Heat Transfer Around a Circular Cylinder In a Separated Flow

Shinya AIBA, Takuya OSAWA* and Kazuya SATO*

(1994年8月22日受理)

Introduction

A large number of studies on heat transfer and flow have been devoted to a circular cylinder placed traversely in a uniform stream. However, there have been relatively few investigations of the heat transfer around the cylinder placed in the separated flow that is often occured in practice. One of the present authors has carried out investigations of the heat transfer characterestics in the case of the circular cylinder placed near a plane boundary, relating with the diamer of the cylinder, the thickness of boundary layer and the clearance between the cylinder and the plane wall[1]. Furthermore, Aiba[2] has reported the heat transfer of the third of four cylinders aligned in-line in the neighborhood of the plane wall, as seen in the combustion chamber of the water tube boiler[2]. However, it is very difficult to clear the phenomenon, owing to the complicating flows around the cylinder, which are the separated ones from the wall or from the forward cylinder of the test cylinder, for example.

The heat transfer characterestics of the separeted flow region have been numerously investigated in the down-step[3,4] or around the blunt flat plate[5]. However, a few studies have been published concerning with the heat transfer around the circular cylinder positioned in the separated flow region, although it is very important to clear in practice.

The objective of the present study is to clarify systematically the convective heat transfer characteristics of the circular cylinder in a separeted cross flow of air behind the fence situated vertically to the plane wall and to research the possibility of the heat transfer control by the separated flow.

Nomenclature

C_p = $(p-p_\infty)/(1/2)\rho U_\infty^2$ = static pressure coefficient
D = cylinder diameter
H = height of fence
h = $q/(T_w-T_\infty)$ = heat transfer coefficient
Nu = hD/λ = Nusselt number
p = static pressure
q = heat flux
R_{ed} = $U_\infty D/\nu$ = Reynolds number
T = temperature
U = flow velocity
$\sqrt{\overline{U'^2}}/U_\infty$ = stream turbulence intensity
X = distance between cylinder center and edge of fence
Y = distance between cylinder center and wall
x = axial distance from edge of fence

*Former student

y = vertical distance from wall
θ = circumferential angle from geometric forward stagnation point
λ, ν, ρ = thermal conductivity, kinematic viscosity, and density of air at T_∞

Subscripts

m = mean
r = reattachment
∞ = undisturbed uniform stream

Experimental Apparatus and Procedures

Experiments were carried out in an open wind tunnel with a rectangular test section 190 mm wide and 325 mm high. A fence was vertically situated on the bottom wall of the test section. The fence, 10 mm in thickness and 60 mm (= H) in high, had a sharp edge (β = 45 deg) as shown in Fig. 1 (which also shows the coordinate system employed), and was sppaned the wind tunnel horizontally. A slit of the test section was oppened at the frontal face of the fence, in order to prevent the incease of the boundary layer along the bottom plane wall. The slit with 10 mm width and 190 mm long was positioned at 380 mm long from the entrance of the test section. It was confirmed that the separated flow after the fence had similar characters in those of the blunt flat plate situated in pararell in the uniform flow. That is, in the case of the blunt flat plate the length of the separation bubble separeted from the leading edge of the plate (angle of edge equal to 90 degree) have been reported to be identical with approximately 10 W (thickness of the plate = 2 W) in the Rynolds number Re range (based on 2 W) = $10^4 \sim 10^5$[5]. Furthermore, the position of maximum height of the bubble has been said to appear at about 5 W, and that height at about 1.3 W[6]. In this experiment, the length and the maximum height of the bubble were about 11 H and 1.7 H, respectively. The height of the bubble is larger about 0.4 H than that of the blunt flat plate, assuming that the height of fence H equals to W. Therefore, it may be suitable for the objective of the present experiment because that a interference between the test cylinder and the bottom wall of the test section is assumed to be little unless the clearance between these is very small.

