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Adaptive Separation Control System Using Vortex Generator Jets for Time-Varying Flow

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ABSTRACT

Flow separation is mostly an undesirable phenomenon and boundary layer control is an important technique for flow separation problems on airfoils and in diffusers. Longitudinal (streamwise) vortices are produced by the interaction between jets and a freestream. This technique is known as the vortex generator jet method of separation, or stall control. The vortex generator jet method is an active control technique that provides a time-varying control action to optimize performance under a wide range of flow conditions because the strength of longitudinal vortices can be adjusted by varying the jet speed. In the present study, an active separation control system using vortex generator jets with rectangular orifices has been developed. The active separation control system can be practically applied to the flow separation control of a two-dimensional diffuser. It was confirmed that the proposed active separation control system could adaptively suppress flow separation for the flow fields caused by some changes in freestream velocity and the divergence angle of the diffuser.

Keywords: Separation, Boundary Layer, Jet, Longitudinal Vortex

NOMENCLATURE

Cp	wall pressure recovery coefficient $=2dp/\rho U_0^2$
Cp_L	local pressure recovery coefficient of diffuser
Cp_{th}	ideal pressure recovery coefficient $=0.60$
dp	differential pressure
Δp	differential pressure between inlet and outlet of diffuser
t	control time
T	non-dimensional control time $=U_0t/L$
L	distance from the jet orifice to the control point
U_0	local freestream velocity
U	mean velocity in streamwise direction
V	mean velocity in normal direction
W	mean velocity in spanwise direction
V_j	jet mean speed
VR	ratio, V_j/U_0
X	streamwise coordinate
Y	vertical coordinate
Z	spanwise coordinate
α	divergence angle of lower wall
η	diffuser effectiveness $=Cp_L/Cp_{th}$
ϕ	jet pitch angle
θ	jet skew angle
ρ	density
ω_x	streamwise component of mean vorticity

Subscript

e	diffuser outlet X=250 mm
i	diffuser inlet X=−10 mm

1. INTRODUCTION

Flow separation is an undesirable problem on airfoils of aircraft and fluid machinery because it entails large energy losses. Boundary layer control has been widely used in aerodynamic applications to inhibit flow separation. Boundary layer mixing is an effective method by which to prevent separation. In mixing, fluid particles that have large freestream energy are supplied to decelerated fluid particles in the boundary layer by the secondary flow of longitudinal vortices. Boundary layer control techniques using longitudinal vortices are classified into passive or active methods. Passive control techniques with solid vortex generators have practical applications in stall control on airfoils and in diffusers. For example, solid vortex generators installed on airfoils are useful for improving flight performance during aircraft take-off and landing. However, solid vortex generators do not have the ability to adapt time-varying flow fields. Furthermore, solid vortex generators are always exposed in the flow and increase drag.

On the other hand, jets issuing through small holes in a wall into a freestream have proven effective in the control of boundary layer separation. Longitudinal vortices are produced by the interaction between jets and a freestream. This technique is known as the vortex generator jet method, an active control technique that provides a time-varying control action to optimize performance under a wide range of flow situations. The vortex generator jet method can adjust the strength of longitudinal vortices by varying the jet speed. The vortex generator jets can achieve adaptive control by properly adjusting the jet speed corresponding to flow parameters such as the angle of attack of an airfoil, the divergence angle of the diffuser, and the freestream velocity. Furthermore, in flow fields in which the separation control is not needed, parasitic drag can be avoided with the jet flow turned off. The vortex generator jet method may accomplish separation control only when necessary, and therefore the method is useful for both design and off-design conditions. If the control device operates only when it is necessary and can adaptively suppress flow separation, the ideal flow corresponding to the flow under its design condition is always attained without changing the design of the airfoil or the diffuser.

