shear stress of the two flow states at $\gamma = 0.25$: the bubbly flow state (top) and the liquid-dominant flow state (bottom). The distributions are obtained at three downstream positions. The distributions of CBI and the liquid-single-phase flow without bubble injection are presented for comparison.

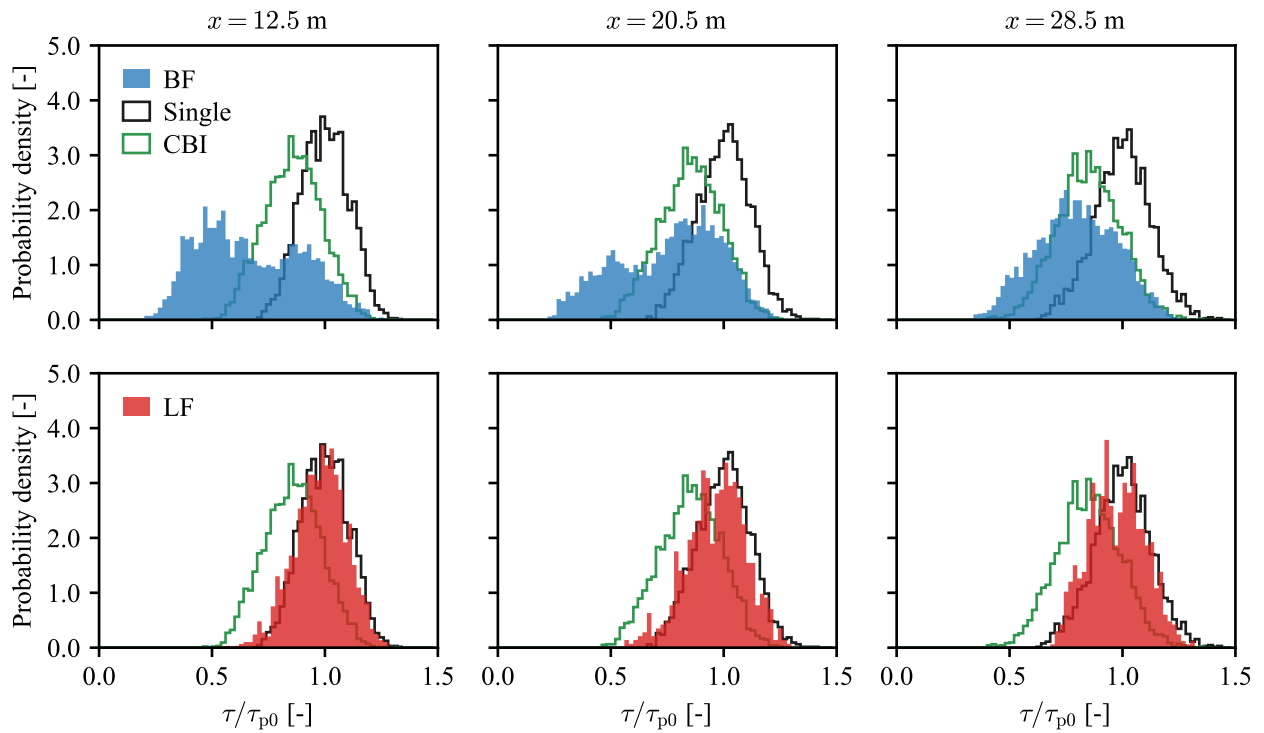


Figure 7.6: Probability density distribution of the wall shear stress of the two flow states at $\gamma = 0.50$: the bubbly flow state (top) and the liquid-dominant flow state (bottom). The distributions are obtained at three downstream positions. The distributions of CBI and the liquid-single-phase flow without bubble injection are presented for comparison.

7.4 Periodical fluctuation of wall shear stress

In the 5.0 s measurement, the wall shear stress experiences periodical fluctuation until 5π in the phase θ at the repetition frequency of 0.5 Hz (Fig. 7.4). To evaluate the characteristics of the periodical fluctuation, the phase-averaged waveform of the wall shear stress are obtained. The start point of one period is determined using the switch from the liquid-dominant flow state to the bubbly flow state. We find two points, θ_1 and θ_2 , in a waveform. The one period is extracted as

$$[\tau]_{z_l, m, n}(\phi) = \tau_{z_l, w_m}(\theta - \theta_n), \quad (7.7)$$

where z_l and m indicate the spanwise positions ($l = 1, 2, 3, 4$) and the trial number in the experiment ($m = 1, 2, 3$). The phase ϕ is defined for the phase averaging and valid in $0 \leq \phi < 2\pi$. In the extraction, three kinds of the upper limit of θ need to be considered: until one period after θ_n , no extraction duplication, and the flow state identification. Therefore, the limitation for the extraction is given by

$$\theta_n \leq \theta < \min(\theta_n + 2\pi, \theta_{n+1}, \theta_{\max}). \quad (7.8)$$

For the averaging, a factor is defined to denote whether data is collected:

$$\delta_{z_l, m, n}(\phi) = \begin{cases} 1 & (\theta < \min(\theta_n + 2\pi, \theta_{n+1}, \theta_{\max})) \\ 0 & (\theta \geq \min(\theta_n + 2\pi, \theta_{n+1}, \theta_{\max})) \end{cases}. \quad (7.9)$$

Then, the phase average is conducted by

$$\langle \tau \rangle(\phi) = \frac{\sum_{l, m, n} [\tau]_{z_l, m, n}(\phi)}{\sum_{l, m, n} \delta_{z_l, m, n}(\phi)}. \quad (7.10)$$

The number of data used in the average was normally twenty-four, but it decreases at $\phi \approx 2\pi$ due to the limitation for the sampling by Eq. (7.8).

The result of the phase average is shown in Fig. 7.7. The phase of the switch from the bubbly flow state to the liquid-dominant flow state was also acquired in the process of average. At $\gamma = 0.25$, $\langle \tau \rangle$ is close to τ_{p0} at the beginning of the bubbly flow state, and then a large drag reduction emerges in the later part of the state. The occupation of the bubbly flow state in one period becomes longer as the downstream distance owing to the dispersion of bubbles. However, the elongation weakens the drag reduction in the later part of this state. Instead of this, a small drag reduction is obtained in the former part of the bubbly flow state at the downstream position ($x = 28.5$ m). In the liquid-dominant flow state, the wall shear stress is returning to the magnitude in the single-phase flow. The redevelopment of the wall shear stress occurs across the switch of the flow states. This indicates the drag-reduction effect remains after the bubble swarm has passed.

The trends found at $\gamma = 0.25$ commonly appears at $\gamma = 0.50$. The decay of the strong drag reduction in the bubbly flow state proceeds during the downstream migration and leads to the relatively flat waveform of $\langle \tau \rangle$ at $x = 28.5$ m. The comparison of the waveforms of $\gamma = 0.25$ and

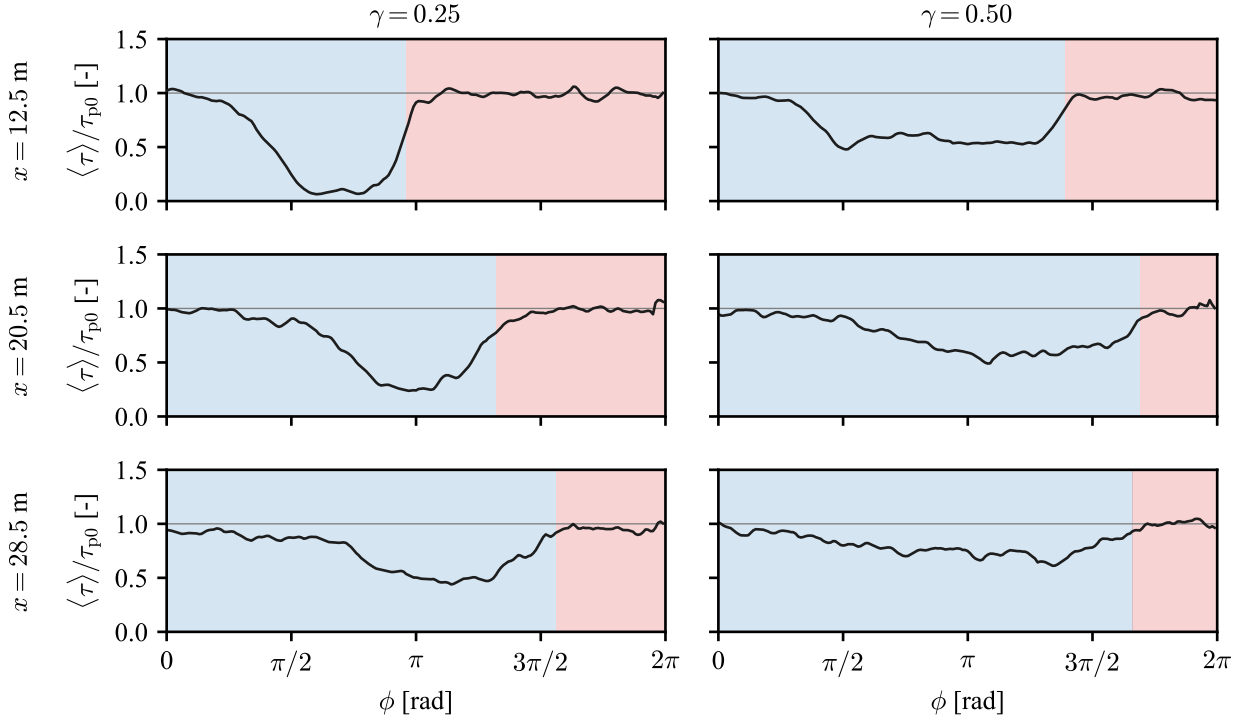


Figure 7.7: Phase-average of the wall shear stress at the frequency of 0.5 Hz at three downstream distances at $\gamma = 0.25$ (left) and $\gamma = 0.50$ (right). The blue and red areas respectively denote the bubbly flow state and the liquid-dominant flow state.

0.50 at the same downstream distance suggests the relationship with the minimum $\langle \tau \rangle / \tau_{p0}$. The drop of $\langle \tau \rangle / \tau_{p0}$ is approximately half at $\gamma = 0.50$ relative to $\gamma = 0.25$. Likewise, the instantaneous maximum air flow rate at $\gamma = 0.50$ is half of that at $\gamma = 0.25$. This correspondence infers the largest drag reduction in a period is determined by the initial condition at the air injection throughout the boundary layer along tens of meters.

To visualize the contribution of the instantaneous drag reduction to the total performance, a cumulative function is defined for the phase-averaged wall shear stress of RBI:

$$F(\phi) = \frac{1}{2\pi} \int_0^\phi \left(1 - \frac{\langle \tau \rangle}{\tau_{p0}} \right) d\phi. \quad (7.11)$$

Here, F starts from zero at $\phi = 0$ and reaches the time-averaged drag-reduction ratio, DR , at $\phi = 2\pi$. The function is rewritten for CBI as

$$F(\phi) = \frac{\phi}{2\pi} \cdot DR. \quad (7.12)$$

for the comparison. The variation of F to the phase is shown in Fig. 7.8. The result indicates the contribution in the later part of the bubbly flow state is the most dominant in a period. The rise of the function of RBI around $\phi = 0$ is slower than that of CBI. The start-up characteristics become better in downstream regions. The curve of RBI at $\gamma = 0.50$ gets to resemble the line of CBI as

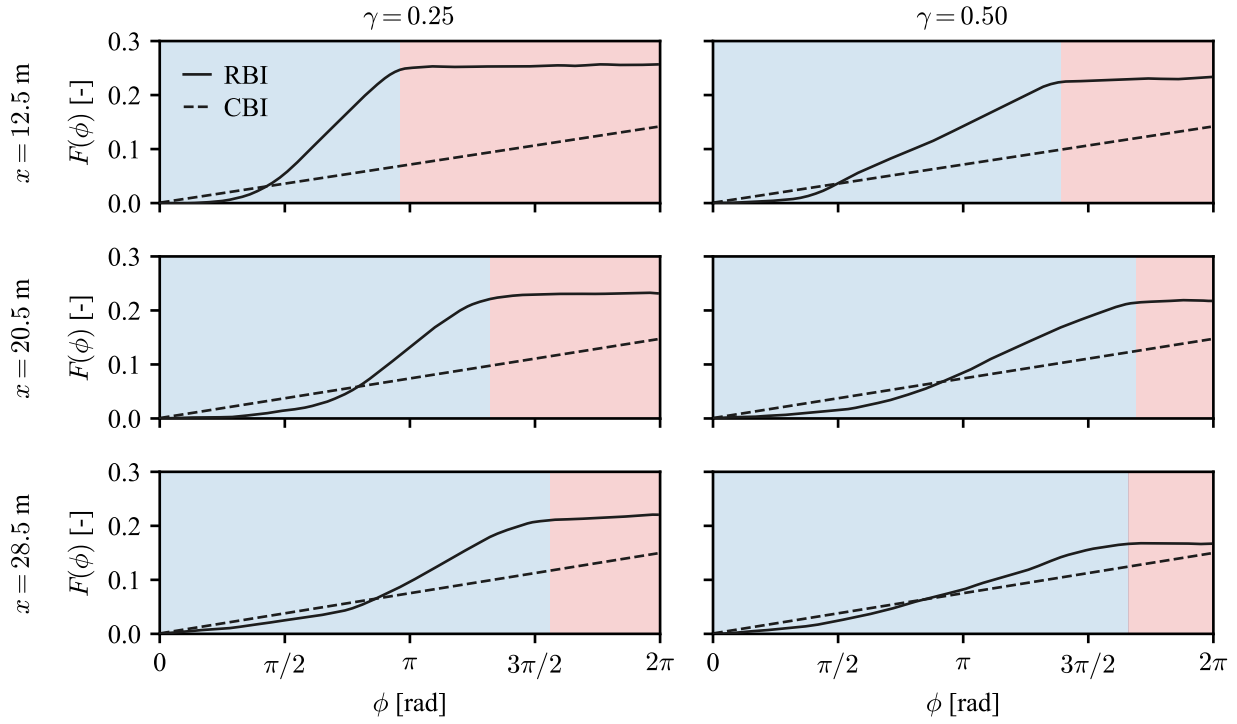


Figure 7.8: The cumulative function of the instantaneous friction reduction at three downstream distances: $\gamma = 0.25$ (left) and $\gamma = 0.50$ (right). The blue and red areas respectively denote the bubbly flow state and the liquid-dominant flow state.

the downstream distance, and it is thought to match the line in further downstream regions. The friction reduction in the liquid-dominant flow state gives a little increase of F . The contribution in this state mainly attributes to the remained drag-reduction effect at the switch of the flow state.

