01 Sep 1975

Separation of Low Reynolds Number Flows Around a Corner

T. Matsui

M. Hiramatsu

M. Hanaki

SEPARATION OF LOW REYNOLDS NUMBER FLOW
AROUND A CORNER

T. Matsui, M. Hiramatsu and M. Hanaki
Gifu University
Kakamigahara, Gifu 504, Japan

ABSTRACT

It was shown experimentally that low Reynolds number flows around a sharp corner do not separate at the corner, and separation points move downstream from the corner with decrease in Reynolds number. For the flow in a channel with a backward-facing step, the experimental results showed a good agreement with those of numerical calculation for the position of separation points and the length of standing vortices.

INTRODUCTION

It is usually thought that a real, viscous flow around a sharp corner separates from the corner. However, on the course of experimental studies of the mechanism of reattachment of separated boundary layers, it was found that low Reynolds number flows around a sharp corner made of two flat plates did not separate at the corner, but separated at a point downstream from the corner. This phenomenon is contrary to the usual idea of separation in a flow around a sharp corner. The phenomenon of separation downstream from a sharp corner was first found experimentally by Hama (1965) in a backstep-type laminar supersonic flow. In numerical studies of the flow in a channel with a backward-facing step, that is the case where the deflecting angle is 90 degrees, Kawaguti (1965) shows a small dotted line segment below the full line indicating dividing streamline near the corner. It was informed by a private communication from Kawaguti that the dotted line is the actual computed dividing streamline, as was conjectured by Roache and Mueller (1970). They show a regular movement of the separation point down the base as the Reynolds number is decreased in their numerical studies. Then, an experimental study of the flow was made in order to confirm the movement of separation points with decrease in Reynolds number.

EXPERIMENTAL ARRANGEMENTS AND PROCEDURES

The experimental arrangement to observe the flow around a sharp corner made of two flat plates is shown in Fig. 1. A channel with parallel walls was used in order to minimize the effect of pressure gradient in the outer flow. Reynolds number, $R_{\delta^*} = U\delta^*/\nu$, was varied by the length L of upstream flat plate and the velocity U of outer flow, where δ^* denotes the calculated displacement thickness of the boundary layer at the corner assuming a semi-infinite flat plate, that is $\delta^* = 1.72\sqrt{\nu L/U}$, and ν denotes the kinematic viscosity. A channel with a backward-facing step is shown in

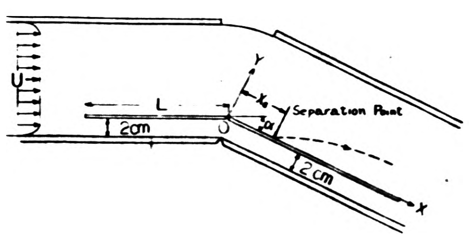


Fig.1. A sharp corner made of two flat plates.

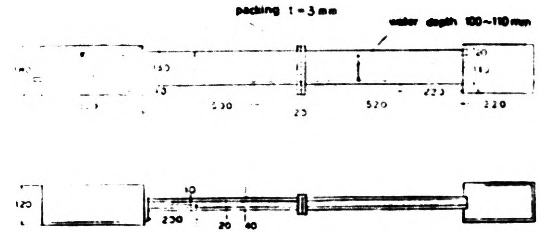


Fig.2. A channel with a back-step.

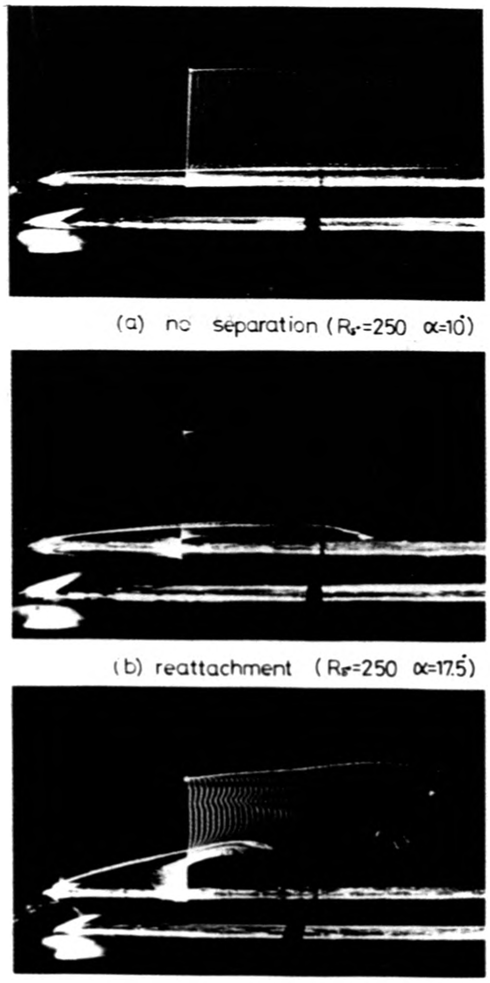
Fig. 2. The width of the channel upstream of the step is 10 mm, that of downstream being 20 mm, so that the height of the step is 10 mm. The channel is long enough to secure the Poiseuille profile both far upstream and downstream from the step according to the assumption in Kawaguti's calculation. The flow was