The vortex generator jet method was first examined almost 50 years ago by Wallis (1956) and Wallis and Stuart (1958), primarily for the purpose of delaying shock-induced separation of turbulent boundary layers. In recent years, the application of vortex generator jets to control of the dynamic stall produced by changing the angle of attack of the airfoil have been reported, Petz and Nitsche (2004), Magill and McManus (1998). However, the control system does not have the ability to adaptively suppress the flow separation caused by changing flow conditions. Applications of vortex generator jets to time-varying flow fields have not yet been reported. The objective of the present study was to develop an active separation control feedback system and to confirm the effectiveness of vortex generator jets with rectangular orifices for time-varying flow fields. In a previous study, we concluded that the suppression effect was affected by the jet orifice shape and that the suppression effect of vortex generator jets can be improved by a rectangular orifice shape, Yoshikawa *et al.* (2003). In order to obtain the beneficial effect of separation control, rectangular-jet vortex generators were selected for use in the proposed system.

2. EXPERIMENTAL APPRATUS AND METHOD

2.1 Experimental Apparatus

Figure 1 shows a schematic diagram of the test section. Experiments were conducted in a low-speed wind tunnel. The freestream velocity U_0 was varied from 0 to 12 m/s. The test section inlet dimensions were 250×120 mm (W × H). The test section has the function of a variable diffuser, which can adjust the divergence angle of the diffuser α between 0 and 30 deg using a stepping motor controlled by a personal computer. Separation occurs at α = 20 deg in all freestream velocities. The jet flow was delivered through a valve after accumulating the air in a tank using a compressor. Figure 2 shows the configuration of jets and the coordinate system used to describe the flow field. Three jet orifices were placed 55 mm upstream of the divergent portion. The orifices were placed on the right-hand side of the test section. The generation of streamwise mixing vortices with vortex generator jets that are pitched at an acute angle relative to the main flow surface and skewed with respect to the local main flow direction is useful for separation control, Compton and Johnston (1992), Hasegawa and Matsuuchi (1998). In the present study, the jets were skewed at 90 deg (θ = 90 deg) with respect to the freestream direction and were pitched at 30 deg (ϕ = 30 deg) to the lower wall. In the control system, rectangular orifices with an aspect ratio of 6.4 were used, and the long side of the orifice was set in the spanwise (Z) direction (see Fig. 2).

2.2 Experimental Method

Figure 3 shows the locations of static pressure holes. The wall static pressure hole of the downstream side was set on the center line of the divergent portion. The flow condition is judged by measurements of wall static pressure at two points upstream of the divergent portion (X = −150 mm, unstalled region) and in the divergent portion (X = 110 mm). Static pressure measurements were carried out using a differential pressure transducer that has the ability to measure very small differential pressure (0.001 Pa). In the present study, the flow conditions were made changeable by varying the freestream velocity and the divergence angle of the diffuser. The vortex generator jet method could adjust the strength of longitudinal vortices by varying the jet speed. Adaptive control was achieved by adjusting the jet speed corresponding to the degree of separation. The magnitude of the jet flow rate is characterized by the jet-to-freestream velocity ratio VR (= V_j/U_0). The values of freestream velocity U_0 and jet velocity V_j used here are nominal values. That is, these values are the freestream conditions with no-jet flow and jet conditions with no freestream, respectively. This system consists mainly of a differential pressure transducer, a valve with a controller, and a personal computer. The valve was actuated by an electric signal from a personal computer. Figure 4 shows a flowchart of this system. This system initially samples a differential pressure to judge the flow situation. If flow separation is detected, the vortex generator jet device operates automatically and controls the jet speed to suppress the flow separation. The system achieves sufficient pressure recovery and judges the attainment of the control after which it maintains a constant jet speed. The system senses the unstalled flow field and cuts off the jets completely for the situation in which no flow separation occurs. When flow separation is caused by a change in the flow situation (e.g., freestream velocity and divergence angle of the diffuser) the system restarts automatically.

