HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

EFFECT OF A SPANWISE FLOW ON THE LAMINAR-TURBULENT TRANSITION

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ABSTRACT

The boundary-layer transition to turbulence has been the subject of research for a long time. The transition process, however, has not yet been fully explained though the final stage of the boundary-layer transition has been explained that some small turbulent sources (turbulent spots) occur suddenly in the boundary layer. As these turbulent spots fill up the boundary layer, they induce a transition to turbulence of a laminar boundary layer. The most important process is the turbulent-spot appearance in the transitional boundary layer because a progression to turbulence that is not present in the laminar state is promoted. The process of the transition from the prior state to turbulent spots, however, has not been ascertained. Thus, the mechanism of turbulent-spot appearance has only been explained as the word "breakdown". The computational simulation by Brandt [1] demonstrates that the breakdown is induced by the interaction of streaks which move laterally and slowly. Meanwhile, we investigate a downstream development of a single hair-pin-type vortex generated by an artificial small jet. From the velocity field measured in detail, this vortex grows and increases in number downstream, and finally the developed vortices constitute a spot. In the initial stage of downstream development where the vortices propagate in the streamwise direction, the velocity perturbations in a spot reiterate the in-phase wave form. In addition, the low- and the high-speed streaks in the spot are elongated straight in streamwise direction. In the transition stage, it is shown that the amplitude in the instantaneous velocity signals in the spot become irregular locally, where the low- and the high-speed streaks distort laterally. Further downstream, it is clarified that the occurrence of the momentum-transfer accompanied with local and temporary ejection movements and sweep movements become irregular in the spot, where the low-speed and the high-speed streaks cross one another and switch their positions with each other in spanwise direction. The appearance of the crossover of the streaks shows the break-up of the spot structure, i.e., the beginning of its breakdown. A crossover of the streaks produces a new crossover in a chain reaction, so that the transition to turbulence (breakdown) progress rapidly. And finally the spot enter into a turbulent region. The irregularity in the velocity field, showing the other distinct feature of the spot, is occurred owing to the distortion of streaks in spanwise direction and, therefore, the streaks cross one another. Thus, we considered that these characteristics of velocity field are induced by a spanwise flow. In this study, we pay much attention to a spanwise flow and investigate its effect on the boundary-layer transition. From the measurement of the streamwise and spanwise component of velocity using a small X-type hot-wire probe, we found that the spanwise distortion of the velocity field and the irregularity of the velocity perturbation are caused by the spanwise flow in the spot. These results show that the spanwise flow have a critical role in laminar-turbulent transition.

INTRODUCTION

The boundary-layer transition from laminar state to turbulent one remains unexplained, though many researchers have spent a considerable effort on its study. Emmons [2] observed that small turbulent source occurred in natural transition of the critical Reynolds number and it spread out downstream in all direction, finally grew up into turbulent spot. Gaster and Grant [3] investigated the downstream development of ‘wave packet’ generated by the weak impulse-like jet. Furthermore, Amini and Lespinard [4] investigated experimentally a laminar disturbance, artificially generated by a small jet, in subcritical transitional boundary layer and surveyed its downstream development in detail using hot-wire anemometer. Recently, Komoda et al. [5] found such a spot even in supercritical boundary layer and named it ‘a laminar spot’ because it resembled a turbulent spot in shape. Moreover, Matsumoto [6] explored its downstream development in detail using a rake type 16-channel hot-wire probe and found the following features of its downstream development; A laminar spot develops to downstream while consecutively inducing a new low-speed protuberance. At the first stage of its development, furthermore, the spot has its maximum width at 0.2δ and grows up slowly in the spanwise direction. The half of lateral growth-angle is about 5°; this angle is almost half of a turbulent-spot growth as shown in Figure 1. At the next stage, lateral-growth is repressed. After then, it evolves with the same growth-angle, about 10°, as that of a turbulent spot.

