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Heat Transfer in Separated Flow behind a Double Step at Entrance to a Duct

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Abstract

Heat transfer rate at a reattachment point is investigated in a wide range of Reynolds numbers. Experiments are performed by using water and oil under the condition of constant heat flux. Reynolds number ranged from 3.8×10 to 3.5×10^3 and step height is varied between 0.14 and 1.50.

In this paper, it is found that the characteristics of heat transfer at the reattachment point are well understood by connecting the characteristics with the fluctuating motion of dividing streamline.

Nomenclature

Cp,	Specific heat;
h,	Step height;
L,	Entrance height;
Nu_L,	Local Nusselt number defined by equation (1);
$Nu_{L,max}$,	Maximum Nusselt number at a reattachment point;
Pr,	Prandtl number, $Cp\mu/\lambda$;
q_w,	Heat flux at wall;
Re_L,	Reynolds number based on entrance height, UL/ν;
t,	Fluid temperature;
t_w,	Local wall temperature;
U,	Fluid velocity at entrance;
x_R,	Reattached length;
α,	Local heat transfer coefficient;
λ,	Thermal conductivity;
μ,	Viscosity;
ν,	Kinematic viscosity.

1. Introduction

Convective heat transfer in the separated and reattached regions has been investigated by many researchers, but by reason of the complexity of turbulent flow mechanism, it leaves many problems unsolved. Most of works reported previously were experimental studies, since neither the basic heat transport mechanisms, nor the fluid mechanics, of separated flow have been completely understood. For the purpose of clarifying the heat transfer characteristics in separated and reattached regions, the present authors investigate them in a duct with step

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expansion. Heat transfer for turbulent flow in the separated and reattached regions is studied with air by Seki et al[1]. and Filetti et al[2]. for a rectangular duct. On the other hand, in a low Reynolds number range, Seki et al[3]. studied using oil under the condition of constant heat flux. In this study, characteristics of heat transfer are extensively investigated for a wide range of Reynolds numbers.

Furthermore, the behaviors of a separated dividing streamline, connecting with the change of heat transfer rate are observed by flow visualization which is accomplished by injecting Indian ink into flowing water. Maximum heat transfer rate is expected to occur at the reattachment point, but the heat transfer rate at the downstream region from the reattachment point approaches a corresponding value to a fully developed flow. However, in this study, the heat transfer rate at the reattachment point is representatively considered.

Experiments are performed under the condition of constant heat flux and of a uniform velocity profile at the entrance. Data are obtained at three step heights $h/L=0.14$, 0.50 and 1.50, respectively. Reynolds numbers based on entrance height, ranges approximately from 3.8×10 to 3.5×10^3 and Prandtl number is evaluated at 9.57 for water and 215 for oil.

2. Experimental apparatus and instrumentation

Essential components of the apparatus consist of a pump, an orifice, two fluid tanks, a contraction and a test section. The control of flow rate is accomplished by valve control, while the flow rate is estimated by the reading of water or oil column of a manometer connected to the orifice in a pipe system. Two grids are installed in an inlet-side tank in order to reduce the disturbance of flowing fluid. The capacity of each fluid tank is 300 mm × 300 mm × 400 mm. The cross sectional area of the test section and its length are 40 mm × 150 mm and 800 mm, respectively. A shell-and-tube type heat exchanger is used to eliminate the heat convected from the heated walls.

Fig. 1 shows an exploded view of the test section. In order to observe the behavior of a dividing streamline, the test section are made of transparent lucite boards. The step height is changed in three kinds; $h=4.3$, 10.0 and 15.0 mm, respectively. Stainless-steel foils of 50 microns in thickness and 45 mm in width are used as the heaters of the test section, which are fixed onto the lucite boards. The heated section is divided in three segments as shown in Fig. 1. However,

