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Behavior of Heat Transfer with Turbulence in a Free Shear Layer in a Separated Flow

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Abstract

The influence of turbulent fluctuation in a free shear layer on heat transfer rate is investigated in a separated flow associated with a double step at entrance to an enlarged flat duct. Experiments are carried out with air under the condition of uniform heat flux. Measurement of the turbulent fluctuation in the free shear layer is made by using a hot-wire anemometer. The ratio of step height to entrance height, h/L, is adopted as 0.44, and the Reynolds number is varied from 8×10^4 to 2×10^5.

It is found that the behavior of heat-transfer rate in the separated and reattached regions is closely connected with that of turbulent fluctuation in the free shear layer.

Nomenclature

- Cp, Specific heat;
- h, Step height;
- L, Entrance height;
- Nu_L, Local Nusselt number, $\alpha L/\lambda$;
- q_t, Heat transported by turbulence in the normal direction to mean flow, $Cp\rho\overline{v't'}$;
- q_w, Wall heat flux;
- Re, Reynolds number, UL/ν;
- t, Temperature;
- T, Non-dimensional temperature, $\lambda(t_w-t_c)/q_wL$;
- u', Velocity fluctuation in the direction of mean flow;
- $\overline{u'v'}$, Average of the product of velocity fluctuations in the parallel and normal directions of mean flow;
- $\overline{v't'}$, Average of the product of velocity and temperature fluctuations in the normal direction of mean flow;
- U, Entrance velocity;
- x, Distance from a step;
- x_R, Distance between reattachment point and step;
- α, Heat-transfer coefficient;
- λ, Thermal conductivity;
- ν, Kinematic viscosity;
- ρ, Density.

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1. Introduction

Turbulent heat-transfer in a separated flow is of a considerable importance in practical technological problems. However, the basic heat transport mechanisms and the like have not fully been understood so far due to a complexity of the heat-transfer characteristics and a difficulty of the experimental technique for the investigation thereof. The majority of the previous work related to the heat-transfer in the separated flow are concerned with limited flow configurations.

For example, Krall and Sparrow[1] investigated the heat-transfer rate of water for a variety of diameter ratios of pipe to orifice under the condition of constant heat flux. From their results, it was found that the heat-transfer rate at the reattachment point is about 3~8 times as large as that for a fully-developed flow.

On the other hand, Filetti and Kays[2] measured the heat-transfer rate of air for a rectangular cross-sectional duct with a double backward facing step under the condition of constant wall temperature. As a result, it was indicated that the heat-transfer rate at the reattachment point for long or short stall has respective different values.

In addition, the authors[3] examined the heat-transfer rate of air for long and short stalls in a rectangular cross-sectional duct with a wide range of step height under the condition of constant heat flux. They found that the heat-transfer rate at the reattachment point was well correlated with a reattached length of long or short stall.

While, Mori and Daikoku[4] measured the turbulent intensity in a downward flow from a two-dimensional roughness element placed on a wall by using an electro-chemical method. Consequently, it was shown that the behavior of heat-transfer coefficient is closely related to that of turbulence near the wall.

In the present experiment, the effect of turbulence in a free shear layer on heat-transfer coefficient in the separated and reattached regions is examined. The turbulent intensity in the free shear layer is easily changed by the vinyl tips attached on a step edge. Measurements are carried out with air for a rectangular cross-sectional duct having a double step at its entrance under the condition of uniform heat flux. Reynolds number ranges approximately from 8×10^4 to 2×10^5, and the ratio of step height to entrance height is 0.44.

2. Experimental Apparatus

Experiments are performed using a Gottingen type wind tunnel of which test section is consisted essentially of a contraction, steps and heated plates. Data are obtained for a step height of $h=58$ mm and an entrance height of $L=132$ mm. Stainless-steel foils having a thickness of 50 microns fixed onto the test plates by a binding agent are used as the heater of the test section. A condition of uniform heat flux is obtained by passing a-c electric current through the foil.

Heat loss to the surrounding is minimized by covering with thermal insulating material over the test section, thus, an uncertainty of the data for heat flux in the present investigation is to be within 3.2%. Further, to reduce the heat flow through the heater in a transverse flow direction, the heating section is divided into five segments as shown in Fig. 1, however, only central one is used to measure the wall temperature.