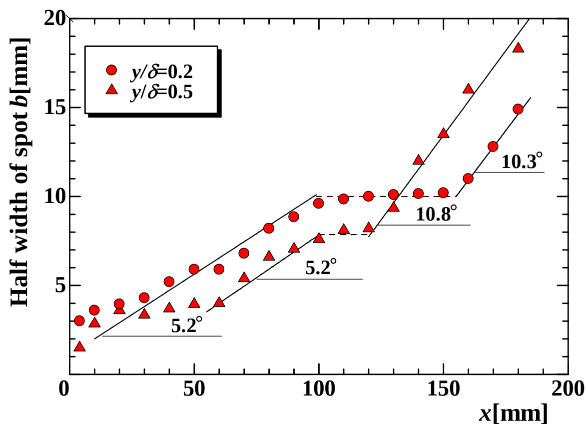


Figure 1 Lateral growth of a spot

More recently, from the simultaneous measurements of the longitudinal and the normal velocity-component using the new hot-wire probe, Sekiya and Matsumoto [7] confirmed that the low-speed protuberances in a spot were produced by the hairpin-type vortices and the half angle of 5° in the lateral growth of the spot was related to the generation and the development of some U-shaped vortices. Moreover, Sekiya and Matsumoto [8] showed that irregularities of the velocity waves during the laminar-turbulent transition of the spot appeared locally in the low-speed region away from the wall and spread wide close to the wall. In the beginning, the lateral distortion of velocity profile due to the vortex-interaction caused the irregularity of the velocity-wave amplitude in the boundary between the low- and high-speed regions in the spot. In addition, the crossover of legs of the longitudinal vortices occurred incidentally in the spot and generated a local ejection of low-momentum fluid as shown in Figure 2.

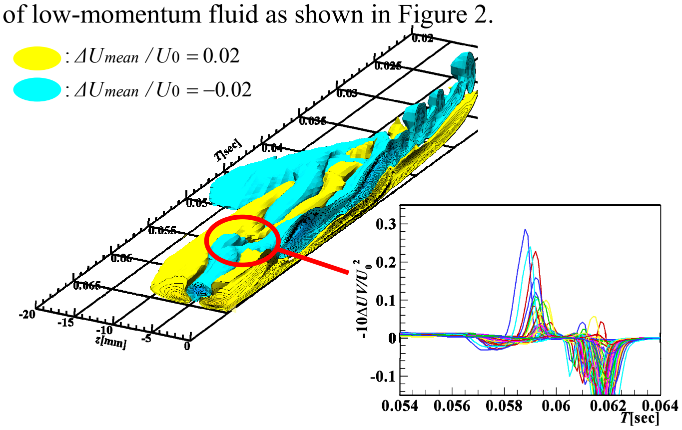


Figure 2 Iso-surfaces of the longitudinal velocity and velocity signals of the transitional stage

Afterwards, some crossovers of legs were produced in a chain reaction. Consequently, the reproducibility in the velocity waves disappeared almost at downstream and turbulent regions increased rapidly everywhere in the spot. We thought that these phenomena of flow field related to the breakdown, lateral distortion of velocity field and crossover of vortices, were because of a spanwise flow. The purpose of this study is to clarify the effect of a spanwise flow during the laminar-turbulent transition of the spot.

NOMENCLATURE

T	[sec]	Time since the driving voltage is triggered
x	[m]	Streamwise distance from orifice
y	[m]	Wall-normal distance
z	[m]	Spanwise distance from the centre of flat plate
U_0	[m/s]	Free stream velocity
U	[m/s]	Streamwise velocity component
ΔU	[m/s]	Deviation of streamwise velocity from the Blasius profile
W	[m/s]	Spanwise velocity component
δ	[m]	Boundary-layer thickness
δ^*	[m]	Displacement thickness of boundary layer
R_{δ^*}	[-]	Reynolds number $= U_0\delta^* / \nu$

Subscripts
mean Ensemble averaged value

EXPERIMENTAL SETUP AND PROCEDURES

Wind tunnel and flat plate

Experiment was performed in a low speed wind tunnel. This wind tunnel was a closed return-circuit type and contained a test section 1 m × 0.45 m × 3.1 m in size as shown in Figure 3. The smooth flat plate was made out Bakelite of length 2.5 m and width 1 m, and mounted vertically in the test section. This plate has a small orifice of 1 mm in diameter at 750 mm downstream from the leading edge. The origin of the coordinate axes was taken at the orifice.

