4. EFFECT OF BOUNDARY LAYER CONDITION ON SEPARATION CONTROL

In general, the boundary layer condition must be known before performing separation control. In this chapter, the effect of the boundary layer condition on separation control is investigated for the vortex generator jet method. It is clarified that it is not necessary to know in advance whether the boundary layer is laminar or turbulent.

4.1 Experimental Method

A detailed diagram of the test section is shown in Fig. 3.2. In this experiment, two freestream velocities U_0=6.5 and 11.1 m/s were chosen and the jet orifice was 2 mm in diameter. The jets were skewed at 90 degrees to the freestream direction and pitched at 45 degrees to the lower wall. A tripping wire which was 1.6 mm in diameter was set at X=-100 mm (X=0 indicates the location of issuing jets). The diameter of the tripping wire D_t which can cause a transition from laminar to turbulent flow was so determined as to satisfy $D_t \geqq 900\,\nu / U_0$ (*cf.* Chapter 5 in Reference [35]), where U_0 is the freestream velocity and ν is the kinematic viscosity. The velocity measurements in the boundary layer were carried out at 0.2 mm intervals in the normal direction from the position which was 0.3 mm from the lower wall of the test section (see Fig. 3.2). The boundary layer probe shown in Fig. 3.8 was used. The surface tuft method was adopted as a flow visualization technique. In this study, tufts were made of light and thin paper. In this experiment, the diffuser's divergence angle was set at 20 degrees (α=20 degrees).

4.2 Results and Discussion

4.2.1 Transition with a Tripping Wire

Figure 4.1 shows the streamwise velocity profiles with a tripping wire in comparison with those without a tripping wire for U_0=6.5 m/s. In Fig. 4.1, the velocity profiles without a tripping wire are comparable with the Blasius solution. The shape factor is calculated from Eqs. (2.3), (2.4), and (2.5). Equations (2.3) and (2.4) are integrated along the distance Y from the lower wall from Y=0 (lower wall) to $Y=\delta$. The upper limit of integration of Eqs. (2.3) and (2.4) could here be replaced by $Y=\delta$, which is defined as the distance of U/U_0=0.99. The velocity profile in the boundary layer is assumed to be the fourth (for the case without a tripping wire) or eighth (for the case with a tripping wire) power polynomial of the distance Y from the lower wall. For the cases of Figs. 4.1(a) and 4.1(b) the shape factor indicates H_{12}=2.27 and H_{12}=2.13, respectively. On the other hand, for the case with a tripping wire in Figs. 4.1(a) and 4.1(b) the shape factor indicates H_{12}=1.49 and H_{12}=1.77, respectively. Hence it is concluded that the boundary layer condition has been changed from laminar to turbulent flow by a tripping wire.

Figure 4.2 shows the flow visualization results in the divergent portion of the test section for an unforced (non-issuing jets) case. Figure 4.3 shows the flow visualization results when jets are issuing to suppress the flow separation. The air flows from left to right in these figures. From Fig. 4.2, it is seen that the separation point moves downstream by a tripping wire because the transition from laminar to turbulent boundary layer occurs. On the other hand, for the case of issuing jets it is clear that the control effect is not influenced by the boundary layer condition (see Fig. 4.3). This indicates that longitudinal vortices generated by the interaction between the jets and the freestream is dominant in comparison with the disturbance due to a tripping wire.

4.2.2 Transition without a Tripping Wire

Figure 4.4 shows the streamwise velocity profiles for the case without a tripping wire. This profile gives H_{12}=1.89. The boundary layer thickness δ for a flat plate at zero incidence is expressed as

$$\delta = 5.0\left(\frac{\nu x}{U_0}\right)^{1/2} = \frac{5x}{\sqrt{R_{ex}}} \quad , \tag{4.1}$$

where

$$R_{ex} = \frac{U_0 x}{\nu} \quad ,$$

and x is the length from the leading edge of the plate. According to Eq. (4.1), the boundary layer thickness on a flat plate increases in proportion to $\sqrt{x}$. The boundary layer on a plate is always laminar near the leading edge and becomes turbulent further downstream. The smallest Reynolds number with which transition occurs on a flat plate is the critical Reynolds number, as determined by

$$R_{ex,crit} = \left(\frac{U_0 x}{\nu}\right)_{crit} = 3.2\times 10^5 \quad . \tag{4.2}$$