If the rate of pressure recovery of the diffuser is defined near the center axis of the wind tunnel, then pressure losses may be neglected. The local pressure recovery coefficient Cp_L is then given by

$$Cp_L = \Delta P \Big/ \frac{1}{2}\rho U_i^2 \qquad (1)$$

$$\Delta P \approx \frac{1}{2}\rho\left(U_i^2 - U_e^2\right) \quad (2)$$

where subscript i and e indicate the inlet and outlet of the diffuser, respectively. In the present study, U_i is measured at $X = -10$ mm and U_e at $X = 250$ mm. The diffuser effectiveness η is defined by $\eta = Cp_L/Cp_{th}$, where Cp_{th} is the ideal pressure recovery coefficient ($Cp_{th} = 0.6$ at $\alpha = 20$ deg). In this diffuser, the value of the diffuser effectiveness was 0.2 at $\alpha = 20$ deg under no control.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The surface tuft method was used as a diagnostic technique to observe the suppression effect of the active separation control system on separated flows. Figure 5 shows the instantaneous photographs in the divergent portion of the test section for $U_0 = 6.5$ m/s and $\alpha = 20$ deg. The freestream is always from left to right, and tufts are placed on the lower wall on the centerline of the diffuser ($Z = 125$ mm). The tuft on the downstream side in this photograph is set at $X = 210$ mm. The flow visualizations show that the surface flow in the divergent portion is observed, and the flow separation can be suppressed by operating the system.

The vortical field generated by the interaction of the jet and the freestream was measured using an X-type hot-wire probe that was supported by a three-axis computer-controlled traverse unit. The streamwise vorticity ω_x is given by

$$\omega_x = \frac{\partial W}{\partial Y} - \frac{\partial V}{\partial Z} \quad (3)$$

where V and W indicate the velocity in the Y and Z directions, respectively. In the present study, the vorticity is defined as negative for vortices of clockwise rotation as viewed from downstream. The vorticity is calculated by the velocity in the Y-Z plane measured at equal intervals of 5 mm, in both the Y and Z directions. Figure 6 shows the contours of the streamwise vortices at $X = 110$ mm. Figure 7 shows the secondary flow vectors, corresponding to the vortical field (see Fig. 6) in the Y-Z plane at $X = 110$ mm. Figures 6(a) and 7(a) show the flow situation when the system attains suppression, in which the value of the diffuser effectiveness was 0.6. On the other hand, Figs. 6(b) and 7(b) show the flow situation before the system attains suppression, in which the value of the diffuser effectiveness was 0.4. When the system does not suppress separation, the jet speed ($VR = 4.5$) is lower than that for the attainment of suppression ($VR = 9.5$). Since three pairs of positive and negative vortices are aligned corresponding to the three jet orifices, the longitudinal vortices and the downwash of the secondary flow in the region close to the lower wall are strong for $VR = 9.5$, in contrast to those for $VR = 4.5$. In general, the large energy of the freestream is supplied to decelerated fluid particles in the boundary layer by longitudinal vortices, and separation control is achieved. Therefore, for effective separation control, it is important that the secondary flow toward the lower wall is strong in the region close to the lower wall.

Figure 8 shows the differential pressure variations after the system began to suppress flow separation. The abscissa denotes the control time normalized by the time during which fluid particles move from the position of the jet orifice ($X = 0$ mm) to the controlled point ($X = 110$ mm). In these figures, point S indicates the time at which the system starts. Point A indicates the point at which the separation control is attained. In Model-A, the jet flow rate per control step is maintained constant for various flow situations. Figure 8(a) shows the differential pressure variation under control for Model-A. The differential pressure is increased by operating the system for all freestream velocity. For $U_0 = 10$ m/s, the response is faster than in other cases, because effective pressure recovery is accomplished by the strong longitudinal vortices due to faster freestream velocity. For Model-A, the system is affected by the freestream velocity because the jet flow rate per control step is maintained constant. The strength of longitudinal vortices is related to the freestream velocity, and longitudinal vortices become stronger in the same jet flow rate as the freestream velocity increases.

