VISUALIZATION OF NEAR WALL REGION IN A TURBULENT BOUNDARY LAYER OVER TRANSVERSE SQUARE CAVITIES WITH DIFFERENT SPACING.

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ABSTRACT:

Laser induced fluorescence technique was used to visualize the near wall region in a turbulent boundary layer over transverse square cavities with different spacing. The observations reveal strong interactions between the cavity and boundary layer flows some of the time. The evidence suggests that low-speed streaks are formed by the quasi-streamwise vortices which are responsible for the ejection of fluid out of a cavity.

INTRODUCTION

The flow over a d-type roughness (regularly spaced two-dimensional square cavities placed normal to the flow, one element width *w* apart in the streamwise *x* direction) is particularly interesting because of the possibilities that the boundary layer may be exactly self preserving (Rotta 1962). Also, the drag over a d-type surface should not be much different from that of a smooth wall; Tani (1987) has suggested that it may be even slightly smaller, though this has not been verified experimentally (e.g. Djenidi et al., 1994). To date, the physics of this flow, especially the effect of the cavities on the overlying shear layer is poorly understood. It is therefore important that the speculations which describe the mechanism of the flow over a d-type rough wall as well as over a single square cavity are clarified. In this experiment, flow visualization is used to examine the interaction between the cavity and the "outer" flow (flow above the cavity). Along with a d-type rough wall, flows over a single square cavity and widely separated cavities are also studied.

EXPERIMENTAL DETAILS

The experiments were performed in a closed circuit constant-head vertical water tunnel (Zhou and Antonia 1992). On one of the walls of the 2m high working section (250 mm square), transverse 5mm square cavities were machined across the entire span. on the wall with a separation of 100mm. For the flow over a single cavity, the d-type rough wall was replaced by a smooth wall with a single 5mm square cavity machined at a distance of 0.9m from the boundary layer trip. In the case of widely separated cavities, the spacing between two consecutive cavities are 100mm. Fig.1 shows the geometry of the walls. The flow was visualized using the laser induced fluorescence (LIF) technique. A sodium fluorescein solution (2 mg/litre of water), with light absorption and emission wavelengths of 510 and 540 nm respectively, was injected through a 150mm wide spanwise slot with an opening of 0.25 mm. The angle at which the dye was introduced was kept as shallow as possible, and the dye injection rate was controlled so as to minimize any disturbance to the boundary layer. The dye was illuminated using a 0.5mm thick laser light sheet, generated from a 5 Watt Ar-ion laser (the maximum power used was about one Watt), with a combination of a convex lens and a 5 mm diameter cylindrical lens. The light sheet was either perpendicular or parallel to the surface, and views in the *x-y* and *x-z* plane were filmed using either a CCD video-camera (25fps) or a high speed video camera (400 fps). The images were processed on a Silicon Graphics workstation fitted with an Indigo Video™ board.

