Augmentation of Turbulent Heat Transfer on a Flat
Plate with Three-dimensional Protuberance
(2nd Report, Shape Effect and Row of Protuberances)*

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In the 1st report, concerning a single finite circular cylinder placed on a flat plate, it was made clear that the three-dimensional reattachment of a blow down flow from upper end of the cylinder and the formation of a pair of longitudinal vortices play an important role in the augmentation of heat transfer.

Following this, this report describes the experimental results on the flow structure and local heat transfer characteristics influenced by (I) the change in the shape of protuberance (cube, square cylinder and circular cone) and (II) the mutual interaction of longitudinal vortices produced in a row by row of protuberances.

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

1. Introduction

Concerning the turbulence promoter for the purpose to augment the convective heat transfer, hitherto, many studies have been done on the two-dimensional protuberance, but very few done on the three-dimensional protuberance.⁽¹⁾⁻⁽³⁾

Generally, heat transfer coefficient in the separated flow region just behind a two-dimensional protuberance shows a poor performance. As shown in the former report⁽⁴⁾, the separated flow region behind a three-dimensional protuberance becomes considerably short, and little reduction of heat transfer coefficient occurs in this region. These points are profitable in making the heat exchangers compact and applicable in the practical use. From these viewpoints, this study made clear the three-dimensional flow structure and heat transfer mechanism around three-dimensional protuberances, in order to obtain the fundamental data on the optimum shape and optimum arrangement of the protuberances as a three-dimensional roughness element on the heating surface.

In the former report, concerning a single finite-length circular cylinder, as

an example of three-dimensional protuberance, it was made clear that the three-dimensional reattachment of a blow-down flow from the upper end of protuberance and the formation of pair of longitudinal vortices play an important role as fundamental flow structures in the augmentation of heat transfer.

By the way, it is well known that a necklace vortex is formed around a protuberance by the separation of the boundary layer. The formation of longitudinal vortices at the downstream of protuberance was formerly attributed to the necklace vortices, and in connecting with this point, the study on the wake behind a row of spheres on the flat plate by Schlichting⁽⁵⁾ is famous for the detection of the wake acceleration effects (negative wake effects). However, it was stated in the former report that, as a cause of the formation of longitudinal vortices, there is a factor other than the necklace vortex for some shape of protuberance, i.e., the trailing vortices arising behind the protuberance.

This paper deals with the experimental results concerning the following effects on the wake structure of a protuberance and on the local augmentative characteristics of heat transfer from a flat plate:

- (1) The difference of the formation process of longitudinal vortices, which is examined by comparison between a circular cone, a square cylindrical protuberance and a circular cylindrical protuberance.
- (2) The mutual interaction of longitudinal vortices in a row which are produced by a row of circular cylindrical protuberances in various spacing pitches.

This study treats a case when the

* Received 28th February, 1983.

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protuberance's height is equivalent to the thickness of a turbulent boundary layer. In this case, the perturbation to the boundary layer becomes the same scale as the boundary layer thickness.

Nomenclature

- C_p : pressure coefficient $= (p - p_\infty) / (\rho U_\infty^2 / 2)$
 c_p : specific heat of air
 D : width of protuberance defined with the projected front view
 H : height of protuberance
 h : local heat transfer coefficient
 p : surface pressure
 p_∞ : static pressure of free stream
 S : spacing pitch of protuberances in a row (Fig.1)
 St : local Stanton number $= h / c_p \rho U_\infty$
 $\bar{St}$: spanwise averaged Stanton number [Eq. (5)]
 $\bar{St} / \bar{St}_x$: areal average of augmentation rate of heat transfer [Eq. (6)]
 X, Y, Z : rectangular coordinates (Fig.1)
 U_∞ : free stream velocity
 u : velocity component in the free stream direction
 ρ : density of air
 ν : kinematic viscosity
Suffixes
 max : maximum value
 min : minimum value
 I : two-dimensional region at same X position

2. Experimental Apparatus and Method

Experiments have been conducted in the same wind tunnel of former report at a free-stream velocity of 24 m/s. The protuberances are set on the floor plate of measuring section at 420 mm ($=X_0$)

Fig.1 Coordinate system and arrangement for the row of protuberances

downstream from the virtual origin of the turbulent boundary layer on the flat plate. The momentum thickness of the turbulent boundary layer at this position is $\theta = 1.12$ mm.