7.5 Conclusions

The present study explores the characteristics of the periodical fluctuation of the local wall shear stress induced by the void wave propagating in a turbulent boundary layer. The flow visualization and the measurement of the wall shear stress were performed on a 36-m-long flat-bottom model ship towed at 8.0 m/s. The data are provided by the large-scale experiment described in Chapter 5, which inevitably yields the limitation of the length of observation time. Analysis methods specified for the existing data are established to enhance the reliability of results in this work.

The switch of the flow states of the bubbly flow and the liquid-dominant flow in repetitive bubble injection is judged using the brightness of the bubble image. In addition, the advection velocity of the void wave is obtained by a method based on the time difference in the streamwise direction observed in the sequential images. These processes enable the identification of the flow states on the wall shear stress measured downstream of the flow visualization. The probability density distributions of the wall shear stress denote the modification of wall friction separately for each flow state. The distribution of the bubbly flow has double peaks in the upstream region, and the whole distribution gets similar to that of continuous bubble injection in the downstream region.

To elucidate the periodical fluctuation of the wall shear stress, the phase average is performed with the determination of zero-phase using the identified flow state. The phase-averaged wall shear stress indicates that the drag reduction is small at the beginning of the bubbly flow state and the large drop emerges in the later part of the state. The occupation of the bubbly flow state in a period increases as the downstream distance owing to the dispersion of bubbles. The elongation of the bubbly flow state accompanies the weakening of the large drag reduction and spread of the phase giving a small reduction. The cumulative function of the phase-averaged wall shear stress denotes the dominant contribution of the large drop in the bubbly flow state to the total effect. Whereas, the improvement of the start-up of counteracts the loss of the large drop in the downstream regions. The findings of the present study in the response of the wall shear stress to the void wave are expected to support the development of the optimal control of the boundary layer via bubble injection.

CHAPTER 8

Temporal response of turbulent flow to sudden decrease in local void fraction

Preface

This chapter investigates the temporal response of turbulent flow to the sudden decrease in local void fraction. The interest in the flow modification occurring at the end of bubble swarms is encouraged by the results of previous chapters. Methods for image preprocessing and particle tracking velocimetry are established to perform liquid-velocity measurements of bubbly flow. The statistical analysis discovers the strong mitigation of turbulent flow during the transition to single-phase flow.

8.1 Introduction

Modification of the original liquid-flow structure caused by bubbles added to the fluid has been a focus of multiphase flow research. A single bubble placed in a liquid rises due to buoyancy and induces wakes behind itself (Wegener 1973 Spherical Cap). Multiple bubbles have bubble-bubble interaction to generate a more complicated liquid-velocity field and behavior of bubbles (Takagi and Matsumoto [92]). The mechanism to yield the two-phase flow field comes from the two-way interaction of liquid and bubbles. The effect of flow modification can spread the entire flow not limited to the vicinity of bubbles. Lots of bubbles injected in upward pipe flow replace the state from laminar flow to turbulent flow known as bubble-induced pseudo turbulence (Hosokawa and Tomiyama [93]).

Bubbles injected into turbulent boundary layers cause a reduction of wall frictional drag (e.g., Murai [14] and Ceccio [26]). The bubble drag reduction is utilized for ship power-saving, and detailed studies on the behavior of liquid flow and bubbles were performed to date. A single bubble larger than the thickness of the turbulent boundary layer induces vortices in front and behind itself (Oishi and Murai [52] and Kim *et al.* [60]). A large number of bubbles affect the entire boundary layer in different manners depending on the bubble size. Microbubbles smaller than the turbulent length scale concentrate in the core of turbulent vortices to depress the action (Ferrante and Elghobashi [62]). This effect is strong to decrease the vortical structures of the boundary layer (Park *et al.* [69]). For small bubbles of comparable size to the turbulent coherent structures, they disperse in the boundary layer. The bubble deformation relaxes turbulent flow and decreases the Reynolds shear stress (Kitagawa *et al.* [20]). Moreover, larger bubbles concentrate on the region close to the top wall due to buoyancy. The formation of a dense bubbly layer causes drag reduction (Sanders *et al.* [45], Jha *et al.* [58], and Hazuku *et al.* [61]). In addition to those behaviors in horizontal systems, Yoon *et al.* [90], [91], [94] presented models of bubble motion in boundary layers on inclined walls for various angles for the purpose of predicting the behavior of bubbles on the three-dimensional-shaped hulls.

The two-way interaction between liquid and bubbles returns density patterns of bubbles in the flow. Park *et al.* [55] observed spontaneous emergence of a quasi-periodic pattern of bubble crowds beneath a flat-bottom model ship. The periodical passage of bubble swarms accompanies temporal fluctuation of local void fraction, termed void wave. Park *et al.* [57] discovered the spontaneous emergence of void waves promotes drag reduction. Based on this finding, an investigation of the behavior of bubble swarms was performed using void waves synthesized by air flow rate control. The advective development of single void pulse (Park *et al.* [89]) and periodical void waves (Chapter 2) was evaluated by apparent diffusion coefficients to give a prediction of the deformation of bubble swarms in a long distance like a ship hull. The artificial void waves promote drag reduction relative to the continuous bubbly flow at the same time-averaged void fraction (Park *et al.* [54], Chapter 2, Chapter c3, Chapter c5). Chapter 7 measured the temporal variation of the wall shear stress caused by the periodical void wave. It reveals an uneven drag reduction effect, namely high drag reduction at the later part of the bubble swarm, during the passage of a bubble swarm. In the present study,

a flow velocity measurement is performed to clarify the temporal response of the flow structure. A sudden decrease in local void fraction was imposed on the flow by cutting off the air supply, and velocity was measured by particle tracking velocimetry (PTV).

8.2 Experimental methodology

8.2.1 Experimental setup

A schematic of the experimental apparatus is presented in Fig. 8.1. The test section was an acrylic horizontal channel with a height ($2h$) of 40 mm, a width of 160 mm, and a length of 10 m. The x , y , and z coordinates respectively denote the streamwise distance from the channel inlet, vertical distance from the top wall, and spanwise position. The test fluid was tap water circulated by a pump. The liquid velocity U_1 was set at 1.5 m/s in the absence of bubbles. The Reynolds number defined by

$$Re = \frac{U_1 h}{\nu_1} \quad (8.1)$$

was 3.0×10^4 , where ν_1 is the kinematic viscosity of the water. The friction velocity and friction length are estimated to be $u_\tau = 7.2 \times 10^{-2}$ m/s and $l_\tau = 1.3 \times 10^{-5}$ m. The Reynolds number and Froude number based on u_τ defined by

$$Re_\tau = \frac{u_\tau h}{\nu_1}, \quad Fr_\tau = \frac{u_\tau}{\sqrt{gh}} \quad (8.2)$$

are $Re_\tau = 1.4 \times 10^3$ and $Fr_\tau = 0.16$. The upper wall of the channel at 3.9 m downstream from the inlet has spanwise arrayed thirty holes of 1 mm in diameter. Compressed air was supplied to a chamber equipped above the holes to inject bubbles into the channel flow. The bubbles in the flow were removed in a tank placed at the end of the test section. The liquid velocity increases during the bubble injection due to the addition of total fluid volume.

The air flow rate was controlled by an electromagnetic valve to generate a sudden decrease in local void fraction in the flow. The volumetric ratio of the gas phase to the total fluid α was 9.0% in injecting bubbles. With the conditions of Re and α , film-like large bubbles are formed in the top region close to the wall (e.g., Jha *et al.* [58]). After sufficient time to form the steady two-phase flow in the channel, the valve was sharply closed to stop bubble injection. This operation imposes

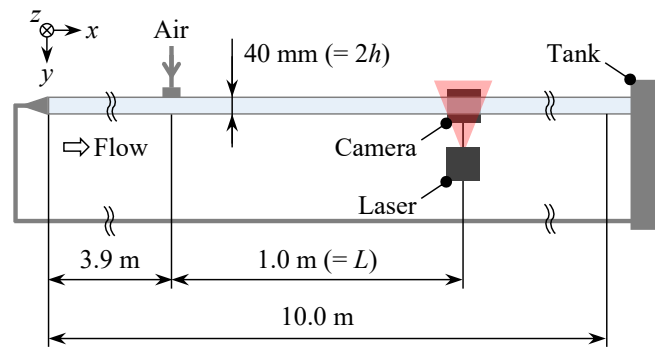


Figure 8.1: Schematic of the experimental apparatus. x , y , and z coordinates respectively denote the streamwise distance from the inlet of the channel, vertical distance from the top wall, and spanwise position.

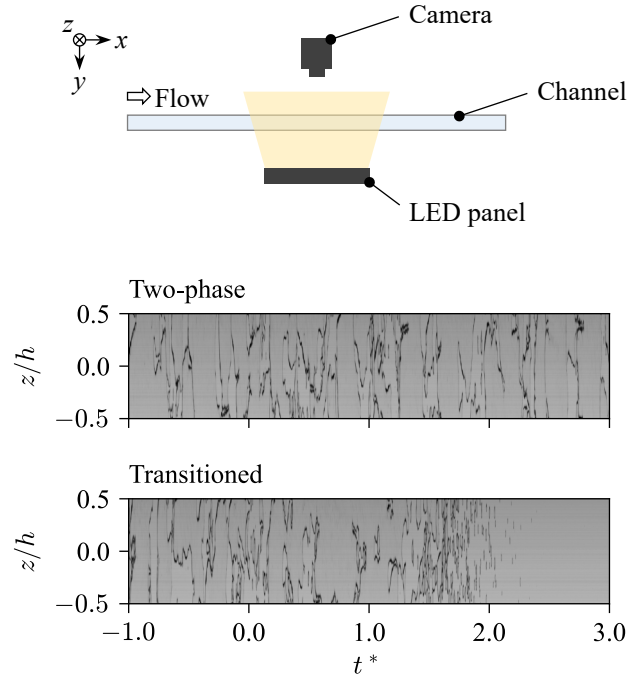


Figure 8.2: Observation of the bubble distribution: schematic of the image acquisition system (top) and timeline images of the flow (bottom)

a transition of the flow state from the two-phase flow to the single-phase flow. The top view of the steady two-phase flow and the transitioned flow at $L = 1.0$ m downstream from the bubble injector, namely $x = 4.9$ m, is shown in Fig. 8.2. The images were captured by a backlight photograph of the channel using a camera and a white LED panel that the gas-liquid interface looks black shadow area. We define the normalized time,

$$t^* = \frac{tU_1}{L}, \quad (8.3)$$

setting $t^* = 0$ to the instant of the valve closure. The bubble distribution of the transitioned flow at $t^* < 0$ looks similar to that of the two-phase flow. Bubbles appear after $t^* = 1$ owing to the slower migration of bubbles than the bulk liquid velocity. The large bubbles emerge until $t^* \approx 1.5$, followed by discrete smaller bubbles until $t^* \approx 2.0$.

8.2.2 Image preprocessing

The liquid velocity was measured at the same location as the bubble observation, $x = 4.9$ m, via PTV. Particles consisting of silver-coated hollow glass spheres (mean diameter $10 \mu\text{m}$, density 1.4 g/cm^3 , Dantec Dynamics) were seeded in the water as tracer particles. A continuous wave red laser (wavelength 450 nm , DPRLu-5W, Japan Laser Co.) illuminated the vertical plane of the flow at the spanwise center of the channel. A high-speed video camera (FASTCAM Mini AX200, Photoron) was fixed perpendicular to the plane to record images. Image acquisition was performed at $3,000 \text{ fps}$ with a resolution of $4.5 \mu\text{m/px}$. We need to preprocess the image before performing PTV to remove bright patterns associated with bubbles. Based on the method of removing non-stationary objects

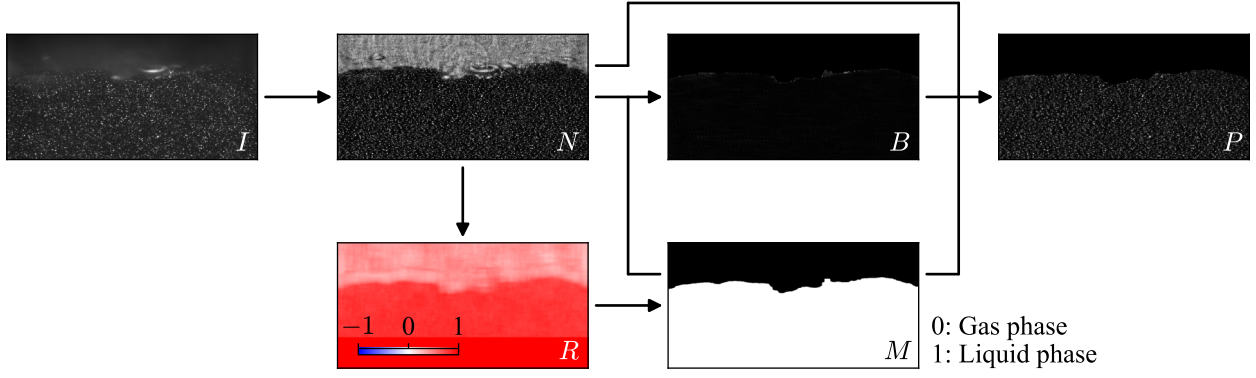


Figure 8.3: Procedure of image preprocessing to remove bubbles: original image I , normalized image N , short-time background image B , particle image P used for the subsequent PTV, map of normalized cross-correlation coefficient R between N and a template, and mask image M displaying liquid phase

presented by Deen *et al.* [95], we built a method to eliminate bubbles concentrated on the top region (Fig. 8.3).

