Augmentation of Turbulent Heat Transfer on a Flat

Plate with a Three-dimensional Protuberance*

(1st Report, Local heat transfer characteristics and flow pattern around a finite length circular protuberance)

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In order to obtain the fundamental data on the high performance roughened heating surface, we tried to clarify the augmentative effects of a three-dimensional protuberance, whose height was the same order as boundary layer thickness.

In this paper, the local heat transfer characteristics and flow field around a single and finite length circular cylindrical protuberance have been investigated experimentally, under the condition of $H/D=0.5\sim1.0$, $H/\theta=5\sim15$ and $Re_H=5\times10^3\sim3\times10^4$. Consequently, the most effective shape parameter for the augmentation of heat transfer was indicated, and a wake flow structure was proposed. And an arrangement of maximum heat transfer coefficient was presented experimentally as a function of shape parameter.

Key Words : Convective Heat Transfer, Heat Transfer Augmentation, Wake Flow, Cylindrical Protuberance, Turbulent Boundary Layer, Trailing Vortex

1. Introduction

For the purpose of the augmentation of forced convective heat transfer, many studies have been conducted on various shaped surface roughnesses on the heating wall. However, the shapes of the roughness elements dealt with in these studies were limited to two-dimensional ones; that is, the same sectional form continued normal or obliquely to stream⁽¹⁾⁽²⁾. At the present time, the heat transfer performance of these roughnesses has been estimated to a certain degree⁽³⁾.

As a roughness wall with a three-dimensional shaped protuberance, Mantle⁽⁴⁾ examined a cubical roughness attached on the heating surface and indicated that the performance of heat transfer was comparable with that of two-dimensional roughened wall. Recently, Meyer⁽⁵⁾ reported that, by means of a suitable arrangement of various three-dimensional protuberances, a better performance of heat transfer was obtained than the two-dimensional one. However, these were the results based on the average measurements over the whole roughened wall. On the other hand, as an example of the measurement of the local heat transfer coefficient,

Seban et al.⁽⁶⁾ reported the effect of a sphere attached on a flat plate, and Edwards et al.⁽⁷⁾ reported that of a cube and a triangular vortex generator. However, the flow field around these protuberance was not clarified enough, so they had not touched on the relation of the local heat transfer coefficients with the flow field.

On the other hand, dealing with the flow around a three-dimensional protuberance, formerly, Schlichting⁽⁸⁾ reported a velocity acceleration effect in the wake of the protuberance (negative wake effect) from his measurements of velocity distribution behind a row of spheres. According to the recent reports by Okamoto et al.⁽⁹⁾⁽¹⁰⁾, the same effects were also found in the wake behind a cone or a finite circular cylinder on a flat plate. From the measurements of the wake of a cube whose perpendicular edge was directed to the stream, by means of a pulsed hot-wire, Castro et al.⁽¹¹⁾ indicated generation of a pair of trailing vortices from the free-end of a cube similar to the delta wing. Moreover, the authors⁽¹²⁾ performed some velocity measurements and visualizations of the wake flow behind a finite circular cylinder placed on a flat plate, and presented a flow model of the wake flow behind a circular protuberance.

Based on these results, we tried to make clear the augmentative effects of forced convective heat transfer by three-dimensional protuberance, when height of the protuberance was equivalent to the boundary layer thickness. In that case, it is expected that a strong perturbation (as classified by Bradshaw et al.⁽¹³⁾) is generated, which is the order of the boundary layer thickness. At first,

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concerning a single and various shaped three-dimensional protuberances, the characteristics of local heat transfer coefficients and of the flow field around these protuberances were examined experimentally. Then, the augmentative mechanism of the heat transfer is considered. Next, concerning a row of protuberances, we will try to clarify the mutual interference of these augmentative effects. From these systematic studies, the fundamental data on the optimum shape and optimum arrangement of the protuberances will be obtained. As a first report, the results obtained with a single and finite circular cylindrical protuberance are presented.

