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HEAT TRANSFER IN THE SEPARATED AND REATTACHED FLOW OVER BLUNT FLAT PLATES —EFFECTS OF NOSE SHAPE

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Abstract—Heat-transfer measurements have been conducted in the separated, reattached and redeveloped regions of two-dimensional air flow over flat plates with blunt leading edges of various shapes. Especially investigated are the nose shape effects upon the heat-transfer characteristics in these flow regions. Temperature, velocity, and turbulence profiles are also measured in the above-mentioned flow regions. It is found that the behaviors of the separated shear layer play very important parts upon the heat transfer in the separated and reattached regions, and that the correlation between the reattachment Nusselt number and the Reynolds number is developed independently of the nose shape when the reattachment length is employed as the reference length in both of them.

NOMENCLATURE

$2H$,	plate thickness;
h,	heat-transfer coefficient $= q/(T_w - T_\infty)$;
h_{mx},	mean heat-transfer coefficient between $x = 0$–x;
h_R,	heat transfer coefficient at reattachment point;
l,	distance from separation point to reattachment point;
Nu,	Nusselt number $= hH/\lambda$;
q,	heat flux per unit area and unit time;
Re,	Reynolds number $= U_\infty H/\nu$;
T,	temperature;
T_w,	wall temperature;
T_∞,	temperature at upstream uniform flow;
U,	mean flow velocity;
U_∞,	velocity at upstream uniform flow;
u,	turbulent fluctuating velocity parallel to flow direction;
x, y,	coordinates.

Greek symbols

α,	apex angle of wedge;
λ,	thermal conductivity of air;
ν,	kinematic viscosity of air.

INTRODUCTION

PREDICTION of heat transfer in the separated, reattached, and redeveloped regions of incompressible or subsonic flow is very important in relation to various engineering aspects, and there have been many works on the wide variety of flow configurations. Examples include downward or upward surface steps [1–7], abrupt circular channel expansions or contractions including orifice induced separations [8–10], and roughness elements attached to flat surface [11–13]. These works have recently been reviewed in a paper by Fletcher *et al.* [14]. In many of these cases, the flow separation and reattachment may be strongly affected by the characteristics of the boundary layer just upstream of the separation point. However for cases where these effects are expected to be small (e.g. blunt bodies, stalled aerofoils, and finned surfaces), it appears that there are little informations as to the heat transfer characteristics.

From this standpoint, the present authors have presented experimental studies of heat transfer in the separated, reattached, and redeveloped flow over a blunt flat plate [15] and also of that over a longitudinal blunt circular cylinder [16], in which the leading edges are sharply cut at an angle of 90° in order to settle the flow separation point there and the boundary layer at the same point can be considered to be very thin. Temperature and velocity profiles have also been measured in the boundary layers for the purpose to investigate the correlation between the heat-transfer characteristics and the flow ones. It is supposed from these results that the behavior of the separated shear layer plays a very important part upon the heat transfer in the separated and reattached flow regions. However the mutual correlations between them are still not clear. Furthermore the nose shapes investigated may be considered to be special ones.

The purpose of the present study is to investigate the heat-transfer characteristics in the separated, reattached, and redeveloped regions of two-dimensional incompressible air flow over flat plates with various nose shapes. Especially considered are the nose shape effects upon the heat-transfer characteristics in such flow regions. Behaviors of flow and thermal boundary layers are also clarified through temperature, velocity, and turbulence measurements. Furthermore the mutual correlations of the heat-transfer characteristics and the shear layer behaviors are investigated in detail.

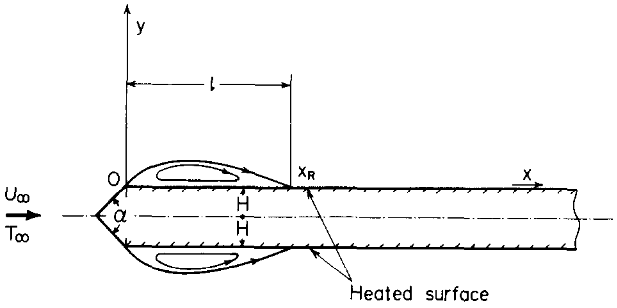

FIG. 1. Flow configuration and coordinate system.

The flow configuration* investigated in the present study is schematically shown in Fig. 1 which includes the coordinate system employed, though the actual flow has very complex features. The flow separates at the corner, where the nose of wedge shape is connected to the flat plate of constant thickness $2H$, and then reattaches on the plate surface. The turbulent boundary layer subsequently develops in the downstream direction. Heating of the plate begins at the corner mentioned above so that the starting point of heating coincides with the separation point. In addition, a semi-circular nose is also used to study the case in which there is no sharp corner and therefore it is considered not to produce a large separation bubble near the leading edge.

EXPERIMENTAL APPARATUS AND TECHNIQUE

The wind tunnel used in the present study is the same as that employed in the previous work by the authors [15]. The test plate (22 mm thick, 100 mm wide, and 550 mm long) was made of two bakelite plates and plywood which was inserted between bakelite plates as reinforcing material. The leading edge of the plate was made to be able to exchange the nose shape in order that the separation and reattachment of flow can be controlled. Nose shapes selected in the present study are wedges of apex angle $\alpha = 180$, 120, 90 and 60°, and also a semi-circular cylinder of 22 mm in diameter. Minute attention was paid not to produce steps at the corner where the nose was connected to the plate. The ratio of plate thickness to tunnel height is 0.055.