The original image I is first normalized locally by a min/max filter,

$$I'(\mathbf{x}) = \frac{I(\mathbf{x}) - I_{\min}(\mathbf{x})}{I_{\max}(\mathbf{x}) - I_{\min}(\mathbf{x})}, \quad (8.4)$$

and then normalized globally using minimum and maximum intensities of I' by

$$N(\mathbf{x}) = \frac{I'(\mathbf{x}) - I'_{\min}}{I'_{\max} - I'_{\min}}. \quad (8.5)$$

Here, $I_{\min}(\mathbf{x})$ and $I_{\max}(\mathbf{x})$ are respectively the local minimum and maximum intensities in a rectangular window of 20×6 px. The window size was selected to be larger than the particle size and smaller than the size of the interrogation window in the subsequent PIV. The normalization mainly aims to reduce uneven illumination. Additionally, this operation transforms bubbles into a bright noisy pattern. As a template T of particle-laden flow, a two-dimensional Fourier transform of bubble-free 64×64 px images was generated. Then, a map of normalized cross-correlation coefficient R was calculated between T and N . Thresholding of R gives masks M displaying the domain of liquid phase in the image, where the threshold value was set to 0.6. We confirmed smaller image size used for making T caused many wrong detections in the thresholding. For the valid domain $N[M == 1]$, minimum brightness in a short time, the reference frame and its ± 2 frames, is acquired as a background image B . The particle image P used for PTV is finally obtained by the background subtraction $P = N - B$, followed by substitution of the gas-phase domain as $P[M == 0] = 0$.

8.2.3 Particle tracking velocimetry

The liquid velocity is measured by PTV utilizing the relaxation method (Ohmi *et al.* [96]) for the two-frame particle-tracking scheme. The advantages of the relaxation method are the robustness

and accuracy of the tracking in high-density particle images. For the first step of the procedure, particle image velocimetry (PIV) was applied using the image deformation scheme (Raffel *et al.* [97]). The interrogation window size $S_x \times S_y$ was declined as 120×32 , 60×16 , and 40×8 px through the three-step recursive iteration. S_y is set to be smaller than S_x in each step, considering the larger velocity gradient in the vertical direction.

Using the particle position detected by particle mask correlation (Takehara and Etoh [98]), the velocity field obtained by PIV is applied for the initial estimation of the particle displacement. The relaxation method assumes the quasi-rigidity condition, i.e., the displacement of neighbor particles is similar to the reference particle. Implementation of this concept needs to set three conditions: (i) possible area A_p as the maximum difference of the estimation to the consequent displacement, (ii) neighborhood area A_n to search the neighbor particles the reference particle, and (iii) quasi-rigidity radius R_s as the maximum difference of the displacements of the neighbor particle to that of the reference particle. In this study, we set $A_p = 10 \times 4$ px and $A_n = 20 \times 4$ px to be square sections according to the interrogation window of PIV, and $R_s = 1.0$ px. The consequent pair of particles in two frames was determined by iterative calculation of the pairing probability given by Pereira *et al.* [99]. The convergence threshold applied to the probability was set to 1.0×10^{-2} . Convergence was achieved in less than 20 iterations.

We performed PTV on the single-phase flow to assess the validity of the method. Images recorded 5.0 s were used for the calculation of turbulent statistics. For single-phase flow, average velocities in the streamwise direction $\bar{u}_s$ and the wall-normal direction $\bar{v}_s$ take general profiles of turbulent channel flow (Fig. 8.4(a)). The experimental result also matches the general profile for the turbulent intensities in the respective directions, $\tilde{u}_s$ and $\tilde{v}_s$ (Fig. 8.4(b)). Although the Reynolds shear stress $-\overline{u'v'_s}$ (Fig. 8.4(c)) does not become zero at the channel vertical center, we confirmed that our facility caused a small distortion of the velocity profile probably due to the long test section.

In addition, experimental results of liquid-phase velocity measurement in the steady two-phase flow are presented in Fig. 8.4. The data were obtained for $y/h \geq 0.4$ because the top area was

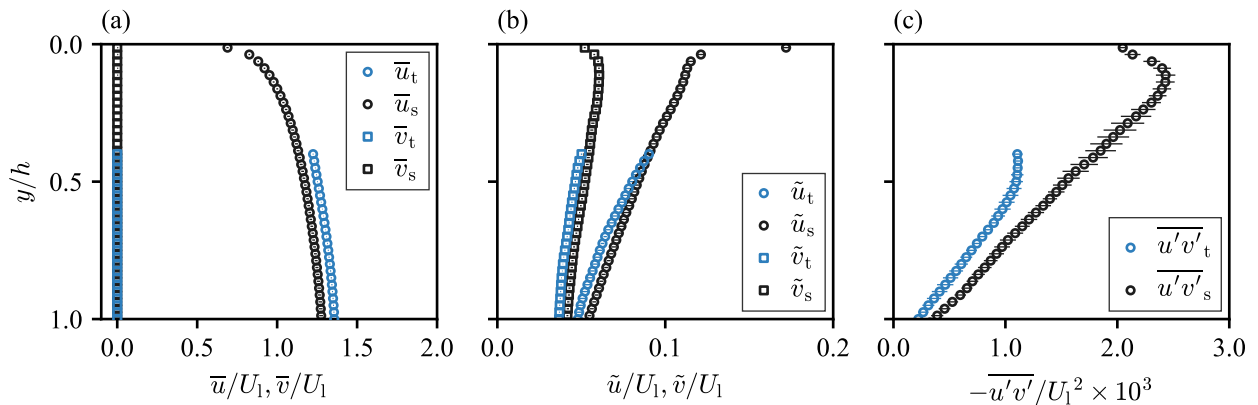


Figure 8.4: Application of the present PTV to the steady single-phase and two-phase flow: vertical profiles of (a) average velocity, (b) turbulent intensity, and (c) Reynolds shear stress. Horizontal error bars indicate standard deviations across five trials.

occupied by the bubbles. The streamwise average velocity $\bar{u}_t$ increases relative to the single-phase flow. The increment is approximately 10% at each y and is attributed to the acceleration of the liquid velocity due to the bubble injection. The Reynolds shear stress $-\overline{u'u'_t}$ decreases in the region close to the bubbles, indicating a reduction of the wall friction.

8.2.4 Ensemble averaging for the transitioned flow

Evaluation of temporal change of velocity profile during the transition requires sufficient temporal resolution. We employ ensemble average across repeated trials defined for arbitrary physical quantities f by

$$\bar{f}(y, t) = \frac{\sum f(Y, T, p)}{\sum n(Y, T, p)} \quad (8.6)$$

with

$$\begin{aligned} y - \frac{\Delta y}{2} &\leq Y \leq y + \frac{\Delta y}{2}, \\ t - \frac{\Delta t}{2} &\leq T \leq t + \frac{\Delta t}{2}. \end{aligned} \quad (8.7)$$

Here, p is the trial number, and n is the number of data in p -th trial satisfying Eq. (8.7). Δy and Δt determine the spatial and temporal resolutions of the averaging. Using the averaged quantity, the fluctuation is defined by

$$f'(y, t, p) = f(y, t, p) - \bar{f}(y, t). \quad (8.8)$$

We performed one-hundred trials of the measurement of transitioned flow, i.e., $p = 1-100$, to allow a high resolution of the averaging as $\Delta y = 0.5$ mm and $\Delta t = 0.05$ s. It corresponds to $\Delta y \approx 40l_\tau$ and $\Delta t \approx 250l_\tau/u_\tau$ in comparison with the wall friction scales. The temporal averaging applied for the single-phase flow and the steady two-phase flow (Fig. 8.4) can be interpreted as the same definition as Eq. (8.6)–(8.8) modifying Δt to 5.0 s and $p = 1$.

For the transitioned flow, flow velocity was measured at 4.5 s from 1.0 s before the valve closure, namely $t^* = -1.5$ to 5.2. The ensemble-averaged velocity at the first and last time steps are shown in Fig. 8.5. The profile agrees that of the two-phase flow before stopping bubble injection

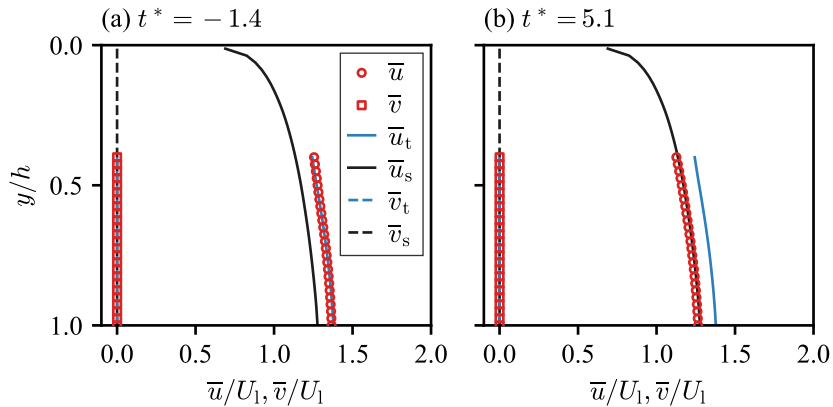


Figure 8.5: Profiles of ensemble-averaged velocity of the transitioned flow (a) before stopping bubble injection and (b) sufficient after the stop

(Fig. 8.5(a)) and that of single-phase flow sufficient after the stop (Fig. 8.5(b)). The ensemble averaging gives consistent results to the temporal averaging. Each averaged data were calculated of $O(10^6)$ numbers of PTV data samples. We found data samples of $O(10^5)$ numbers were insufficient to obtain consistency stably. The agreement for the turbulent intensity and the Reynolds shear stress is confirmed as shown in the following section.

8.3 Results and discussions

8.3.1 Temporal variation during the transition

The temporal variation of the turbulent statistics, i.e, average velocity ($\bar{u}$, $\bar{v}$), turbulent intensity ($\tilde{u}$, $\tilde{v}$), and Reynolds shear stress ($-\overline{u'v'}$) is shown in (Fig. 8.6). The profile of each quantity matches that of the two-phase flow at $t^* = 0$ and that of the single-phase flow at $t^* = 2$. The stop of bubble injection causes the transition of the flow state as expected. In the transition, the y-directional gradient of $\bar{u}$ is almost constant and the profile shifts in parallel. The wall-normal velocity has no change from the profile at $\bar{v}(y) = 0$.

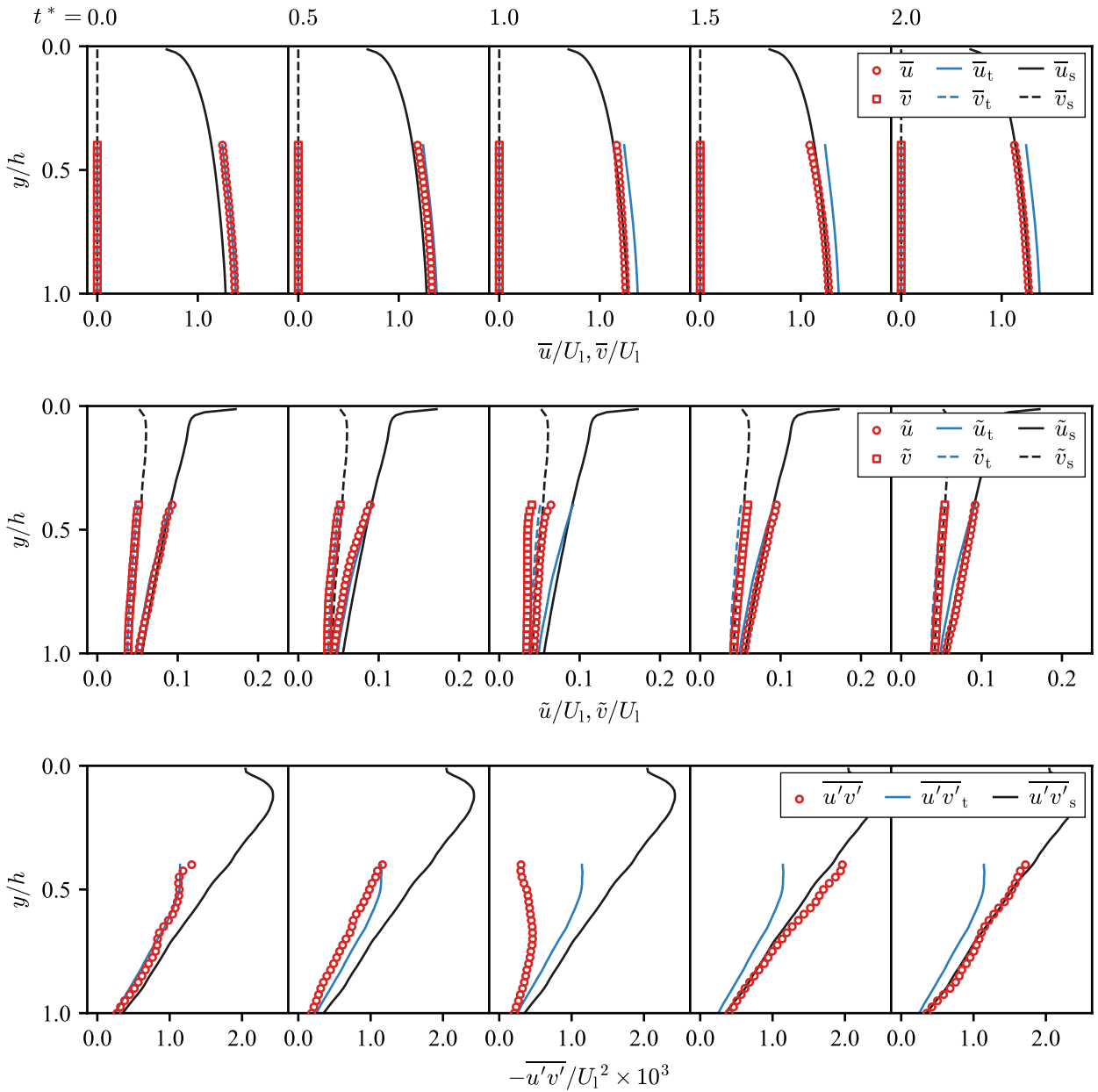


Figure 8.6: Transition of vertical profiles of average velocity (top), turbulent intensity (middle), and Reynolds shear stress (bottom) induced by the sudden decrease of local void fraction