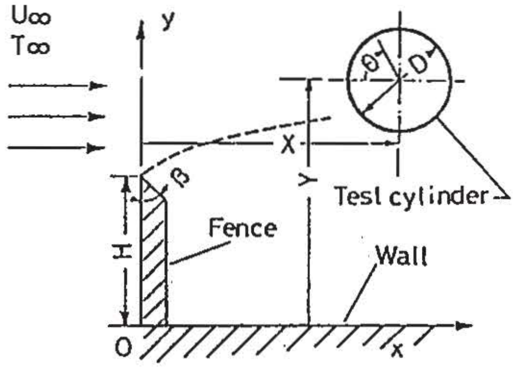


Fig. 1 Arrangement of cylinder and coordinate system

A constant-temperature hot-wire anemometer with a single tungsten wire of 0.005 mm diameter with a linearizer as the sensing element was used for measuring the distribution of the velocity and turbulence intensity in the flow field around the test section. The turbulence intensity was calculated from the mean and r.m.s. voltage reading from the hot-wire anemometer with a linearizer. No corrections were made for flow direction[7].

A circular cylinder with diameter of 25.2 mm was used for the measurements of the heat transfer around the cylinder. Another cylinder used for the measurements of the pressure distribution was smaller by 0.2 mm. Reynolds number, based on the uniform stream U_∞ above the fence and the cylinder diameter d, ranged from 3×10^4 to 6.5×10^4.

A stainless steel ribbon wound helically around the center section of a plexiglass tube was electrically heated for the heat transfer measurements. The inside of the tube was filled with rigid urethane foam in order to minimize the heat loss by conduction. The wall temperatures were measured with 0.065 mm copper-constantan thermocouples affixed to the back of the stainless steel sheet at angular intervals 10 deg. In addition, the maximum temperature of the cylinder surface was kept under 38°C to reduce the radiative heat loss as much as possible. The heat loss by radiation from the cylinder surface was estimated to be about 0.6 percent of the heat supplied to the tube. The present data were obtained under the condition of constant heat flux. The local heat tranfer coefficient and the corresponding Nusselt number are defined, respectively, as follows: $h_\theta = q/(T_w - T_\infty)$; $Nu_\theta = h_\theta D/\lambda$. The apparatus and technique for the heat transfer are almost the same as those used in previous studies[1,2,7] by one of the present authors. The correction of the loss by conduction in the radial direction amount to less than 1 percent of the electric power input.

The surface pressure was measured at angular intervals of 10 deg with another cylinder having a static pressure hole of 0.5 mm in diameter. Oil flow patterns showed the flow field to be two dimensional in the case of without cylinder in the flow field except the vicinity of the side walls of the test section.

Experimental Results and Discussion

Flow Charcterestics without Cylinder. No corrections were made for flow direction and the turbulence intensity were calculated from the mean and r.m.s. voltage readings from the hot wire anemometer with a linearizer.

The distributions of time-mean velocity in the x-direction and turbulence intensity in the flow field over the test field without cylinder are shown in Fig. 2 and Fig. 3 for $Re_d = 3.0 \times 10^4$ with parameter x/H, respectively. The velocity gradient in the free shear layer perpendicular to the main flow decreases in the downstream direction and the thickness of this layer increases with increasing x/H. At the position of x/H = 0.5, it can be seen that linear and abrupt change of the velocity occures in the range of y/H = 1.25~1.35, and maximum value of U/U_∞ equals to about 1.16 in this range. Moreover, in the range of y/H < 1.20, the velocity is very small, that is, $U/U_\infty = 0.05 \sim 0.1$. In the range of x/H = 0.5 ~5.0, the poisitions of y/H where occur maximum of U/U_∞ increase with increasing x/H. These positions are not cleared in the range of x/H > 5.0.

A reattached point of the shear layer from the fence has been comfirmed at about x/H = 11.7 by observing the behaviors of wool tufts attached to the bottom wall of the test section. Therefore, it can be said that the results of x/H = 11.7 are equivalent to those of the reattached point.

Figure 3 shows the distributions of the turbulence intensity $\sqrt{\overline{U'^2}}/U_\infty$. The positions (y/H) of maximum turbulent intensity occur at the maximum velocity gradient shown in Fig. 2 and are not clearly recognized in the range of x/H ≧ 6.67. The thickness of the free shear layer generated by the fence shown in Fig. 2 increases and the region of the high turbulence intensity can be seen in the wide range of y, in the downstream direction.