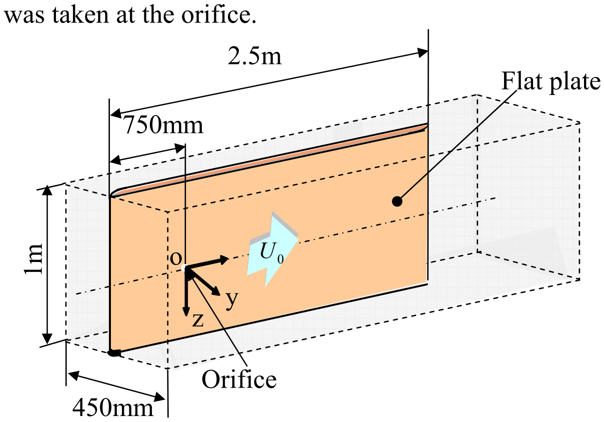


Figure 3 Wind tunnel and flat plate

Hot-wire anemometry

For the simultaneous measurements of streamwise and spanwise velocity components, we manufactured the small X-type probe as shown in Figure 4. This probe consisted of two tungsten wires of 2.5 μm in diameter, and they intersect at right angles and was 0.14 mm adjacent in thickness so as to increase the spatial resolution and to avoid the influence of the wall-normal velocity gradient.

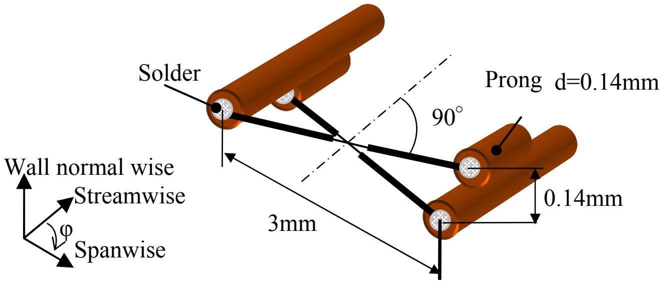


Figure 4 Schematic diagram of the X-type probe

Configuration of a jet for initial disturbance

A jet which disturbed the two-dimensional laminar boundary layer on the flat plate was ejected from the orifice by a loudspeaker applied the impulsive voltage. Figure 5 shows the configuration of a driving voltage of a loudspeaker and that of a velocity of a jet measured in the absence of free stream at the center of the orifice and at y=0.4 mm. We used two kinds of pulse-like jets to investigate the effect of initial disturbance for downstream development of a laminar spot. The relative jet-velocity were U_j/U_0 =0.8 and 0.7, and the half-value width, $\tau_{Uj/2}$, of them was the same in 1.5 msec. We named the spots generated by these jets 'developing spot' and 'decaying spot' respectively. The ejection-frequency of jet was fixed to 4 Hz so as to avoid some interaction between consecutive spots.

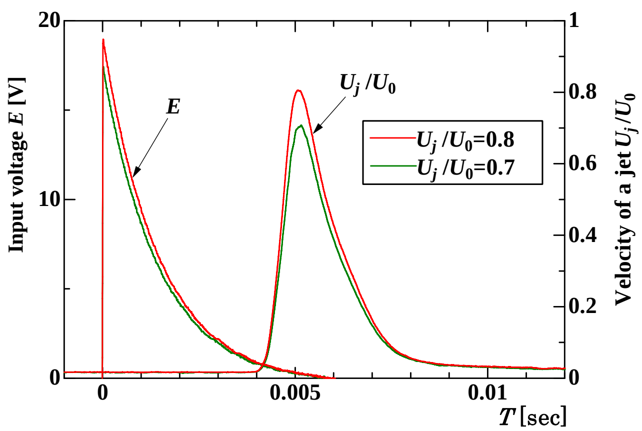


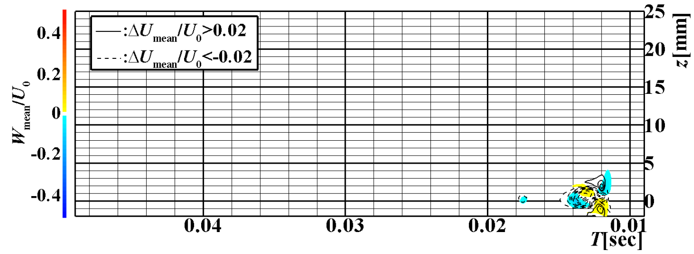
Figure 5 Configurations of the input voltage of laudspeaker and velocity profiles of jets