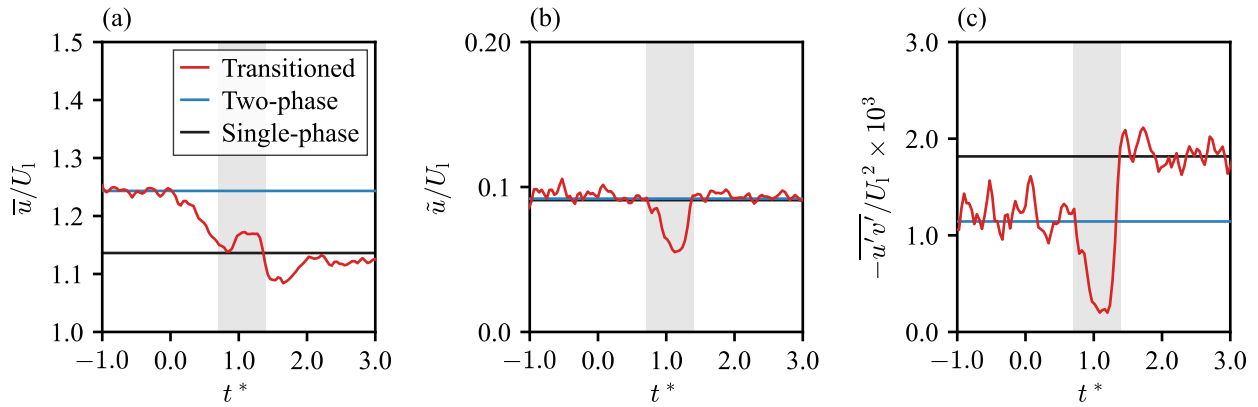


Figure 8.7: Temporal variation of the transitioned flow at $y/h = 0.4$: (a) average velocity, (b) turbulent intensity, and (c) Reynolds shear stress. The gray background denotes the duration $0.7 \leq t^* \leq 1.3$.

In contrast to the gradual shift of $\bar{u}$, the modulation of the turbulent intensity and the Reynolds shear stress shows complicated behavior. At $t^* = 1.0$, both $\tilde{u}$ and $\tilde{v}$ decreases especially in the region close to the bubbles on the top wall. This decrement is a significant characteristic of the transition since the single-phase and the two-phase flows have small differences in the profiles. Simultaneously, the Reynolds shear stress is largely decreased. The arched shape of the profile at $t^* = 1.0$ denotes suppression of momentum transfer due to loss of turbulent coherence in the near-bubble region. It infers enhancement of wall friction reduction during the transition of the flow state.

The detailed information on flow velocity was given by Kitagawa *et al.* [20] and Zhang *et al.* [22] as for the continuous injection of sub-millimeter-sized bubbles. The small bubbles can disperse in the vertical direction owing to the turbulent dispersion. Their measurement of liquid-phase velocity revealed a slight or almost no change of turbulent intensity but a decrease of the Reynolds shear stress caused by the bubble injection. The flow structure of the steady two-phase flow is similar to these prior results though large bubbles concentrate on the top region in our case. The simultaneous large decrease of the turbulent intensity and the Reynolds shear stress during the transition is distinct from the phenomena of the steady state.

As the feature of transition of flow structure observed in the region close to the bubbles, we focus on the values at $y/h = 0.4$, which is the top position reliable numbers of PTV data could be collected in the averaging. The temporal variation of $\bar{u}$, $\tilde{u}$, and $-\overline{u'v'}$ is shown in Fig. 8.7. The average velocity of the transitioned flow gradually decreases from $t^* = 0$ and fluctuates around $t^* = 1$ before settling to the magnitude of the single-phase flow. For the turbulent intensity, the suppression around $t^* = 1$ stands out. The instantaneous maximum decrement of $\tilde{u}$ is approximately 40%. The Reynolds shear stress has certain fluctuation even before $t^* = 0.0$. However, the large drop around $t^* = 1$ can be recognized as a significant change. The reduction ratio is 80% relative to the two-phase flow and 90% in comparison to the single-phase flow.

The Reynolds shear stress is determined by the correlation of u' and v' . There are four kinds of events classified according to their signs known as the quadrant analysis: outward motion (first

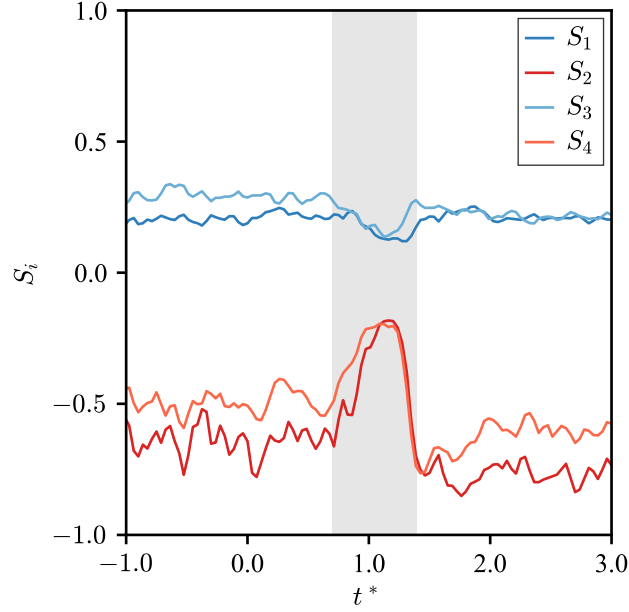


Figure 8.8: Temporal variation of the fractional contributions of each quadrant to the Reynolds shear stress during the transition. The gray background denotes the duration $0.7 \leq t^* \leq 1.3$.

quadrant as $u' > 0$ and $v' > 0$), motion associated with the ejection (second quadrant as $u' < 0$ and $v' > 0$), inward motion (third quadrant as $u' < 0$ and $v' < 0$), and motion associated with the sweep (fourth quadrant as $u' > 0$ and $v' < 0$). We evaluate relative importance of each event on the Reynolds shear stress for the transitioned flow by

$$S_i(y, t) = \frac{\langle u'(y, t)v'(y, t) \rangle_i}{\overline{|u'(y)v'(y)|}_s}, \quad (8.9)$$

where $\langle u'v' \rangle_i$ is the conditional average for data belonging to the i -th quadrant and $\overline{|u'v'|}_s$ is the averaged intensity of $u'v'$ in the single-phase flow. Note that S_i does not satisfy $\sum_i S_i = 1$ like the ordinary quadrant analysis (e.g., Lu and Willmarth [100]) since the present definition is the ratio of the intensity in the transitioned flow to that of the single-phase flow. The magnitude of S_i indicates the fractional contribution of i -th quadrant. The temporal variation of S_i at $y/h = 0.4$ is shown in Fig. 8.8. The fraction of the ejection event and the sweep event ($|S_2|$ and $|S_4|$) is larger than the other events before $t^* = 0$. After stopping bubble injection, the magnitudes do not change immediately and all the $|S_i|$ are decreased around $t^* = 1.0$. At this moment, most structural events are eliminated in the flow and the contribution of the small isotropic turbulent fluctuations remains. The contribution of each event recovers after the suppression.

8.3.2 Response to bubble passage

The measurement and the statistical analysis of the liquid velocity have discovered the significant decrease in the turbulent intensity, the Reynolds shear stress, and the contribution of quadrants in the transitioned flow. In Fig. 8.7 and 8.8, the gray background points out the duration $0.7 \leq t^* \leq 1.3$.

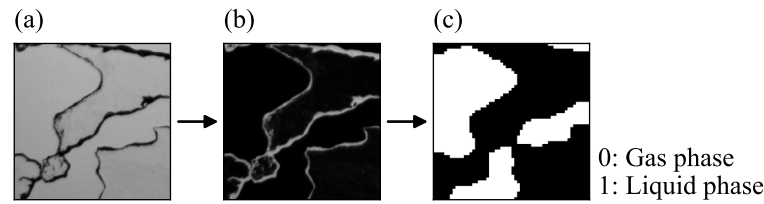


Figure 8.9: Image processing to estimate projection void fraction: (a) original top-view image, (b) monochrome inverted image produced by background subtraction, and (c) binarized image displaying area of gas-phase

We can confirm those features of the transitioned flow emerge simultaneously, and the temporary increase of the average velocity occurs at the same time. Since the flow modulation is caused by the change of local void fraction, the effect of the bubble distribution on the flow field needs to be clarified. The top-view images obtained by the backlight photograph (Fig. 8.2) are used to measure the bubble distribution.

The acquisition of bubble images was performed at 3,000 fps with a resolution of 0.17 mm/pix. The recorded area is around the spanwise center of the channel and a square shape whose length of a side corresponds to the streamwise length of the particle image. Subtraction of the bubble image (Fig. 8.9(a)) from a background image made by the average of bubble-free images provides the monochrome inverted image (Fig. 8.9(b)). The gas–liquid interface and the inside of bubbles are brighter than the liquid phase in the inverted image since these areas are originally dark owing to the refraction of the backlight. Thresholding of the inverted image produces a binarized image that distinguishes between the gas and liquid phases (Fig. 8.9(c)). Projection void fraction β is estimated by the ratio of the gas-phase area to the total image area. This procedure potentially overestimates the projection void fraction by several percentages owing to the unclear edge of the interface. However, it is enough for the use of evaluating the large temporal change appearing during the transition.

The measurement of β was repeated ten times and the average in the trials is presented in Fig. 8.10. β becomes almost unity at $t^* = 1.0$, indicating the formation of large bubbles insulating the main flow from the top wall. Then, the bubble is thought to act on the turbulent flow like an air-filled grove made on a wall (Kitagawa *et al.* [101]). The turbulent fluctuations notably decay because the gas–liquid interface supplies little energy stimulating turbulent eddies in contrast to the solid surface. The mitigation of fluctuations causes the decrease of turbulent intensity and the Reynolds shear stress (Fig. 8.7(b), (c)). Moreover, the streamwise velocity close to the bubble is accelerated (Fig. 8.7(a)) by the slippage on the continuous gas–liquid interface.

We found quasi-periodical fluctuations in the waveform of β (Fig. 8.10). Similar fluctuations exist in the waveform of a single trial, indicating an intermittent passage of large bubbles. However, the intermittency is irregular among the trials except for the last large bubble appearing at $t^* \approx 1.0$. In this context, the stable emergence of large bubbles is thought to be a key to the transient behavior of the turbulent flow. The reason for the stable development at the end of bubble injection needs

further investigation.

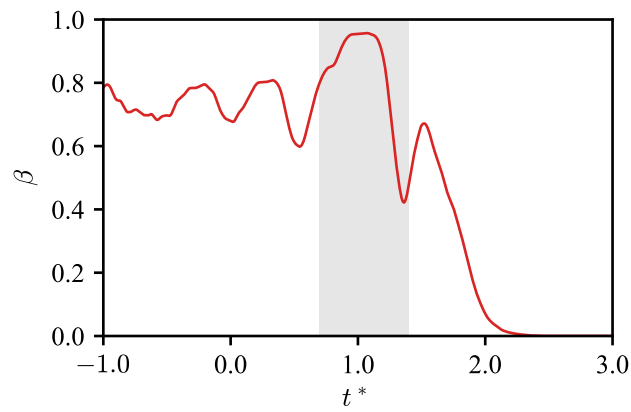


Figure 8.10: Temporal change of projection void fraction, where the gray background denotes the duration $0.7 \leq t^* \leq 1.3$.

8.4 Conclusions

This study experimentally clarified the temporal change of flow structure during the transition from the two-phase flow to the single-phase flow in the turbulent horizontal channel. After the generation of the bubbly flow at $Re = 3.0 \times 10^4$ and $\alpha = 9.0\%$, the bubble injection was suddenly stopped to induce the flow transition. We implemented image processing to remove advecting bubbles and PTV utilizing the relaxation method for the particle-tracking scheme. The performance of the measurement procedure was validated through application to the steady single-phase flow and two-phase flows. The calculation of the turbulent statistics of the transitioned flow introduces the ensemble averaging across 100 trials to ensure the reliability of the results.