The heat transfer characteristics around a circular cylinder have been examined in a such separated flow reigion.

Local Heat Transfer. Typical distributions of local Nusselt numbers Nu_θ are presented in Fig. 4 for X/H = 0.5 with Y/H (where, X and Y are the distances between the cylinder center of the and the edge of fence, and the wall of the test section, respectively) in the range of $Re_d = 4.9 \times 10^4 \sim 5.08 \times 10^4$ including the results for the single cylinder in the uniform stream obtained by Aiba and Yamazaki[7]. The results are given as $Nu_\theta/Re_d^{2/3}$ in order to omit the effect of the small differences of Re_d by experiment, noting that the average Nusselt number in the turbulent wake region is proportional to $Re_d^{2/3}$. In the range of Y/H ≦ 1.05, Nu_θ of the entire surface of the cylinder is very small compared with the case of the uniform stream as indicated by the dotted line, although the Nu_θ for Y/H increase sligtly with increasing Y/H in this range. These results indicate that the flow velocity around the cylinder is

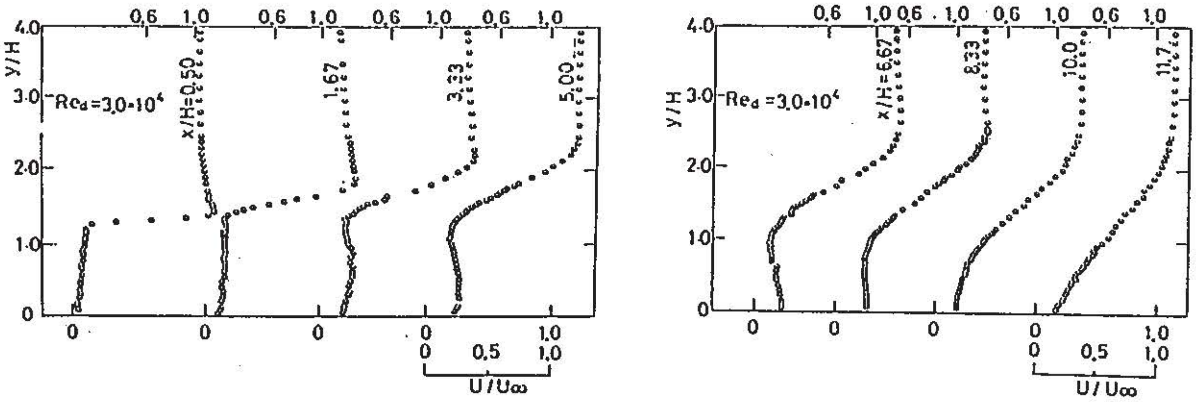


Fig. 2 Distribution of velocity over the test field without cylinder

very slow comapared with the case of the uniform flow field as shown in the Fig. 2.

In the case of Y/H = 1.22 (this position of Y is about 0.1 H lesser than that for a peak of the turbulence intensity at the section of x/H = 0.5 as shown in Fig. 3), the distribution of Nu_θ is extremely complex and the values of Nu_θ increase drastically compared with the case of Y/H $\leqq$ 1.05. That is, in the lower surface of the cylinder (0 deg $\geqq \theta \geqq -180$ deg) there are two peaks of Nu_θ at around $\theta = -10$ deg and at around -100 deg, and in the upper surface of the cylinder (0 deg $\leqq \theta \leqq +180$ deg) the distribution of Nu_θ is almost similar to the case of uniform flow field as shown by the dotted line except the front surface of the cylinder. From the case of the without cylinder as shown in Fig. 2, the upper surface of the cylinder may be considered to bury in the shear layer from the edge of fence and the lower surface of the cylinder in the stagnant separated flow region. However, there exist a strong through flow along the cylinder surface between the cylinder and the top of the fence as indicated in the C_p distribution around the cylinder as shown in Fig. 5. The distribution of Nu_θ in the lower surface of the cylinder may be extremely affected by this flow. In the distribution of C_p for Y/H = 1.22, it can be seen that C_p falls down from 1.0 to -1.0 in the angular range of $\theta = 0$ deg~ -30 deg. Such an abrupt change of C_p does not occur in the case of the uniform flow field indicated by a dotted line, but in the two dimensional jet[8,9]. That is, the separated flow from the fence impinges itself on the point of attachment at around $\theta = 0$ deg and a part of the flow is conveyed along the lower surface of the cylinder. As shown in Fig. 4,when Y/H = 1.22, the heat transfer rates around the front face ($-40 \leqq \theta \leqq +20$ deg) have taken the high value among the results treated in this study. Furthermore, a peak of Nu_θ at around $\theta = -100$ deg can be observed. Such a behavior of Nu_θ around the cylinder can be seen in the heat transfer of the impinging jet[8]. In the vicinity of $\theta = -50$ deg, the laminar boundary layer along the lower surface of the cylinder may vary to the turbulent boundary one, as pointted out by Kumada et al[8,9]. On the other hand, the distribution of Nu_θ at about $\theta > 30$ deg is almost identical with the case of the uniform flow field as indicated by the dotted line in Fig. 4.