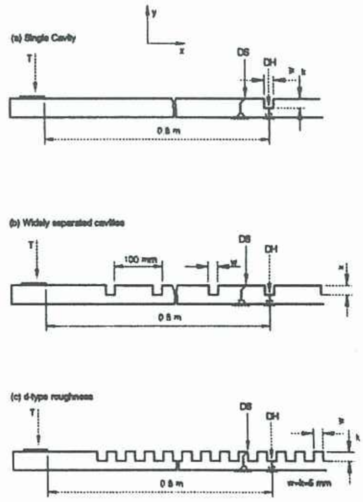

Figure.1 Wall geometry

OBSERVATIONS FROM FLOW VISUALIZATION

The experiments were performed at $R_\theta = 700$. The flow visualization reveals different types of communication between the cavity and the outer flow. For all the wall geometries investigated the communication between the cavity and the boundary layer flows is almost similar. The observations over the d-type rough wall are discussed here. There is a recirculation of fluid within the cavity with random ejections of fluid out of the cavity (there is no regular time interval between ejections). Fluid inflows into the cavity, and periods where the outer flow skims over the cavity with no significant exchange of fluid are also observed. Both ejections and inflows occur only at the downstream region of the cavity. The circulatory pattern within the cavity is not entirely destroyed during an ejection, while it appears to be strengthened during an inflow. A time sequence in the x-y plane (Figure 2) shows that the ejection of fluid from the upstream cavity precedes that into the downstream cavity (Figure 3). For the views in Figures 2 and 3, the dye injection slot is $4w$ distance upstream of the cavity on the left, and the flow is left to right. In Figure 2a, there is no exchange of fluid between the cavity and the outer flow. Figure 2b shows that, while an ejection has started in the first cavity, there is no activity (except for the recirculation of the fluid) in the second cavity. The ejection from the cavity is also visible in the far left hand corner. After a time lapse, an ejection starts in the downstream cavity (Figure 2c). In this picture, ejections from two cavities upstream of the first cavity can be identified. The downstream evolution of ejections, with the one in the first cavity preceding that in the second, is seen in Figures 2d-2f. The sequencing of the exchange of fluid between the cavity and the outer flow is more clearly seen when four consecutive cavities are viewed (Figure 4). An inflow following the ejection is also evident in the first cavity of Figure 4. The ejection and inflows may be either strong or weak, an observation consistent with Townes and Sabersky (1966) for a turbulent boundary layer over transverse square slots.

From this sequence of ejections and inflows, the communication between the cavities and the outer flow is best interpreted in terms of a response to relatively organised motions which are convected in the streamwise direction. The interaction between the cavity fluid and the outer layer is somewhat similar to that described by Tantirige et al., (1994) for a

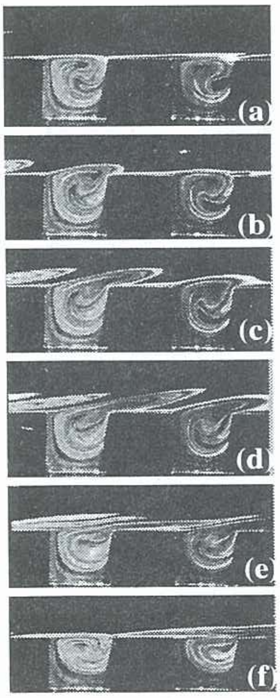

Fig.2

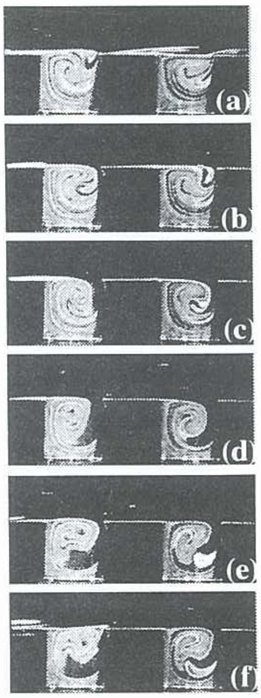

Fig.3

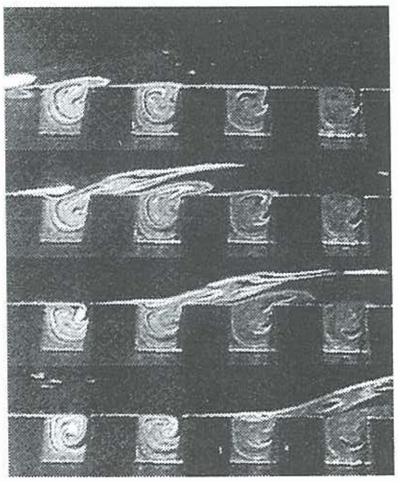

Fig.4

Figure.2 Time sequence showing ejections - view in x-y plane

Figure.3 Time sequence showing inflows

Figure.4 Views of four consecutive cavities showing the evolution of ejections. The inflows after the ejection is also seen in the first cavity.