Only the plate of 22 mm thick was employed in the present study. It may be presumed that the plate thickness, or more essentially the Reynolds number based on the plate thickness affects upon the flow and heat-transfer characteristics. However the behavior of the separated shear layer does not vary with the Reynolds number when it exceeds some transitional Reynolds number [18, 19]. That is, the separated shear layer changes to the turbulent one just downstream of the separation point and the turbulent shear layer reattaches onto the body surface, or the turbulent boundary layer separates. Therefore the flow field does not vary, in essence, with the Reynolds number [20, 21]. In the present study, the main items to be investigated are the heat-transfer characteristics in such flow regime. Therefore it may be presumed that the present study does not lose its generality due to the limitation of plate thickness. Furthermore the authors have made some experiments of the flow over blunt flat plates of 25.5 mm and 12.8 mm thick respectively [20, 22], and it has been found that there is no essential difference among those plates and the present one.

Heating of the plate was made by conducting electric current to a stainless steel sheet (0.05 mm thick, 100 mm wide and 1122 mm long) stuck to the bakelite plates and the experiments were made under the condition of constant heat flux. Temperatures on the heating surface were measured with 0.07 mm copper-constantan thermocouples soldered on the back of the stainless steel sheet. Twenty-five thermocouples were located in the flow direction at midspan, 11 in the spanwise direction at three cross-sections ($x/H = 1.0$, 8.0 and 24.0), and three in the flow direction which was slightly slipped out of midspan near the leading edge. Furthermore three stuck to the back of bakelite were used to estimate the heat loss from the test surface to the side walls of the wind tunnel. The positions of thermocouples will be clear in the following figures which show the experimental results.

The experimental procedure was almost the same as that in the preceding study [15]. The temperature differences between the wall and the upstream uniform flow were at most 44°C which occurred at the most downstream section. The heat loss estimated from the temperature difference across the bakelite was at most 1% of supplying heat, and therefore it was neglected in the following results. Thermal conductivity and kinematic viscosity of air were estimated at the free stream temperature. The velocity of upstream uniform flow U_∞ ranged from 3.6 m/s to 24.9 m/s and the corresponding Reynolds number $Re = U_\infty H/\nu$ from 2700 to 18 600. The preliminary experiments confirmed the two-dimensionality of wall temperature, though the slight deviation appeared in the reattachment region of the flow.

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* After the authors had finished this work, they noticed the work of Kottke *et al.* [17] which measured the mass transfer for the similar flow configurations to the present ones.

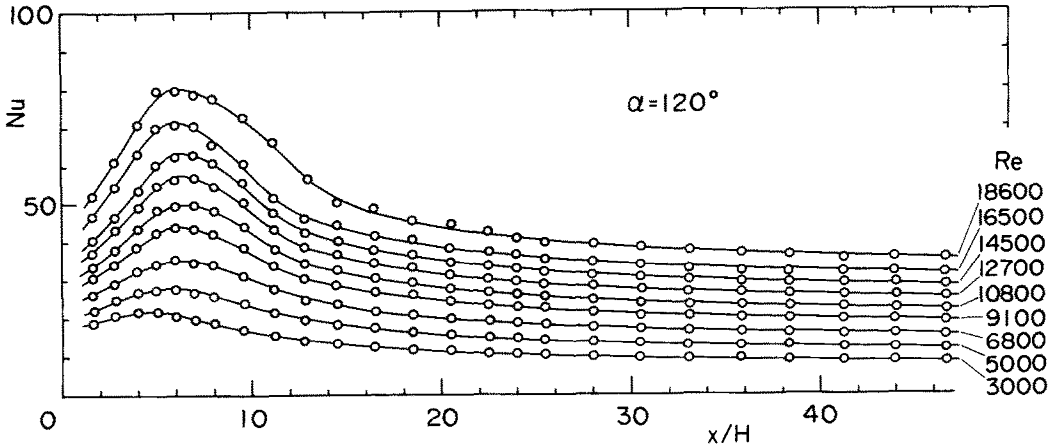

FIG. 2. Local Nusselt number distribution, α = 120°.

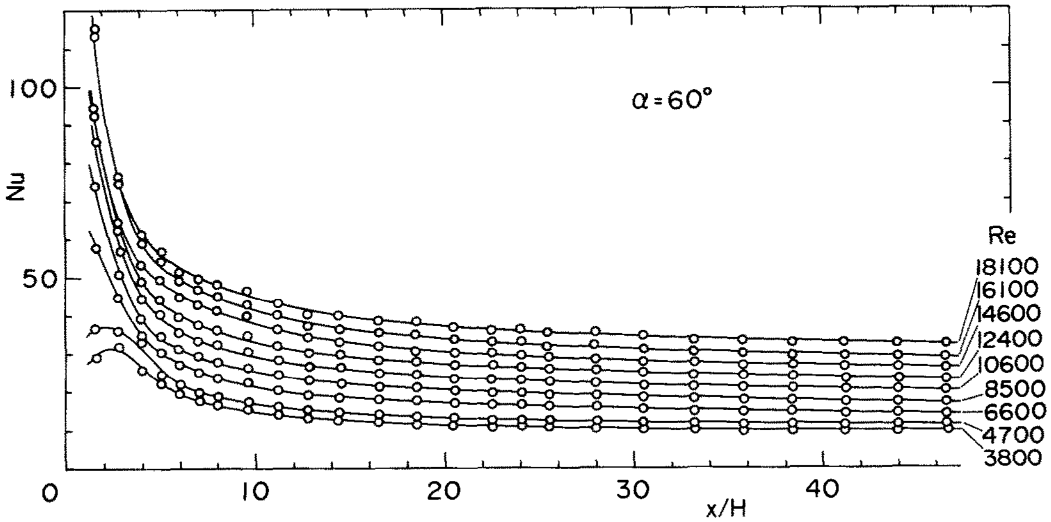

FIG. 3. Local Nusselt number distribution, α = 60°.

