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On the Coefficient of Heat Transfer and Static Pressure in a Separated Flow

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Abstract

An experimental study was carried out to examine the characteristics of heat transfer rate and static pressure behind a step at entrance to enlarged flat duct.

The working fluid was air and a test plate was heated under a condition of constant heat flux. Reynolds number based on entrance height ranged from 9.76×10^4 to 3.26×10^5 and step height was varied in seven kinds.

It was found that the heat transfer rate at reattachment point varied in the same manner as the pressure difference between reattachment point and separated region.

Nomenclature

Cp_w,	Static pressure coefficient on a wall;
Cp_{atm},	Static pressure coefficient based on atmospheric pressure;
h,	Step height;
L,	Entrance height;
$Nu_{L,max}$,	Maximum Nusselt number at a reattachment point;
p,	Pressure;
Re_L,	Reynolds number, UL/ν;
u,	Velocity component in x-direction;
U,	Fluid velocity at entrance;
x_R,	Reattached length;
Y,	Non-dimensional transverse coordinate, y/L;
ρ,	Density;
λ,	Thermal conductivity.

1. Introduction

Separation phenomena of flowing fluid in tubes or ducts are often found in industrial practice. And it is well known that such a flow separation occurs in abruptly diverging or converging sections of tubes or ducts. Investigations have been made so far simpler flow configurations such as a backward facing step, and heat transfer characteristics in separated, reattached and developed flow regions have been studied. However, there are some difficulties in clarifying these phenomena because of a complexity of basic turbulent transport mechanism.

Krall and Sparrow[1] studied the heat transfer characteristics of water in separated, reattached and redeveloped flow regions in a circular tube. And Filetti and Kays[2] experimented using air in a rectangular duct. In their paper, the heat

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transfer in separated, reattached and developed flow regions are investigated for various step heights. However, the relation between heat transfer rate and static pressure coefficient still remains to be clarified.

In this paper, the static pressure and heat transfer rate in separated, reattached and developed flow regions are measured for a turbulent flow field with an abruptly enlarged area change of a duct.

Experiments are run under conditions of constant heat flux and a uniform velocity profile at the entrance of the enlarged flat duct. The working fluid is air. Data are obtained for seven step heights; $h/L=0.44$, 0.37, 0.32, 0.27, 0.22, 0.18 and 0.15, where h is a step height and L is an entrance height. Reynolds number based on entrance height ranges from 9.76×10^4 to 3.76×10^5 and the Prandtl number is 0.716.

2. Experimental apparatus

The flow geometry is shown in Fig. 1. Essential components of the apparatus consist of a contraction, steps and heated plates, respectively, which are installed in the test section of a Gottingen type wind tunnel. The enlarged height between both heated plates is 248 mm and the step height is varied between 28 mm and 70 mm.

Stainless-steel foils of 50 microns in thickness are used as the upper and lower heated plates. To minimize a heat loss through the heated plates, the outer face is covered with thermal insulating materials. And also to reduce a heat flow in the transverse flow direction, the heating section is divided into five segments as shown in Fig. 2, however only the central one is used to measure the wall temperature.

Heating of the test plates is accomplished by passing $a-c$ electric current

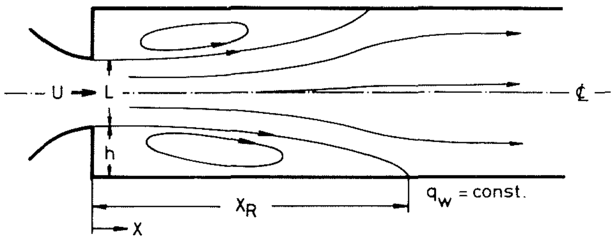

Fig. 1 Configuration and coordinates

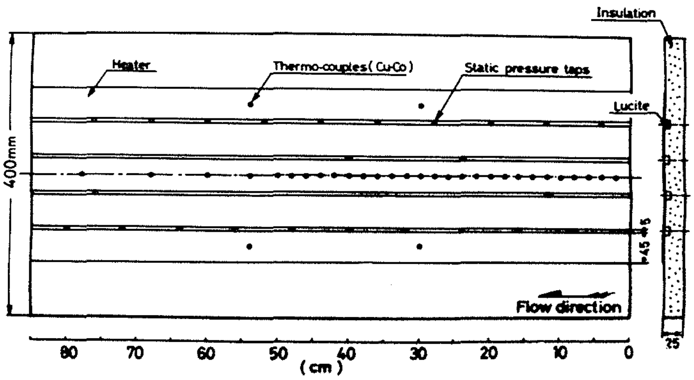

Fig. 2 Detail of test plate

through the stainless-steel foils. The wall temperature of the heated plates is measured by $C-C$ thermocouples of 0.3 mm in diameter, which are affixed to each back side of the stainless-steel foils. Static pressure on the wall is detected by pressure taps of 0.8 mm in diameter, which are placed between each heating segment.