Model-A was improved in order to adapt the flow situations more quickly for $U_0 = 6.5$ and 8.5 m/s. The alteration point from Model-A to the improved system, Model-B, is that the jet flow rate per control step varies adaptively for various flow conditions. Figure 8(b) shows the differential pressure variation with time for Model-B. For $U_0 = 10$ m/s, the control time in Model-B becomes similar to that in Model-A. However, the control time is improved for $U_0 = 6.5$ and 8.5 m/s in Model-B. Comparing Fig. 8(a) with Fig. 8(b), the control time of Model-B is found to be shorter than that of Model-A for $U_0 = 6.5$ and 8.5 m/s, and the number of steps until the system judges the attainment of the separation control decreases. For Model-A, the $U_0 = 10$ m/s case indicates the effective pressure recovery and attains faster control compared with the $U_0 = 6.5$ and 8.5 m/s cases. On the other hand, in Model-B, the system indicates the same trend of the pressure recovery for each freestream velocity. If flow separation occurs in the jet-off situation, the large increment of the jet flow rate is required. The jet flow rate per control step is made large in order to decrease the number of steps until which the system operates at the optimal jet speed. Moreover, the system can decrease the jet flow rate when the system approaches the optimal performance in order to prevent the overshooting of the target value. The alternation point is useful in reducing the number of control steps by which the system adjusts the jet flow rate by the large pressure recovery because the difference between the differential pressures of the stalled and unstalled flow fields is large. If pressure fluctuations are neglected in contrast to a large pressure recovery, the system can be operated stably and can be controlled more quickly.

Figure 9 shows the differential pressure plotted with respect to the control time for the flow field, which causes flow separation. Model-B was applied to the time-varying flow fields caused by changes in the freestream velocity and the divergence angle of the diffuser. In this figure, point S indicates that the system senses the change in the flow field and starts to accomplish the separation control. Point A indicates the point at which the separation control is attained by operating the system. At point C, the flow condition is changed. In this example, separation occurs initially, and the system tries to suppress flow separation at point

S_1. In addition, the differential pressure increases. The system attains suppression at point A_1 and maintains the jet speed constant beyond point A_1. The differential pressure decreases slightly when the freestream velocity is changed from U_0 = 10 to 6.5 m/s at point C_1. As mentioned above, the strength of the longitudinal vortices is related to the freestream velocity for the vortex generator jets, and the suppression is accomplished by the strong vortices due to faster freestream velocity if the jet speed is constant. Therefore, in this situation, the system cannot suppress the flow separation with the present jet speed and requires the increment of the jet flow rate because of the decrement of the freestream velocity. The system starts to increase the jet flow rate again at point S_2, and the differential pressure is recovered. The suppression is attained at point A_2, and the system maintains the jet speed after the suppression. The divergence angle of the diffuser is changed from 20 to 0 deg in 10 seconds (2 deg/s) at point C_2. At point S_3, the system cuts off the jets completely after the divergence angle is reached at an angle of 10 deg. In this diffuser, the flow separation does not occur at α = 10 deg for all freestream velocities. The flow condition indicates the stalled flow field again after the divergence angle is changed from 0 to 20 deg at point C_3. At point S_4, the system senses flow separation and starts to reissue the jets. The system adjusts the jet speed, and the suppression is attained at point A_4. After this time, the system maintains the jet speed constant.

4. CONCLUSIONS

An active separation control system using vortex generator jets with the ability to adapt time-varying flow fields has been developed. The findings of the present study are summarized as follows:

(1) The proposed active separation control feedback system can adaptively suppress the flow separation for flow fields caused by some changes in freestream velocity and the divergence angle of the diffuser.

(2) In the proposed system, the flow conditions can be judged by wall static pressure measurements at two points alone, and separation control is made in reference to the differential pressure.

(3) Model-B can attain the faster response because the jet flow rate per control step varies adaptively for various flow conditions. Model-B is useful for reducing the unstable operation of the system by the large pressure recovery per control step. In other words, the pressure fluctuations are negligible compared to the large pressure recovery and the system can be operated stably and faster separation control can be achieved.