The significant feature of the flow transition is observed at the passage of the tail of bubble swarms. The turbulent intensity and the Reynolds shear stress are strongly suppressed at the moment. In the region close to the bubble, the intensity decreases by 40% and the Reynolds shear stress by 90% in comparison with the single-phase flow. Evaluation of the fractional contribution of the quadrants to the Reynolds shear stress reveals mitigation of all the components. This means the weakening of structural events in the turbulent flow including the motion associated with the sweep and ejection.

Suppression of both the turbulent intensity and the Reynolds shear stress is a behavior of single-phase flow totally insulated from the wall surface by air layer (Kitagawa *et al.* [101]) rather than two-phase flow containing bubbles (Kitagawa *et al.* [20] and Zhang *et al.* [22]). Observation of bubble distribution by the backlight photograph indicates bubbles large enough to cover the measurement region of flow velocity are stably generated at the end of bubble swarms. The decay of turbulent fluctuations is caused by the lack of energy supply to the flow at the gas–liquid interface of the large bubble.

CHAPTER 9

Concluding remarks

9.1 Summary

This thesis investigated bubble drag reduction (BDR) utilizing spatiotemporal fluctuation of local void fraction, termed void wave, artificially generated by repetitive bubble injection (RBI). It was a work composing multiple experimental studies using different scale facilities to clarify the performance of RBI especially in comparison with the conventional method of BDR, namely continuous bubble injection (CBI). The experimental scale continued to expand from Chapter 2 to Chapter 5, reaching a quasi-full-scale test of RBI. Chapter 6 estimated the net power saving on a full-scale ship by RBI based on the experimental results. Then the experimental environment went back to the laboratory scale through Chapter 7 and 8 to perform detailed measurements of the two-phase turbulent flow to give understandings of the phenomena causing drag reduction.

As background subjects, this thesis addresses both aspects of BDR research: ship engineering and fluid mechanics. Ship engineering primarily requires RBI to be useful in practical conditions. A series of experiments were conducted to clearly demonstrate the utility of BDR. The further development of BDR requires knowledge from a perspective of fluid mechanics, as indicated by the history of the proposal of void-wave drag reduction by fluid mechanics researchers. The new findings about the mechanism of drag reduction is essential for the optimal control in the future development.

In Chapter 3–Chapter 5, three experiments were conducted to demonstrate the utility of RBI, that is the superiority of RBI to CBI, which has already achieved power saving of ships. Chapter 3 performed RBI in turbulent channel flows at a high-speed condition equivalent to the ship speed. The strongest drag reduction was obtained at the repetition frequency $f = 2.0$ Hz of the experimentally examined range $f = 1.0$ – 6.0 Hz. At this condition, the drag-reduction ratio was almost twice that of the CBI at the same time-averaged air flow rate. Chapter 4 is a preliminary experiment to obtain reference data about the performance of CBI in a turbulent boundary layer beneath a 36-m-long model ship towed at 8.0 m/s. It revealed the streamwise decay of the drag-reduction effect to propose a model (Eq. 4.23) describing the spatial distribution of the local friction coefficient under bubble drag reduction. Chapter 5 conducted a quasi-full-scale test of RBI in the same facility. RBI reduced the frictional drag of model ship by 24%, which was 5% higher than that of CBI. Application of the formula developed in the previous chapter indicated the downstream persistence of the drag-reduction effect along more than 100 m. This is the remarkable advantage of RBI relative to the persistence of 8 m at CBI. Moreover, Chapter 6 gave the estimation of the net power saving on ships following the experimental results. This resulted in the improvement of net performance by the use of RBI. Consequently, this thesis provided experimental results presenting the utility of RBI in practical conditions and fundamental methods to examine the design of RBI to ships.

In the other chapters, three experiments were performed to understand the behavior of void waves and their relationship to the wall shear stress. Chapter 2 gave the estimation of the streamwise development of void waves generated by RBI based on the experiment using a 4-m-long flat-bottom model ship. The evaluation by a one-dimensional advection-diffusion equation model indicated the potential persistence of void waves became tens of meters. Chapter 7 analyzed the temporal

Table 9.1: Function of repetitive bubble injection related to the main topics listed in Chapter 1

Downstream persistence	
Chapter 2	Void waves potentially persist tens of meters. Best repetition frequency is $f = 4.0$ Hz (half the spontaneous frequency).
Chapter 5	Void waves persist to the end of 36-m-long model ship at $f = 0.5$ Hz. Delay of breakup of large bubbles to the equilibrium size
Chapter 7	Longer persistence of void waves in case of a lower duty cycle of RBI
Local drag reduction	
Chapter 2	Promotion of local drag reduction by 15% at $f = 3.0$ Hz
Chapter 3	Doubled local drag reduction at $f = 2.0$ Hz
Chapter 4 & 5	Local drag-reduction promotion in upstream regions at $f = 0.5$ – 2.0 Hz
Chapter 7	Main body of the local drag reduction is the later part of bubble swarms.
Chapter 8	Suppression of Reynolds shear stress at the end of bubble swarm
Total drag reduction	
Chapter 4 & 5	Improvement of total drag reduction by 5% at $f = 0.5$ Hz
Chapter 5	Long persistence of local drag reduction at $f = 0.5$ Hz
Chapter 6	Improvement of net power saving in an estimation based on experimental results

variation of local wall shear stress under RBI using the data obtained in quasi-full-scale model-ship experiment. This reveals the transition of drag reduction during the passage of a single bubble swarm. The main body occurring in the drag reduction appears in the later part of the bubble swarm. Chapter 8 conducted a measurement of turbulent flow structure during sudden decrease of void fraction. Suppression of the turbulent intensity and the Reynolds shear stress occurs at the passage of the tail of bubble swarm. The effect is strong to decrease the turbulent intensity by 40% and the Reynolds shear stress by 90% in comparison with the single-phase flow. These studies revealed the characteristics of the propagation of void waves and accompanying drag reduction in turbulent boundary layers.

Brief descriptions of the findings on the main topics listed in Chapter 1 are presented in Table 9.1. These outcomes contribute to advancing the implementation and further development of BDR utilizing void waves on ships.

9.2 Perspectives

The experiments using different scale facilities demonstrate that RBI is useful as a technology in practical ship environments, and it is controllable by the ideas proposed from physical understandings. Let me note the perspectives on the further development of RBI. To solve these problems, more detailed measurements of the bubbly turbulent boundary layer are essential. Research of BDR needs to be open for hypothesis because the tough environment prevents direct evidential measurement results. However, these difficult problems can truly be solved through a series of down-to-earth discussions. We believe the answer and the solution process are greatly beneficial to the future development of BDR, which possibly overwhelms the present RBI, and the exploration of fluid mechanics.

9.2.1 Process giving longer downstream persistence

We observed from the bubble image that the velocity of the later part, i.e., the upstream part, of the bubble swarm becomes slower. Thus, the unsteadiness of the flow given by the void wave is not just the periodical alternation of the bubbly flow to the single-phase flow but the temporal and spatial development in the bubbly flow. The slow velocity of the bubbles possibly causes bubble accumulation to the part by the relative velocity to the liquid phase (Fig. 9.1). It maintains a dense bubbly region giving large local drag-reduction for long distances. This is an idea to explain the long persistence of drag reduction by RBI. The reason for the ununiform velocity distribution is unclear. It totally depends on the two-way interaction of bubbles and liquid in the turbulent boundary layer.

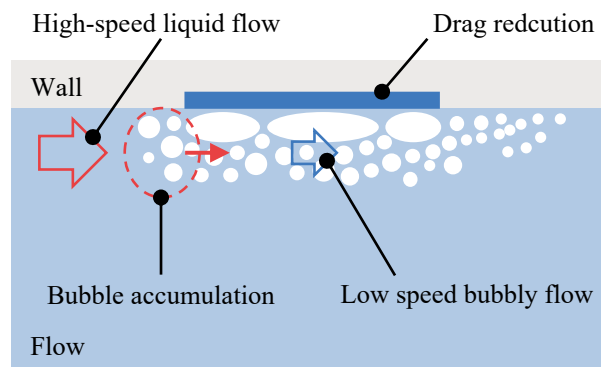


Figure 9.1: Schematic of bubble accumulation to the upstream part of swarms owing to the relative velocity of bubbly flow to the liquid flow

9.2.2 Reason for promotion of drag reduction

The important question on RBI is why drag reduction is promoted. If the instantaneous drag reduction $\widetilde{DR}$ is merely a proportional function to the instantaneous void fraction $\tilde{\alpha}$,

$$\widetilde{DR}(t) = C_1 \tilde{\alpha}(t), \quad (9.1)$$

the time-averaged total drag-reduction ratio $\overline{DR}$ is identical among RBI and CBI as a function of the void fraction $\overline{\alpha}$,

$$\begin{aligned} \overline{DR}_{\text{RBI}} &= \int \widetilde{DR}(t) dt \\ &= C_1 \int \int \tilde{\alpha}(t) dt \\ &= C_1 \overline{\alpha} \\ &= \overline{DR}_{\text{CBI}}. \end{aligned} \quad (9.2)$$

However, the drag reduction differs as proved by multiple works (Park *et al.* [54], Chapter 2, Chapter 3, Chapter 5, Chapter 7). The idea explaining the difference is the non-linear dependence of $\widetilde{DR}$ on $\tilde{\alpha}$,

$$\widetilde{DR}(t) = C_2 \tilde{\alpha}(t)^m. \quad (9.3)$$

and the transition of the regime of phenomena at a critical void fraction $\tilde{\alpha}_c$ causing jump of drag-reduction ratio (Murai [14] and Elbing *et al.* [25]),

$$\widetilde{DR} = \begin{cases} C_3 \tilde{\alpha} & (\tilde{\alpha} < \tilde{\alpha}_c) \\ C_4 \tilde{\alpha} + C_5 & (\tilde{\alpha} \geq \tilde{\alpha}_c) \end{cases}. \quad (9.4)$$

Adoption of Eq. (9.3) and void wave generation with square waveforms like the model ship experiment in Chapter 5 (see Fig. 5.3) yields

$$\begin{aligned} \overline{DR}_{\text{RBI}} &= \int \widetilde{DR}(t) dt \\ &= C_2 \int \tilde{\alpha}(t)^m dt \\ &= C_2 \gamma \left(\frac{\overline{\alpha}}{\gamma} \right)^m \\ &\neq \overline{DR}_{\text{CBI}}, \end{aligned} \quad (9.5)$$

where γ is the duty cycle. Note that Eq. (9.5) reads $\overline{DR}_{\text{RBI}} > \overline{DR}_{\text{CBI}}$ for $\gamma > \overline{\alpha}$, which is a result that can only be established by a simplified mathematical statement. The promotion of drag reduction is not evident for arbitrary conditions, but the concept implies the change of $\overline{DR}$ depending on the control of void waves.

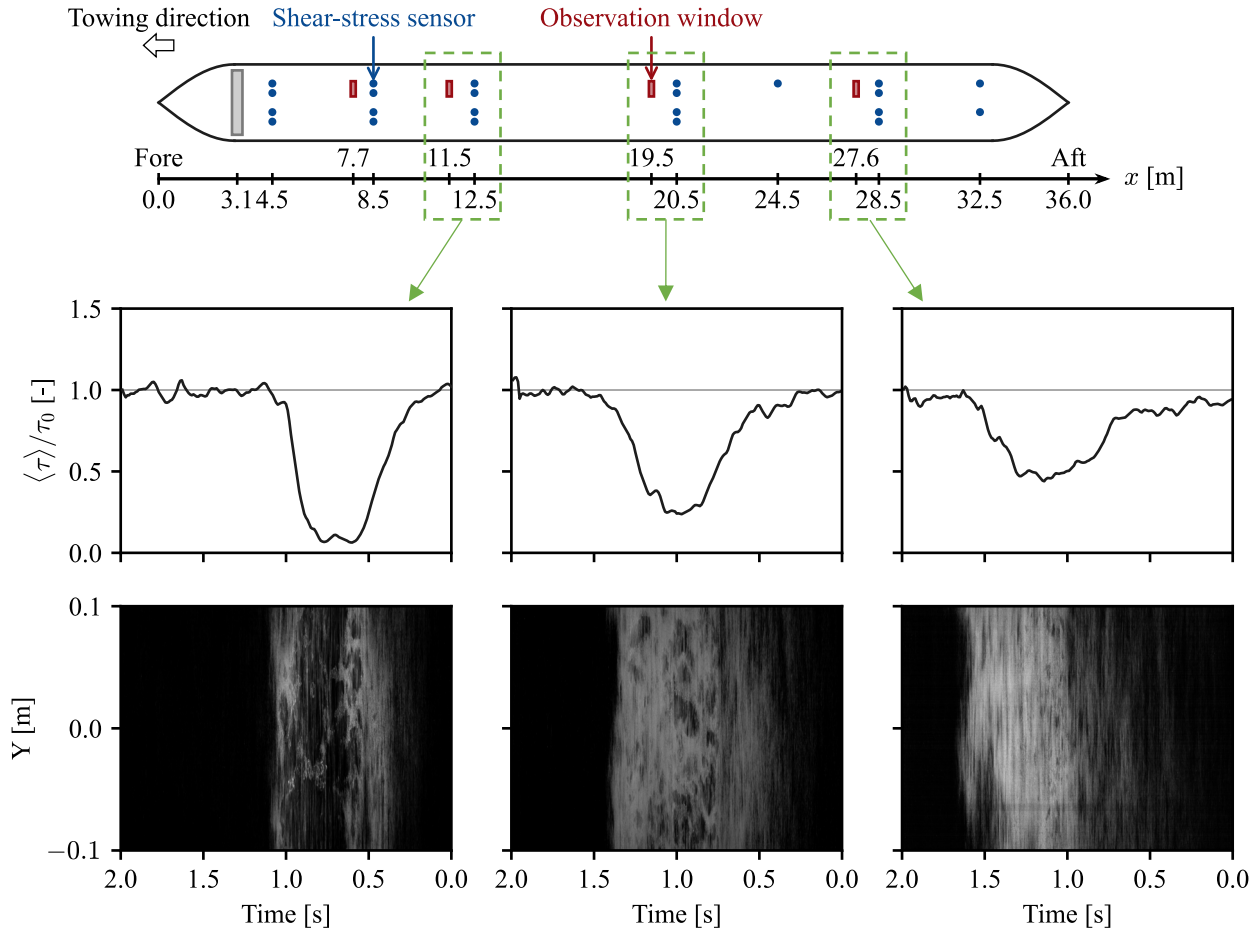


Figure 9.2: Phase-averaged wall shear stress and distribution of bubbles referred from Chapter 7. The abscissa is inverted to match the x -direction of the model ship.