Two dimensionality of the flow field is checked by both wall temperatures and static pressures.

Measurements are performed in a steady state. The wall temperatures and temperature profiles in the flow field are recorded with a YOKOGAWA ER 12-90 Z-122 self-compensating readout unit and a YOKOGAWA TYPE 3047 pen-recorder, respectively. The pressure is read from either a Gottingen or a Chattock type manometer. The heat flow rate from the wall is evaluated by readings of both a voltmeter and an amperemeter.

3. Results and discussion

In order to clarify the characteristics of the flow field, some hydrodynamic quantities are measured. A graphical presentation of the measured results under $u=10.3$ m/s and $h/L=0.37$ is given in Fig. 3. Fig. 3 (a) shows non-dimensional mean velocity profiles in the x-direction. It is observed that the separated flow forms a free shear layer and the velocity profile changes into a turbulent one at the downstream of the reattachment point. Velocity profile in the free shear layer is ascertained to agree with that of half jet. Fig. 3 (b) shows streamlines with each non-dimensional stream function defined by equation (1).

$$\Psi_i=\int_0^{Y_i} \frac{u}{U}\,dY \tag{1}$$

From an inspection of Fig. 3 (c), it is found that the static pressure coefficient decreases in the separated region and tends to recover in the developed flow region. Temperature profiles and local Nusselt numbers are shown in Figs. 3 (d) and (e), respectively. It may be observed from Fig. 3 (e) that the Nusselt number has its peak value at the reattachment point.

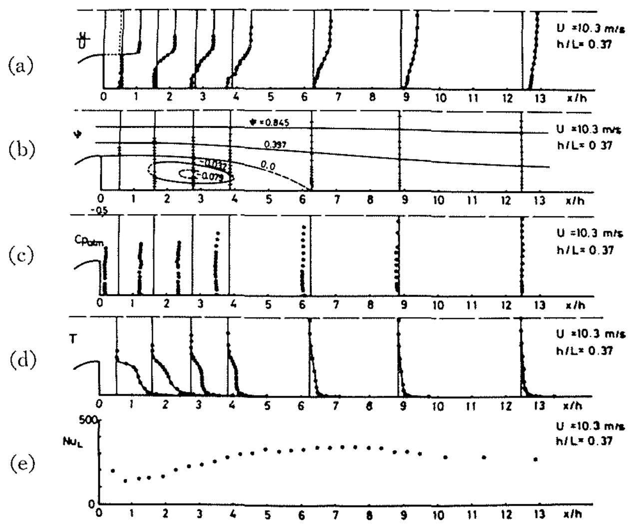

Fig. 3 Measured results in flow field

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

$$Nu_L=\frac{\alpha L}{\lambda}=\frac{q_w L}{\lambda(t_w-t_c)} \tag{2}$$

where q_w is a heat flux per unit area and unit time, L is an entrance height, t_w and t_c are the walls and the center-line temperatures, respectively.

The static pressure coefficient on the wall is also defined as

$$Cp_w=\frac{p_w-p_0}{\rho U^2/2} \tag{3}$$

where p_w and p_0 are the wall and the entrance pressures, respectively.

The variations of local Nusselt number and of wall static pressure coefficient are shown in Fig. 4. It may be observed that the local Nusselt numbers decrease

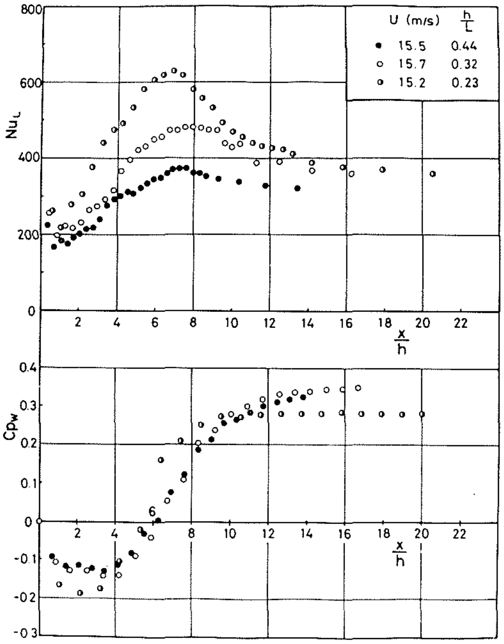

Fig. 4 Measured results of local heat transfer coefficients and wall static pressures

