DISSERTATION SUMMARY

博士の専攻分野の名称　博士（工学）　氏名　Tiwari Neetu

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CFD assisted quantitative flow measurement of Newtonian and non-Newtonian fluid flows

(ニュートン・非ニュートン流体に対する計算流体力学支援型の流体計測技術の開発)

Distributions of velocity, pressure are important to understand the fluid flows of practical importance such as flow over bluff bodies, industrial flows and environmental flows. Velocity distribution can be measured in three dimensions by PIV (Particle image velocimetry) but direct measurement of pressure distribution is still impossible. So, several counter techniques have been proposed for pressure estimation from PIV in literature. These techniques allow simultaneous measurement of velocity and pressure non-intrusively, which also enables the measurement of forces on immersed structures. However, estimated pressure field often suffers from errors propagated from uncertainty of velocity measurement. Error in pressure estimation depends on spatial and temporal resolution of measurement, domain size, aspect ratio and boundary conditions. Through past efforts, pressure estimation had been well investigated for transparent Newtonian fluids. But not discussed for opaque and non-Newtonian fluids which are commonly found in industries and these are inseparable from our daily needs. Existing pressure estimation techniques based on PIV measurement is not valid for opaque fluids and Non-Newtonian fluids and no study have been performed in this area. Present study is the first attempt to introduce the pressure estimation techniques for opaque Newtonian, opaque non-Newtonian and transparent non-Newtonian fluids. The estimated pressure field often suffers from noise propagation from velocity uncertainty of measurement.

These error produce curl in the pressure field. So, to reduce the curl a novel irrotational correction framework is also proposed.

In chapter 1, background of pressure estimations in Newtonian fluids is discussed. Limitations of existing experimental techniques and governing equations of pressure estimation in non- Newtonian and opaque fluids are described. Motivation and objective of the research work is followed by outline of thesis.

In chapter 2, experimental arrangements and conditions are described. Vortex shedding behind circular cylinder is studied in present work. Measurements were conducted in Newtonian and non-Newtonian fluids by UVP (Ultrasonic velocity profiler) and PIV techniques in towing tank facility.

In chapter 3, a novel pressure estimation technique is discussed for opaque fluid flows. PIV was substituted by UVP (Ultrasonic velocity profiler) for collecting velocity data due to its capability of measurement in opaque fluids. UVP can only give the velocity information in 1C-1D (one component- one dimensional) which added a new challenge of pressure estimation because 1C-1D data is insufficient to estimate pressure from Navier-Stokes or Pressure Poisson equations. Also, to deal with the noise in experimental data, a Unique filtering technique is developed by combination of FFT (Fast Fourier transform) and POD (Proper orthogonal decomposition) to determine unknown component of velocity from equation of continuity. Then to estimate pressure, 2D velocity data substituted in Navier stokes equation. This algorithm was demonstrated for vortex flow in water and milk. In wake region alternating low and high-pressure regions were obtained as per staggered arrangement of von-Karman vortices.

It was found that UVP measurement with Taylor Frozen hypothesis were suitable for accurate pressure estimation in wake of cylinder.

In chapter 4, another pressure estimation algorithm is developed for transparent shear thinning fluids based on PIV measurements. Navier Stokes and pressure Poisson equation cannot be used directly for pressure estimation in these flows. So, momentum equations modified with rheological model are used. Power law and Carreau-Yasuda models are compared by estimating their capability of evaluation the 2D (two dimensional) distribution of viscosity field. This algorithm was tested for cylinder flow in steady and unsteady cases. In steady case, low pressure region at vortex cores were accurately obtained which corroborates the accuracy of algorithm. In addition, the quantitative assessment of relation between material and dynamic property of fluid were performed with cross-correlation analysis. It was found that during development of vortices viscosity is negatively correlated with enstrophy and the pressure lowering was intensified at vortex cores with time due to shear thinning property of fluid. Wake stabilization also increases with time. So, the shear thinning property works against the momentum diffusion. In unsteady cylinder flow, it was found that for slowly developing vortices, the present algorithm successfully reconstructed the pressure field, but for separated wake flow it is invalid. Generally, in Newtonian fluids, the pressure Poisson equation is very useful for unsteady flows. But for shear thinning fluid it is invalid. So, a new pressure Poisson is derived for shear thinning fluids. This equation could not be utilized for pressure estimation because the limited spatial resolution of PIV is insufficient to solve new pressure Poisson equation which has four additional source terms consisting of viscosity and its derivatives. This open problem is addressed in next chapter. An error propagation from uncertainty of velocity to pressure is analyzed by linear precision propagation analysis to understand the specific role of shear thinning in error propagation. It was found that the error propagation is directly proportional to error in viscosity magnitude. And shear thinning property can reduce the error propagation. Another factor is spatial resolution of data, high spatial resolution could reduce the error in diffusion terms but helps error increment in convection term.

In chapter 5, PIV is substituted by UVP for velocity measurement which can provide a better spatial resolution of velocity data. This also gives the advantage of its application in opaque fluid flows. So, a novel pressure estimation algorithm is developed for shear thinning opaque fluids using UVP. The new pressure Poisson equation for shear thinning fluids is solved for separated wake with UVP data to obtain pressure field. The alternating pattern of low-pressure regions in wake is successfully reconstructed which assures the good performance of algorithm. Parameteric study is presented for Re=55-293. I have found that with increasing Re vortex shedding frequency increases but Strouhal number decreases because shear-thinning increases the vortex sustainability and their stay in wake. By analyzing correlation with Re, it was found that viscosity is negatively correlated with pressure. It was also observed that as Re increases the dependency of viscosity on shear stress became weaker and at Re=293 viscosity equally depends on normal and shear stress components which conveys that the rheometers experiments using shear stresses only do not valid for high Re flows.

In chapter 6, an irrotational correction method based on Helmholtz decomposition theorem is proposed for curl correction in estimated pressure from velocity data. The pressure gradient field are decomposed into rotational and irrotational parts using Helmholtz decomposition theorem. Then by taking divergence rotational part is canceled out and a new pressure Poisson Eq. is derived which has Laplacian source term. Filtered pressure is calculated from irrotational part. Present method utilizes the curl correction characteristic of Laplacian operator to reduce the curl in pressure field. It is applicable in pressure fields estimated from

Navier-Stokes and pressure Poisson equation. Present method is tested in analytical field and experimental data of PIV. Then it was compared with two published studies of error reduction. It reduces the curl in significant amount and its capability of curl correction is insensitive to noise level. Although low resolution velocity data with high correlation error could lessen its performance of curl correction. This method was further tested in PIV data collected at t=12 Sec in flow over cylinder in water. Four set of pressure data are obtained by solving pressure Poisson equation for unfiltered, median, FFT and POD filtered velocity data. FFT and POD filtering can reduce the magnitude of curl of pressure field to half. The result of curl correction in PIV data showed that curl is reduced to almost zero and it encourages the refusal of velocity filtering techniques which often filter the information of true flow data. If Navier-Stokes is employed for pressure gradient estimation, present method can provide the error free pressure field without performing integration and saves the computational cost a lot. It reduces the three-step procedure of error field reconstruction, subtraction from measured pressure gradient to just one-step method.  And shows a potential to replace multiple path integration approaches to estimate pressure from pressure gradient.

In chapter7, conclusions are drawn from present research work and future feasible research directions are discussed.