Furthermore, the actual phenomenon is more complicated than the concept. The wall shear stress and corresponding bubble distribution beneath the 36-m-long model ship are shown in Fig. 9.2 referred from Chapter 7. It displays an uneven drag reduction ratio within the passage of a single bubble swarm. This infers the existence of the time lag of the drag reduction to the void wave similar to the time lag to the bubble clusters (Oishi *et al.* [59]). The detailed measurement of the flow with temporal variation of local void fraction is provided in Chapter 8. In addition, the streamwise variation of drag reduction caused by the development of void waves (Chapter 2, 5, and 7) needs to be considered for the discussion of total drag reduction.

9.2.3 Optimal frequency of local drag reduction

A conceptual illustration of the enhancement of the drag reduction by utilizing void waves is shown in Fig. 9.3. For CBI, the time-averaged drag reduction ratio is dealt with as a function of the time-averaged bulk void fraction in the flow (Fig. 9.3(a)). Previous experimental results (e.g., Murai *et al.* [46] and Park *et al.* [54]) show the existence of a critical void fraction, α_c , for reducing drag. At a void fraction lower than α_c , bubbles rather enhance turbulence, which should be avoided in

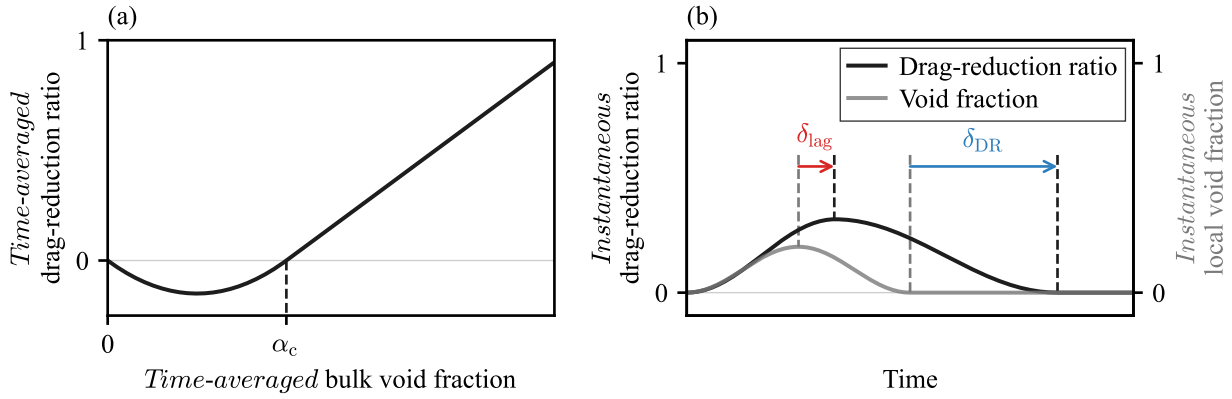


Figure 9.3: Schematics of (a) drag reduction by CBI based on previous experimental results (e.g., Murai *et al.* [46] and Park *et al.* [54]) and (b) the expectation of drag reduction due to RBI. α_c is the critical void fraction required to reduce drag in CBI. The time lag, δ_{lag} , and duration of the drag reduction, δ_{DR} , are predicted characteristics of the transient response of the drag-reduction ratio to the instantaneous local void fraction in RBI.

actual application. RBI controls the air flow rate of the bubble injection to periodically fluctuate. The fluctuation of the instantaneous local void fraction in RBI is considered to induce a transient response of the drag (Fig. 9.3(b)). Time lag, δ_{lag} , between peaks of the local void fraction and the local drag reduction, and duration of drag reduction, δ_{DR} , after running out of the local void fraction are predicted to exist.

The results of RBI at the repetition frequency $f = 1.0\text{--}6.0$ Hz in the high-speed horizontal channel flow (channel height $H = 20$ mm, bulk velocity $U_m = 5.1\text{--}7.3$ m/s) in Chapter 3 show that the best repetition frequency for promoting local drag reduction, f_{best}^L , is 2.0 Hz for common Reynolds number $Re_m (= U_m H / \nu_l)$ and bulk void fraction α_m . The corresponding Strouhal number, $St (= f_{best} H / U_m)$, is less than 1.0×10^{-2} . This indicates that the time scale of the best RBI is considerably larger than the inertia time scale of the channel flow simply defined by the channel height and the bulk velocity, H / U_m . We infer that there is another factor determining the optimal frequency of local drag reduction and discuss the possible candidates.

The void-wave equation derived by Park *et al.* [55] indicates that the drag reduction correlates to the development of the spatial distribution of the local void fraction. In the previous experiment by Park *et al.* [57] confirmed that drag reduction was largely enhanced with the emergence of spontaneous void waves in CBI. From these results, we deduce that f_{opt} is related to the spontaneous frequency. The spontaneous frequency, f_s , falls into frequencies of several flow instabilities as discussed by Park *et al.* [57]. The frequency of the gravity wave due to the vertical density stratification of $d\rho/dy$ is estimated as

$$f_s = \frac{1}{2\pi} \sqrt{\left(\frac{1}{\rho} \frac{d\rho}{dy}\right) g} \sim \frac{1}{2\pi} \sqrt{\frac{\alpha_m g}{h}}, \quad (9.6)$$

where h and g are the half height of the channel and the gravity acceleration. Under the experimental conditions in Chapter 3, the frequency of the gravity wave is $0.5 \text{ Hz} \leq f_s \leq 1.2 \text{ Hz}$. This range is

on the same order as f_{best}^L ($= 2.0$ Hz). However, gravity waves hardly arise in the high-speed flows, where the Froude number,

$$Fr = \frac{U_m}{\sqrt{gh}}, \quad (9.7)$$

is larger than 15. As the next candidate, the Richardson wave is known to emerge even in such high-Froude-number flow through the existence of a diffused density interface in shear flows. The upper limit of the frequency of the Richardson wave in bubbly flow is estimated as

$$f_{s, \max} = \frac{V}{\delta_d} \sim \frac{U_m}{h}, \quad (9.8)$$

where V and δ_d are respectively the mean fluid velocity of bubbly flows and the thickness of the density interface (Park *et al.* [57]). In the case of the present channel flows, $f_{s, \max}$ is 500–700 Hz, and the frequency range of the Richardson wave covers f_{best}^L .

Another factor possibly determining the optimal frequency is the streamwise length required for the redevelopment of the turbulent channel flow after the passage of bubble swarms. On the basis of the hydraulic entrance length of duct flow (McComas [102]), fully development of turbulent flows requires a streamwise distance, λ , which is approximately scaled as

$$\lambda \approx \frac{h}{c_{fc0}} \quad (9.9)$$

with

$$c_{fc0} = 0.073 Re_m^{-\frac{1}{4}}. \quad (9.10)$$

λ can be used also to roughly estimate the streamwise redevelopment length of the channel flow; i.e., the recovery distance so called. λ has a corresponding frequency:

$$f_\lambda = \frac{U_m}{\lambda}. \quad (9.11)$$

Here, U_m is selected for the velocity scale as a primary bulk quantity of the channel flow. Alternatively, the velocity might be replaced with the flow speed of a point around 10 wall units from the wall if universal log-law stands. However, the law would not stand for unsteady bubbly two-phase boundary layer. In the experiment of Chapter 3, f_λ is 2.5 Hz. Approximations using Eq. (9.9) can give a range several times wider than the exact value. Thus, the estimated recovery frequency f_λ is thought to match the experimentally discovered best frequency f_{best}^L ($= 2.0$ Hz).

On the basis of this correspondence of frequencies, the optimal drag reduction due to RBI is deduced by the relationship between the instantaneous local void fraction and instantaneous drag reduction ratio at a stationary position as illustrated in Fig. 9.4. Once a bubble swarm passes (i.e., the local void fraction increases), the drag reduction effect continues for a duration $1/f_\lambda$ before the next passage of the bubble swarms. At $f = f_{\text{lambda}}$, the successive bubble swarm arrive at the expiration of the drag reduction induced by the passage of the former bubble swarm (Fig. 9.4(a)). At $f < f_{\text{lambda}}$, however, the next swarm passes after the expiration of the drag reduction, yielding

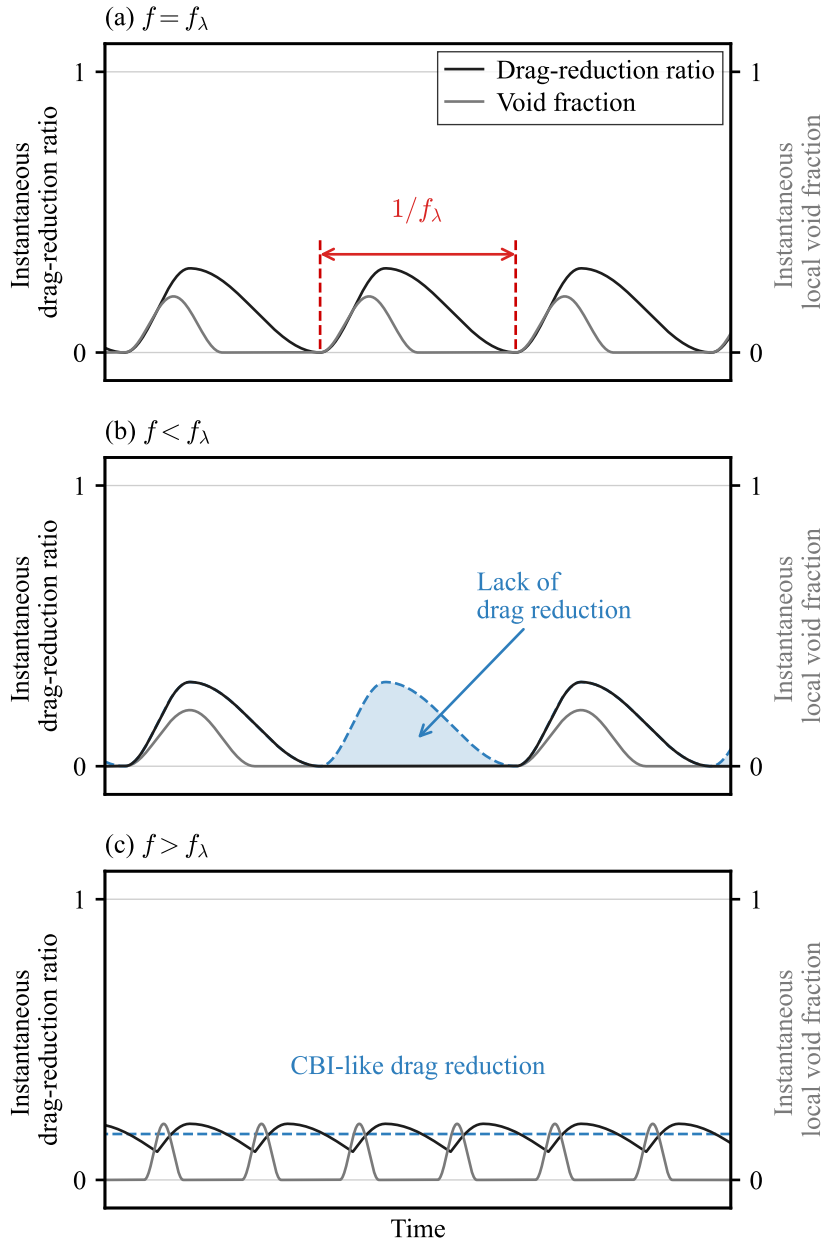


Figure 9.4: Schematics of the difference in the drag reduction due to RBI dependent on the repetition frequency f , where f_λ is a frequency corresponding to the recovery length of the turbulent channel flow estimated using Eq. (9.11).

a period in which there is no drag reduction (Fig. 9.4(b)). This clearly decreases the time-averaged drag reduction ratio relative to the case of $f = f_{\text{lamnda}}$. In the case that $f > f_{\text{lamnda}}$, the frequent passage of bubble swarms entirely alternates the flow (Fig. 9.4(c)), and the flow does not recover to the single-phase turbulent state anywhere in the channel. The wall shear stress loses the expected transient response to the local void fraction (Fig. 9.3(b)), resulting in a drag reduction analogous to that of the CBI. This leads to a higher time-averaged drag reduction ratio at $f = f_{\text{lamnda}}$ compared with $f > f_{\text{lamnda}}$ for the same α_m . Because the level of turbulence suppression during passage of a bubble swarm depends on f , the exact recovery distance may vary with f . Simultaneously, drag

Table 9.2: Comparison of the experimentally discovered best frequencies ($f_{\text{best}}^T, f_{\text{best}}^L$) and the recovery frequencies ($f_{\lambda}', f_{\lambda}$), and the range of the experimental condition of the repetition frequency (f) in studies of RBI. f_{λ}' is calculated for from the bubble injector to the end of model ship.