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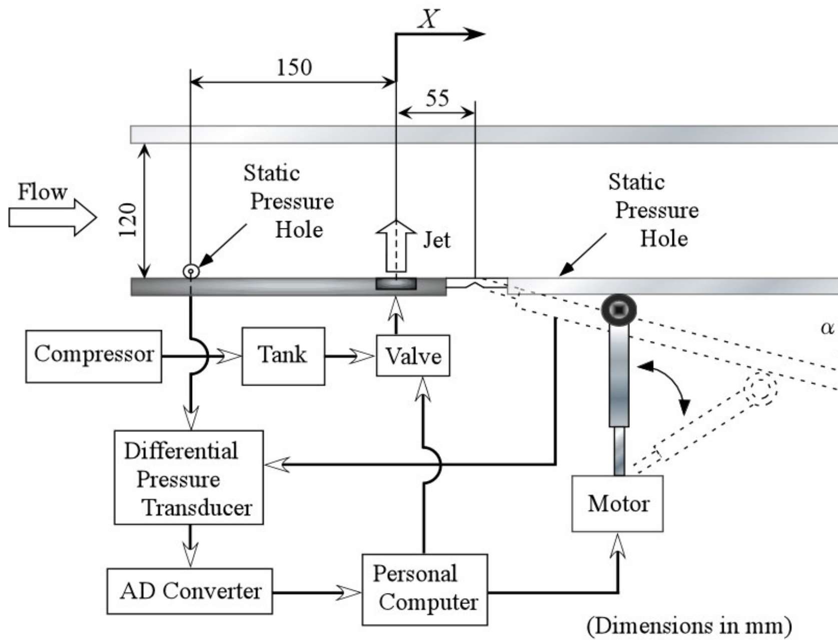


Fig.1- Schematic diagram of test section.

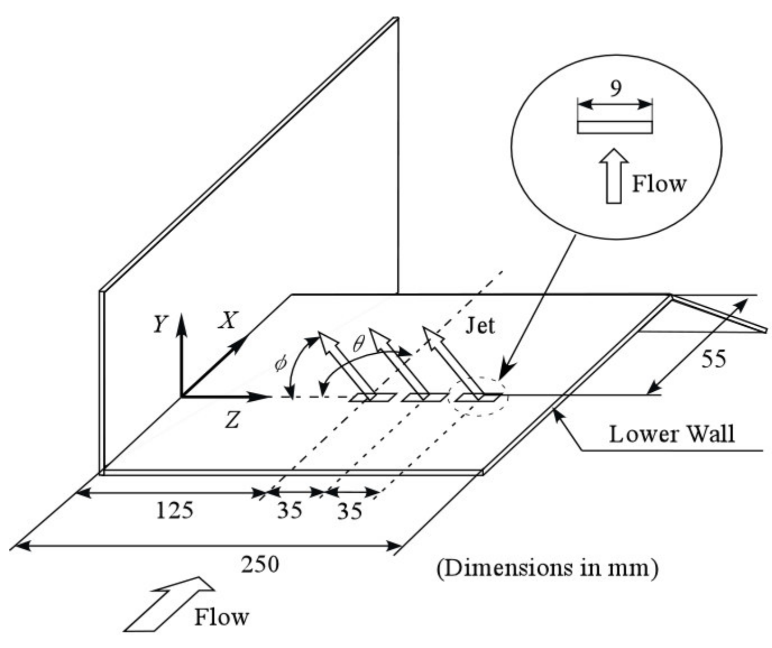


Fig.2- Jet configurations in test section.

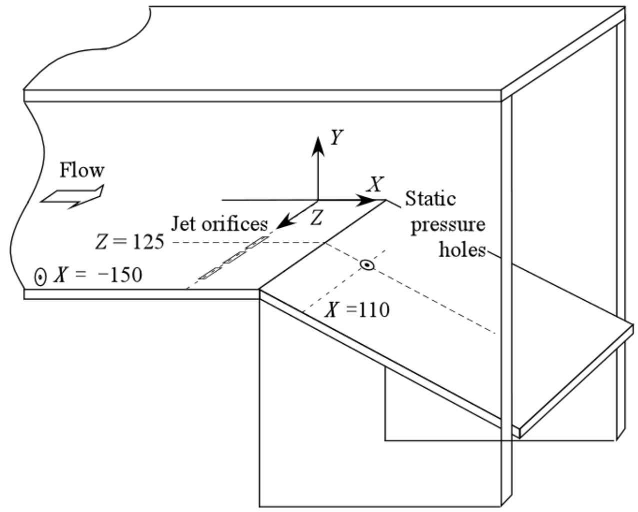


Fig.3- Position of static pressure holes.