Measurements of velocity profiles in a laminar boundary layer with a spot

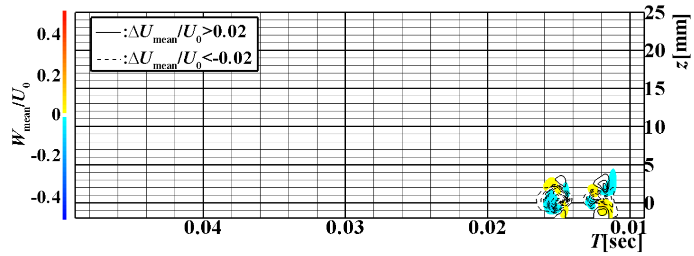
Measurements were performed at some x positions at the characteristic layers of both $y/\delta = 0.2$ and 0.5. The free-stream velocity was controlled to keep the Reynolds number based on the displacement thickness, R_{δ^*} , constant to 990 at the orifice. The instantaneous streamwise and spanwise velocity components, U and W respectively, were simultaneously measured using an X-type probe which was manufactured for measuring of multi velocity component in the thin boundary layer. Velocity-data samples of 32, 64 or 128 were collected repeatedly by the frequency of 10 kHz using 12bit A/D converter synchronized with the positive edge of input-voltage wave of loudspeaker. After then, we carried out ensemble-averaging to them for the statistical consideration.

EXPERIMENTAL RESULTS AND DISCUSSION

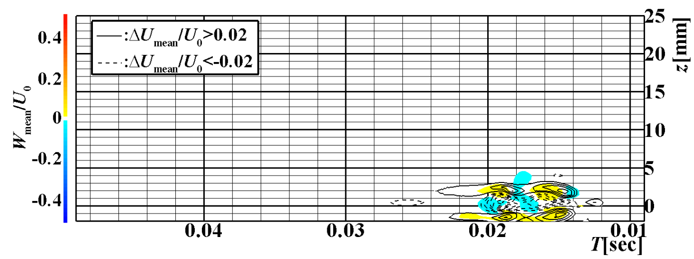
Figure 6 shows contour maps of the spanwise velocity component, W_{mean}/U_0 , superposed on the contour of the deviation of streamwise velocity component, $\Delta U_{mean}/U_0$, at x=30 mm where a spot remain a laminar state, thus, this stage prior to transition was referred to *Laminar spot* region.



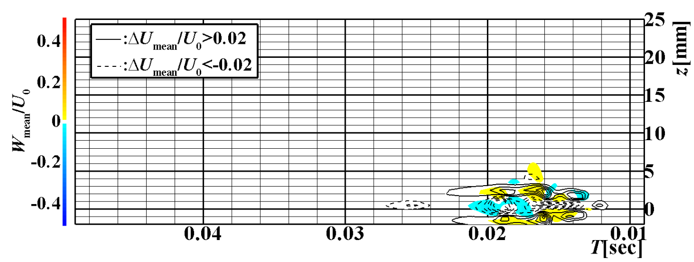
(a) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.5$



(b) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.5$



(c) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.2$



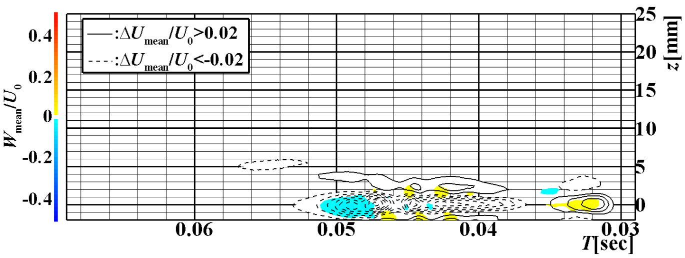
(d) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.2$