Nomenclature

- C_p : pressure coefficient $= (p - p_\infty) / (\rho U_\infty^2 / 2)$
 C_p : specific heat of air
 D : diameter of protuberance
 H : height of protuberance
 h : local heat transfer coefficient
 L_h : maximum heat transfer position measured from center of protuberance
 L_p : reattachment length measured from center of protuberance
 Pr : Prandtl number of air
 p : surface pressure
 p_∞ : static pressure of free-stream
 Re_H : Reynolds number of protuberance $= U_\infty H / \nu$
 St : Stanton number $= h / (C_p \rho U_\infty)$
 U_∞ : free-stream velocity
 u : velocity component in X-direction
 X, Y, Z : rectangular coordinates (Fig. 2)
 X_0 : streamwise distance measured from virtual origin of turbulent boundary layer
 θ : momentum thickness of turbulent boundary layer at the center of protuberance
 ρ : density of air
- Suffixes
 max : maximum value
 min : minimum value
 II : two-dimensional region at same X position

2. Experimental Apparatus and Method

The wind tunnel used in this experiment was a blow-down type one, and had a measuring section of 300x300 mm and 2 m long, which was connected to the nozzle exit with a contraction ratio of 3/8. The zero pressure gradient of free-stream was satisfied by adjusting the flexible ceiling plate. The experiments were conducted in a turbulent boundary layer developed on the floor plate of the wind tunnel. In order to facilitate the transition of the boundary layer, a #80 sandpaper with 60 mm

Fig. 1 Characteristics of turbulent boundary layer on the floor plate

width was adhered to the floor plate immediately downstream of the nozzle exit.

The typical free-stream velocity of the experiment was 24 m/s, and the free-stream turbulence intensity at this velocity was about 0.5 %. The streamwise variation of the momentum thickness (θ) and the shape factor ($\bar{H}$) of the boundary layer at this velocity are shown in Fig. 1. The variation of the momentum thickness agreed with the result of the turbulent boundary layer on the flat plate without a pressure gradient. The velocity and turbulence intensity profiles at the typical setting position of the protuberance ($X_0 = 420$ mm and 720 mm) almost agreed with the results obtained by Klebanoff. The inner layer velocity profiles satisfied the wall law by Clauser, and the relation between the friction velocity and the shape factor ($\bar{H}$) satisfied Hama's relation. From these results, the boundary layer developed on the floor plate was concluded as a fully developed turbulent boundary layer.

Figure 2 shows a coordinate system. The origin of the coordinate is located at the center of the protuberance on the floor plate. The X-axis on the floor plate is called axial line. In order to vary the parameters H/D and H/θ , which indicate the shape of protuberance and the immersed ratio of the protuberance to the boundary layer respectively, about 30 pieces of circular cylindrical protuberances were provided. The heights and diameters of these protuberances ranged $H = 2.5 \sim 15$ mm and $D = 5 \sim 30$ mm respectively. For the same purpose, the setting position of the protuberances was changed in the free-stream direction. The protuberances for the measurements of flow field were made of brass, and the protuberances for the measurements of the heat transfer coefficient were made of bakelite in order to reduce the heat transmission from protuberance itself.

The surface pressure measurements on the flat plate around the protuberance were conducted on a steel plate with many pressure taps (0.5 mm ϕ). To grasp the flow pattern on the flat plate, flow visualization experiments were conducted by the oil-film method (carbon-black dissolved in kerosene was used as a tracer). In order to clarify the behavior of the vortices behind the protuberance, some surveys with a small wind mill were conducted in the same way as in the former report⁽¹²⁾. And to clarify the effects of the vortices on the turbulent boundary layer, some measurements of the velocity

Fig. 2 Coordinate system

and turbulence intensity were conducted with a hot-wire anemometer and I-type probe.

The measurements of the heat transfer coefficients were made under the condition of a constant heat flux, which was obtained by electrical heating of a 30 μm thick stainless foil adhered on a 10 mm thick bakelite plate with D.C. stabilized power source. The temperatures of the heating surface were measured by about 80 pieces of 70 μm^2 Cu-Co thermocouple, which were soldered on the rear side of the stainless foil. And to increase the actual measuring points, the setting position of the protuberance was shifted in small steps. In order to confirm the accuracy of this measuring system, the turbulent heat transfer coefficient of a smooth flat plate without a pressure gradient was measured. The results agreed fairly well with those obtained by Johnson-Roubesin.