The velocity, turbulence and temperature measurements were made with a constant temperature hot-wire anemometer with a linearizing circuit and a temperature probe of 0.07 mm copper–constantan thermocouple respectively. The single wire probe used was calibrated in the upstream uniform flow. The hot-wire was mounted at 90° to the flow direction in the plane parallel to the plate surface. Thus only mean and turbulent fluctuating velocities in the flow direction were determined from linearized mean and root mean square fluctuating voltage readings. The mean voltage reading was corrected for temperature effects by the equation,

$$E_\infty = E_a(T_{hw}-T_\infty)^2/(T_{hw}-T_a)^2 \qquad (1)$$

where T_{hw} is the temperature of hot-wire and E_a denotes mean voltage reading at a point of temperature T_a, and E_∞ corresponds to that at the same point but at temperature T_∞ at which the calibrations were made. Equation (1) is easily derived from Kramers' formula [23] under the assumption that constants found in Kramers' formula are independent of the fluid temperature, and this may be presumed to be reasonable in the present study, for which the temperature variation in the boundary layer is quite small. No corrections were made for the tunnel wall effects upon the flow and heat-transfer characteristics.

EXPERIMENTAL RESULTS AND DISCUSSION

Shown in Figs. 2 and 3 are representative examples of local Nusselt number distribution, $Nu = hH/\lambda$, for the wedges of $\alpha = 120$ and 60°, respectively. In case of $\alpha = 120°$, it is clear that there are peak values in the neighborhood of the leading edge. This reveals that the flow separates at the corner of nose and plate and then reattaches on the plate surface. Furthermore the positions of these peaks are nearly independent of the Reynolds number, and about $x/H = 6$. The heat-transfer coefficient increases in the downstream direction in the separated flow region and attains a maximum at the reattachment point, and subsequently decreases monotonically with the longitudinal distance.

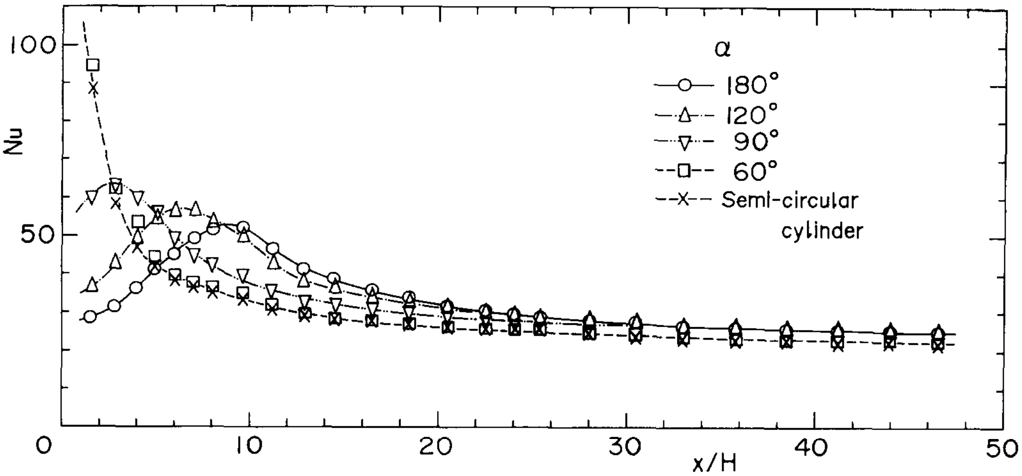

FIG. 4. Nose shape effects on Nusselt number at $Re = 12\,500$.

On the other hand, in case of $\alpha = 60°$ shown in Fig. 3, there is no peak near the leading edge in the range of Reynolds number higher than about $Re = 5000$. However peak values are observed at around $x/H = 3$ in the range of Reynolds number lower than $Re = 5000$. This low Reynolds number regime is presumed to be the transitional one, where the separated shear layer changes to the turbulent one halfway from the separation point to the reattachment one, and the reattachment length decreases steeply as increasing the Reynolds number [19]. It is inferred from this fact and the results of Fig. 5 yielding the correlation between the reattachment length and the wedge angle that in case of the wedge of $\alpha = 60°$, the flow separating at the corner reattaches onto the plate surface at about $x/H = 1.7$ in the range of Reynolds number higher than $Re = 5000$. Peak values are also observed for the semi-circular cylinder in the range of Reynolds number lower than about $Re = 5000$. This may be originated from the reattachment of the shear layer which separates in laminar state from the circular nose.

The effects of nose shape upon the local Nusselt number distribution at $Re = 12\,500$ are typically shown in Fig. 4. There are peak values for the wedges of $\alpha = 180$, 120, and 90°, but not for the wedge of $\alpha = 60°$ and the semi-circular cylinder. It is quite interesting to notice that the reattachment length decreases as decreasing the wedge apex angle and, on the other hand, the peak value of Nusselt number at the reattachment point increases reversely with the decrease of wedge angle. The behaviors of the separated shear layer play very important parts upon these results of the reattachment Nusselt number, which will be discussed later in detail. The heat-transfer coefficient downstream of reattachment decreases monotonically in the flow direction.