Figure 6 Contour maps of velocities at x=30 mm

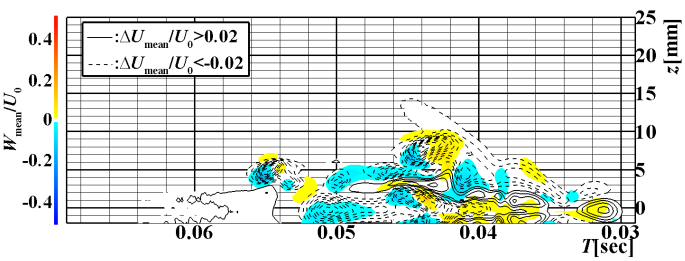
At $y/\delta = 0.5$, velocity field in the spot had no significant difference between a decaying and a developing spot except for the number of the low speed ($\Delta U_{mean} < 0$) region accompanied with high speed ($\Delta U_{mean} > 0$) regions in both outsides of a spot. Spanwise velocity component, W, was distributed in the same locations of low- and high speed region as induced by neck of the hair-pin type vortex. There are, namely, the flows toward the centre of the spot at front edge of the high speed region, and the flows toward outside of the spot at the back of the high speed region. Near the wall of $y/\delta = 0.2$, the velocity contours of each spot were almost the same as shown in Figure 6 (c) and (d).

At further downstream of x=150 mm, where the transition to turbulent spot began in the developing spot, the difference of flow appeared between both spots.

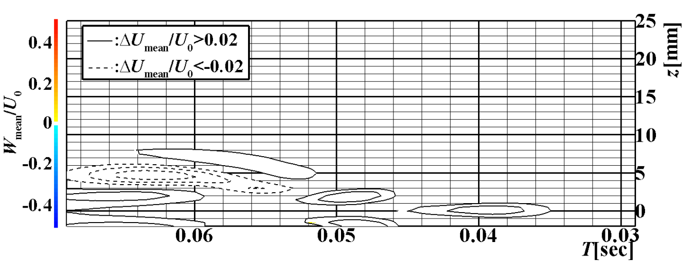
From contour map of the developing spot at $y/\delta = 0.5$ (Figure 7 (a)), a wing-like low speed region spread spanwise at the outermost part of the spot, moreover, velocity field inside of the developing spot was distorted spanwise as shown in Figure 7 (b) and (d). By contrast, velocity field inside of the decaying spot was elongated streamwise without the distortion spanwise. Furthermore, a strong flow occurred widely inside the developing spot, while the flow inside the decaying spot was small and weak. Moreover, we note that the inward flow ($W_{mean} < 0$) occurred at the low speed region distorted toward the centre of the spot (at z=3.0 mm and T=0.041 sec), and the outward flow ($W_{mean} > 0$) occurred at high speed region distorted toward to outside of the spot (at z=5.0 mm and T=0.042 sec, at z=3.0 mm and T=0.045 sec). This result indicates that the spanwise distortion of velocity field arose from the spanwise flow.



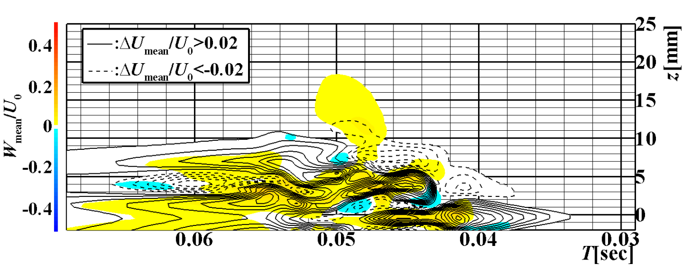
(a) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.5$