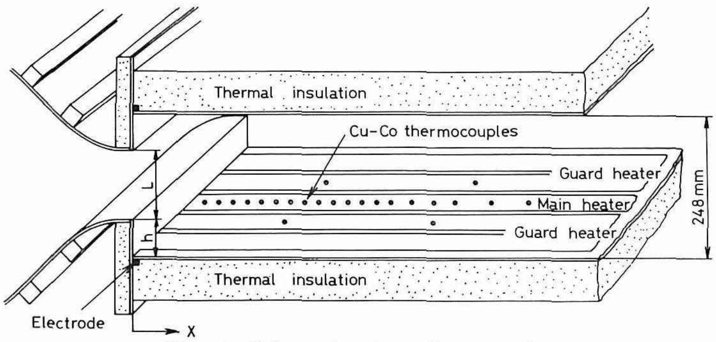

Fig. 1 Schematic view of test section

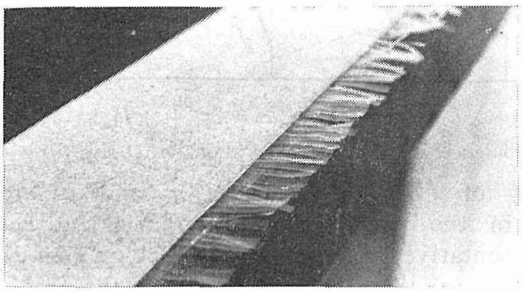

Fig. 2 Appearance of vinyl tips

The heat flux from the wall is evaluated by readings of a voltmeter and an amperemeter. And the wall temperature is detected by Cu–Co thermocouples fixed to the back of the stainless-steel foils. The reattachment point, where the heat-transfer coefficient indicates a maximum value[2)], is decided from the temperature distribution of the wall.

Two-dimensionality of flow in the reattached region is examined with three pairs of thermocouples as shown in Fig. 1 and confirmed by a flow visualization using an oil film method.

Vinyl tips (10 mm × 3 mm of each) as shown in Fig. 2, whose thickness is 15 microns, are attached to the step edge in order to artificially change the turbulent intensity in the free shear layer. The fluctuations of $\sqrt{\overline{u'^2}}$, $-\overline{u'v'}$ and $\overline{v't'}$ are measured with a hot-wire anemometer using a method reported by Shigetomi and Seki[5)]. The hot-wire probe and the thermocouple for measuring of temperature distribution in a flow field, are put into the test section from a side wall in such a way as to prevent an undesirable flow disturbance.

Seven cross-sections in a flow direction are prepared for the measurement of turbulent fluctuation, temperature and velocity distributions. These stations are situated at a distance of 30, 85, 145, 205, 330, 470 and 660 mm far from the step, respectively. The entrance velocity measured by a Pitot static probe shows a uniformness of its profile. All of the measurements are performed in a steady state.

3. Results and Discussion

The measured values of $\overline{u'^2}$ together with those of $-\overline{u'v'}$ along a long stall

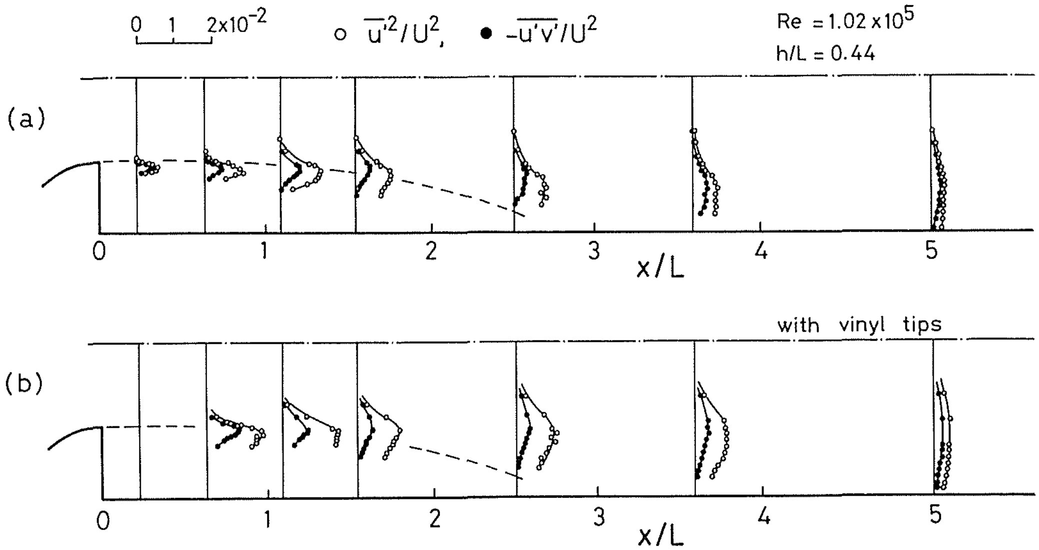

Fig. 3 Turbulence distribution (a) Without vinyl tips (b) with vinyl tips

for entrance velocity of $U=12$ m/s, where u' and v' are the components of fluctuating velocity in the parallel and the normal direction to a mean flow respectively, are representatively shown in Fig. 3 by a non-dimensional expression. It is indicated in Fig. 3 (a) that the turbulence in the free shear layer develops firstly in the separated region and then decays gradually until the turbulent structure reaches such a characteristic state as in a fully-developed duct flow. This tendency has the same trend as the results by Mueller and Robertson[6] who measured the velocity fluctuations generated by a two-dimensional roughness element.