The wedge of $\alpha = 180°$ corresponds to the blunt flat plate studied in the previous paper [15]. Some difference is found between the present and the previous data of local Nusselt number in the neighborhood of the leading edge. This may be due to the fact that the sizes of copper electrode, which locates at the most upstream part of the plate and constitutes the corner, are different from each other, that is, the electrode width is 5 mm in the present study and 10 mm in the previous one. It may also be a factor that the shapes of leading edge are not exactly the same between them. It is not easy to obtain quantitatively correct data in the neighborhood of the corner. However it may be inferred that the heat-transfer coefficient increases steeply with approaching the corner as observed in the previous work, because of the strong shear layer locating very close to the plate surface [17].

As shown in Fig. 5, the distance l from the corner to the reattachment point, which is defined as the point of maximum Nusselt number, increases with the wedge angle and it is nearly independent of the Reynolds number with some scatter in the experimental range investigated, though the case of $\alpha = 60°$ is an exceptional one as noted before. Mean values of non-dimensional reattachment length are

$$\left.\begin{aligned} l/H &= 9.0 \quad \text{for } \alpha = 180°,\\ l/H &= 6.0 \quad \text{for } \alpha = 120°,\\ l/H &= 3.0 \quad \text{for } \alpha = 90°,\\ l/H &= 1.7 \quad \text{for } \alpha = 60°. \end{aligned}\right\} \tag{2}$$

The value for $\alpha = 60°$, which is presumed to be valid in the range of about $Re > 5000$, has been estimated from the best fitted experimental curve obtained in Fig. 5 and that curve is approximately expressed in the form of

$$l/H = a(\alpha/\pi)^b. \tag{3}$$

However the determination of values of a and b needs additional experiments. The reattachment Nusselt number for the wedge of $\alpha = 60°$, which will be shown later, is defined as Nusselt number at $x/H = 1.6$ which is the most upstream position of thermocouple, because that is nearly equal to $x/H = 1.7$ obtained above. It has been confirmed in the

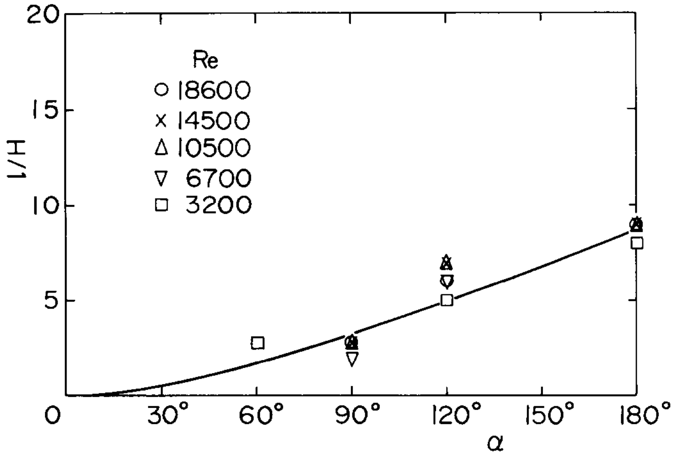

FIG. 5. Variation of reattachment length.

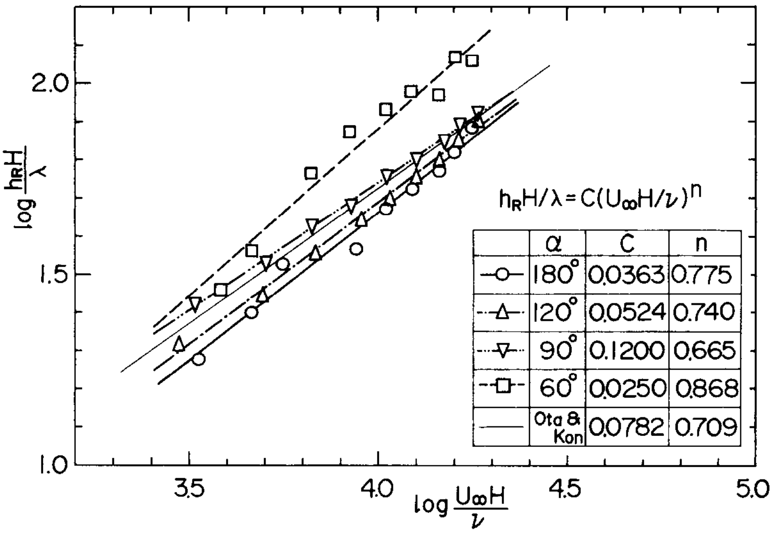

FIG. 6. Nose shape effects on reattachment Nusselt number.

previous studies [15, 16] that the point of maximum Nusselt number is nearly equal to the reattachment point which is defined as a point of zero skin friction and is also determined by tuft probe exploration [20, 21].

The correlation of the reattachment length with the wedge angle in the form of equation (3) may not be extended to the wedge of very small apex angle, because in such flow configuration, the laminar boundary layer develops before the corner is approached and the characteristics of the shear layer just upstream of the separation point may become quite different from that in the present flow situation, for which the shear layer can be thought to separate in laminar state at the corner and change to the turbulent one just downstream of the separation point, and finally the turbulent shear layer reattaches onto the plate surface. This conjecture is based on the fact that the reattachment length is nearly independent of the Reynolds number as shown in Fig. 5.