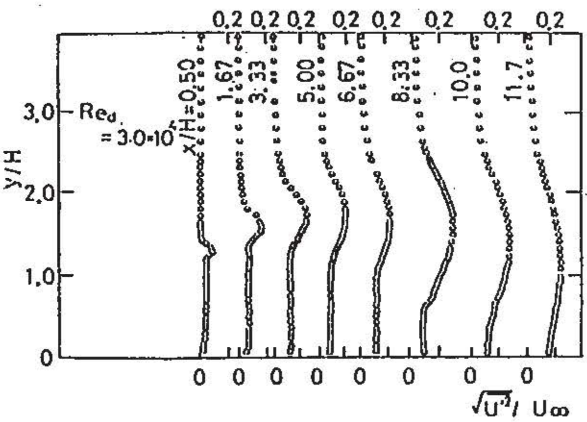


Fig. 3 Distribution of turbulence intensity over the test field without cylinder

At Y/H = 1.30, the distribution of Nu_θ is entirely different from the case of Y/H = 1.22 in spite of

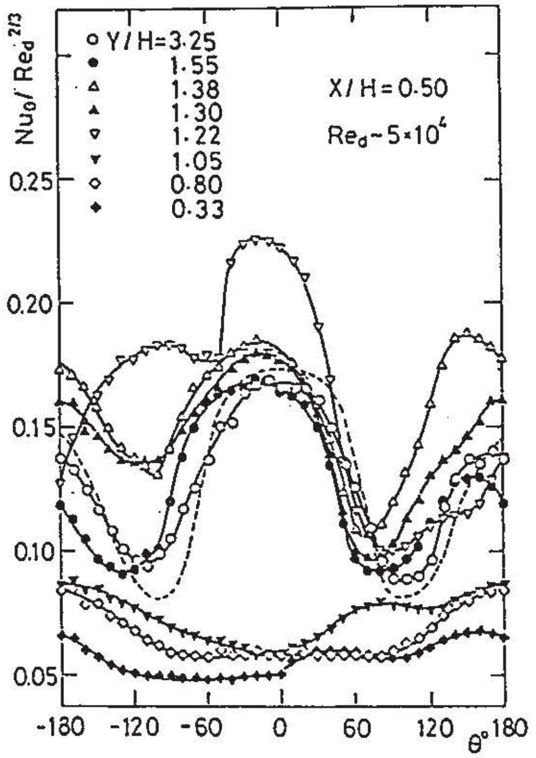


Fig. 4 Variation of local Nusselt number with Y/H, for X/H = 0.50, $Re_d \sim 5\times10^4$, (……, Y/H = ∞)