On the other hand, Fig. 3 (b) shows the typical results of velocity fluctuation in case of attaching the vinyl tips on the step edge. It is observed that the turbulence just after the step shows a larger value than the case of Fig. 3 (a) owing to the vibrating of the vinyl tips. Further, the large turbulence goes on decaying gradually as the reattachment point is approached. Especially, an interesting feature in Fig. 3 (b) is the behavior of distribution of velocity fluctuation at each cross section. That is, the dissipation of turbulence occurs more rapidly than in the case of being without the vinyl tips.

Then, the variation of local heat-transfer coefficient resulting from the change of turbulence in the free shear layer is given in Fig. 4. In Fig. 4, the ordinate indicates the Nusselt number and the abscissa, x/L, the non-dimensional distance from the step divided by entrance height.

In the present study, Nusselt number Nu_L is defined as

$$Nu_L=\alpha L/\lambda \qquad (1)$$

where λ is the thermal conductivity of air. Further, the heat-transfer coefficient α is defined as

$$\alpha=q_w/(t_w-t_c) \qquad (2)$$

where q_w, t_w and t_c are the wall heat flux, the wall temperature and the center-line fluid temperature, respectively.

In Fig. 4, the reattachment point is estimated from a peak feature in Nu_L, and the heat-transfer rate in case of attaching the vinyl tips, which has a

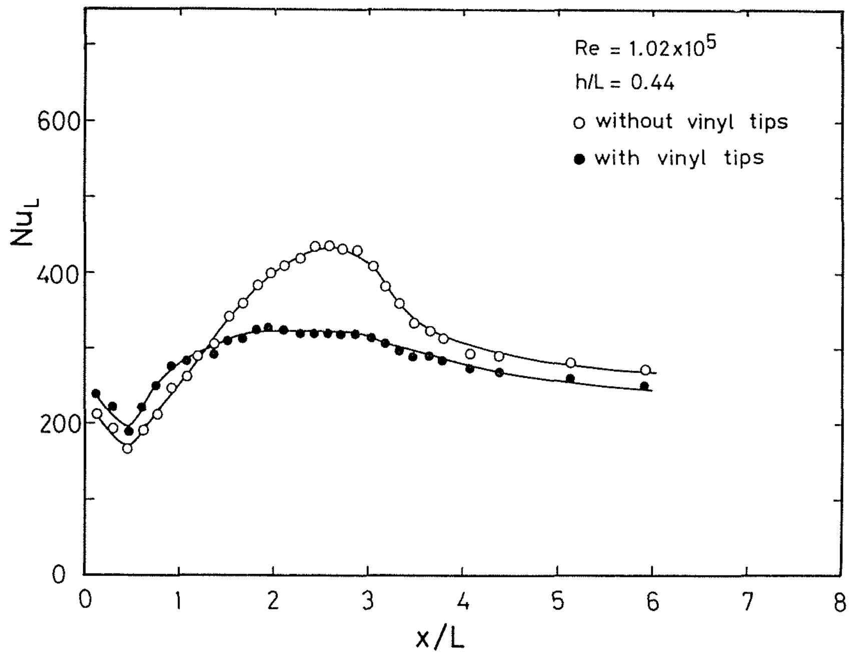

Fig. 4 Dependability of local Nusselt number on whether attaching the vinyl tips or not on the step edge