(b) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.5$

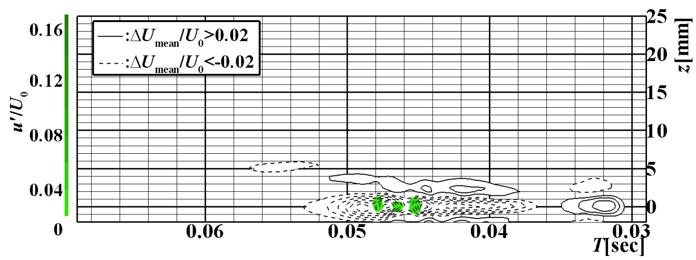


(c) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.2$

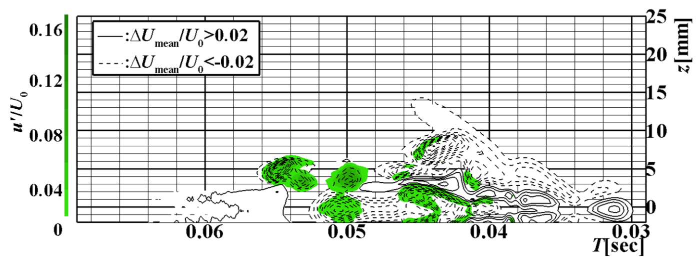


(d) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.2$

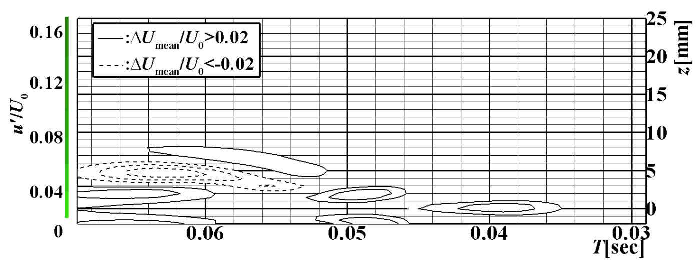
Figure 7 Contour maps of velocities at x=150 mm



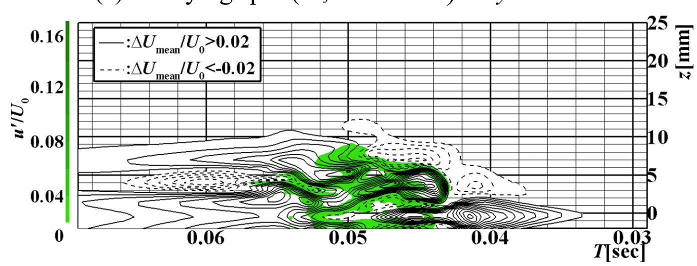
(a) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.5$



(b) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.5$



(c) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.2$

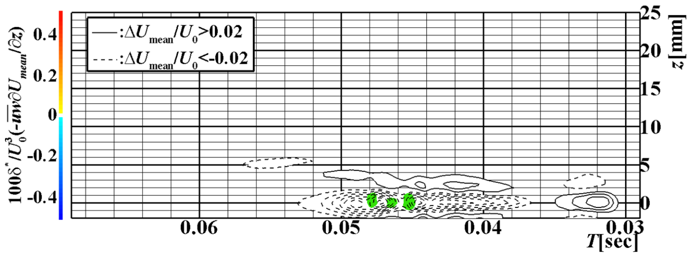


(d) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.2$

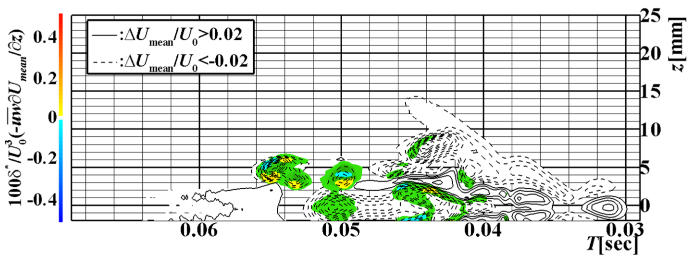
Figure 8 Contour maps of turbulent velocity at x=150 mm

Figure 8 shows the distribution of the streamwise turbulent intensity, u'/U_0, superposed on the contour of $\Delta U_{mean}/U_0$. An increase of turbulent intensity shows arising and growth of an irregularity in the spot, namely, it shows the beginning of a transition to the turbulent spot. In the decaying spot, weak turbulent occurred locally in the spot and its value was 2% of free stream. In the developing spot, strong turbulent of 8% of free stream occurred widely in the contour of $\Delta U_{mean}/U_0$ distorted spanwise as shown in Figure 8 (b) and (c). These results indicate that spanwise flow contributed not only the spanwise distortion of the velocity field but also the generation of turbulence. Thus, we estimated one of the production terms of streamwise turbulence.

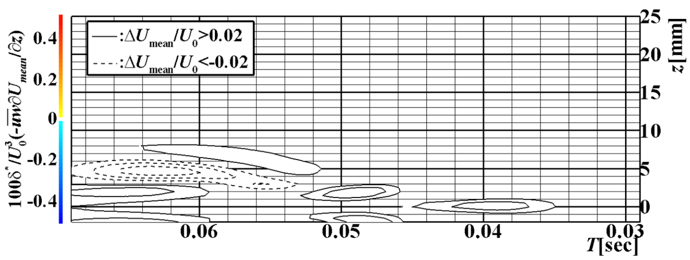
Figure 9 shows the distribution of the production term of streamwise turbulence, $-\overline{uw}\partial U_{mean}/\partial z$, normalized by δ^* and U_0, superposed on the contour of $\Delta U_{mean}/U_0$.