visualized by the hydrogen bubble technique. Dye method was also used to measure the position of separation on the wall downstream from the corner. Water was used as a working fluid for the flow around a sharp corner made of two flat plates, whereas glycerin solution was used for the flow in a channel with a step as lower Reynolds numbers were required to compare with the calculated results.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Flow Around a Sharp Corner Made of Two Flat Plates

Patterns of flow around a corner by the hydrogen bubble method are shown in Fig. 3, in which time-lines



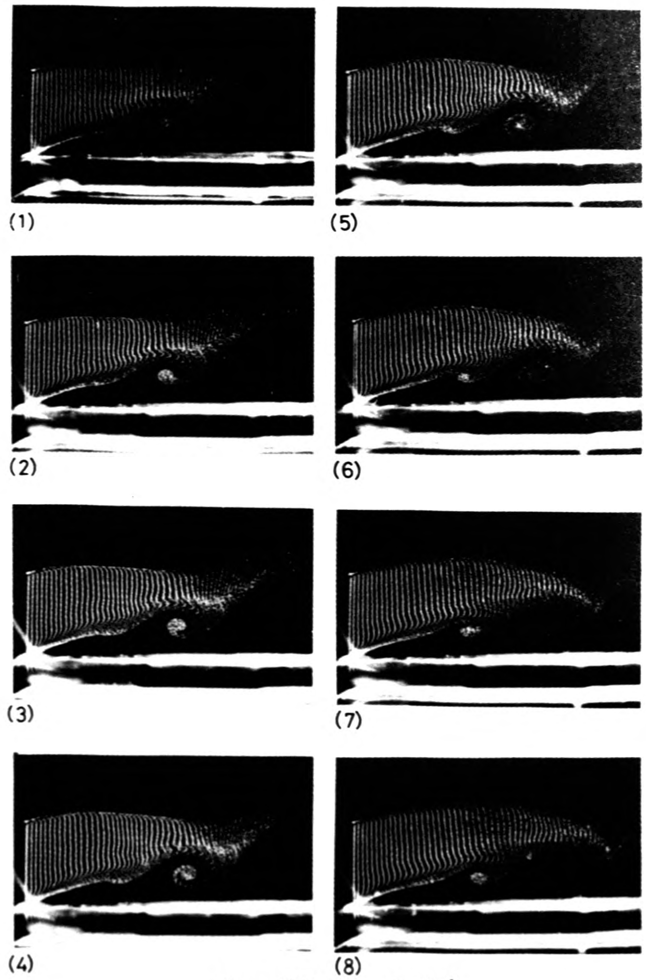
(a) no separation (R_{δ^*}=250 α=10°)

(b) reattachment (R_{δ^*}=250 α=17.5°)

(c) no reattachment (R_{δ^*}=175 α=30°)

Fig.3. Flow around a sharp corner.

are seen with a streak line streaming from a point near the corner. When the angle of deflection of the downstream flat plate, α, is 10 degrees and the displacement thickness Reynolds number, R_{δ^*}, at the corner is 250, the flow advances along the downstream plate with no separation, as is shown in Fig. 3, (a). For α = 17.5°, the flow does separate, and then reattaches to the downstram plate, as seen in Fig.3,(b). In Fig.3,(c), the flow for R_{δ^*}= 175 and α = 30° is shown. The flow does not reattach after separation. The process of vortex formation in the separated shear layer is shown in Fig.4. When α = 20° and R_{δ^*}= 210,