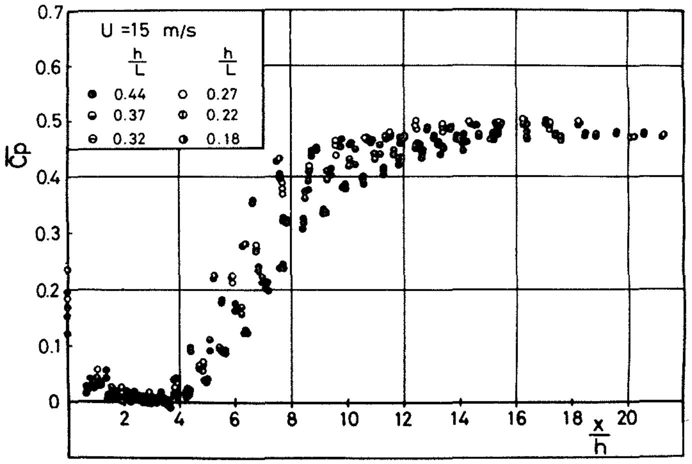

Fig. 5 Values of pressure rise on the wall

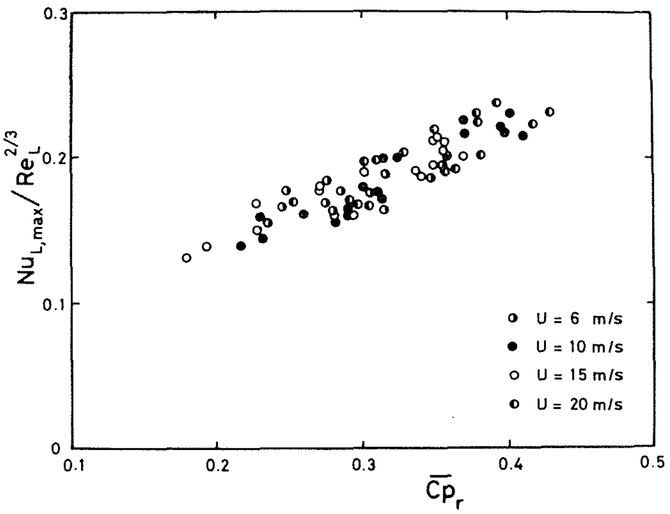

Fig. 6 Correlation between values of pressure rise at the reattachment point and maximum Nusselt number

as the step height increases. In case of a large step height, fluid velocity at the test section is far more decelerated because of the large cross-sectional area change of a duct. That is, the reattaching velocity decreases as the step height increases and then the heat transfer rate decreases. Such a tendency of heat transfer rate agrees with the results by Filetti and Kays.

The reattached length estimated from the peak point of local Nusselt number is about 6～8 times as large as step height, which agrees well with the results of Abbott and Kline[3].

A pressure rise coefficient $\overline{Cp}$ is defined by the following expression,

$$\overline{Cp}=Cp_w-Cp_{w,min} \tag{4}$$

where $Cp_{w,min}$ is the minimum value of static pressure coefficient in the separated region. In Fig. 5, values of $\overline{Cp}$ are plotted as a function of x/h for various step heights under $u=15$ m/s. It is indicated in this figure that the static pressure along the wall recovers rapidly with decreasing step height. In other words, the static pressure at the reattachment point increases as the step height decreases, that is, static pressure difference between the reattachment point and the separated region becomes larger.

Moreover, it is suggested that the reverse flow velocity in separated region, and simultaneously the reattaching velocity, increases with decreasing step height.

From these considerations, it may be predicted that there is a relation between the pressure rise coefficient and heat transfer rate. The pressure rise coefficient $\overline{Cp}_r$ versus the maximum Nusselt number at the reattachment point is shown in Fig. 6. In this figure, the ordinate is adopted as the maximum Nusselt number divided by $Re_L^{2/3}$, because the maximum Nusselt number is proportional to $Re_L^{2/3}$ in general. The results in Fig. 6 show that $\overline{Cp}_r$ is apparently correlated with $Nu_{L,max}/Re_L^{2/3}$ within the experimental range performed by the authors.

4. Conclusion

An experimental investigation is performed on a relation between heat transfer rate and static pressure coefficient in separated and reattached turbulent flows behind a double step at entrance to an abruptly enlarged flat duct. Step height ratios varied in $0.15 \lesssim h/L \leqq 0.44$, and Reynolds numbers ranged from 9.76×10^4 to 3.26×10^5. The following conclusion is obtained.

The pressure rise coefficient at the reattachment point is apparently correlated with the maximum heat transfer rate.

References

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