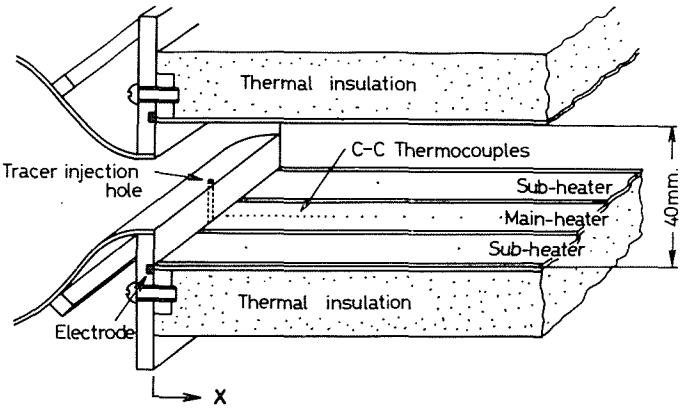

Fig. 1 Exploded view of the test section

only the central one is used to measure the wall temperatures. And also to minimize the heat loss, the outer side of the test section is covered by a thermal insulating material. Heating of the test section is accomplished by passing $a-c$ electric current through the stainless-steel foil and the power is supplied from a secondary of a 2 KVA transformer. Wall temperatures of the test section are measured by $C-C$ thermocouples of 0.3 mm in diameter, which are affixed on back side of each stainless-steel foil sheet. These thermocouples are situated at 34 longitudinal stations along the test section. The distance between adjacent couples is small near the upstream end of the duct; the details of these thermocouples will be evident in Fig. 1. The heat flux per unit area and unit time from the walls is evaluated by readings of both a voltmeter and an amperemeter.

To visualize the flow pattern, especially the dividing streamline, a tracer injection hole of 0.8 mm in inner-diameter, is made near the step edge and its surface is polished carefully with tooth powder. Indian ink is used as a tracer and the tracer tank is placed near the water surface of the inlet tank. In operating the system, it is found that about one hour is required to reach a steady state. A visualized flow is pictured under the same condition as heat transfer performance.

3. Results and discussion

3.1 Reattached length

The reattached length is estimated by wall temperature distribution. Variation of the reattached length with Reynolds numbers is shown in Fig. 2 for three kind of step height. The results for the smallest step height in this experiment, $h=4.3$ mm are indicated in Fig. 2 (a). A striking feature in this graph is the fact that the reattached length increases proportionally with the Reynolds number to the maximum value at $Re_L=10^3$ and then it decreases with Reynolds numbers approaching the asymptotical value of $x_R/h=6\sim8$. It is interesting to note that the reattached length has its peak at $Re_L=10^3$ before approaching the above mentioned asymptotical value.

For convenience sake of discussion, it is defined temporarily as shown in Fig. 2 (a) where the laminar region denotes the increasing region of the reattached length, the transient region the decreasing one and the turbulent region the constant one. In the laminar region, it may be estimated that the behavior of dividing streamline is laminar over a separated flow length which increases monotonously with Reynolds numbers. Considerations may now

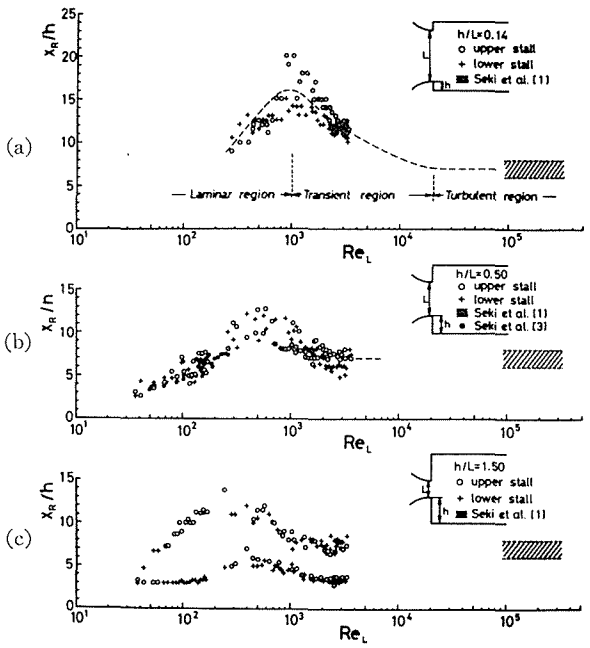

Fig. 2 Reattached length as a function of Reynolds number
(a) $h=4.3$ mm, (b) $h=10.0$ mm, (c) $h=15.0$ mm

be given to these results. In fact, a mixing motion should not exist in laminar flow, therefore, the fluid flowing into the test section flows straight forward by its inertia force, and consequently, the reattachment point is shifted downstream with increasing Reynolds number.