The protuberances used in this study on the effects of the shape are four kinds, that is, a circular cylinder, a circular cone, a square cylinder facing the stream ($\phi = 0^\circ$) and a cube whose forward face is slanted to free-stream at angle of 45° ($\phi = 45^\circ$). The height of these protuberances is $H = 11.2$ mm which is nearly equal to the boundary layer thickness. And their widths are $D = 16$ mm, which are defined with the projected front view (in the case of the circular cone, the diameter of base circle). The ratio of height to width corresponds to an optimum shape parameter for the circular cylinder ($H/D = 0.7$) as indicated in the former report. The Reynolds number based on the height of the protuberance is $Re_H = 1.8 \times 10^4$, and the immersed ratio of protuberance to the boundary layer is $H/\theta = 10$. In the case of a row of protuberances, circular cylinders are employed, whose sizes are the same as above. Figure 1 shows the arrangement of protuberances. The spacing of protuberances (S) is varied mainly in the range of $S/D = 1.5 \sim 4$.

The methods for the measurements of flow field and heat transfer coefficient are similar to those in the former report.

The Stanton number for a smooth flat plate (St_x), which is used as a base for the processing of the results, is given by the following equation :

$$St_x = 0.037 (U_\infty (X + X_0) / \nu)^{-0.2}$$

This equation agrees with the experimental equation by Johnson et al.⁽⁷⁾

3. Effects of the Shape of Protuberance

3.1 Flow pattern on the flat plate

Figure 2 shows contour maps of pressure coefficient on the flat plate and surface flow pattern visualized by oil film method for several shaped protuberances. In all cases, a necklace vortex is formed by the separation of boundary layer in front portion of protuberances,

Fig.2 Contour maps of pressure coefficient on the flat plate and surface flow patterns visualized by oil film method

which are clearly observed in the oil-film traces around the protuberances. Behind the protuberance, a pair of minimum pressure coefficients ($C_{p_{min}}$) by twin vortices exist, and oil-film is pooled at this place. And downstream of these vortices, a maximum pressure coefficient ($C_{p_{max}}$) appears on the axial line by reattachment of the blow-down flow. These results are the same as those for the circular cylindrical protuberance ($H/D \sim 1$) as shown in the former report.

However, the $C_{p_{min}}$ value behind a cube of $\phi = 45^\circ$ is considerably lower, and the area of negative pressure region extends beyond that behind the circular cone or a square cylinder of $\phi = 0^\circ$. Moreover, $C_{p_{max}}$ for the cube of $\phi = 45^\circ$ has a considerably higher value than that for a circular cone or a square cylinder of $\phi = 0^\circ$. These characteristics of the cube of $\phi = 45^\circ$ are the same as those of the circular cylinder $H/D \sim 1$, and they suggest some change in the wake flow structure.

Figure 3 shows flow patterns on the upper end surfaces of a cube of $\phi = 45^\circ$ and a square cylinder of $\phi = 0^\circ$. In the case of a cube of $\phi = 45^\circ$, oil-film concentrates along a forward swept-back edge like a willow leaf, and at the downstream of it, the trace of oil-film spreads radially. This indicates the reattachment of the blow-up flow from side wall on the upper end surface and arising of a pair of longitudinal vortices from rear edge in a similar manner to a delta-wing. In the case of a circular cylinder, a pair of trailing vortices also arise from rear of protuberance, but in a slightly different manner, as shown in the former report. On the other hand, in the case of a square cylinder of $\phi = 0^\circ$, flow pattern on the end surface indicates a reversing flow over all the area. And the trailing vortices can not be observed with a small wind mill.

Figure 4 shows the contour maps of rotational number of a small wind mill for a circular cylinder and a cube of $\phi = 45^\circ$ obtained just ahead of the reattachment point. The maximum rotational number (Mark Δ) which is located at the rear of a protuberance obviously corresponds to the trailing vortex. And this maximum value is extremely higher than that by necklace

Fig.3 Flow patterns on the upper end surfaces of cube and square cylinder

vortex (Mark Δ) which appears at the side of the protuberance. Then, it is realized that the change in $C_{p_{min}}$ and $C_{p_{max}}$ with the shape of protuberance are closely related to the existence of trailing vortices.