R_{δ^*}=185 α=30°

Fig.4. Vortex formation in a separated shear layer.

vortices formed in the separated shear layer go downstream one after another, and the outer flow reattaches to the downstream wall intermittently. The streamlines in this flow are shown in Fig.5, which are drawn by connecting points of the same rate of flow calculated from the measured velocity profiles at downstream sections from the corner. In this figure, the streamline for zero rate of flow is seen to meet the wall at a point downstream from the corner. Accordingly, the flow does not separate at the corner, but it turns around the corner and then separates at a further downstream point. Dye was painted on the wall downstream from the separation point so that the position of the front of reverse flow, that is the separation line, might be measured directly. An example of measured results is shown in Fig.6, where x_s denotes the distance between the corner and the separation point. It is seen in the figure that the separation point comes

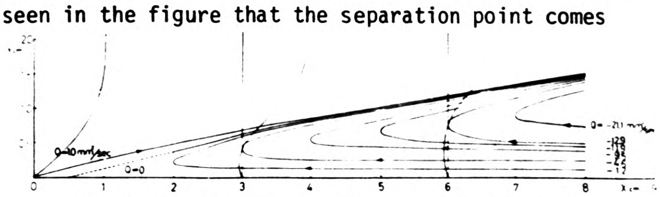


Fig.5. Streamlines in the separated region.

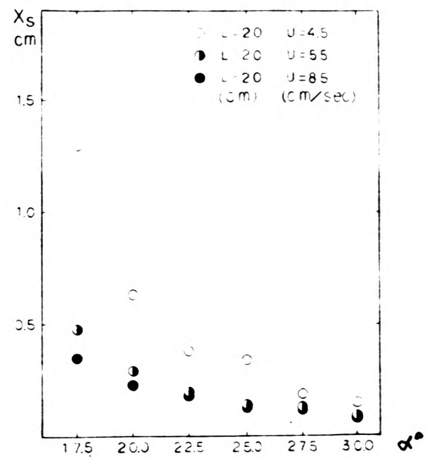


Fig.6. Position of separation point.

nearer to the corner with increase in the angle and the velocity. Also, it was found that the separation point approaches the corner as the length of upstream plate is decreased. When δ_s^* denotes the displacement thickness at the separation point, $R_{\delta_s^*} = U\delta_s^*/\nu$, the Reynolds number, and $P = \delta_s^{*2}/\nu\, |du/dx|_{x=x_s}$, the nondimensional pressure gradient, the log-log plot of x_s/δ_s^* versus $-P/R_{\delta_s^*}$ results in a straight line as shown in Fig.7. Here, δ_s^* is calculated from the assumed length of flat plate longer by x_s than the actual length of upstream plate, and $|du/dx|_{x=x_s}$ is calculated at the section x_s downstream from the corner on the streamline in a potential flow $w = Uz^n$, which passes the point δ from the corner on the bisector of the corner angle, $\delta = 5.2\sqrt{Ux/\nu}$ being the boundary layer thickness at the corner calculated from the length of upstream plate. Then, the actual pressure gradient at the separation point is assumed to have the value of that on the streamline in a potential flow around a corner δ off from the corner. In the same figure, the results of numerical calculation for the flow over a step by Kawaguti is also shown, where the intersecting point of a small dotted line to the rear face of a step was read in his figures as the actual separation point and the displacement thickness was calculated by assuming the center of the upstream channel as the edge of the boundary layer. It may be noted that the results by Kawaguti are also on a straight line almost parallel to the former. Thus, it can be said that the nondimensional distance of separation point from the corner, x_s/δ_s^*, depends on some power of the nondimensional pressure gradient at the separation point, $-P/R_{\delta_s^*}$, regardless of the corner angle, the value of power being a constant. This relation may be suggested by the

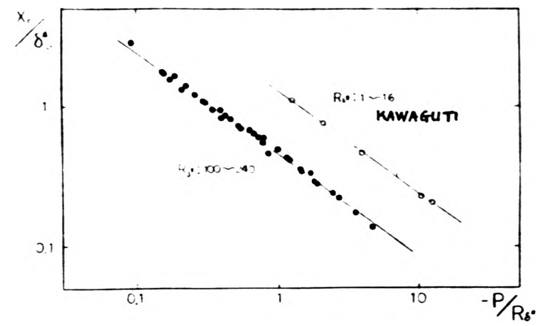


Fig.7. Position of separation point versus pressure gradient.

physical meaning of the nondimensional pressure gradient which is the ratio of pressure force to viscous force.