However, owing to the velocity gradient of a free shear layer, it may be expected that at a certain Reynolds number the dividing streamline begins to be disturbed at the reattachment point. Under the state of disturbed dividing streamline, the fluid element near the dividing streamline is dragged towards the wall by the mixing motion in a vertical direction. Therefore, the reattached length decreases with the increasing disturbed part on the dividing streamline. This range of Reynolds number corresponds to the aforementioned transient region. In the transient region, a part of the dividing streamline remains undisturbed. Thereafter, it is likely to change into a turbulent region. The same tendency as shown in Fig. 2 (a) is also observed for different step heights. In case of the largest step height in this experiment, $h=15.0$ mm as indicated in Fig. 2 (c), the measured results are more scattered than in the case of smaller step heights due to the difference of reattached length between upper and lower sides. This tendency coincides well with the results by Abbott and Kline[4].

3.2 Visualization of dividing streamline

The flow visualization is experimented in order to observe the behavior of the dividing streamline in laminar, transient and turbulent regions, respectively. Because, in consideration of the foregoing chapter, it is expected that the heat transfer rate in separated and reattached flow may be strongly related to the behavior of the dividing streamline. The pictures for the smallest step height in this investigation, $h=4.3$ mm are shown in Fig. 3 and another one for the largest step height, $h=15.0$ mm are in Fig. 4. Further, the experimental conditions for Fig. 3 and for Fig. 4 correspond to Fig. 2 (a) and Fig. 2 (c), respectively. The Reynolds number in Fig. 3 (a) belongs to the laminar region, in Fig. 3 (b) to the beginning of the transient region and in Fig. 3 (c) to the transient region.

Although only several photographs are shown in this figure, a detailed obser-

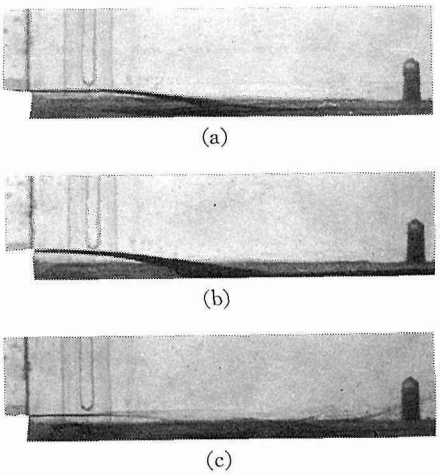

Fig. 3 Flow visualization of dividing streamline, $h=4.3$ mm
(a) $Re_L=600$, (b) $Re_L=1010$,
(c) $Re_L=2380$

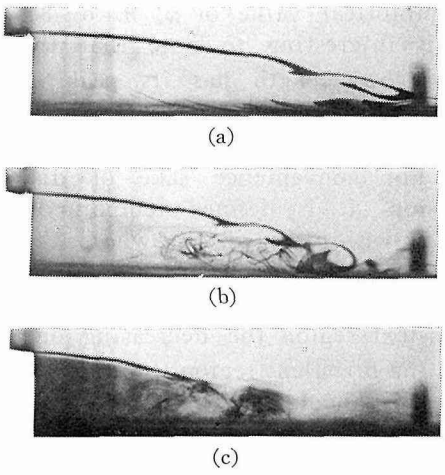

Fig. 4 Flow visualization of dividing streamline, $h=15.0$ mm
(a) $Re_L=520$, (b) $Re_L=780$,
(c) $Re_L=2510$

vation shows that the behavior of the dividing streamline is in laminar flow over the entire length and when the streamline begins to be disturbed from the neighborhood of the reattachment point, it is transfered to the transient region. In view of these findings, it is clear that the aforementioned three regions are closely related to the behavior of dividing streamline. In Fig. 4, a most interesting feature of the dividing streamline can be observed. It may be seen that the disturbance of dividing streamline is generated by the vortex motions resulting from the shear stress in the free shear layer. Furthermore, it is clear that the reattached length in the turbulent region shown in Fig. 4 (c) is shorter than the one in Fig. 4 (b), and the tendency coincides well with the aspect of Fig. 2 (c). Although it is impossible to make a distinction between transient and turbulent regions clear, it is likely that in the turbulent region the disturbed length extends over the entire length of the dividing streamline. From the foregoing considerations, it is understood that the reattached length depends on the behavior of the dividing streamline to a certain extent.