3.2 The distance of the reattachment position

The distance to the $C_{p_{max}}$ point from the protuberance position (L_p) is significant because it indicates the scale of separated flow region behind the protuberance, and near this point a high heat transfer coefficient appears.

Table 1 shows the arrangement of the reattachment position L_p for each protuberance. In the case of a circular cylinder, the relation of $L_p \sim 2.8\sqrt{DH}$ holds independently of H/θ in the range of $5 \leq H/\theta \leq 15$, and $0.4 \leq H/D \leq 1.2$. When L_p is arranged in the same manner using the projected area A_p , the value of $L_p/\sqrt{A_p}$ become $2.4 \sim 2.9$ for each protuberance. In the case of a square cylinder of $\phi = 0^\circ$, L_p (measured from the rear surface, which intercepts the entrainment with the separated shear layer) is nearly equal to that of a circular cone, that is,

$$L_p \cong 2.4\sqrt{A_p} \quad (1)$$

and L_p for the circular cylinder and a cube of $\phi = 45^\circ$ are approximated to,

$$L_p \cong 2.8\sqrt{A_p} \quad (2)$$

Thus the values of L_p change with the existence of trailing vortices. Hereafter, for convenience' sake, the cases with generation of trailing vortices (the circular cylinder and the cube of $\phi = 45^\circ$) are called shape type I, and the cases without generation (the circular cone and the square cylinder of $\phi = 0^\circ$) are called shape type II.

Fig.4 Contour maps of rotational number of a small wind mill

Table 1 Comparison of the distance of reattachment points

Shape of Roughness	H/D	L_p/D	L_p/H	$L_p/\sqrt{DH}$	$L_p/\sqrt{A_p}$
Circular Cone	0.7	1.4	2.0	1.7	2.4
Square Cylinder ($\phi=0^\circ$)	0.7	2.4(1.9)	3.4	2.9(2.3)	2.9(2.3)
Circular Cylinder	0.7	2.4	3.4	2.8*	2.8
Cube ($\phi=45^\circ$)	0.7	2.5	3.5	2.9	2.9

* Mean Value, $0.4 < H/D < 1.2$, $5 < H/\theta < 15$; () Measured from Rear Face

3.3 The vortex flow behavior downstream of the protuberance and a wake acceleration effects

The streamwise variation of the spanwise positions of vortex center is examined by using a wind mill. The results are shown in Fig.5. In this figure, marks $\circ$, $\bullet$ and $\otimes$ indicate the necklace vortex, trailing vortices and reattachment point, respectively. In the case of shape type II, only the necklace vortex is observed at the downstream of protuberance. On the other hand, in the case of shape type I, the longitudinal vortex (Mark $\otimes$) is observed, which is formed by merger of the necklace vortex with the trailing vortices. Castro et al.⁽⁶⁾ indicated that, for a cube of $\phi=45^\circ$ at $H/\theta \approx 100$, these two vortices do not merge, and for $H/\theta \approx 1$, does not appear distinct reattachment. These facts are in strong contrast to the result of this experiment.

Figure 6 shows the spanwise variation of the axial velocity component near the reattachment point. In the case of a square cylinder of $\phi=0^\circ$ (Fig.6(a)), velocity drops monotonously toward the axial line, that is, it shows the usual wake profile. On the other hand, in the case of a cube of $\phi=45^\circ$ (Fig.6(b)), the velocity profile shows once a minimum value, and increases again to a maximum on the axial line. Obviously, this fact is due to the wake acceleration effect (negative wake effect) caused by the trailing vortices.

In order to clarify the condition of a distorted velocity profile in the re-developing turbulent boundary layer downstream of the reattachment point, the spanwise variation of the axial velocity

Fig.5 Streamwise change of the position of vortex center

Fig.6 Velocity distribution in the re-attachment section: (a) Square cylinder ($\phi=0^\circ$) (b) Cube ($\phi=45^\circ$)

component at the height of the vortices' center in the section of $X/D=7.5$ is shown in Fig.7. The ordinate of this figure is non-dimensional velocity defect, that is, the difference with the two-dimensional region divided by free-stream velocity. It is found from this figure that the wake acceleration effect on the axial line ($Z/D=0$) in the case of shape type I is greater than that in the case of shape type II. The difference of the maximum value of $(u-u_\infty)/U_\infty$ (Δ) is considered a scale indicating the distortion of the velocity profile due to longitudinal vortices. The value of Δ is 0.24 for shape type I, and 0.09 for shape type II. It indicates that the circulation of the longitudinal vortices in the case of shape type I is greater than that in the case of shape type II.