3. Flow Pattern and Local Heat Transfer Distribution on the Flat Plate

3.1 Flow pattern on the flat plate

Figure 3 shows typical examples of surface pressure distribution on the flat plate, and surface flow pattern visualized by oil-film method. In all cases, a pair of the minimum pressures, C_p (mark ∇ in Fig.3) occurred immediately downstream of the protuberance. Therefore, oil-film pooled at this place, and swirling traces were observed when $H/D=2.0$ and 0.75 (Figs.3 (a) and (b)). This negative pressure was caused by vorticity concentration of the separated shear layer from side wall of the cylinder. Hereinafter, these were referred to as twin vortices. However, as stated in former report⁽¹²⁾, no periodical vortex shedding was observed.

Figure 4 shows the change of the center position of the twin vortices by H/D , which were obtained from the C_p distribution and the oil-film photographs.

At $H/D=3$, single $C_{p_{min}}$ point located only on the axial line, but, at smaller H/D , a pair of $C_{p_{min}}$ points appeared on both sides of the axial line, and moved close toward the protuberance. These are caused by the interruption of the mutual interaction of the separated shear layer from both side walls by blowing down of a flow from the free-end to the wake. The distance between the twin vortices became a maximum at $H/D=0.7$, and that is nearly equal to the diameter of the protuberance.

As H/D became smaller, the positions of $C_{p_{min}}$ came closer to the rear wall of the cylinder, and the distance between twin vortices became narrow again. Furthermore, when $H/D \leq 3$, it came extremely close to the rear wall of the cylinder. This is due to the fact that the ratio of the side separated flow running into the wake becomes smaller than that of the blow-down flow.

At all H/D , a wide positive pressure area was formed downstream of the negative pressure area. In this area, the oil-film traces spread in the downstream direction.

This fact indicates the existence of a mean flow directed to the flat plate on the axial line. Figure 5 shows a typical C_p distribution on the axial line ($H/\theta = 6.7$). The maximum pressure coefficient, $C_{p_{max}}$, increased with an increasing H/D , and became a maximum at $H/D=0.7$. When H/D was larger than 0.7 , $C_{p_{max}}$ decreased conversely, and when $H/D \geq 1.5$, $C_{p_{max}}$ could not be found clearly. From these facts, it is known that the blow-down flow reattaches on the flat plate evidently when $H/D < 1.5$; on the other hand, when $H/D \geq 1.5$, the reattachment becomes very weak or does not occur. Furthermore, when $H/D \leq 0.3$ (Fig.3(c)), the positive pressure area formed a belt-like pattern directed to Z axes, as indicated by the contour line of $C_p=0.03$. This can be explained by a uniform reattachment of the blow-down flow in the Z direction, that is, the

Fig.3 Pressure distribution on the flat plate and surface flow pattern

Fig.4 Center position of twin vortices

reattachment phenomenon becomes two-dimensional.

3.2 Merger of the necklace vortex with the trailing vortex

When the height of the cylindrical protuberance exceeds enough the boundary layer thickness, as indicated in the former report⁽¹²⁾, a pair of trailing vortices arise from the rear surface immediately beneath the free-end of the cylinder, and also a necklace vortex is formed around the foot of the cylinder. When the cylinder's height becomes equivalent to the boundary layer thickness, that is the object of this study, it is expected that these vortices interfere with each other. In order to make clear these interferential behavior, swirling flow was observed using a small wind mill at the downstream of the cylinder in the case of $H/D=0.7$ and $H/\theta=10$. The results are shown in Fig.6 as contour maps of the rotation number. At a section just behind the cylinder ($X/D=1.25$), two peaks of rotation (mark $\blacktriangle$ in Fig.6) were seen, whose rotational directions were the same. Judging from the positions and directions of rotation, the swirl located at the rear of the cylinder corresponded to the trailing vortex, and the swirl located at the side of the cylinder corresponded to the necklace vortex. It is known from this figure that the central rotation of the trailing vortex is extremely stronger than that of the necklace vortex.