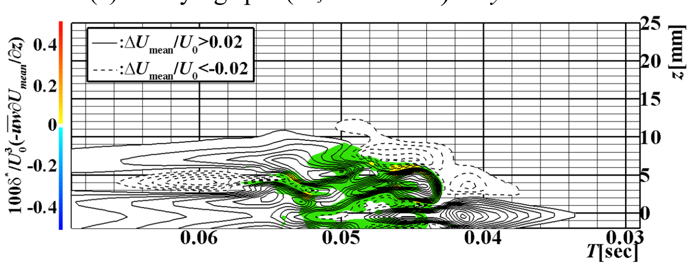
(a) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.5$



(b) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.5$



(c) Decaying spot ($U_j/U_0 = 0.7$) at $y/\delta = 0.2$



(d) Developing spot ($U_j/U_0 = 0.8$) at $y/\delta = 0.2$

Figure 9 Contour maps of the production term, $-\overline{uw}\partial U_{mean}/\partial z$, at x=150 mm

The region of positive value of $-\overline{uw}\partial U_{mean}/\partial z$ indicates that the lateral transfer of the streamwise momentum caused by that spanwise high shear-layer was perturbed by the weak spanwise disturbance w. As a result, the streamwise velocity fluctuation u was generated. In the developing spot, the positive value of $-\overline{uw}\partial U_{mean}/\partial z$ was distributed in the strong turbulent region except the centre of the spot (z=0 mm) as shown in Figure 9 (b) and (c). These results claimed that the spanwise flow contributed considerably the production of turbulence.

From above results, it was clarified that the spanwise flow played a crucial role in transitional process to the turbulent spot.

Figure 10 shows the maximum value of spanwise velocity, $|W_{mean}/U_0|_{\max}$, at each streamwise location. In the initial stage of downstream development of a spot, the value of spanwise velocity was no significant difference between the decaying spot and the developing one. At further downstream, spanwise flow of the developing spot begun to become strong from x=100 mm, while that of the decaying spot gradually declined. This streamwise location of x=100 mm was the same as that of the birth of the wing-like low speed region which exhibited the beginning of transition to the turbulent spot.

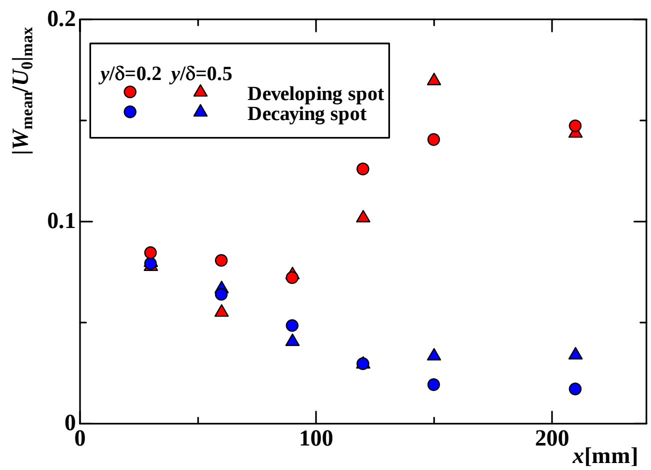


Figure 10 Downstream development of $|W_{mean}/U_0|_{\max}$

CONCLUSION

We measured two velocity components, U and W, in the spot using an X-type probe. From the results obtained, we found that spanwise flow greatly contributed to the transitional process of the turbulent spot. Results obtained are summarized as follows:

(1) In the laminar spot stage, the velocity field in the spot was no significant difference between the decaying spot and the developing spot.

(2) The spanwise distortion of the velocity field was caused by the spanwise flow, thus generating intense turbulence in this region.

(3) In the region distorted spanwise, the streamwise-velocity fluctuation u was generated by momentum transfer laterally caused by the weak spanwise-velocity fluctuation w.

(4) Spanwise flow became stronger at the same time as the beginning of transition to turbulent spot, suggesting that it played a crucial role in transitional process of a spot.

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