3.4 Characteristics of the local heat transfer coefficient

Figure 8 shows the contour maps of St/St_∞ , that is local Stanton number distribution normalized by Stanton number of smooth flat plate at corresponding X position. Figure 9 shows the St/St_∞ distribution on the axial line. It is common to all protuberances that a maximum heat transfer coefficient (Mark $\blacktriangle$) appears on the axial line slightly upstream of the reattachment point, and the augmented heat transfer area follows it.

Fig.7 Velocity distribution at the height of vortex center in the reattachment section

Fig.8 Contour maps of St/St_∞ (effect of protuberance shape): (a) Circular cylinder (b) Cube ($\phi=45^\circ$) (c) Circular cone (d) Square cylinder ($\phi=0^\circ$)

The position of St_{max} (L_h) is for the shape type I,

$$L_h = 2.4\sqrt{A_p} \dots\dots\dots (3)$$

And for the shape type II,

$$L_h = 1.8\sqrt{A_p} \dots\dots\dots (4)$$

(in the case of a square cylinder of $\phi = 0^\circ$, L_h is measured from the rear face) Thus the reattachment lengths of these three-dimensional protuberances are extremely shorter than that of a two-dimensional protuberance.

However, as shown in Fig.9, the value of St_{max}/St_{II} shows a remarkable change with the existence of the longitudinal vortices. That is, in the case of shape type I, a high maximum heat transfer coefficient is obtained because of a strong reattachment of the blow-down flow.

And, in the case of shape type II, the value of St_{max}/St_{II} is the same order as that of a two-dimensional transverse rib type protuberance. And this difference between the two shape types continues for long period toward downstream.

Anyway, the heat transfer coefficient just behind the two-dimensional protuberance shows poor characteristics than that behind the three-dimensional protuberances.

Fig.9 Distribution of St/St_{II} on the axial line

Fig.10 Contour maps of C_p on the flat plate (effect of spacing of the row)

4. Row of the Protuberances

4.1 Flow field

The flow field around a row of protuberances, i.e., the protuberances placed in a line normal to the stream, is examined with the row of circular cylindrical protuberances as a typical example of the shape type I, in the case of $H/D=0.7$ and $H/\phi=10$.

Figure 10 shows contour maps of C_p on the flat plate in the case of $S/D=2$ and 1.5, for example. The contour map pattern for $S/D=2$ (Fig.10(a)) resembles that for a single protuberance. For example, the positions of C_{pmax} and C_{pmin} agree with those of a single protuberance. This fact is common to the cases for $S/D \geq 1.75$. However, both values of C_{pmax} and C_{pmin} drop with a decrease of S/D , and the area of positive pressure region shrinks. The drop of C_{pmin} is due to the growth of a negative pressure behind the protuberance by the acceleration of the flow through the gap of protuberances, and C_{pmax} drops with this growth of negative pressure because C_{pmax} is produced by reattachment of a blow-down flow on this negative pressure field as a base. On the symmetrical line between the protuberances, a slight rise of pressure appears in the contour line of $C_p = -0.02$ and -0.01 . This is attributable to the interaction of the longitudinal vortices, which is referred to later.

In the case of $S/D=1.5$ (Fig.10(b)), a pressure rise on the axial line is also found just behind the protuberance as in the case of $S/D=2.0$, but a positive peak pressure does not appear and the downstream of the protuberance is covered with negative pressure. And the contour lines of C_p show a slightly asymmetrical pattern with the axial line. These facts suggest some change in the flow field.

In order to clarify this phenomenon, the surface flow is visualized by oil-film method. The surface flow patterns of $S/D=1.5$ and $S/D=2$ (Fig.11(b) and (a)) are almost similar. However, in the case of $S/D=1.5$ (Fig.11(b)), the surface flow slightly deflects in the downstream of the reattachment point. Especially, in the case of $S/D=1.25$ (Fig.11(c)), the reattached flow deflects strongly to the right over all span.