3.3 Maximum value of local Nusselt number

The local Nusselt number Nu_L at a distance x from the step is defined as

$$Nu_L=\frac{\alpha L}{\lambda}=\frac{q_w L}{\lambda(t_w-t_c)} \tag{1}$$

In Fig. 5, the present results are compared with Filetti's data which were obtained with air under a condition of constant wall temperature for a rectangular duct. The ordinate is the maximum Nusselt number divided by both the effect of reattached length and $Pr^{0.5}$. It may be observed that authors' data are well correlated by this representation. Furthermore, it may be seen that the maximum Nusselt number in the turbulent region can be correlated by the following equation (2), as shown in Fig. 5.

$$Nu_{L,max}=1.18\left[0.446-0.238\left(\frac{x_R}{L}\right)^{0.161}\right]Pr^{0.5}Re_L^{2/3} \tag{2}$$

The most interesting point to be noted is the fact that the heat transfer rate deviates from the result by equation (2) with decreasing Reynolds number. It may be also observed that the increasing rate of maximum Nusselt number becomes

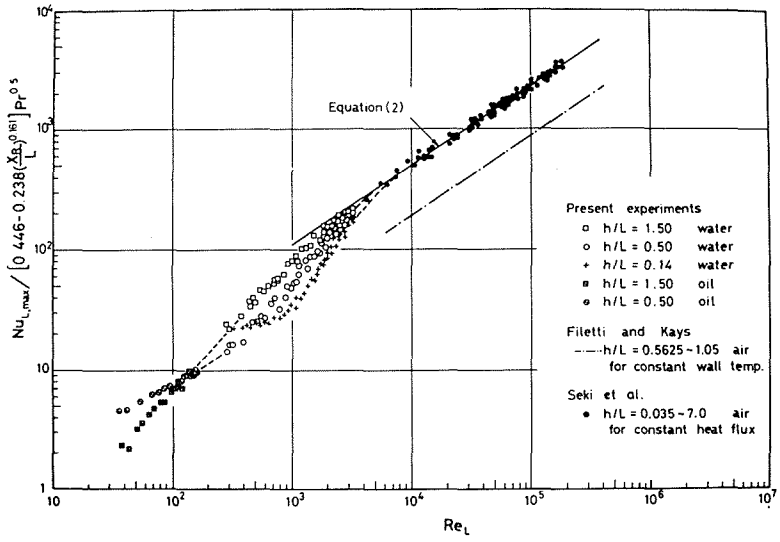

Fig. 5 Result of Maximum Nussult number

larger in the transient region than in the turbulent region. This phenomena may be caused by the occurrence of disturbance in the dividing streamline. In other words, the increase of heat transfer rate at the reattachment point is contributed by the augmentation of the disturbed length in dividing streamline. On the other hand, at the beginning of the turbulent region, the dividing streamline is disturbed almost over the entire length. Then, with further increase in Reynolds number, no more increases are seen the disturbed length of dividing streamline. In consideration of this, it may be expected in the turbulent region that the increase of turbulence intensity at the dividing streamline contributes to the increasing rate of the maximum Nusselt number. And, this point is essential for the clarification of the heat transfer mechanism in the separated flow, and also it is an important problem to investigate the effect of turbulence intensity on heat transfer rate.

The behavior of heat transfer rate at the reattachment point is changeable with step heights. That is to say, the state of dividing streamline for a large step height is easily shifted to the transient region. And it approaches to the turbulent region expressed by equation (2) more rapidly than in the case of a small step height. Another interesting feature in Fig. 5 is that the critical value of Reynolds number from the laminar region to the transient one, and from the transient region to the turbulent one agrees with the results expected from reattached lengths in Fig. 2. In conclusion, it is considered that the heat transfer rate of reattachment point depends strongly on the behavior of dividing streamline.

4. Summary and conclusions

An experimental investigation of heat transfer characteristics in the separated and reattached flow behind a double step at the entrance to an abruptly enlarged flat duct are carried out. Measurements are made for three kinds of step height; $h/L=0.14$, 0.50 and 1.50. Heating of the test section is accomplished under the condition of constant heat flux. Working fluids are water and oil, whose Prandtl numbers are 9.57 and 215, respectively. The following facts are concluded.

(1) The behavior of dividing streamline results in division of three regions, namely, laminar, transient and turbulent regions. Based on this concept, the relation between the reattached length and the heat transfer rate of the reattachment point are clearly understood.

(2) With the increase in Reynolds number, the reattached length increases in the laminar region, decreases in the transient region and is constant in the turbulent region.

(3) It is found that the Nusselt number at the reattachment point can be correlated with Reynolds number, step height and Prandtl number as a following equation :

$$Nu_{L,max}=1.18\left[0.446-0.238\left(\frac{x_R}{L}\right)^{0.161}\right]Pr^{0.5}Re_L^{2/3}$$

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