<u>Flow in a Channel with a Back-Step</u>

This experiment was made to test the calculated results by Kawaguti. In his calculation the flow is assumed to have the Poiseuille profile both upstream and downstream of a step. So, at first, the velocity profile in the channel was measured, and it is shown

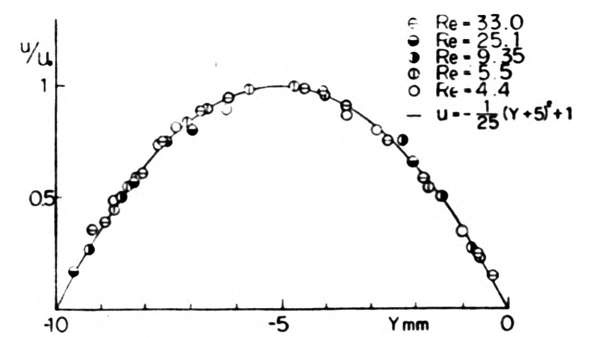
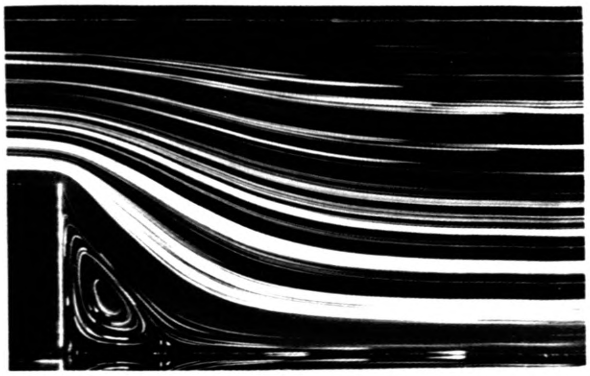
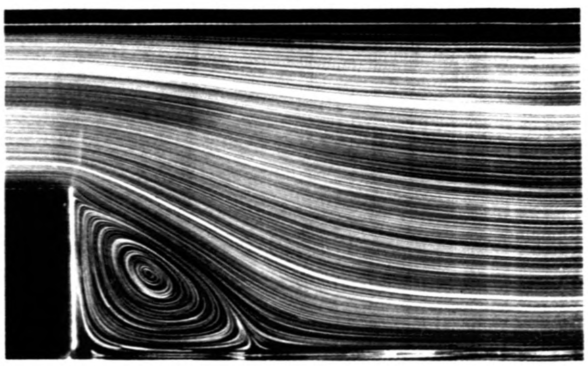


Fig.8. Velocity profile in a channel at the section 8.0 cm upstream from the step.

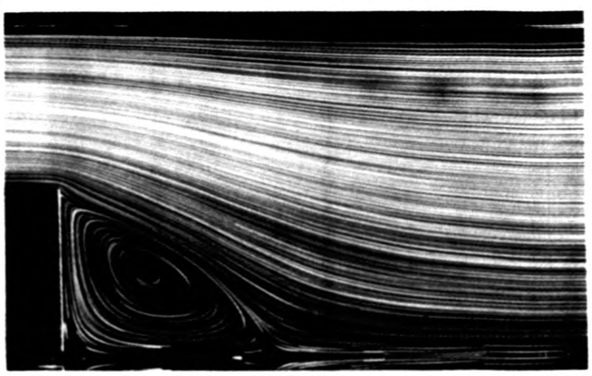
in Fig.8, where the Reynolds number $R = Q/\nu$, Q being the rate of flow. The velocity profile is seen to be parabolic. Flow patterns by hydrogen bubble method are shown in Fig.9. Streamlines over a step near the surface go downward immediately downstream the corner and the separation is seen to occur at a point below the corner. Thus, the measured position of separation point is compared to the calculation by Kawaguti in Fig.10. The measured length of standing vortex and