	Configuration	f_{best}^T [Hz]	f_{best}^L [Hz]	$f_{\lambda}', f_{\lambda}$ [Hz]	f [Hz]
Park <i>et al.</i> [54]	Channel flow	0.2	0.2	0.5	0.2–0.5
Chapter 2	Model ship	-	3.0	0.7–0.1	1.0–4.0
Chapter 3	Channel flow	2.0	2.0	2.5	1.0–6.0
Chapter 5	Model ship	0.5	0.5–2.0	0.5–0.05	0.5–2.0

reduction by the swarm of bubbles elongates the recovery distance.

9.2.4 Optimal frequency of total drag reduction

The recovery frequency f_{λ} was suggested to be a possible indicator of the optimal frequency of local drag reduction, f_{opt}^L , based on the experimental results of turbulent channel flow. For turbulent channel flows, the optimal frequency of the total drag reduction, f_{opt}^T , on the target plane corresponds to f_{opt}^L since the flow is uniform in the streamwise direction. In contrast, f_{opt}^T can differ from f_{opt}^L in the spatially developing turbulent boundary layer on a plate. However, f_{opt}^T matches f_{opt}^L of some location on the plate because local effectiveness is necessary for total effectiveness. The definition of f_{λ} in the turbulent channel flow can be expanded to the turbulent boundary layers as

$$f_{\lambda}'(x) = \frac{U}{\lambda'(x)}, \text{ where } \lambda'(x) = \frac{\delta(x)}{c_{\text{fp}0}(x)} \quad (9.12)$$

with

$$c_{\text{fp}0}(x) = (2 \log_{10} Re_x - 0.65)^{-2.3}, \quad \delta(x) = 0.37x Re_x^{-\frac{1}{5}}, \quad (9.13)$$

where the the downstream-distance-based Reynolds number is defined by $Re_x = Ux/\nu_1$ using ship speed U . In this definition, f_{λ}' decreases streamwise for developing turbulent boundary layers.

The comparison of the experimentally discovered best frequencies of local drag reduction and total drag reduction ($f_{\text{best}}^T, f_{\text{best}}^L$) and the recovery frequencies ($f_{\lambda}', f_{\lambda}$) is presented in Table 9.2 for four studies, namely Park *et al.* [54], Chapter 2, Chapter 3, and Chapter 5. It shows that correspondence of the best frequencies and the recovery frequencies except for Chapter 2, where the experimental condition does not cover f_{best}^L . In the experiment in Chapter 5, f_{best}^T corresponds to the recovery frequency at the bubble injector $f_{\lambda}' = 0.5$ Hz. This infers that the use of a far lower repetition frequency than 0.5 Hz, which was not examined owing to the restrictions of the facility, reduces the local drag reduction, especially in the upstream region immediately after the injector. Note that elucidation of the RBI process needs more investigation from the viewpoints of two-phase fluid dynamics, bubble dynamics, and scale dependence. The models described by Eqs. (9.11) and (9.12) are proposed in the discussion based on the previous and the present experimental results.

Bibliography

- [1] United Nations, “Sustainable Development Goals,” 2020. [Online]. Available: <https://www.un.org/sustainabledevelopment/news/communications-material/> (visited on 09/27/2022).
- [2] United Nations Development Programme, “GOAL 13: CLIMATE ACTION,” 2018. [Online]. Available: <https://web.archive.org/web/20180813130618/http://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-13-climate-action.html> (visited on 09/27/2022).
- [3] International Maritime Organization, “Fourth IMO Greenhouse Gas Study 2020,” 2021.
- [4] International Maritime Organization, “Initial IMO Strategy on reduction of GHG emissions from ships,” 2018.
- [5] E. A. Bouman, E. Lindstad, A. I. Rialland, and A. H. Strømman, “State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review,” *Transportation Research Part D: Transport and Environment*, vol. 52, pp. 408–421, 2017.
- [6] M. E. McCormick and R. Bhattacharyya, “Drag reduction of a submersible hull by electrolysis,” *Naval Engineers Journal*, vol. 85, no. 2, pp. 11–16, 1973.
- [7] Y. Kodama, M. Hinatsu, T. Hori, *et al.*, “A full-scale air lubrication experiment using a large cement carrier for energy saving (result and analysis),” in *The Japan Society of Naval Architects and Ocean Engineers*, 2008, pp. 163–166.
- [8] S. Mizokami, C. Kawakita, Y. Kodan, S. Takano, S. Higasa, and R. Shigenaga, “Development of air lubrication system and verification by the full scale ship test,” *Journal of the Japan Society of Naval Architects and Ocean Engineers*, vol. 12, pp. 69–77, 2010.
- [9] I. Kumagai, Y. Takahashi, and Y. Murai, “Power-saving device for air bubble generation using a hydrofoil to reduce ship drag: Theory, experiments, and application to ships,” *Ocean Engineering*, vol. 95, pp. 183–194, 2015.
- [10] S. Mizokami and R. Kuroiwa, “Installation of air lubrication system for ro-pax ferry and verification of its effect in actual seas based on onboard measurement data,” *Journal of the Japan Society of Naval Architects and Ocean Engineers*, vol. 29, pp. 1–9, 2019.
- [11] American Bureau of Shipping, “Air lubrication technology,” 2019. [Online]. Available: <https://ww2.eagle.org/en.html>.
- [12] G. A. Pavlov, L. Yun, A. Bliault, and S.-L. He, *Air Lubricated and Air Cavity Ships*. Springer, 2020.

- [13] Y. Murai, H. Sakamaki, I. Kumagai, H. J. Park, and Y. Tasaka, "Mechanism and performance of a hydrofoil bubble generator utilized for bubbly drag reduction ships," *Ocean Engineering*, vol. 216, p. 108 085, 2020.
- [14] Y. Murai, "Frictional drag reduction by bubble injection," *Experiments in Fluids*, vol. 55, no. 7, p. 1773, 2014.
- [15] B. R. Elbing, S. Mäkiharju, A. Wiggins, M. Perlin, D. R. Dowling, and S. L. Ceccio, "On the scaling of air layer drag reduction," *Journal of Fluid Mechanics*, vol. 717, pp. 484–513, 2013.
- [16] S. A. Mäkiharju and S. L. Ceccio, "On multi-point gas injection to form an air layer for frictional drag reduction," *Ocean Engineering*, vol. 147, pp. 206–214, 2018.
- [17] S. Gokcay, M. Insel, and A. Odabasi, "Revisiting artificial air cavity concept for high speed craft," *Ocean Engineering*, vol. 31, no. 3-4, pp. 253–267, 2004.
- [18] L. Wang, S. Qin, H. Fang, D. Wu, B. Huang, and R. Wu, "Boundary layer analysis of ventilated partial cavity for friction drag reduction," *Ocean Engineering*, vol. 239, p. 109 799, 2021.
- [19] Y. Murai, Y. Oishi, Y. Takeda, and F. Yamamoto, "Turbulent shear stress profiles in a bubbly channel flow assessed by particle tracking velocimetry," *Experiments in Fluids*, vol. 41, no. 2, pp. 343–352, 2006.
- [20] A. Kitagawa, K. Hishida, and Y. Kodama, "Flow structure of microbubble-laden turbulent channel flow measured by PIV combined with the shadow image technique," *Experiments in Fluids*, vol. 38, no. 4, pp. 466–475, 2005.
- [21] K. Hara, T. Suzuki, and F. Yamamoto, "Image analysis applied to study on frictional-drag reduction by electrolytic microbubbles in a turbulent channel flow," *Experiments in Fluids*, vol. 50, no. 3, pp. 715–727, 2011.
- [22] J. Zhang, C. Gabillet, and J.-Y. Billard, "Experimental study of the bubbly drag reduction in the recovery region of a separated turbulent boundary layer," *International Journal of Multiphase Flow*, vol. 142, p. 103 697, 2021.
- [23] K. Fukuda, J. Tokunaga, T. Nobunaga, T. Nakatani, T. Iwasaki, and Y. Kunitake, "Frictional drag reduction with air lubricant over a super-water-repellent surface," *Journal of Marine Science and Technology*, vol. 5, no. 3, pp. 123–130, 2000.
- [24] K. I. Matveev, "Three-dimensional wave patterns in long air cavities on a horizontal plane," *Ocean Engineering*, vol. 34, no. 13, pp. 1882–1891, 2007.
- [25] B. R. Elbing, E. S. Winkel, K. A. Lay, S. L. Ceccio, D. R. Dowling, and M. Perlin, "Bubble-induced skin-friction drag reduction and the abrupt transition to air-layer drag reduction," *Journal of Fluid Mechanics*, vol. 612, pp. 201–236, 2008.

- [26] S. L. Ceccio, "Friction drag reduction of external flows with bubble and gas injection," *Annual Review of Fluid Mechanics*, vol. 42, no. 1, pp. 183–203, 2010.
- [27] K. Lay, R. Yakushiji, S. Mäkiharju, M. Perlin, and S. Ceccio, "Partial cavity drag reduction at high reynolds numbers," *Journal of Ship Research*, vol. 54, pp. 109–119, 2010.
- [28] E. L. Amromin, B. Metcalf, and G. Karafiath, "Synergy of resistance reduction effects for a ship with bottom air cavity," *Journal of Fluids Engineering*, vol. 133, no. 2, p. 021 302, 2011.
- [29] J. Jang, S. H. Choi, S.-M. Ahn, B. Kim, and J. S. Seo, "Experimental investigation of frictional resistance reduction with air layer on the hull bottom of a ship," *International Journal of Naval Architecture and Ocean Engineering*, vol. 6, no. 2, pp. 363–379, 2014.
- [30] J. Butterworth, M. Atlar, and W. Shi, "Experimental analysis of an air cavity concept applied on a ship hull to improve the hull resistance," *Ocean Engineering*, vol. 110, pp. 2–10, 2015.
- [31] E. Amromin, "Analysis of interaction between ship bottom air cavity and boundary layer," *Applied Ocean Research*, vol. 59, pp. 451–458, 2016.
- [32] S. A. Mäkiharju, B. R. Elbing, A. Wiggins, *et al.*, "On the scaling of air entrainment from a ventilated partial cavity," *Journal of Fluid Mechanics*, vol. 732, pp. 47–76, 2013.
- [33] F. Cucinotta, E. Guglielmino, and F. Sfravara, "An experimental comparison between different artificial air cavity designs for a planing hull," *Ocean Engineering*, vol. 140, pp. 233–243, 2017.
- [34] H. Wu and Y. Ou, "Analysis of air layer shape formed by air injection at the bottom of flat plate," *Ocean Engineering*, vol. 216, p. 108 091, 2020.
- [35] H. Fang, S. Qin, S. Sun, *et al.*, "Numerical investigation on the cavity behavior and hydrodynamic performance of a planing air cavity ship," *Ocean Engineering*, vol. 241, p. 110 042, 2021.
- [36] X. Zhao and Z. Zong, "Experimental and numerical studies on the air-injection drag reduction of the ship model," *Ocean Engineering*, vol. 251, p. 111 032, 2022.
- [37] M. M. Guin, H. Kato, H. Yamaguchi, M. Maeda, and M. Miyanaga, "Reduction of skin friction by microbubbles and its relation with near-wall bubble concentration in a channel," *Journal of Marine Science and Technology*, vol. 1, no. 5, pp. 241–254, 1996.
- [38] O. Watanabe, A. Masuko, and Y. Shirose, "Measurements of drag reduction by microbubbles using very long ship models," *Journal of the Society of Naval Architects of Japan*, vol. 1998, no. 183, pp. 53–63, 1998.
- [39] H. Kato, T. Iwashina, M. Miyanaga, and H. Yamaguchi, "Effect of microbubbles on the structure of turbulence in a turbulent boundary layer," *Journal of Marine Science and Technology*, vol. 4, no. 4, pp. 155–162, 1999.