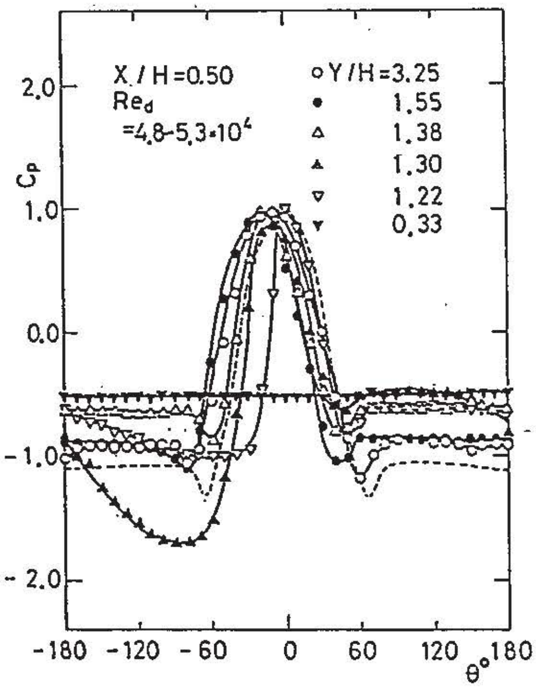


Fig. 5 Variation of local static pressure with Y/H, for X/H = 0.50, $Re_d = 4.8\times10^4 \sim 5.3\times10^4$, (……, Y/H = ∞)

a small difference of Y/H. That is, Nu_θ at around the frontal face of the cylinder levels down and Nu_θ of the rear face levels up compared with the cases of Y/H = 1.22, and the peak at around $\theta = -100$ deg observed at Y/H = 1.22 can not be done. In the uniform flow field, the heat transfer rate of the rear face exceeds one of the frontal face at about the $Re_d = 10^5$. In the case of Y/H = 1.30, the behaviors of the heat transfer are similar to those of the uniform flow field at the Reynolds number $Re_d = 10^5$, being affected by the turbulence of the shear layer from the fence, though the Reynolds number is lesser than $Re_d = 10^5$. In the distribution of C_p for Y/H = 1.30, a minimum of C_p (= −1.75) appears in the vicinity at around $\theta = -90$ deg. These behaviors of C_p show that the flow along the lower surface of the cylinder has a larger velocity than that of the case of the uniform flow field. That is, in the case of Y/H = 1.30 the attachment point of the separeted flow from the fence occurs at the position where is higher 0.08 H than that of Y/H = 1.22 and then the flow with the large velocity approaches toward the lower surface of the cylinder. As a result, C_p at around $\theta = -50$ deg~ -170 deg take the small values compared with the other cases of Y/H.

The results of Nu_θ for Y/H = 1.38 are almost identical with these of Y/H = 1.30, though the results of C_p are different each other as shown in Fig. 5. In the range of Y/H ≧ 1.55, the behaviors of Nu_θ are similar to these of the uniform flow. However, the peaks of the Nu_θ around the front face of the cylinder occur at around $\theta = -20$ deg~ -30 deg and these of the C_p at around $\theta = -10$ deg~ -20 deg. That is, the maximum local heat transfer coefficient occurs at about 10 deg downstream of the angular position of the maximum static pressure coefficient.

Figure 6 shows the local heat transfer distributions for X/H = 5.58. The distance of X/H = 5.58 is almost equivalent to the half of x_r where is the distance between the edge of fence and the reattachment point. In the position of X/H = 5.58, the thickness of the separation bubble formed in the fence and the wall takes almost the maximum value and the reverse flow against the fence has a maximum velocity near the wall as indicated in Fig. 2. In the case of Y/H = 0.33, the heat transfer rate around the rear part of the cylinder is larger than that around the front part of the cylinder caused by the reverse flow as mentioned above and the overall heat transfer rate around the cylinder is larger than that in the case of $X/H = 0.5$ at the same Y/H. In the range $Y/H \geqq 1.5$, it can be confirmed that the maximum heat transfer coefficient occurs at around $\theta = 20$ deg$\sim$30 deg and the distributions of Nu_θ are different from these of $X/H = 0.5$. Furthermore, the heat transfer rate of the rear face of the cylinder is smaller 50$\sim$70% than that of the front face of the cylinder, in the cases of $Y/H = 1.5$, 1.67. The characterestics of heat transfer are similar to these of the cylinder situated near a plane wall when the cylinder has been buried in the boundary layer along the wall[1].