Figure 6 shows the variation of reattachment Nusselt number $h_R H/\lambda$ for various wedges. It is clear from Fig. 6 that the reattachment Nusselt number increases almost linearly with the Reynolds number for all the wedges investigated, and therefore the correlation of data can be expressed in the form of

$$h_R H/\lambda = c(U_\infty H/\nu)^n. \quad (4)$$

Values of c and n depend on the wedge angle, and included in Fig. 6 are the values which were determined by means of the method of least squares. The reattachment Nusselt number increases with the decrease of the wedge angle at the same Reynolds number as already shown in Fig. 4 and this may be reasonable because as the reattachment length is shorter, the development of the separated shear layer is smaller. Therefore the large velocity and temperature gradients occur at the reattachment region for the wedge of small apex angle comparing with that of large apex angle as shown later.

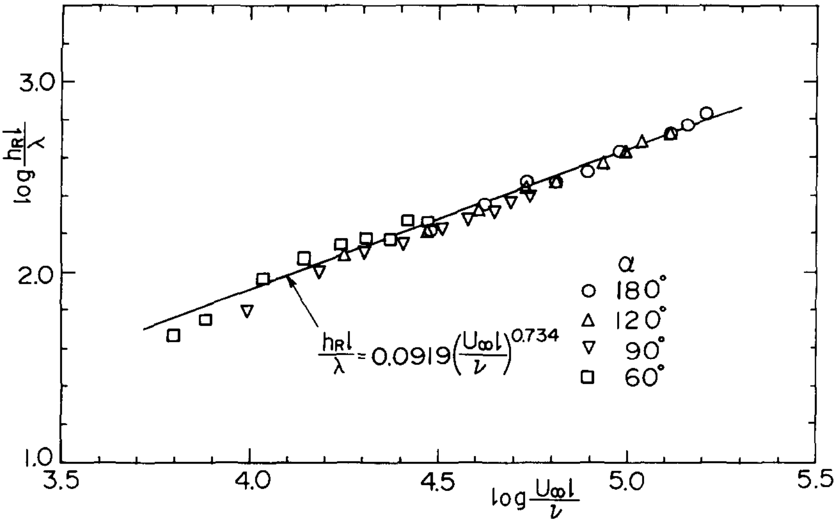

FIG. 7. Correlation of reattachment Nusselt number with Reynolds number.

The correlation between the reattachment Nusselt number and the Reynolds number is shown in Fig. 7 in a modified form, that is, the reattachment length is employed as the reference length in both the Nusselt and Reynolds numbers. It is very interesting to notice that the isolated correlations in Fig. 6 are brought into a single correlation, and the empirical formula obtained by means of the method of least squares is

$$h_R l/\lambda = 0.0919(U_\infty l/\nu)^{0.734}. \quad (5)$$

The idea, that the reattachment length is suitable as the characteristic length to correlate the reattachment Nusselt number with the Reynolds number, may be of use for many other different flow configurations, and an example has already been shown by the authors in the previous work [16], in which the reattachment Nusselt number for the axisymmetric flow is correlated by an equation almost equal to that for the two-dimensional flow, and another example is the study of Seki *et al.* [6].

Figure 8 shows a representative example of the correlation between the local Nusselt number hx/λ and the local Reynolds number $U_\infty x/\nu$ at $Re = 12\,500$. In the separated and reattached flow regions, the characteristic behavior of the correlation strongly depends on the nose shape, and downstream from the reattachment point the local

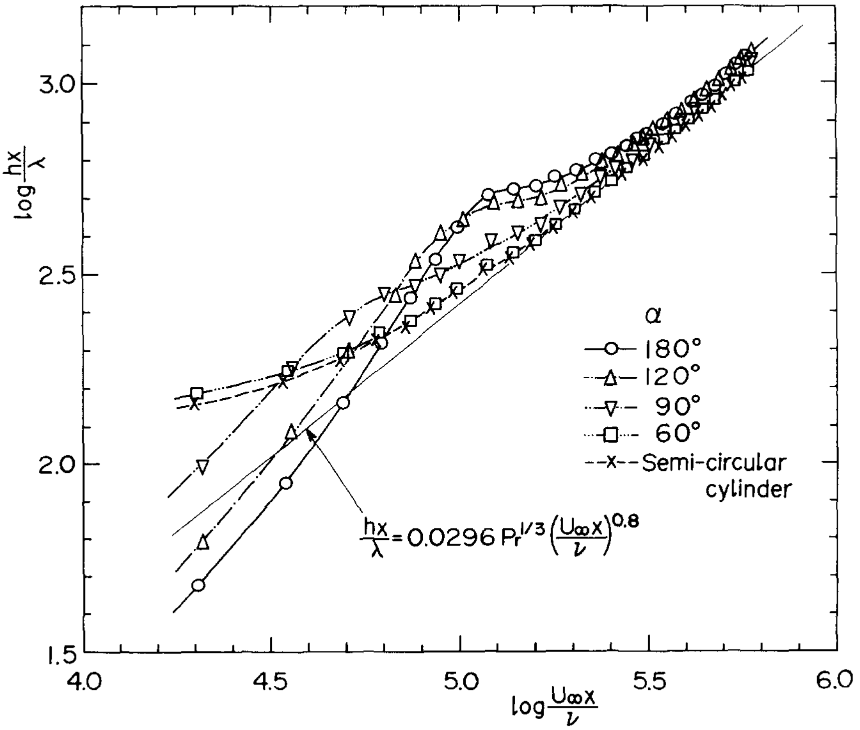

FIG. 8. Nose shape effects on local Nusselt number at $Re = 12\,500$.