The changes in the difference (ΔC_p)

Fig.11 Oil film pattern on the flat plate

between $C_{p_{max}}$ and the minimum pressure coefficient on the axial line are shown in Fig.12. ΔC_p indicates a gentle peak near $S/D=2$, and the values are almost equivalent to the value for a single protuberance. Judging from this fact, the strength of reattachment for a row of protuberances changes little with S/D in the range of $S/D \geq 1.5$. And ΔC_p for the two-dimensional rib type protuberance is only about a half of that for the circular cylindrical protuberances.

4.2 Interaction of the longitudinal vortices

In order to clarify the mechanism of these deflections of the surface flow, the interaction of the trailing vortices arising from each protuberance should be discussed. Figure 13 shows the spanwise variation of the axial velocity component at the height of the protuberance ($Y/H=1.0$) in the section immediately downstream of the row of protuberances ($X/D=1.25$) for the typical spacing, i.e., $S/D=3, 1.75$ and 1.5 . The vertical bars in this figure indicate the symmetrical plane. The velocity profiles for $S/D=3$ and 1.75 are symmetrical to the symmetrical plane. However, the profile for $S/D=1.5$ is asymmetrical, but the periodicity is still retained.

From a fine examination, it is found that the maximum velocity on the axial line which is caused by the wake acceleration effects varies little with S/D , and contrary to this, the maximum velocity near the symmetrical plane decreases with a decreasing S/D . Now, it is considered that the interval of the pair of trailing

vortices for each protuberance is almost constant with the change of S/D as indicated from the fact that the change of the minimum velocity position is not so large. Therefore, the intervals of the neighboring vortices between the protuberances become shorter with a decrease of S/D , and this effect emphasizes the induced ascending flow near the symmetrical plane by these vortices. And, this reduces the maximum velocity near the symmetrical plane, as mentioned above. Thus, the change of the interval of trailing vortex row produces a change in the ascending velocity component of the flow near the symmetrical plane.

For a smaller S/D , the intervals of neighboring vortices between the protuberances become almost equivalent to that of the pair vortices behind a protuberance. In this condition, the center of vortices aligns in the $Y-Z$ plane with counter-revolution taking place alternately. This arrangement of vortex row is unstable, and it is considered that a stable arrangement of the vortex row is a zigzag one like the Karman vortex street. The distortion of the velocity profiles near the symmetrical plane at $S/D=1.5$ in Fig.13 indicates the transformation into such model of vortices' arrangement. And this arrangement of vortices must induce a deflected flow on the flat plate.

It is examined how this behavior of the vortex row influences the re-developing boundary layer downstream of the reattachment point. Figure 14 shows contour maps of the axial velocity component at $X/D=13.1$ for a single protuberance and the row of protuberances of $S/D=4.0$,

Fig.12 Difference between $C_{p_{max}}$ and minimum pressure coefficient on the axial line

Fig.13 Velocity distribution just behind the row of protuberances ($X/D=1.25, Y/H=1$)

Fig.14 Effects of the longitudinal vortices on the velocity distribution of turbulent boundary layer

2.0 and 1.5. Mark $\blacktriangle$ indicates the vortex center obtained by a small wind mill. In the case of $S/D=4$, the center position of vortex and the form of contour lines are almost similar to those of a single protuberance, but the boundary layer near the symmetrical plane becomes thicker due to the ascending flow. In the case of $S/D=2$, the center position of the vortex is close to the axial line because of the approaching of neighboring vortices. Judging from the distortion of contour lines, vortices are damped at this section, and the whole boundary layer becomes thicker. Further, in the case of $S/D=1.5$, the contour lines are parallel with the flat plate, the flow field are two-dimensional, and an asymmetry is not found.

4.3 Local characteristics of heat transfer

In order to consider the relationship between the behaviors of flow field and the heat transfer characteristics, Figure 15 is given showing the distribution of the heat transfer coefficients downstream of the row of protuberances for $S/D=4$, 2 and 1.5 as the contour maps of St/St_{Π} . In the case of $S/D=4$ (Fig.15(a)), the augmented area of heat transfer by re-attachment effect overlaps near the symmetrical line. In the case of $S/D=1.5$ (Fig.15(c)), the interaction of flow field influences over all the region, and the local variation of heat transfer distribution diminish. And distribution of heat transfer coefficients shows a deviation corresponding with the deflection of flow field.