In the case of a plate, the value $R_{ex,crit}=3.2\times 10^5$ should be regarded as the lower limit to produce the transition from laminar to turbulent flow. For the case with a tripping wire (see Fig. 4.1(a)), letting the approximation curve fit the velocity profiles, we have δ =4.94. The boundary layer thickness is defined as the location based on U/U_0=0.99. For the cases of U_0=6.5 and 11.1 m/s, it will be seen from Eqs. (4.1) and (4.2) that the Reynolds number is $R_{ex}=1.8\times 10^5$ and

Re_x=6.9 × 10^5, respectively. This indicates that the boundary layer becomes turbulent for U_0=11.1 m/s in the case without a tripping wire. Figure 4.5 shows the flow visualization results for U_0=11.1 m/s. A difference between the two cases with and without a tripping wire does not appear.

4.3 Conclusions

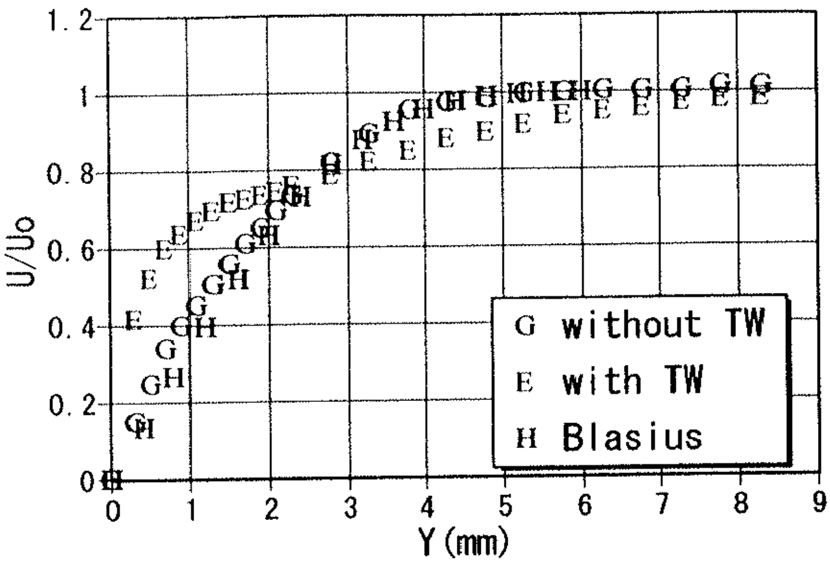
Summarizing the above results on separation control using vortex generator jets, the following conclusions were drawn:

1. In the present wind tunnel, transition from laminar to turbulent boundary layer takes place while increasing the freestream velocity.

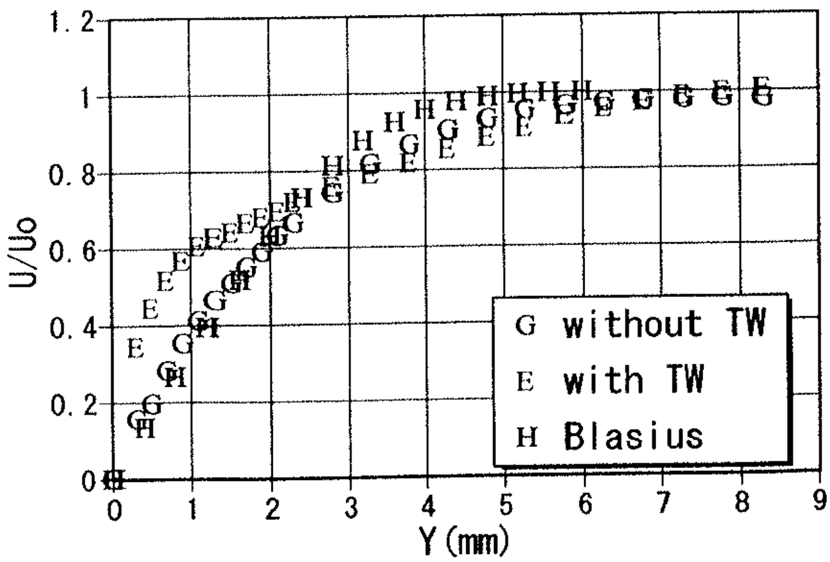
2. A tripping wire changes the boundary layer condition from laminar to turbulent flow and the transition causes the separation point to move downstream.