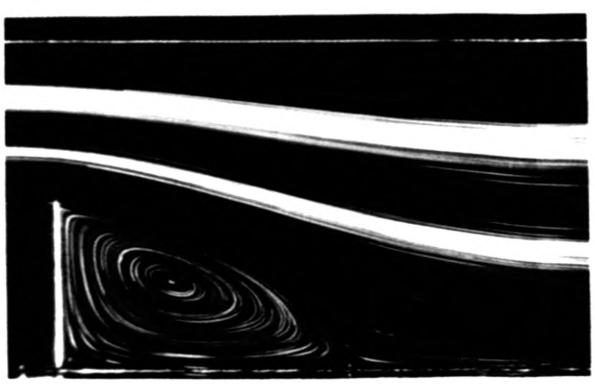
R = 4.8



R = 10.8

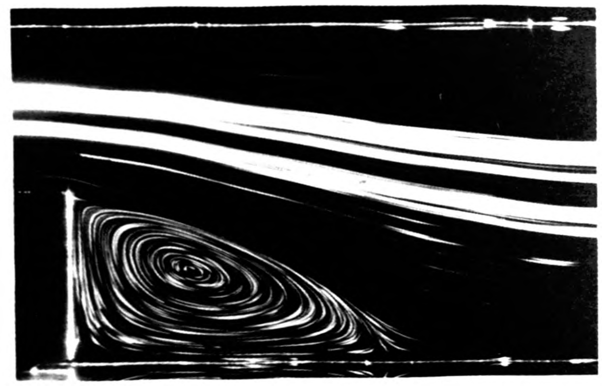


R = 13.1

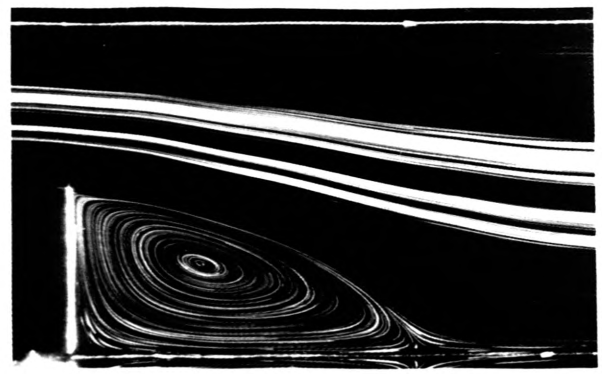


R = 15.7

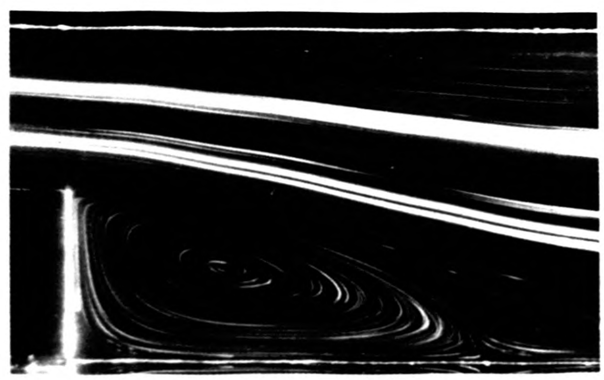
Fig.9. Patterns of flow over a back-step.



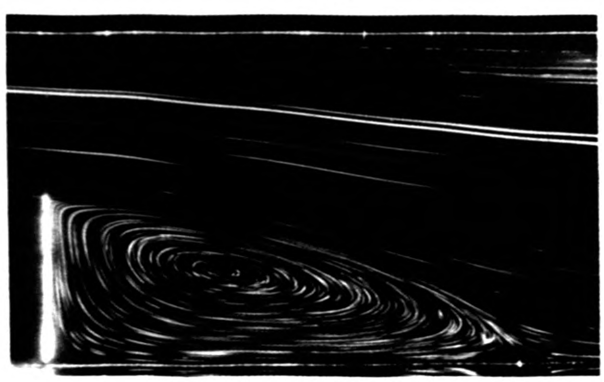
R = 24.2



R = 27.2



R = 38.5



R = 45.5

Fig.9. continued.

the measured position of its center are shown in Fig.11 and Fig.12, respectively, being compared with the calculation. It is seen that the experimental results show a good agreement with the calculated results.

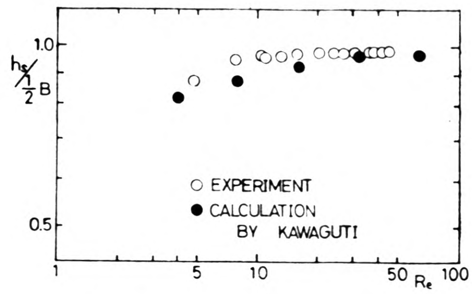


Fig.10. Position of separation point in a flow over a step.