Figure 7 shows the distributions of Nu_θ for $X/H = 11.2$. In this case, even Y/H is small as 0.33, the maximum heat transfer rate occurs at around $\theta = 40$ deg because the reverse flow along the wall does not exist as shown in Fig. 2. Moreover, the Nu_θ distributions for all Y/H are almost identical with the cases of $Y/H = 1.5$, 1.67 for $X/H = 5.58$ as indicated in Fig. 6.

Mean Heat Transfer. The mean Nusselt Number Nu_m for Y/H is shown in Fig. 8 at $X/H = 0.50$. In the range of $Y/H \leqq 1.05$, the results of Nu_m are very small compared with these for $Y/H > 1.05$, because the cylinder is situated in the very stagnant flow behind the fence. The value of Nu_m increases drastically with small increase of Y/H and at $Y/H = 1.22$ becomes about twice to that for $Y/H \leqq 1.05$, independent of Re_d. However, in the ranges of $1.22 \leqq Y/H < 1.55$ and $Re_d < 3.5 \times 10^4$ Nu_m decrease with increasing Y/H and a second peak of Nu_m occurs at around $Y/H = 1.38$ in the range of $Re_d \geqq 4.9 \times 10^4$. This second peak of Nu_m is caused by the increase of the heat transfer rate at around the rear portion of the cylinder as shown in Fig. 9 (the relation of Nu_θ and θ is presented with Re_d for $X/H = 0.50$, $Y/H = 1.38$ in this figure). When the cylinder is situated at the location of the separated stream line (where occurs the maximum turbulence intensity for $x/H = 0.5$ as shown in Fig. 2), the mean heat transfer rate increases in general compared with that for uniform flow indicated by the dotted line[7], independent of Re_d treated in this work. Even though the cylinder is mounted in the shear layer from the fence, for example in the case of $Y/H = 1.55$, the value of Nu_m is not always larger than that of Y/

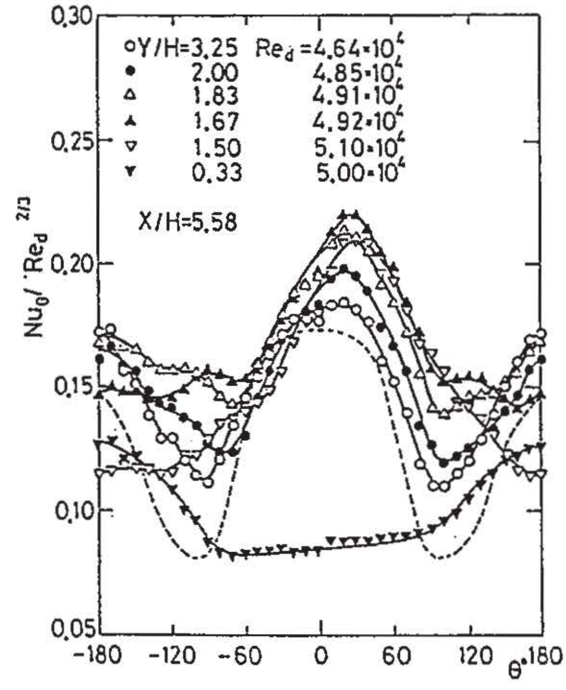


Fig. 6 Variation of local Nusselt number with Y/H, for $X/H = 5.58$, $Re_d = 4.64 \times 10^4 \sim 5.1 \times 10^4$, (……, $Y/H = \infty$)

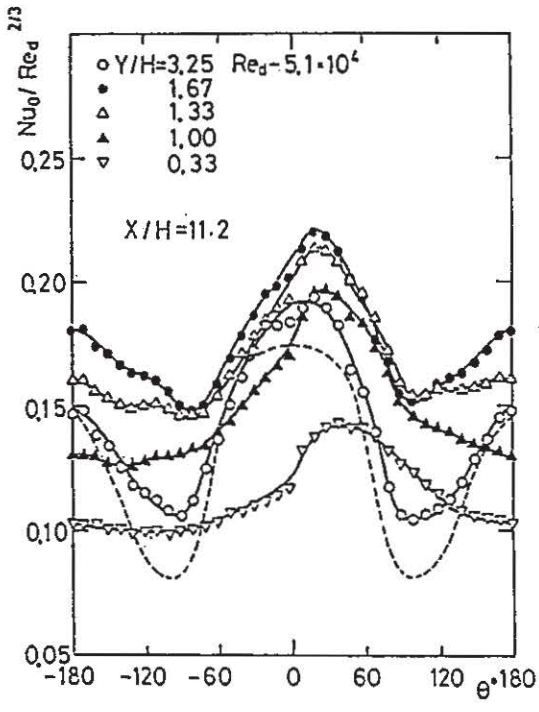


Fig. 7 Variation of local Nusselt number with Y/H, for $X/H = 11.2$, $Re_d \sim 5.1 \times 10^4$, (……, $Y/H = \infty$)