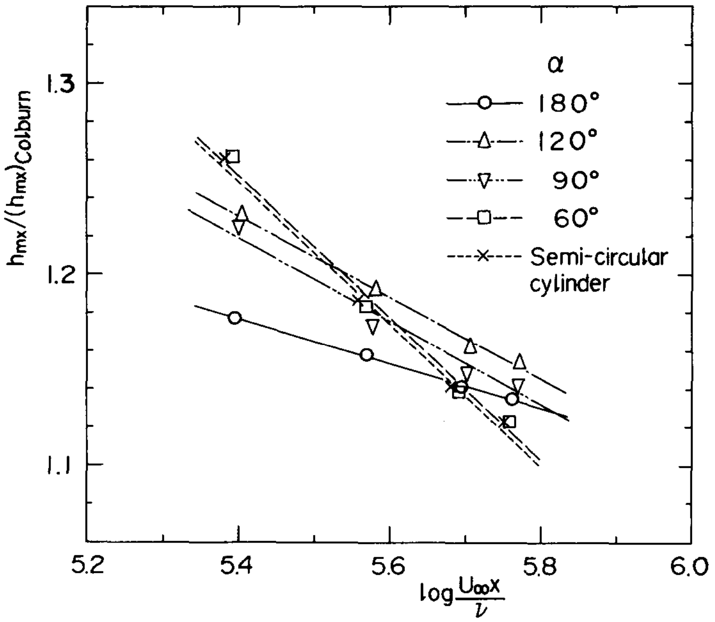

FIG. 9. Variation of mean Nusselt number at $Re = 12\,500$.

Nusselt number approaches Colburn's formula for the ordinary turbulent boundary layer over the flat plate as shown in Fig. 8. In cases of the wedge of $\alpha = 60°$ and the semi-circular cylinder, the approach is quite rapid and the local Nusselt number becomes almost equal to that by Colburn's formula at about $x/H = 20$. However the approach to Colburn's formula becomes slow as increasing the wedge angle and in cases of the wedges of $\alpha = 180$, 120 and 90°, the longitudinal distance investigated in the present study is insufficient to reach the situation where the local Nusselt number takes the same value as the prediction of Colburn's formula. These facts suggest clearly that the separation and reattachment of flow has severe influences upon the heat transfer characteristics for a long distance downstream of the reattachment point.

Figure 9 shows the variation of mean heat-transfer coefficient calculated from

$$h_{mx} = \frac{1}{x}\int_0^x h(x)\,\mathrm{d}x \qquad (6)$$

in the form of the ratio to that by Colburn, for which Prandtl number of air has been assumed to be 0.71.

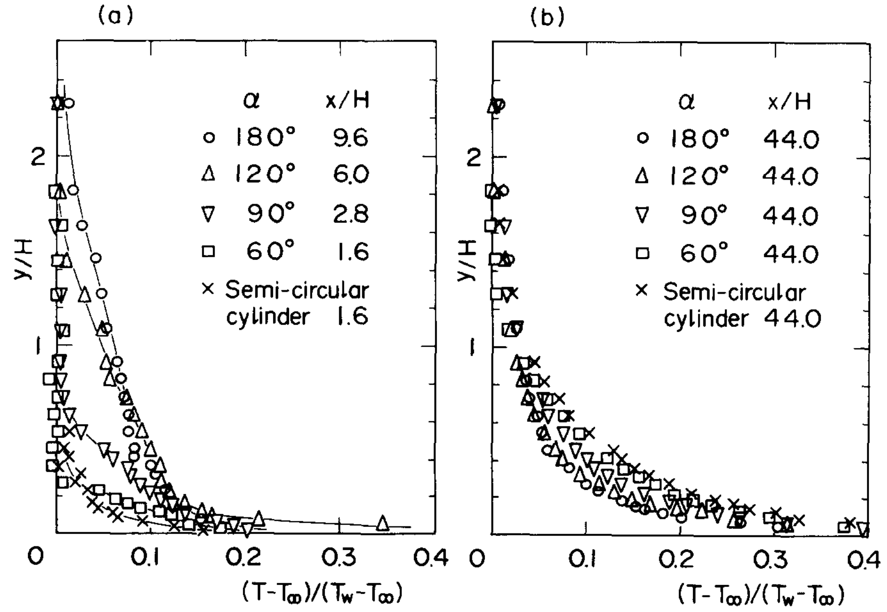

FIG. 10. Nose shape effects on temperature distribution: (a) in reattachment region; (b) far downstream from reattachment point. ($Re = 12\,500$ and $q = 0.84\,\mathrm{kW/m^2}$.)