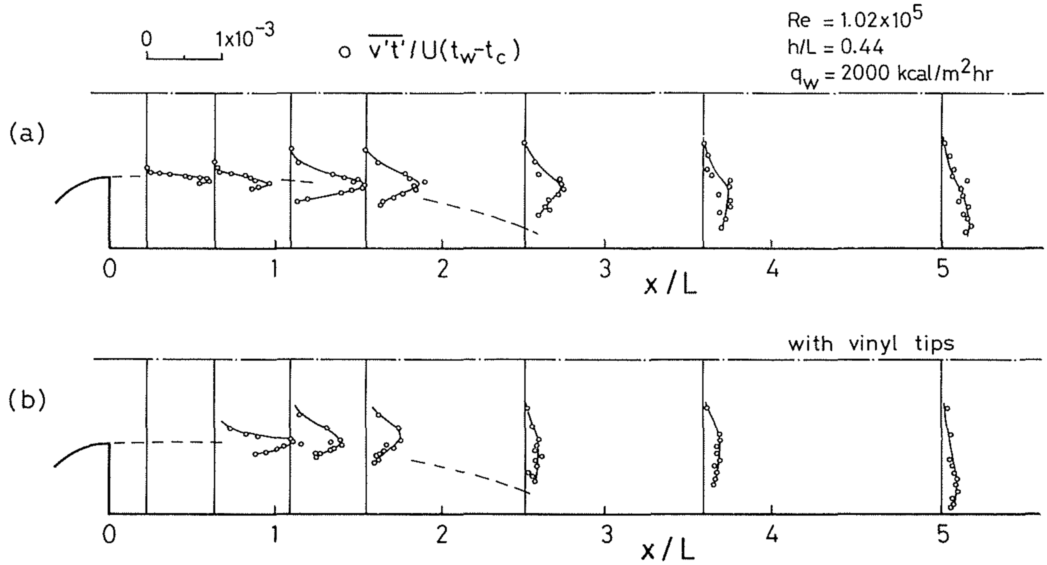

Fig. 5 $\overline{v't'}$ distributions (a) without vinyl tips (b) with vinyl tips

tendency to flatten in the reattached region, is smaller than that in case of their being absent except for the region just after the step. In the sufficiently downward region, Nu_L in both cases may approach to that in a fully-developed duct flow.

On the other hand, it seems that the heat convected from the wall in the separated region is transferred toward the free shear layer by a recirculating flow, and thereafter, is dissipated to the main stream by a velocity fluctuating