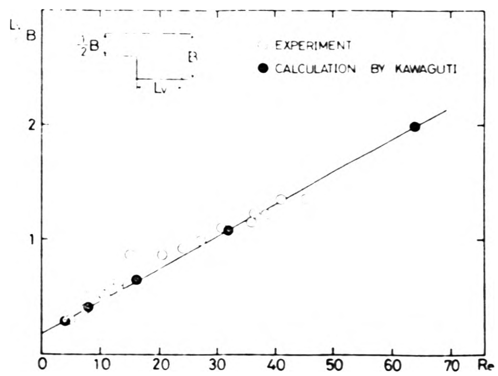


Fig.11. Length of standing vortex.

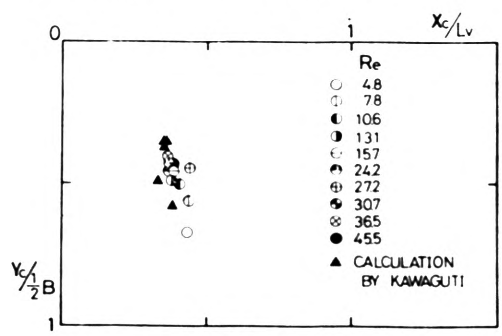


Fig.12. Position of center of standing vortex.

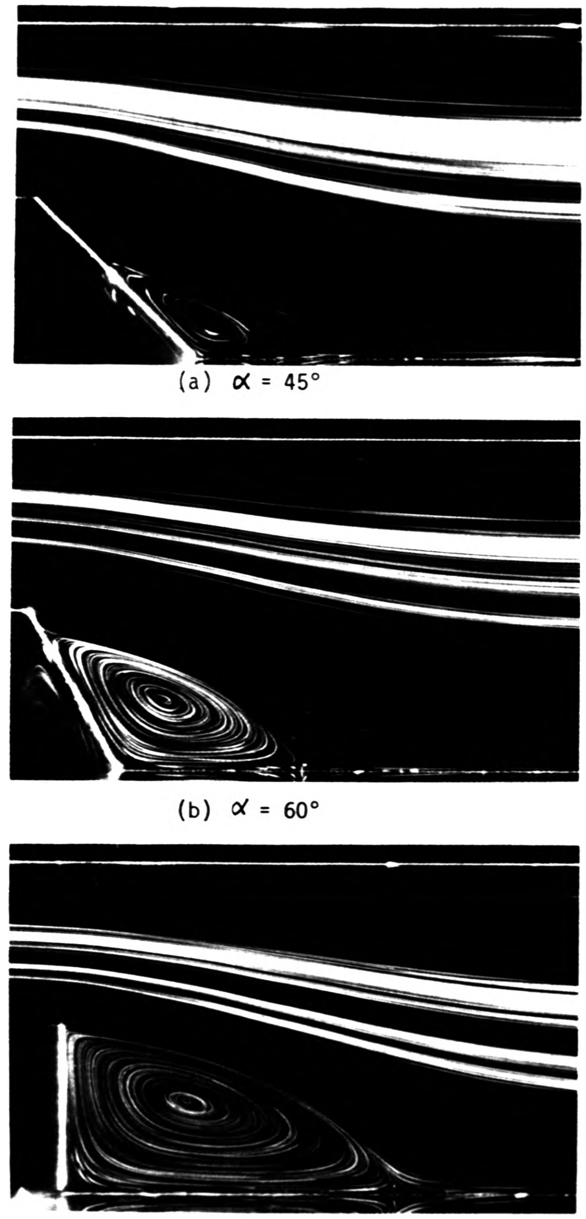
The effect of the step angle on separation is seen in Fig.13, where (a), (b) and (c) are for the step angle α = 45°, 60° and 90°, respectively. It can be seen that the separation point moves to the corner with increase in the step angle.

CONCLUSIONS

It was shown experimentally that low Reynolds number flows around a sharp corner turn around the corner and then separate at a point downstream from the corner. The nondimensional distance of separation point from the corner depends on the ratio of the non-dimensional pressure gradient to Reynolds number, regardless of the corner angle.