- [40] C. Gabillet, C. Colin, and J. Fabre, "Experimental study of bubble injection in a turbulent boundary layer," *International Journal of Multiphase Flow*, vol. 28, no. 4, pp. 553–578, 2002.
- [41] Y. Moriguchi and H. Kato, "Influence of microbubble diameter and distribution on frictional resistance reduction," *Journal of Marine Science and Technology*, vol. 7, no. 2, pp. 79–85, 2002.
- [42] T. Takahashi, A. Kakugawa, M. Makino, and Y. Kodama, "Experimental study on scale effect of drag reduction by microbubbles using very large flat plate ships," *Journal of Kansai Society of Naval Architects*, vol. 239, pp. 11–20, 2003.
- [43] T. H. van den Berg, S. Luther, D. P. Lathrop, and D. Lohse, "Drag reduction in bubbly Taylor-Couette turbulence," *Physical Review Letters*, vol. 94, no. 4, p. 044 501, 2005.
- [44] X. Shen, S. L. Ceccio, and M. Perlin, "Influence of bubble size on micro-bubble drag reduction," *Experiments in Fluids*, vol. 41, no. 3, pp. 415–424, 2006.
- [45] W. C. Sanders, E. S. Winkel, D. R. Dowling, M. Perlin, and S. L. Ceccio, "Bubble friction drag reduction in a high-Reynolds-number flat-plate turbulent boundary layer," *Journal of Fluid Mechanics*, vol. 552, p. 353, -1 2006.
- [46] Y. Murai, H. Fukuda, Y. Oishi, Y. Kodama, and F. Yamamoto, "Skin friction reduction by large air bubbles in a horizontal channel flow," *International Journal of Multiphase Flow*, vol. 33, no. 2, pp. 147–163, 2007.
- [47] T. H. van den Berg, D. P. M. van Gils, D. P. Lathrop, and D. Lohse, "Bubbly turbulent drag reduction Is a boundary layer effect," *Physical Review Letters*, vol. 98, no. 8, p. 084 501, 2007.
- [48] Y. Murai, H. Oiwa, and Y. Takeda, "Frictional drag reduction in bubbly Couette–Taylor flow," *Physics of Fluids*, vol. 20, no. 3, p. 034 101, 2008.
- [49] S.-J. Wu, K. Ouyang, and S.-W. Shiah, "Robust design of microbubble drag reduction in a channel flow using the Taguchi method," *Ocean Engineering*, vol. 35, no. 8-9, pp. 856–863, 2008.
- [50] J. Huang, Y. Murai, and F. Yamamoto, "Quadrant analysis of bubble induced velocity fluctuations in a transitional boundary layer," *Journal of Hydrodynamics*, vol. 21, no. 1, pp. 93–99, 2009.
- [51] D. P. M. van Gils, D. Narezoz Guzman, C. Sun, and D. Lohse, "The importance of bubble deformability for strong drag reduction in bubbly turbulent Taylor–Couette flow," *Journal of Fluid Mechanics*, vol. 722, pp. 317–347, 2013.
- [52] Y. Oishi and Y. Murai, "Horizontal turbulent channel flow interacted by a single large bubble," *Experimental Thermal and Fluid Science*, vol. 55, pp. 128–139, 2014.

- [53] H. J. Park, Y. Tasaka, Y. Murai, and Y. Oishi, "Vortical structures swept by a bubble swarm in turbulent boundary layers," *Chemical Engineering Science*, vol. 116, pp. 486–496, 2014.
- [54] H. J. Park, Y. Tasaka, Y. Oishi, and Y. Murai, "Drag reduction promoted by repetitive bubble injection in turbulent channel flows," *International Journal of Multiphase Flow*, vol. 75, pp. 12–25, 2015.
- [55] H. J. Park, Y. Oishi, Y. Tasaka, and Y. Murai, "Void waves propagating in the bubbly two-phase turbulent boundary layer beneath a flat-bottom model ship during drag reduction," *Experiments in Fluids*, vol. 57, no. 12, p. 178, 2016.
- [56] S. Qin, N. Chu, Y. Yao, J. Liu, B. Huang, and D. Wu, "Stream-wise distribution of skin-friction drag reduction on a flat plate with bubble injection," *Physics of Fluids*, vol. 29, no. 3, p. 037 103, 2017.
- [57] H. J. Park, Y. Tasaka, and Y. Murai, "Bubbly drag reduction accompanied by void wave generation inside turbulent boundary layers," *Experiments in Fluids*, vol. 59, no. 11, p. 166, 2018.
- [58] N. K. Jha, A. Bhatt, and R. N. Govardhan, "Effect of bubble distribution on wall drag in turbulent channel flow," *Experiments in Fluids*, vol. 60, no. 8, p. 127, 2019.
- [59] Y. Oishi, Y. Murai, and Y. Tasaka, "Wall shear stress modified by bubbles in a horizontal channel flow of silicone oil in the transition region," *International Journal of Heat and Fluid Flow*, vol. 86, p. 108 748, 2020.
- [60] S. Kim, N. Oshima, H. J. Park, and Y. Murai, "Direct numerical simulation of frictional drag modulation in horizontal channel flow subjected to single large-sized bubble injection," *International Journal of Multiphase Flow*, vol. 145, p. 103 838, 2021.
- [61] T. Hazuku, T. Ihara, and T. Hibiki, "Reduction of skin friction and two-phase flow structure beneath wall in horizontal rectangular channel," *Ocean Engineering*, vol. 248, p. 110 846, 2022.
- [62] A. Ferrante and S. Elghobashi, "On the physical mechanisms of drag reduction in a spatially developing turbulent boundary layer laden with microbubbles," *Journal of Fluid Mechanics*, vol. 503, pp. 345–355, 2004.
- [63] Y. A. Hassan, C. C. Gutierrez-Torres, and J. A. Jimenez-Bernal, "Temporal correlation modification by microbubbles injection in a channel flow," vol. 32, no. 8, pp. 1009–1015, 2005.
- [64] L. Zhen and Y. A. Hassan, "Wavelet autocorrelation identification of the turbulent flow multi-scales for drag reduction process in microbubbly flows," *Chemical Engineering Science*, vol. 61, no. 21, pp. 7107–7114, 2006.
- [65] S.-J. Wu, C.-H. Hsu, and T.-T. Lin, "Model test of the surface and submerged vehicles with the micro-bubble drag reduction," *Ocean Engineering*, vol. 34, no. 1, pp. 83–93, 2007.

- [66] K. Sugiyama, E. Calzavarini, and D. Lohse, “Microbubbly drag reduction in Taylor–Couette flow in the wavy vortex regime,” *Journal of Fluid Mechanics*, vol. 608, pp. 21–41, 2008.
- [67] B. Jacob, A. Olivieri, M. Miozzi, E. F. Campana, and R. Piva, “Drag reduction by microbubbles in a turbulent boundary layer,” *Physics of Fluids*, vol. 22, no. 11, p. 115 104, 2010.
- [68] T. Watamura, Y. Tasaka, and Y. Murai, “Intensified and attenuated waves in a microbubble Taylor–Couette flow,” *Physics of Fluids*, vol. 25, no. 5, p. 054 107, 2013.
- [69] H. J. Park, D. Saito, Y. Tasaka, and Y. Murai, “Color-coded visualization of microbubble clouds interacting with eddies in a spatially developing turbulent boundary layer,” *Experimental Thermal and Fluid Science*, vol. 109, p. 109 919, 2019.
- [70] J. Lu, A. Fernández, and G. Tryggvason, “The effect of bubbles on the wall drag in a turbulent channel flow,” *Physics of Fluids*, vol. 17, no. 9, p. 095 102, 2005.
- [71] A. Kitagawa, P. Denissenko, and Y. Murai, “Behavior of bubbles moving along horizontal flat plates with different surface wettability,” *Experimental Thermal and Fluid Science*, vol. 104, pp. 141–152, 2019.
- [72] J. H. Lammers and A. Biesheuvel, “Concentration waves and the instability of bubbly flows,” *Journal of Fluid Mechanics*, vol. 328, pp. 67–93, 1996.
- [73] Y. Oishi, Y. Tohge, Y. Tasaka, and Y. Murai, “Bubble clustering in a horizontal turbulent channel flow investigated by bubble-tracking velocimetry,” *International Journal of Multiphase Flow*, vol. 120, p. 103 104, 2019.
- [74] T. Takeuchi and T. Kagawa, “Applicability of frequency response test for stability evaluation of gas pressure regulator,” *Transactions of the Society of Instrument and Control Engineers*, vol. 49, no. 8, pp. 747–754, 2013.
- [75] C. Torrence and G. P. Compo, “A practical guide to wavelet analysis,” *Bulletin of the American Meteorological Society*, vol. 79, no. 1, p. 18, 1998.
- [76] A. Biesheuvel and L. V. Wijngaarden, “Two-phase flow equations for a dilute dispersion of gas bubbles in liquid,” *Journal of Fluid Mechanics*, vol. 148, pp. 301–318, 1984.
- [77] H. Schlichting, *Boundary-Layer Theory*. New York: McGraw-Hill, 1961.
- [78] C. Fureby, S. Toxopeus, M. Johansson, M. Tormalm, and K. Petterson, “A computational study of the flow around the KVLCC2 model hull at straight ahead conditions and at drift,” *Ocean Engineering*, vol. 118, pp. 1–16, 2016.
- [79] Y. Kodama, A. Kakugawa, T. Takahashi, and H. Kawashima, “Experimental study on microbubbles and their applicability to ships for skin friction reduction,” *International Journal of Heat and Fluid Flow*, vol. 21, no. 5, pp. 582–588, 2000.
- [80] J. Xu, M. R. Maxey, and G. E. Karniadakis, “Numerical simulation of turbulent drag reduction using micro-bubbles,” *Journal of Fluid Mechanics*, vol. 468, pp. 271–281, 2002.

- [81] S. Deutsch and J. Castano, "Microbubble skin friction reduction on an axisymmetric body," *Physics of Fluids*, vol. 29, no. 11, p. 3590, 1986.
- [82] R. Lattore, A. Miller, and R. Philips, "Micro-bubble resistance reduction on a model SES catamaran," *Ocean Engineering*, vol. 30, pp. 2297–2309, 2003.
- [83] C. L. Merkle and S. Deutsch, "Microbubble drag reduction in liquid turbulent boundary layers," *Applied Mechanics Reviews*, vol. 45, pp. 103–127, 1992.
- [84] N. K. Madavan, S. Deutsch, and C. L. Merkle, "Measurements of local skin friction in a microbubble-modified turbulent boundary layer," *Journal of Fluid Mechanics*, vol. 156, p. 237, -1 1985.
- [85] S. Pal, C. L. Merkle, and S. Deutsch, "Bubble characteristics and trajectories in a microbubble boundary layer," *Physics of Fluids*, vol. 31, no. 4, p. 744, 1988.
- [86] T. Tanaka, H. J. Park, Y. Tasaka, and Y. Murai, "Spontaneous and artificial void wave propagation beneath a flat-bottom model ship," *Ocean Engineering*, vol. 214, p. 107 850, 2020.
- [87] H. Kawashima, Y. Kodama, M. Hinatsu, *et al.*, "A research project on application of air bubble injection to a full scale ship for drag reduction," in *Volume 1: Symposia, Parts A and B*, San Diego, California, USA: ASMEDC, 2007, pp. 265–274.
- [88] T. Tanaka, H. J. Park, Y. Tasaka, and Y. Murai, "Artificial void wave propagation in a gas-liquid two-phase horizontal turbulent channel flow," *Japanese Journal of Multiphase Flow*, vol. 34, no. 1, pp. 243–253, 2020.
- [89] H. J. Park, Y. Tasaka, and Y. Murai, "Spatial development of single void pulse in a horizontal turbulent bubbly channel flow investigated by a time-resolved two-laser measurement," *International Journal of Multiphase Flow*, vol. 146, p. 103 867, 2022.
- [90] D. Yoon, H. J. Park, Y. Tasaka, and Y. Murai, "Drag coefficient of bubbles sliding beneath a towed model ship with variable tilt angles," *International Journal of Multiphase Flow*, vol. 149, p. 103 995, 2022.
- [91] D. Yoon, H. J. Park, Y. Tasaka, and Y. Murai, "Lift coefficient of bubble sliding inside turbulent boundary layers in an inclinable channel flow," *Physics of Fluids*, vol. 34, no. 5, p. 053 301, 2022.
- [92] S. Takagi and Y. Matsumoto, "Surfactant effects on bubble motion and bubbly flows," *Annual Review of Fluid Mechanics*, vol. 43, no. 1, pp. 615–636, 2011.
- [93] S. Hosokawa and A. Tomiyama, "Bubble-induced pseudo turbulence in laminar pipe flows," *International Journal of Heat and Fluid Flow*, vol. 40, pp. 97–105, 2013.
- [94] D. Yoon, H. J. Park, Y. Tasaka, and Y. Murai, "Behaviors of sliding bubbles in an inclinable turbulent channel flow investigated by optoacoustic measurement," *International Journal of Multiphase Flow*, vol. 158, p. 104 258, 2023.

- [95] N. G. Deen, P. Willems, M. van Sint Annaland, *et al.*, “On image pre-processing for PIV of single- and two-phase flows over reflecting objects,” *Experiments in Fluids*, vol. 49, no. 2, pp. 525–530, 2010.
- [96] K. Ohmi, S. P. Panday, and A. Sapkota, “Particle tracking velocimetry with an ant colony optimization algorithm,” *Experiments in Fluids*, vol. 48, no. 4, pp. 589–605, 2010.
- [97] M. Raffel, C. E. Willert, F. Scarano, C. J. Kähler, S. T. Wereley, and J. Kompenhans, *Particle Image Velocimetry: A Practical Guide*. Cham: Springer International Publishing, 2018.
- [98] K. Takehara and T. Etoh, “A study on particle identification in PTV particle mask correlation method,” vol. 1, no. 3, pp. 313–323, 1999.
- [99] F. Pereira, H. Stüer, E. C. Graff, and M. Gharib, “Two-frame 3D particle tracking,” *Measurement Science and Technology*, vol. 17, no. 7, pp. 1680–1692, 2006.
- [100] S. S. Lu and W. W. Willmarth, “Measurements of the structure of the Reynolds stress in a turbulent boundary layer,” *Journal of Fluid Mechanics*, vol. 60, no. 03, p. 481, 1973.
- [101] A. Kitagawa, Y. Shiomi, Y. Murai, and P. Denissenko, “Transient velocity profiles and drag reduction due to air-filled superhydrophobic grooves,” *Experiments in Fluids*, vol. 61, no. 11, p. 237, 2020.
- [102] S. T. McComas, “Hydrodynamic entrance lengths for ducts of arbitrary cross section,” *Journal of Basic Engineering*, vol. 89, no. 4, pp. 847–850, 1967.