3. In the vortex generator jet method, whether the boundary layer is laminar or turbulent has no influence on separation control.

4. For the vortex generator jet method, separation control can be achieved without surveying the boundary layer condition before control.

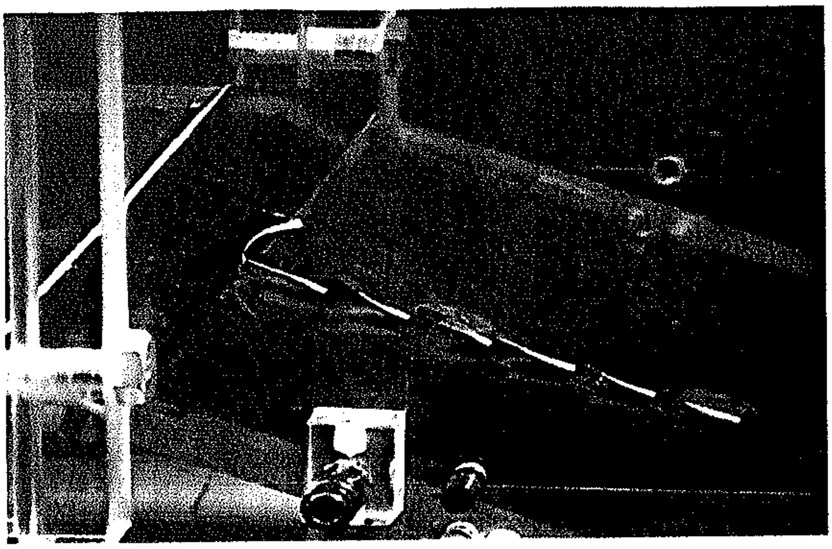


(a) X=0, Z=110 mm

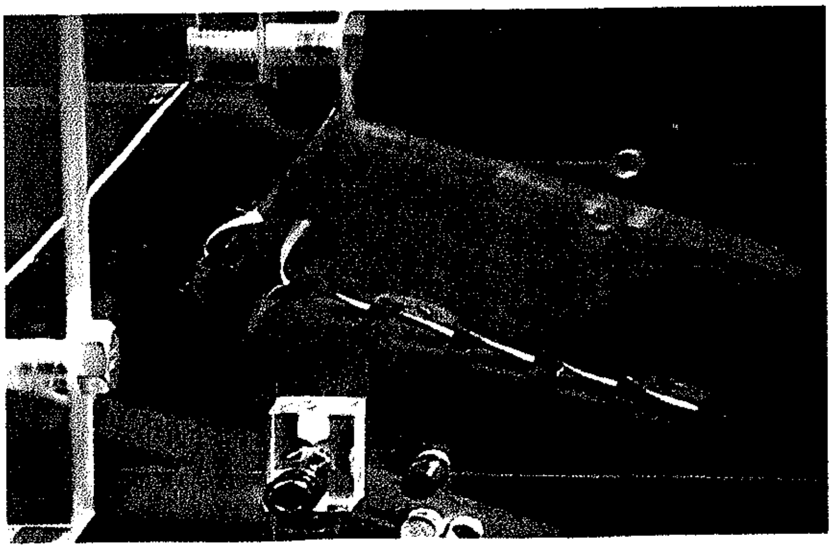


(b) X=0, Z=140 mm

Figure 4.1 Streamwise velocity profiles with and without tripping wire (TW)
(U_0=6.5 m/s, unforced).



(a) Without tripping wire



(b) With tripping wire

Figure 4.2 Surface flow in divergent portion of the test section unforced).