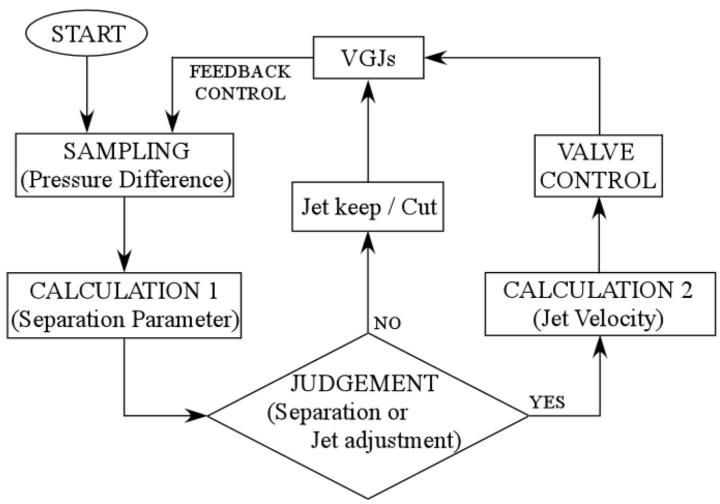
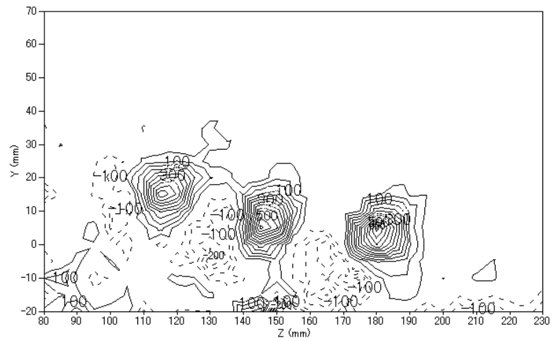


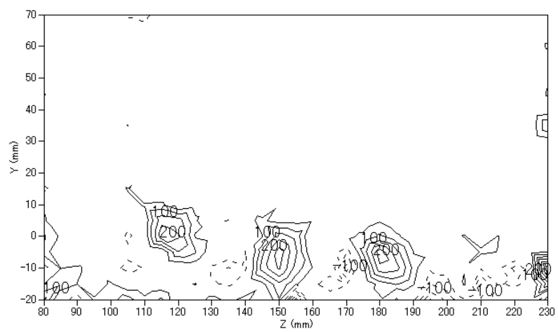
Fig.4- Flowchart.

(a) Under no-control **(b)** Under control

Fig.5- Surface flow in divergent portion of the test section (U_0=6.5 m/s, α =20 deg).