In order to show the details of these changes of the heat transfer distribution, the profiles of St/St_{Π} on the axial line and on the symmetrical line are shown in Figs.16(a) and (b). Concerning the distribution on the axial line (Fig.16(a)), the profile of St/St_{Π} for $S/D=1.75$ is almost equivalent to that for a single protuberance. However, in the case of $S/D=1.5$, it is less than that for a single protuberance, and especially St_{max} decreases remarkably. But, the position of St_{max} does not change with S/D , and it is equal to that for a single protuberance. The value of high heat transfer

Fig.15 Contour maps of St/St_{Π} (Effects of spacing of row)

coefficient in front of the protuberance is reduced with a decrease of S/D . This may be caused by a weakening of necklace vortices.

On the other hand, the distribution of heat transfer coefficients on the symmetrical line (Fig.16(b)) changes with S/D . For the comparison purpose, the results for a single protuberance on the corresponding position are plotted as curved lines. In the case of $S/D=4$, distribution of St/St_{Π} almost coincides with the corresponding value of a single protuberance (chain line). In the case of $S/D=2$ and 1.75, the value of St/St_{Π} exceeds the corresponding value of a single protuberance (broken line and full line, respectively) by the overlap of the augmented area of heat transfer, and the peak of it appears near $X/D=2$. But at the downstream of $X/D>10$, they are slightly less than the corresponding value of a single protuberance. This is attributable to an increase of boundary layer thickness due to the interaction of longitudinal vortices.

4.4 Characteristics of averaged heat transfer coefficient

As data for the practical use, the average heat transfer coefficients are given for the comparison of the augmentative characteristics of three-dimensional protuberance row with that of two-dimensional protuberance.

Figure 17 shows a streamwise change of the spanwise average of local Stanton number,

$$\bar{St} = \frac{1}{S} \int_0^S St(X, Z) dZ \quad (5)$$

normalized by St_{Π} at corresponding X -position. The area beneath the protuberance is included in the integration area as the surface with zero heat transfer coefficient. Therefore, $\bar{St}/St_{\Pi}$ in the region of $-0.5 < X/D < 0.5$ may become smaller than unity. In the case of $S/D > 1.75$, $\bar{St}/St_{\Pi}$ increases monotonously

(a) On the axial line

(b) On the symmetrical line

Fig.16 Distributions of St/St_{Π} on the axial line and symmetrical line

with a decrease of S/D , because the integration area is limited to near the axial line where high heat transfer coefficients appear. But, in the case of $S/D < 1.75$, the increase of $\overline{St}/St_{II}$ is saturated, and the value slightly decreases. This is due to the fact that the drop of heat transfer coefficient on the axial line exceeds the increase of heat transfer coefficient on the symmetrical line.

The maximum value of $\overline{St}/St_{II}$ appears at $X/D=2$ independently of S/D . Results of the two-dimensional rib-type protuberance are also indicated in Fig.17. Heat transfer coefficient just behind the two-dimensional protuberance shows not an augmented value, but an abated value.

Figure 18 shows the areal average of augmented rate of heat transfer defined by next equation.

$$\overline{St}/\overline{St_{II}} = \int_0^L \overline{St}_i dX / \int_0^L St_{II} dX \quad \dots\dots\dots (6)$$

Fig.17 Spanwise average of augmented rate of heat transfer

Fig.18 Areal average of augmented rate of heat transfer

Fig.19 Maximum average of augmented rate of heat transfer

That is, the average of $\overline{St}$ from protuberance position to $X=L$ normalized by the average of St_{II} in the same region. In this figure, the same average for the result of a single protuberance in the same region, which is called "corresponding average for a single protuberance", is plotted with curved lines for comparison.

In the case of $S/D > 2$, $\overline{St}/St_{II}$ increases with a decrease of S/D . However, these values only slightly exceed the corresponding average for a single protuberance at $X/D < 12$. On the other hand, in the case of $S/D < 2$, $\overline{St}/St_{II}$ decreases with a decrease of S/D , and it is less than the corresponding value for a single protuberance.

Maximum value of $\overline{St}/St_{II}$ ($(\overline{St}/St_{II})_{max}$) is obtained at $L/D=3\sim 4$, just downstream of the protuberances. Averaged augmented rate by the same definition for two-dimensional rib-type protuberance is shown in Fig.18. The averaged rate for the rib-type protuberance decreases just behind the protuberance. And in the case of a row of protuberances, high values of $\overline{St}/St_{II}$ are kept after $(\overline{St}/St_{II})_{max}$ point.