The reattachment point in this case was obtained as $X/D=2.3$ from Eq.(1) as described later. At a section slightly upstream of this reattachment point ($X/D=2.6$), the scale of trailing vortex became larger and the rotation number increased. Furthermore, its center position was brought close to the flat plate by the blow-down flow. On the other hand, the necklace vortex was drawn close to the axial line by twin vortices behind the cylinder, then both vortices came close to each other. At a section slightly downstream of the reattachment point ($X/D=4.38$), it was not possible to find the two vortices individually. This fact indicates that the two vortices merge in one vortex twisting around each other, because of their common rotational direction. At this section, the center position of the vortex was the closest to the flat plate. Further, the central rotation number was lower than that of the section $X/D=2.06$. In this manner, a pair

Fig.5 Cp distribution on the axial line

of longitudinal vortices were formed at a further downstream section, whose axes lied in the flow direction. For example, at a section of $X/D=13.1$, the contour line of rotation became almost circular, and the center position of it left the axial line and also the flat plate. And the central rotation was more damped.

In order to show the formation process of the longitudinal vortices, Fig.7 shows the change of the center position of vortices, which was obtained as the maximum position of the wind mill's rotation number, and it is compared with the surface oil-film pattern. It is known from this figure that the merger of the necklace vortex with the trailing vortex took place at $X/D=3.5$. Line A in Fig.7 indicates a three-dimensional ordinary separation line. The center line of the longitudinal vortex located between the axial line and this separation line. The oblique oil-film traces were crossing the vortex center line. Thus, both figures are in good agreement. Next, just behind the protuberance, the trailing vortex passed over the pattern of the twin vortices, and approached the axial line. Opposed to this, the patterns of the twin vortices slanted outside from axial line. Considering these phenomena, it is

Fig.6 Contour maps of a small wind mill's rotation

Fig.7 Streamwise change of the center position of vortices and oil-film flow pattern

expected that the trailing vortices intrude inside the twin vortices, and roll up the twin vortices which probably are inclined downstream. On the basis of these facts, a sketch of the reliable model of the vortices system is shown in Fig.8.

In order to clarify the effects of these longitudinal vortices on the velocity field at the downstream section, some velocity distributions were measured at each section. Figure 9 shows a velocity contour map at the section of $X/D=13.1$. Mark $\blacktriangle$ in Fig.9 indicates the center position of the longitudinal vortices obtained by the small wind mill. From this figure, it is found that the boundary layer near the axial line ($Z/D < 1.0$) becomes extremely thin as compared with the two-dimensional region. These facts indicate that a new re-developing boundary layer is formed near the axial line by the effects of the longitudinal vortices, which implies the appearance of a wake acceleration effect (negative wake effect). On the other hand, at the outside of the vortex center ($Z/D=1.5$) the boundary layer becomes thicker by lift up of the decelerated flow near the flat plate.

3.3 Distribution of the local Stanton numbers

Figure 10 shows the distribution of the local Stanton numbers (St) in the case of Fig.3. St distributions on the flat plate near and downstream of the protuberance, in these figures, are standardized by the Stanton number on the smooth flat plate at the corresponding position (St_{II}).

In the case of $H/D=0.75$ (Fig.10(b)) where the blow-down flow reattached evidently on the flat plate, a maximum of St (St_{max} ; mark $\blacksquare$) appears slightly upstream of the reattachment point, thus a fairly good correspondence was observed with the flow field. From this maximum St point, contour lines of relative high Stanton number stretched to the side separation point of the cylinder. This may be caused by the flow acceleration effect at the side wall of the cylinder. On the other hand, in the case of $H/D=2.0$, where the reattachment was not clear, the position of St_{max} was not in the positive pressure region, but on the axial line just behind the twin vortices. The appearance of the maximum heat transfer coefficient in this case was attributable to the convective transport effect of a large scale motion, i.e. the rolling up flow by twin vortices.