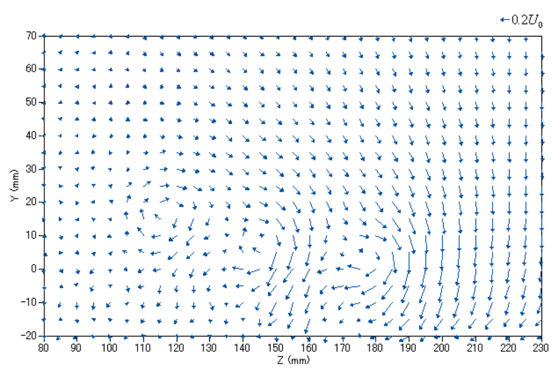


(a) *VR*=9.5

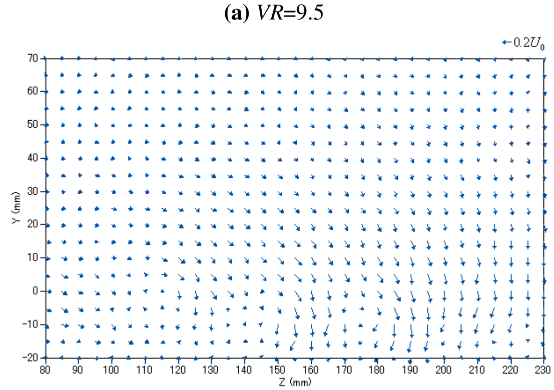


(b) *VR*=4.5

Fig. 6- Contours of streamwise vorticity at X=110mm (U_0=6.5 m/s, α=20 deg, Contour intervals=50 1/s). Dotted lines denote negative vorticity.

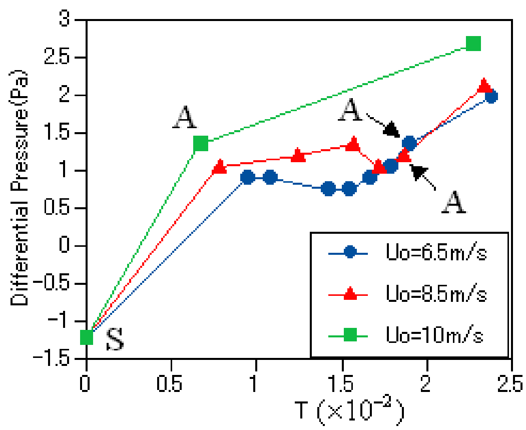


(a) *VR*=9.5

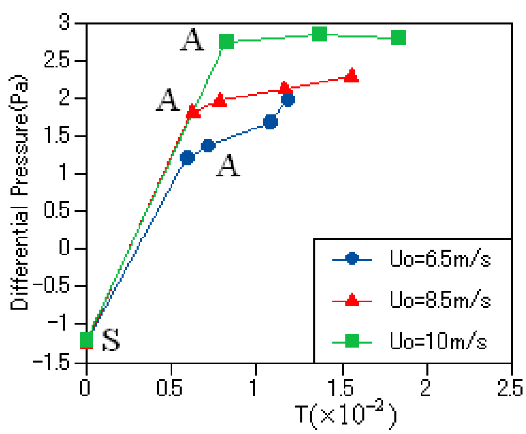


(b) *VR*=4.5

Fig.7- Secondary flow vectors at X=110mm (U_0=6.5 m/s, α=20 deg).



(a) Model-A



(b) Model-B

Fig.8- Variation of differential pressure under control at α =20 deg.

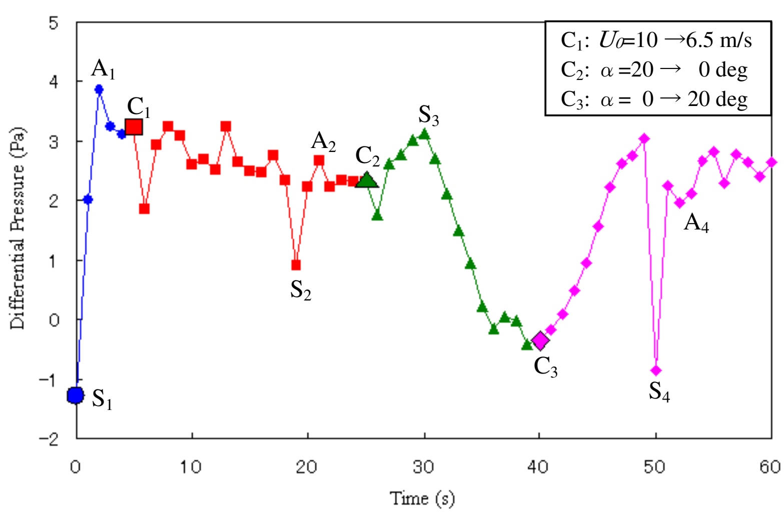


Fig.9- Variation of differential pressure under control for time-varying flow in Model-B.