H =∞ as indicated by the dotted line.

From the above, it may be concluded that the heat transfer control around the cylinder can be carried out by a small locating operation of the the cylinder or of the fence when the thickness of the shear layer is very small.

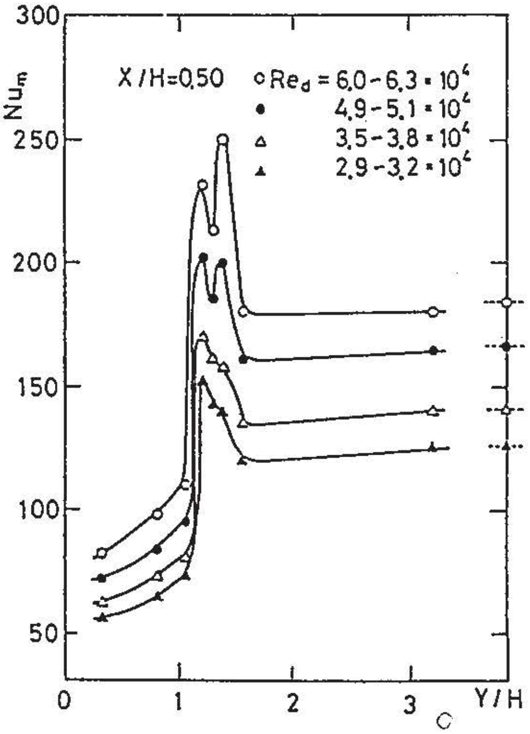


Fig. 8 Variation of mean Nusselt number with Y/H, for X/H = 0.50, $Re_d = 2.9\times10^4 \sim 6.3\times10^4$

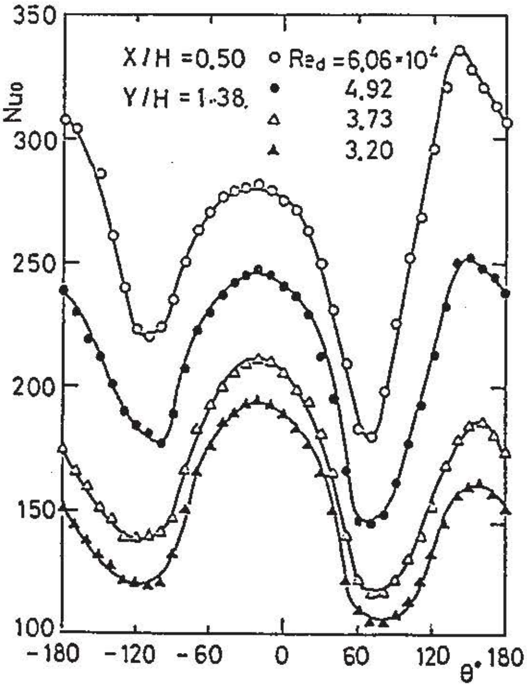
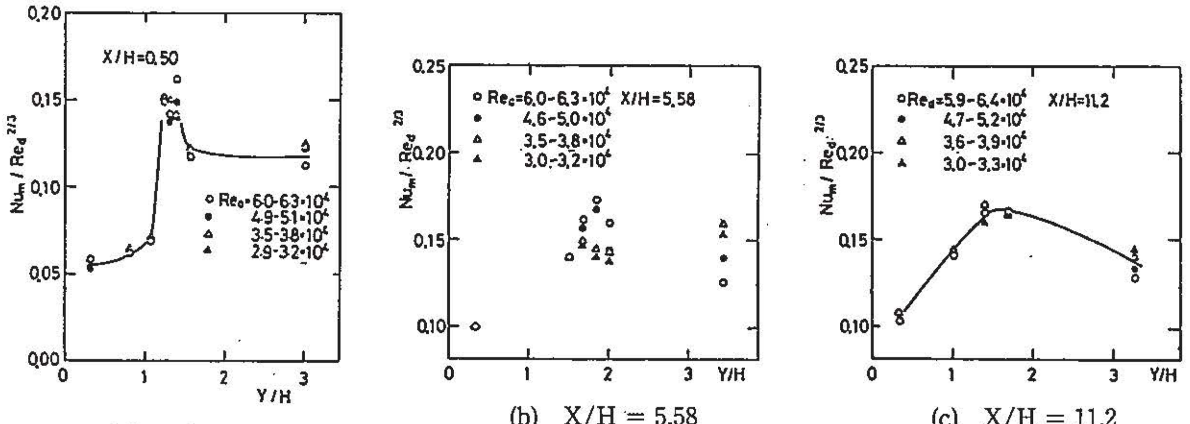