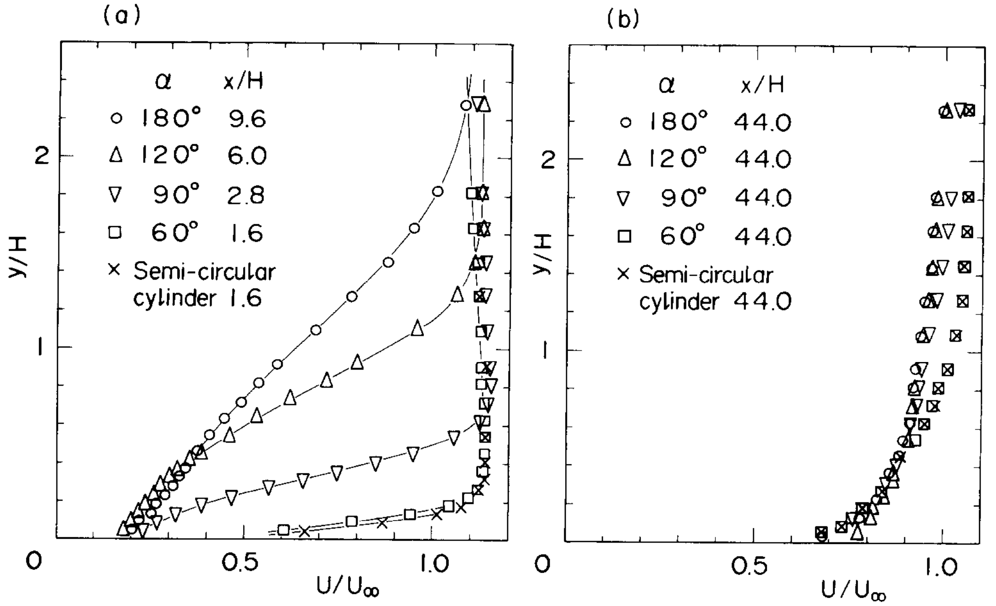

FIG. 11. Nose shape effects on velocity distribution: (a) in reattachment region; (b) far downstream from reattachment point. (Re = 12 500 and $q = 0.84\,\mathrm{kW/m^2}$.)

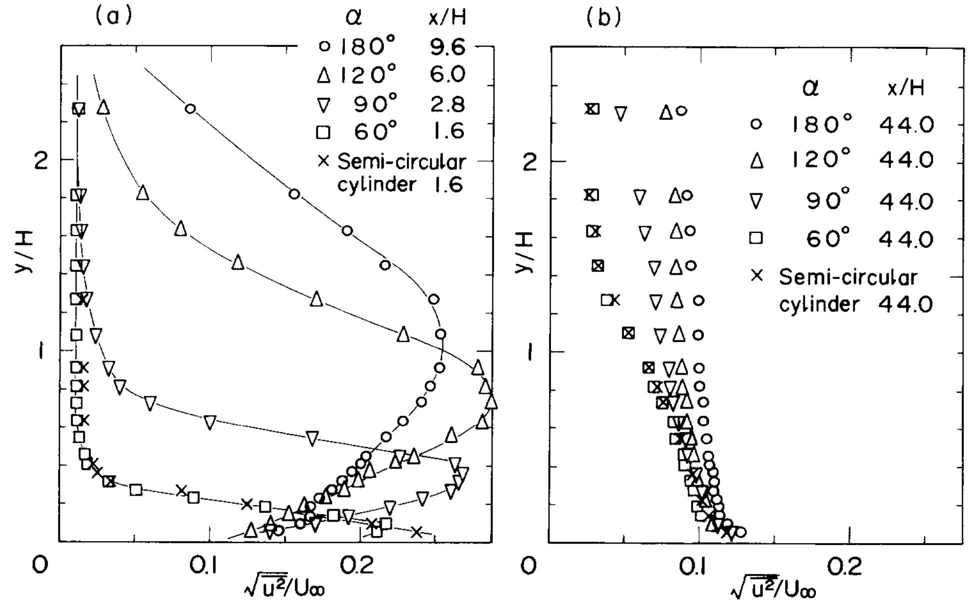

FIG. 12. Nose shape effects on turbulence intensity distribution: (a) in reattachment region; (b) far downstream from reattachment point. (Re = 12 500 and $q = 0.84\,\mathrm{kW/m^2}$.)

The results shown in Fig. 9 are the data evaluated at four longitudinal cross-sections ($x/H = 20.0$, 30.0, 40.0, 46.6) and at $Re = 12\,500$. The value for the wedge of $\alpha = 180°$ is the smallest for a short distance from the corner ($x/H = 20.0$) comparing with those for other nose shapes, however it becomes larger than those for the wedge of $\alpha = 60°$ and the semi-circular cylinder at a downstream cross-section ($x/H = 46.6$). On the other hand, the wedges of $\alpha = 120$ and 90° have relatively high values over the whole plate length comparing with other nose shapes. Furthermore it is found that the mean Nusselt numbers over the whole plate length for all the nose shapes tested are larger by about 10–20% than the values estimated from Colburn's formula in the range of Reynolds number investigated.

Temperature profiles in the boundary layer for various nose shapes are shown in Fig. 10, and velocity and turbulence intensity profiles along the flow direction in Figs. 11 and 12, at $Re = 12\,500$ and $q = 0.84\,\mathrm{kW/m^2}$, respectively. Figures 10(a), 11(a) and 12(a) are the results obtained in the neighborhood of the reattachment point and Figs. 10(b), 11(b) and 12(b) are those obtained at a cross-section far downstream from reattachment.

In the reattachment flow region, all the profiles indicate quite different trends according to the nose shape. Temperature gradient close to the wall for the wedge of small apex angle is larger than that for the one of large apex angle. This may be connected with the fact that the reattachment Nusselt number has a larger value for the wedge of small apex angle than for the one of large apex angle, as previously shown in Figs. 4 and 6. The result for $\alpha = 180°$ does not necessarily show this trend. This may be due to the fact that it was measured at a cross-section a little downstream of reattachment.

It is very clear from Fig. 11(a) that the shear layer is located nearer to the plate surface for the wedge of small apex angle than for that of large apex angle, and the velocity gradient close to the wall is larger for the former than for the latter, since as the reattachment length is shorter, the development of the separated shear layer is restricted in a thin layer. This characteristic behavior of the separated shear layer is connected with the heat-transfer characteristics in the reattached flow region such as found in Figs. 4 and 6.