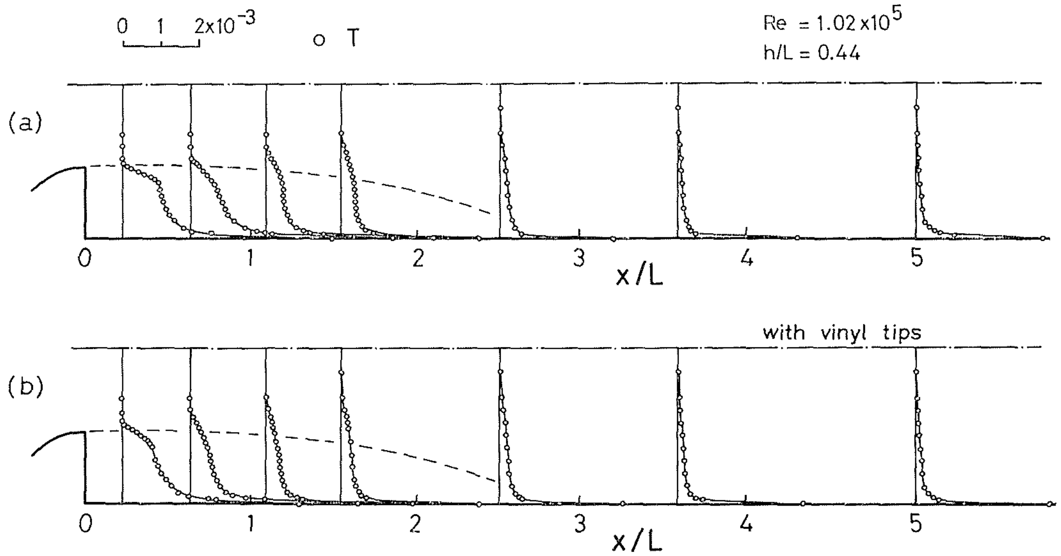

Fig. 6 Temperature distributions (a) without vinyl tips (b) with vinyl tips

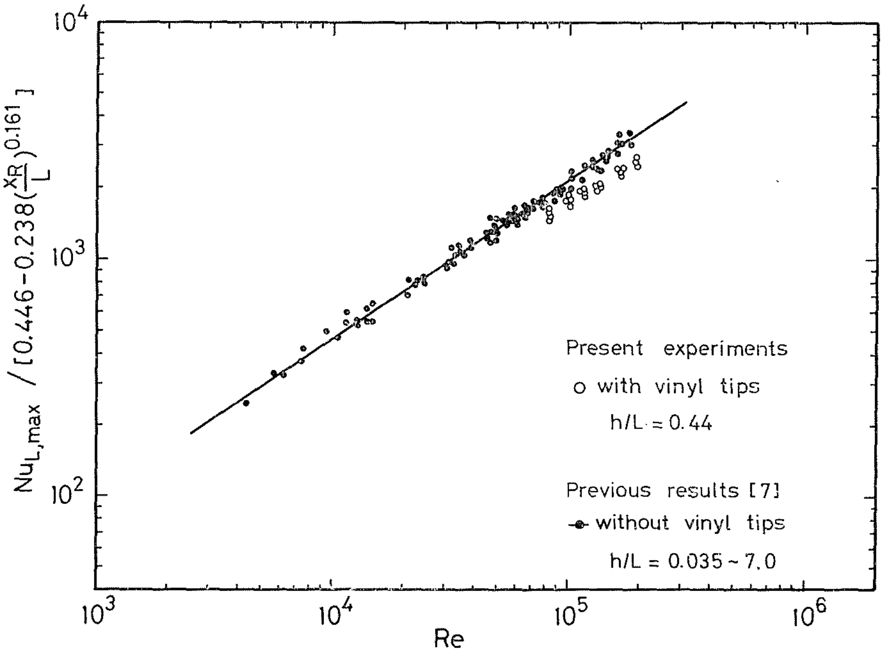

Fig. 7 Dependability of maximum Nusselt number on whether attaching the vinyl tips or not on the step edge

motion normal to the mean flow. Hence, it may be suggested that the behavior of the value of $q_t = Cp\rho\overline{v't'}$ is an important one for the investigation of the present subject.

Figure 5 shows the representative results of $\overline{v't'}$ distribution at each section for an entrance velocity of $U = 12$ m/s and for a wall heat flux of $q_w = 2000$ $kcal/m^2hr$, where $\overline{v't'}$ is divided by both U and the difference between wall temperature t_w and centerline temperature t_c in the flow field. It is shown in Figs. 5 (a) and

5 (b) that each $\overline{v't'}$ distribution has a similar tendency with a maximum value in the free shear layer as the velocity fluctuation. However, the maximum value of $\overline{v't'}$ in case of the results with the vinyl tips as shown in Fig. 5 (b) decreases and dissipates more rapidly than that in case of their being absent as the reattachment is approached. That is to say, when the large fluctuation is artificially given by attaching the vinyl tips on the step edge, the turbulence in the free shear layer goes on decaying, and dissipates more widely than in the case of Fig. 5 (a). Consequently, it might be concluded that the flattening trend of Nusselt number as shown in Fig. 4 is caused by the wide dissipation of turbulence which is reattaching.

Under the circumstance that the heat-transfer rate is affected by the turbulence in the free shear layer, a temperature distribution in the flow field is expected to be also influenced by it. Figure 6 indicates the temperature distribution of T at each section in the flow field, where T is a non-dimensional temperature. The difference between both temperature gradients is observed explicitly in the free shear layer just after the step. That is, the temperature gradient in the free shear layer in case of the results with the vinyl tips is less expressive than their being absent. Such a behavior could be realized by the measured results of $\overline{v't'}$ as shown in Fig. 5 (b). As the $\overline{v't'}$ corresponds to the transported heat by turbulence, the magnitude of $\overline{v't'}$ just after the step as observed in Fig. 5 (b) may cause a gentle temperature gradient in the free shear layer. After all, the heat-transfer coefficient just after the step shows a larger value in case of the results with the vinyl tips than their being absent, as can be seen in Fig. 4. From these results, it is evident that the velocity fluctuation in the free shear layer has a great influence on the heat-transfer coefficient in the separated and reattached regions. In the present experiment, it may also be concluded that the heat-transfer coefficient in the reattached region is decreased by attaching the vinyl tips to the step edge.

Figure 7 shows the maximum Nusselt number in case of the results with the vinyl tips together with the results of their being absent as reported by authors[7]. The ordinate indicates $Nu_{L,max}$ divided by an effect of stall length on the maximum Nusselt number[3], and the abscissa shows Reynolds number. It is clearly observed that the Nusselt number at the reattachment point decreases in case of a large turbulence being given just after the step by attaching the vinyl tips.

4. Summary and Conclusions

The influence of turbulence in a free shear layer of a separated flow associated with a double step at entrance to an enlarged flat duct on heat-transfer rate is examined by means of attaching vinyl tips to the step edge. Experiments are carried out with air under the condition of uniform heat flux. Reynolds number is varied from 8×10^4 to 2×10^5 and the ratio of step height to entrance height, h/L, is adopted as 0.44. The following conclusions are obtained.

1) The heat-transfer coefficient in the separated and reattached regions is closely connected with a behavior of turbulence in the free shear layer.

2) The heat-transfer coefficient in the reattached region is decreased by the large turbulence being given just after the step.

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