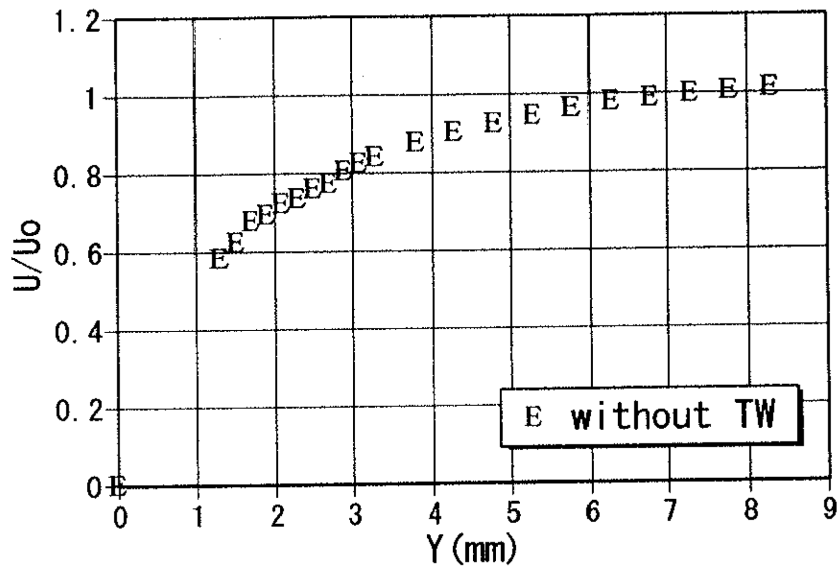
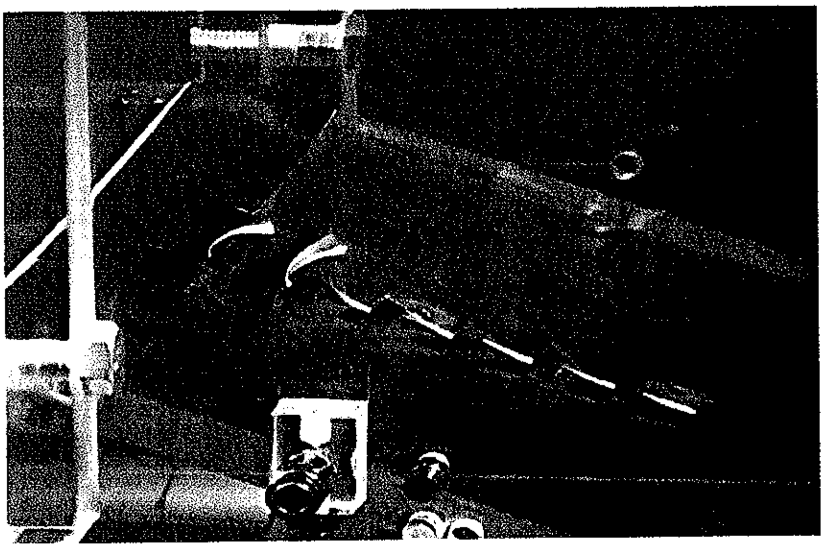
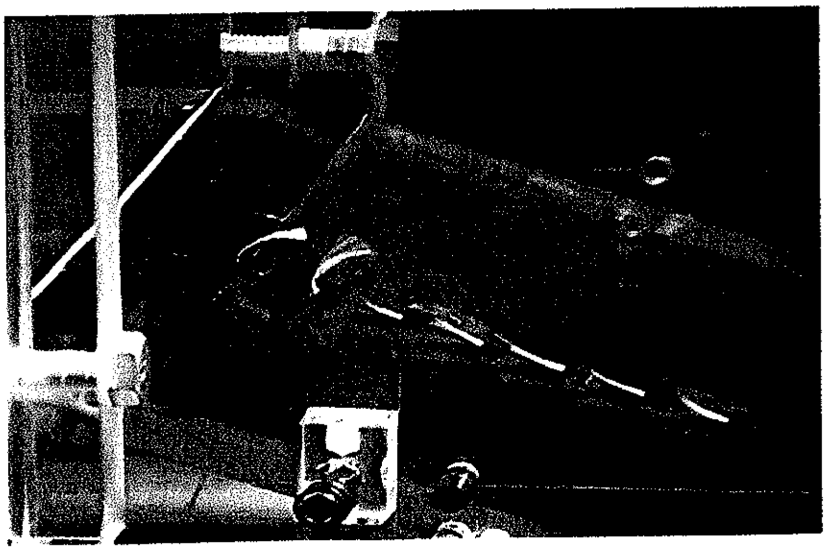


Figure 4.4 Streamwise velocity profile without tripping wire (TW) at X=0, Z=140 mm (U_0=11.1 m/s, unforced).



(a) Without tripping wire



(b) With tripping wire

Figure 4.5 Surface flow in divergent portion of the test section (U_0=11.1 m/s, unforced).