This difference in the formation mechanism of St_{max} influenced strongly the value of St_{max} . Generally, at the same value of H/θ , St_{max} obtained near the reattachment point shows a higher value. For example, in this representative case ($H/\theta=10.4$), the value of St_{max}/St_{II} is 2.6 in the case of $H/D=0.75$, and 1.93 in the case of $H/D=2.0$. By the way, a scale of the augmented area of St in front of the protuberance reached farther upstream in the case of $H/D=2.0$ (about $1.5D$) than in the case of $H/D=0.75$. This is owing to the scale of necklace vortex, that is, as

inferred from Figs.3(a) and (b), the scale at $H/D=2.0$ is greater than that at $H/D=0.75$.

Next, we will describe the common points of the St distribution between Figs.10(a) and (b). At the downstream of the maximum St point, in both cases, a high heat transfer area follows with a width of $2\sim 3$ times the cylinder's diameter. This may be caused by the promotion of the turbulent transport efficiency by the acceleration of wake flow (negative wake effect), as stated in section 3.2. As expected from the oil-film pattern, this effect remains downstream over a distance of several tens times the cylinder diameter. Therefore, the heat transfer coefficient does not fall to that of a smooth flat plate.

Figure 10(c) shows the result in the case of $H/D=0.2$, where the reattachment of the blow-down flow is two-dimensional. Therefore, the distribution of Stanton

Fig.8 Model of the vortices system

Fig.9 Influence of a pair of longitudinal vortices on the velocity field

Fig.10 Contour maps of St/St_{II}

numbers produces a two-dimensional high heat transfer area extending in Z direction with a width of cylinder's diameter. Furthermore, it is found that the asymptotic decrement of St to the value of the smooth flat plate is faster than in the former cases. This is owing to the fact that the longitudinal vortices are not formed clearly in this case, because of the two-dimensional reattachment.

From the foregoing results, it is concluded that the main factor for the determination of the flow field and St distribution patterns around the protuberance is the parameter H/D , and these patterns are classified into three groups bordered by $H/D=0.3$ and $H/D=0.5$. Hereafter, from the standing point of heat transfer augmentation, we present the results in the case of $H/D=0.5 \sim 1.0$, where remarkable effects on heat transfer are expected from the strong reattachment and the longitudinal vortices.

4. Flow Field and Heat Transfer at the Reattachment Region

4.1 Reattachment point and pressure coefficient at this point

As mentioned above, a strong reattachment occurs in the case of $0.3 < H/D < 1.5$. Fig.11 shows the change of the reattachment position which is obtained as the C_p points. The value of L_p/H for each H/D is a constant value independently to H/θ . This fact indicates that the immersed ratio of the protuberance to the boundary layer (H/θ) is not a principal factor for the scale of the three-dimensional cavity. From Fig.11, the following equation is obtained for the reattachment point.

$$L_p/H = 2.8(H/D)^{-1/2} \dots\dots\dots(1)$$

Now, we compare this result with that of two-dimensional protuberances. For a rectangular cylinder laid on the flat plate normal to the free-stream, the values of L_p/H (measured from the rear face) are about $7 \sim 9^{(14)}$ ($5 < H/\theta < 11.3$). For the backward-facing step the value of L_p/H is about $7^{(15)}$ ($H/\theta = 7.5$). In this experiment, reattachment length in the case of $H/D=0.7$ is $L_p/H=3.4$, which is extremely shorter than that of two-dimensional protuberances. According to the report by Tani et al.⁽¹⁵⁾, the scale of the two-dimensional separation cavity is determined by the balance between the shear force of the separated shear layer and the force due to the negative pressure in the cavity. In the case of finite cylindrical protuberance, the separated shear layers from

Fig.11 Reattachment length

left and right sides of protuberance join in this phenomenon, therefore the pressure in the cavity drops and the cavity scale becomes shorter. As expected from this phenomenon, the reattachment length, L_p/H , increases with a decrease of H/D , as shown in Eq.(1). Now, Eq.(1) is transformed to,

$$L_p = 2.8\sqrt{DH} \dots\dots\dots(1')$$

Thus, a scale $\sqrt{DH}$ is obtained as the geometrical scale of the flow field near the reattachment point. Then, the pressure distributions on the axial line are standardized by $C_{p_{max}}$, $(C_p/C_{p_{max}})$, and arranged with the abscissa $X/\sqrt{DH}$ as shown in Fig.12. In the range of $0.5 \leq H/D \leq 1.2$, the pressure distributions are assembled in one curved line; therefore, they are regarded as similar to each other.