The experimental results for the flow in a channel with a back-step shows a good agreement with the calculated results by Kawaguti.

The separation point moves near to the corner as the deflecting angle at the top of a step increases.



(a) α = 45°

(b) α = 60°

(c) α = 90°

Fig.13. Effect of the step angle on separation. R = 27.2.

BIBLIOGRAPHY

1. Hama, F. R.,1965, "Experimental Investigations of the Base Flow Problem. II. Wedge", Space Programs Summary 37-37, Jet Propulsion Lab., Calif., 6, 237.

2. Kawaguti, M., 1965, "Numerical Solutions of the Navier-Stokes Equations for the Flow in a Channel with a Step", Tech. Summary Rept. 574, Mathematics Research Center, Univ. of Wisconsin, Madison, Wis.

3. Roache, P. J. and Mueller, T. J., 1970, "Numerical Solutions of Laminar Separated Flows", AIAA Journal, 8, 530.

DISCUSSION

R. Hummel, University of Toronto: Does your separation point move?

Matsui: It moved to and fro in the flow around a corner made of two plates. It was stationary in the step flow. Generally speaking, the movement of separation point is due to the vortex formation in the shear layer on the top of the separated region and/or the vortex shedding from that region, which are promoted with the increase in Reynolds number.

Hummel: You mentioned that you measured time lines in the portion where you had the hydrogen bubbles in reverse flow. It looked like it would be rather hard to measure individual time lines, that you could measure the thickness, but maybe not the direction. I was wondering if you could comment on how well the student could measure the time lines in the recirculated flow.

V. Goldschmidt, Purdue University: I wonder whether either Kawagutis' analysis or your measurements (as noted in Figure 7) might suggest what would happen to X_s as L (or S_s*) becomes larger and larger (finally approaching infinity or prior to that transition). I suspect that the results of figure 7 will change as that occurs.

Matsui: It is not easy to tell the effect of L on X_s. X_s may have a maximum value for some value of L. In our experiment, X_s had the tendency to increase with the increase in L, which was varied from 10 cm to 40 cm, though X_s for L = 10 cm was maximum for large deflection angles and for low velocities and X_s for L = 20 cm was maximum for small deflection angles and for low velocities. At first, the values of X_s/δ_s^* were plotted against (-P) in log-log plot. The plotted points were not on a single line, and Kawaguti's data were on another line with a different slope. When they are plotted against $(-P)/R\delta_s^*$, they are on a single line and Kawaguti's data are on another line with the same slope as that of the former, as shown in Figure 7. The physical meaning of $(-P)/R\delta_s^*$ is the ratio of assumed adverse pressure force to inertia force on the fluid element in the boundary layer at the section X_s because

$$\frac{P}{R_{\delta_s^*}} = \frac{\delta_s^{*2}}{\nu} \left|\frac{du}{dx}\right|_{X_s} \cdot \frac{\nu}{\overline{U}\delta_s^*} \sim \delta_s^* \left(-\frac{dp}{dx}\right)_{X_s} / \delta\overline{U}^2$$

So, I don't think that the relation between X_s/δ_s^* and $(-P)/R_{\delta_s^*}$ will change for large L, so long as the flow is laminar.

B. Jones, University of Illinois: I have one comment and three questions. I think you are too modest in your appraisal of the level of agreement in Figure 10. It looks good to me. 1) How quantitatively sharp is the corner? For example (radius of curvature/δ*) Could give a measure. 2) In the shallow angle case, such as Figure 13 (a), did the length of the downstream plate influence the separation? 3) It appears that the separated region may be from a forward facing step in Figure 13. Would you speculate on this?

Matsui: 1) The radius of curvature was not measured. The corner was made of two flat plates of 5 mm thickness with a sharp edge less than 0.1 mm thick where the two plates met. 2) The length of the base plate was constant and was long enough not to influence the separation in our experiment. I think it may influence the separation if it is short. 3) I am sorry I do not exactly understand the meaning of your question. We did not use a forward facing step. It seems to relate to your question 2. In Figure 13, as the step height is kept constant, the length of the plate between the top corner and the bottom corner is longer in the shallow angle case, and it influences the separation. In the step flow, the effect of step angle consists of that of deflection angle at the top corner, the length of step surface and the deflection angle at the bottom corner, which are expressed as functions of the deflection angle at the top corner. In Figure 13, the effect of step angle is shown.