Fig. 9 Local Nusselt number distribution with Re_d for X/H = 0.50, Y/H = 1.38



(a) X/H = 0.50 (b) X/H = 5.58 (c) X/H = 11.2

Fig. 10 Variation of Mean Nusselt number arranged as $Nu_m/Re_d^{2/3}$ with Y/H

Figure 10 (a) gives the mean Nusselt number arranged by relations such as $Nu_m/Re_d^{2/3}$ for X/H = 0.50 in the range of $Re_d = 2.9\times10^4 \sim 6.3\times10^4$. It is well known that the mean Nusselt number in the turbulent wake region is proportional to $Re_d^{2/3}$. In this study, the results can be almost arranged as $Nu_m/Re_d^{2/3}$ except the range of Y/H = 1.30~1.38. Accordingly, the data for Y/H = 1.30~1.38 scatter some one. However, the results for X/H = 5.58 can not be arranged as shown in Fig. 10 (b). That is, the data for Y/H = 1.55~3.50 scatter markedly compared with the case of X/H = 0.50. Furthermore, the results for Y/H = 0.33 show larger values than these for X/H = 0.50 at the same Y/H. Therefore, it is clear that the heat transfer characteristics for X/H = 5.58 are not suitable for the heat transfer control. In Fig. 10 (c), the results for X/H = 11.2 are also presented. It can be confirmed that the data are arranged as $Nu_m/Re_d^{2/3}$ and a maximum Nusselt number occurs at about Y/H = 1.5, independent of Re_d.

Summary and Conclusions

The heat transfer characteristics around the circular cylinder in the separeted flow region from the fence that is fixed at the wall have been examined as a function of X/H and Y/H in the range of Re_d = $3.0\times10^4 \sim 6.0\times10^4$. The main results obtained are summarized below.

1 When X/H is very small (such as X/H = 0.5), Nu_θ and Nu_m change drastically by Y/H. That is, the variations of Nu_θ for Y/H $\leqq$ 1.02 are very small compared with these for Y/H > 1.02 and Nu_θ at around front face of the cylinder for Y/H = 1.22 takes about 3.8 times for Y/H = 1.05. Nu_m decrease slightly with decreasing Y/H in the range of Y/H $\leqq$ 1.02, and the values of Nu_m are lower than that for the uniform flow field. In the range of Y/H = 1.22~1.38, the values of Nu_m become about 2 times for Y/H $\leqq$ 1.02.

2 When X/H = 5.58, the variations of Nu_m for Y/H are small compared with that for X/H = 0.50 and the maximum Nu_m occurs at around Y/H = 1.83 in the range of $Re_d \geqq 4.6\times10^4$. The results for X/H = 5.58 have not arranged as $Nu_m/Re_d^{2/3}$ except for X/H $\leqq$ 1.50. The local heat transfer distributions for X/H = 11.2 are similar to these for X/H = 5.58, however the data of Nu_m can be arranged as $Nu_m/Re_d^{2/3}$ and the maximum Nu_m occurs at the small distance of Y/H (at about Y/H = 1.50) compared with that for X/H = 5.58.

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