Next, the change of C_p with H/D is shown in Fig.13. The ordinate in this figure indicates the results of C_p proportional to $(H/\theta)^{2/3}$. This figure indicates that C_p has a maximum at $H/D=0.7$ independently of H/θ . It is interesting that this result corresponds with the maximum distance between twin vortices (Fig.4) in this case.

4.2 Maximum heat transfer coefficient and its position

The position of the maximum heat transfer coefficient, L_h , was obtained from the distribution of the heat transfer coefficients. This result indicated that the values of L_h/H are constant for each H/D independently of H/θ , similar to the results of the reattachment point. The following equation is obtained:

$$L_h/H = 2.4(H/D)^{-1/2} \dots\dots\dots(2)$$

or

$$L_h = 2.4\sqrt{DH} \dots\dots\dots(2')$$

Comparison of Eq.(1') and Eq.(2') shows that the maximum heat transfer point locates slightly upstream of the reattachment point. This result is similar to the usual result about two-dimensional protuberances.

In order to examine the similarity of the distribution of the heat transfer coefficients on the axial line or Z-directional distribution near the maximum point of heat transfer coefficient, the increase of heat transfer coefficient ($St - St_{II}$) are standardized with the maximum increase ($St_{max} - St_{II}$) as ordinate, and arranged with $X/\sqrt{DH}$ or $Z/\sqrt{DH}$ as abscissa. At first, we describe the case when H/θ is constant. Figures 14(a) and (b) show the results for various values of H/D under $H/\theta=10.4$ as a typical example. It is found from this figure that, in the range of $H/D=0.5 \sim 1.0$, the distributions coin-

Fig.12 Similarity of the C_p distribution on the axial line

cide in one curved line for X and Z directions. It is known from Fig.14(b) that the width of the augmented area of heat transfer is about $3\sqrt{DH}$.

Next is the case when H/D is constant. Figures 15(a) and (b) show the results in the case of various values of H/θ under the $H/D=0.7$ as a typical example. The distributions on the axial line upstream of the St_{max} point and on a Z -directed line at the St_{max} coincide with each other. These heat transfer distributions near the reattachment point are dominated by the reattachment effect of the blow-down flow, therefore, similar distributions are obtained in this area by $\sqrt{DH}$ in the same way as Fig.14. However, on the axial line at the downstream of St_{max} point, the distributions of heat transfer coefficients differ slightly with H/θ , therefore, they do not merge in one curved line with $X/\sqrt{DH}$. Namely, the distributions of heat transfer coefficients show a poor similarity. The heat transfer coefficients in this region are dominated by a re-developing boundary layer caused by the reattached flow, and additionally influenced strongly by the convective transport effects based on a large scale motion (longitudinal vortex). This is considered the reason for the poor similarity of heat transfer distributions. The ordinate of Fig.15(a) is standardized by St_{max} (Fig.17), which depends on H/θ more strongly than the region dominated by longitudinal vortices. Therefore, the reduction ratio appears larger for large

H/θ . Thus, the existence of the longitudinal vortices influences the convective transport effects, but it influences little the surface pressure distribution (Fig.12).

A comparison of the St_{max} of cylindrical protuberance with that of two-dimensional protuberance was made. Figure 16 shows the distribution of St/St_H on the axial line of the circular cylindrical protuberance ($H/D=0.7$) and that of a two-dimensional rectangular cylinder laid on a flat plate ($H/B=0.7$, B ; width of the rectangular cylinder). St_{max}/St_H of the circular cylindrical protuberance is about 1.4 times that of the two-dimensional rectangular cylinder, and the position of St_{max} is located extremely further upstream than the two-dimensional one, as stated above. The St value immediately downstream of the two-dimensional rectangular cylinder is extremely lower than that of the circular cylindrical protuberance.