The maximum value of turbulence intensity is rather smaller for the wedge of small apex angle than for that of large apex angle, however its position approaches nearer to the wall for the former than for the latter, as clearly shown in Fig. 12(a). It may be concluded from these results that it is difficult to estimate the heat-transfer characteristics in the reattached flow region only from the maximum value of turbulence intensity. It is presumed from a peak of turbulence existing at a very short distance from the wall that there exists a small separation bubble in the neighborhood of the corner for the wedge of $\alpha = 60°$.

In the turbulent boundary layer far downstream from the reattachment point, it is noted that the temperature gradient near the wall is larger for the wedge of large apex angle than for that of small apex angle, in contrast with the reattached flow region. The turbulence intensity in the boundary layer is larger for the former than for the latter, although the velocity profiles close to the wall are almost equal to each other for all the nose shapes examined. It may be presumed from this fact that in the redeveloped flow region downstream from the reattachment point, as the turbulence intensity inside the boundary layer is higher, the temperature gradient close to the wall is larger, and consequently the wedge of large apex angle attains the heat-transfer coefficient higher than that for the wedge of small apex angle.

CONCLUDING REMARKS

In order to investigate nose shape effects upon the heat-transfer characteristics in the separated, reattached and redeveloped regions of two-dimensional incompressible air flow over blunt flat plates, nose shapes such as the wedges of apex angle $\alpha = 180$, 120, 90 and 60° and also the semi-circular cylinder have been tested in the experiments. Temperature, velocity, and turbulence measurements have also been made in these flow regions.

It has been found from the results obtained that the reattachment length increases with the wedge angle, and on the other hand the reattachment Nusselt number decreases as increasing the wedge angle. However the correlation between the reattachment Nusselt number and the Reynolds number is independent of the nose shape when the reattachment length is employed as the reference length, and an empirical formula has been presented. The behaviors of the separated shear layer play very important parts upon the heat transfer in the reattached flow region.

In the turbulent boundary layer far downstream from the reattachment point, the heat transfer depends strongly upon the turbulence intensity therein, which varies with the size of separation bubble.

Disturbances in the boundary layer originated from the separation and reattachment of flow extend far downstream of the reattachment point, especially for the wedge of large apex angle, and accordingly the approach of heat-transfer characteristics to those for the ordinary turbulent boundary layer over the flat plate is very slow and needs a long distance.

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TRANSFERT THERMIQUE DANS UN ECOULEMENT SEPARE PUIS RECOLLE SUR UNE PLAQUE PLANE EPAISSE: EFFET DE LA FORME DU BORD D'ATTAQUE

Résumé—Des mesures de transfert thermique concernant les régions séparées, recollées et redéveloppées d'un écoulement d'air bidimensionnel sur des plaques planes ayant des bords d'attaque épais de forme variée. On étudie particulièrement les effets de cette forme sur le transfert thermique, pour chaque région d'écoulement dans laquelle sont mesurés les profils de température, de vitesse, de turbulence. On trouve que le comportement de la couche de cisaillement séparée joue un rôle très important pour le transfert thermique dans les régions de séparation et de recollement et que la relation entre le nombre de Nusselt au recollement et le nombre de Reynolds est indépendante de la forme du bord d'attaque si la distance de recollement est prise comme longueur de référence dans leur définition.

DER WÄRMEÜBERGANG IM GEBIET DER ABGELÖSTEN UND WIEDERANLIEGENDEN STRÖMUNG AN STUMPFEN EBENEN PLATTEN—EINFLÜSSE DER FORM DER ANSTRÖMKANTE

Zusammenfassung—Es werden Wärmeübergangsmessungen im Bereich der abgelösten, wiederanliegenden und wiederausgebildeten zweidimensionalen Luftströmung an ebenen Platten mit stumpfen Anströmkanten unterschiedlicher Formen durchgeführt. Besonders untersucht wurde der Einfluß der Formen der Anströmkante auf die Charakteristik des Wärmeübergangs in diesen Gebieten. Temperatur-, Geschwindigkeits- und Turbulenzprofile in den genannten Strömungsbereichen werden ebenfalls gemessen. Es zeigt sich, daß das Verhalten der abgelösten Grenzschicht einen großen Einfluß auf den Wärmeübergang im Bereich der abgelösten und wiederanliegenden Strömung hat und daß der Zusammenhang zwischen der Nusselt-Zahl und der Reynolds-Zahl im anliegenden Bereich unabhängig von der Form der Anströmkante formuliert werden kann, wenn in beiden Kennzahlen die Länge des Weges der wiederanliegenden Strömung als charakteristische Länge verwendet wird.

ПЕРЕНОС ТЕПЛА ПРИ ОБТЕКАНИИ ЗАТУПЛЕННЫХ ПЛОСКИХ ПЛАСТИН ОТРЫВНЫМ И ВНОВЬ ПРИСОЕДИНИВШИМСЯ ПОТОКОМ. ВЛИЯНИЕ ФОРМЫ НОСОВОЙ ЧАСТИ ПЛАСТИНЫ

Аннотация — Проведены измерения переноса тепла в отрывной, вновь присоединенной и вновь развитой областях двумерного потока воздуха на плоских пластинах с затупленными передними кромками различной формы. Особое внимание обращено на влияние формы носовой части на характеристику теплообмена в этих областях потока. Кроме того, для этих областей проведены измерения профилей температуры, скорости и турбулентности. Найдено, что характеристики отделившегося пограничного слоя оказывают большое влияние на перенос тепла в отрывном и вновь присоединившемся потоках, а также, что форма носовой части не влияет на зависимость между числом Нуссельта для области присоединения и числом Рейнольдса, если в обоих числах длина этой области используется в качестве определяющей.