Figure 19 shows the change of $(\overline{St}/St_{II})_{max}$ with S/D . $(\overline{St}/St_{II})_{max}$ shows the highest value at $S/D=2$. Mark $\odot$ in this figure implies the maximum value of corresponding average for a single protuberance. In the case of $S/D > 2$, $(\overline{St}/St_{II})_{max}$ for a row of protuberances slightly exceeds the maximum value of the corresponding average for a single protuberance. But the difference between these values is only about 5%. On the other hand, for $S/D < 2$, $(\overline{St}/St_{II})_{max}$ for the row of protuberances is less than the maximum of the corresponding average for a single protuberance.

5. Conclusions

Concerning the flow structure and the augmentative characteristics of heat transfer around the three-dimensional protuberances, some experimental studies are conducted (I) on the shape change of protuberance, and (II) on the spacing change of a row of protuberances. The form of protuberance is $H/D=0.7$, which is the optimum shape parameter for a circular cylindrical protuberance given by the former report. Main results of these studies give the following conclusions:

(I) On the effects of shape change

- (1) The shapes of protuberances are classified into two types, that is, shape type I which induces trailing vortices, and shape type II which does not induce them.
- (2) In the case of shape type I, a high reattachment pressure and a high heat transfer coefficient appear near the reattachment point.
- (3) The secondary flow caused by a pair of longitudinal vortices for the shape type I is stronger than the one for the shape type II. Therefore, shape type I has high augmentative effect on heat transfer.
- (4) The reattachment position and the

maximum heat transfer position for a three-dimensional protuberance are remarkably closer to the protuberance than those for a two-dimensional protuberance. Therefore, the decreased region of heat transfer coefficient appearing behind the two-dimensional protuberance disappears.

(II) On the effects of spacing change of the protuberance row

(1) The interactive aspects of the row of longitudinal vortices downstream of the reattachment point are classified into two cases. In the case of $S/D > 1.75$, interaction of vortices in a row is remarkable near the symmetrical plane. In the case of $S/D < 1.75$, the row of vortices becomes unstable, then the surface flow shows some deflection. Especially, the deflection extends over full span scale at $S/D = 1.25$

(2) In the case of $S/D \geq 1.75$, local distribution of heat transfer coefficients near the symmetrical line changes with S/D , and that near the axial line does not change. In the case of $S/D < 1.75$, the effect of interaction comes all regions, then the local distribution of heat transfer coefficients is transformed to a two-dimensional distribution.

(3) In the case of $S/D \geq 1.75$, the areal average of augmentation rate of heat transfer can be approximated to the corresponding value for the single protuberance by the same definition. But, in the case of $S/D < 1.75$, it can not be approximated to that for the single protuberance.

(4) Optimum spacing for the row of

circular cylindrical protuberances which gives the largest value of the areal average of augmentation rate of heat transfer, is $S/D \approx 2$.

(5) Maximum values of the areal average of augmentation rate are obtained at $L/D = 3 \sim 4$. And the decreased region of heat transfer, which appears just downstream of the two-dimensional protuberance, disappears behind the row of three-dimensional protuberances.

From the above facts, it is confirmed that the protuberances of shape type I are effective for the members of the row of protuberance. Hereafter, concerning the augmentation of heat transfer for a group of protuberances, it will be necessary to study the optimum streamwise spacing or arrangement mode of protuberances and the fluid dynamic drag of the group of protuberances.

References

- (1) Mantle, P.L., Proc. 3rd Int. Heat Transfer Conf., Vol.1(1966), p.45.
- (2) Edwards, F.J. and Alker, C.J.R., Proc. 5th Int. Heat Transfer Conf., FC6.4(1974).
- (3) Meyer, L., Int. J. Heat Mass Transfer, Vol.25(1982), p.1043.
- (4) Kawamura, T. et al., Bull. JSME, 27-234(1984), to be published.
- (5) Schlichting, H., NACA Tech. Memo. 823 (1937).
- (6) Castro, I.P. and Robins, A.G., J. Fluid Mech., 52(1972), p.113.
- (7) Johnson, H.A. and Rubesin, M.W., Trans. ASME, 71(1949), p.447.