4.3 Arrangement of the maximum heat transfer coefficient

Generally, the maximum heat transfer coefficient may be described by non-dimensional parameter as follows.

$$St_{max} = F(H/D, H/\theta, Re_H, Pr) \dots \dots \dots 3$$

Taking account of the fact that St distributions near the reattachment point are similar independently of H/D for a constant H/θ , Eq.(3) is arranged as follows for air flow :

Fig.13 Change of Cp_{max} with H/D

Fig.14 Similarity of St distribution (various H/D)

Fig.15 Similarity of St distribution (various H/θ)

Fig.16 Comparison with two-dimensional protuberance

Fig.17 St_{max} ($H/D=0.7$) Fig.18 Arrangement of St_{max} ($H/D=0.7$)

$$St_{max} = f(H/D)g(H/\theta, Re_H) \quad (3)$$

At first, the function g is determined for the shape parameter $H/D=0.7$, where the largest St_{max} is obtained. Figure 17 shows the relation between the relation St_{max} and Re_H by the parameter of H/θ . It is found from this figure that St_{max} is proportional to $3/5$ power of H/θ for a constant Re_H . According to this result, Fig.18 shows the rearrangement of Fig.17 by the ordinate of $St_{max} (H/\theta)^{-3/5}$. The dispersion of the experimental data is within $\pm 5\%$ for the solid line in this figure. According to the foregoing results, Eq.(3) is expressed as follows,

$$St_{max} = f(H/D)Re_H^{-1/4} (H/\theta)^{3/5} \quad (4)$$

$(0.5 \leq H/D \leq 1.0, 5 \leq H/\theta \leq 15, Pr = 0.71)$

The function f in the last equation is presented in Fig.19. Now, the function f shows a maximum at $H/D=0.7$, which corresponds to the variation of the C_p (Fig.13).

5. Conclusions

Concerning a single, finite length and circular cylindrical protuberance set in the turbulent boundary layer, the wake structure of the protuberance and local heat transfer characteristics on the flat plate around the protuberance are classified into three groups by shape parameter, i.e. $H/D < 0.3$, $0.3 < H/D < 1.5$, and $H/D > 1.5$.

The range of $0.5 < H/D < 1.5$ is interesting from the stand point of heat transfer augmentation. Therefore, the results in this range are examined including the effects of the immersed ratio of the protuberance to the boundary layer in the range of $5 \leq H/\theta \leq 10$. Consequently, the following conclusions are obtained:

- (1) The reattachment length behind the circular cylindrical protuberance is extremely shorter than that of two-dimensional protuberances. The maximum heat

Fig.19 Function f for St_{max}

transfer coefficients by the circular cylindrical protuberance have a higher value than that by two-dimensional protuberances at the same height and the same immersed ratio of protuberance.

(2) The maximum heat transfer coefficients are obtained at slightly upstream of the reattachment point.

(3) The largest maximum heat transfer coefficient is obtained at shape parameter $H/D=0.7$. This result depends little on the parameter H/θ .

(4) The equation for the arrangement of the maximum heat transfer coefficient is obtained (Eq.(4)).

(5) A pair of trailing vortices arise from the rear surface of cylinder just behind the free-end. And a pair of longitudinal vortices are formed by merger of the necklace vortex with the trailing vortices at the downstream of the reattachment point.

(6) The longitudinal vortices produce an augmented area of the heat transfer coefficient with $3\sqrt{DH}$ width at the downstream of the protuberance.

(7) The patterns of the flow field near the reattachment point are prescribed by $\sqrt{DH}$, and are influenced little by parameter H/D or H/θ . The patterns of the heat transfer distribution are also prescribed by $\sqrt{DH}$ under the condition of $H/\theta = \text{constant}$, but are slightly variable with the change of H/θ , even under the condition of $H/D = \text{constant}$.

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