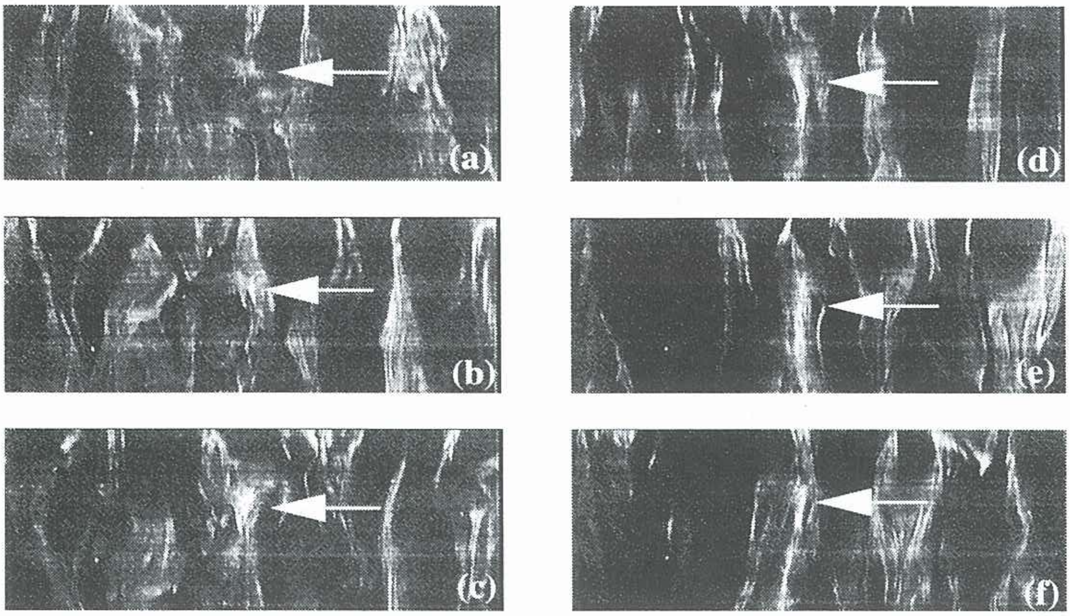

Figure.5 Views in x-z plane showing ejections marked by the arrow (see also fig.6) triggered by the low-speed streaks.

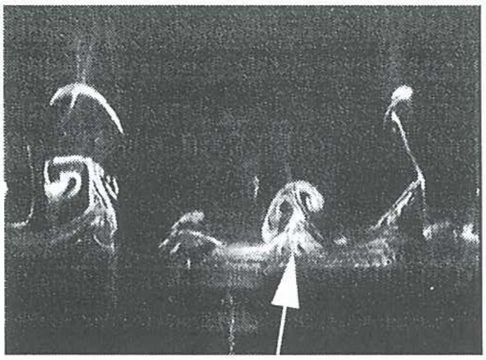

Fig.6

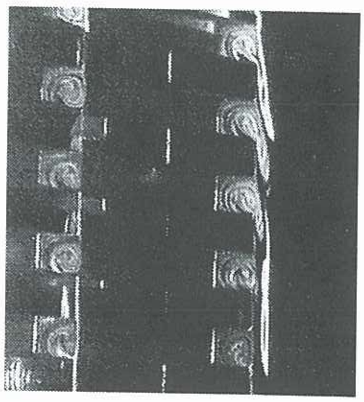

Fig.7

Figure.6 View in plane 135 degrees to positive x-direction. The musroom-like structure, apparently a signature of the quasi-streamwise vortices, is also seen to be pumping fluid out of the cavity. Arrow points the cavity fluid.

Figure.7 View in x-y plane with two light sheets separated by 45mm in spanwise direction (z).

turbulent boundary layer over a single transverse V-groove. These descriptions support the suggestion of Townes and Sabersky (1966) that the initiating mechanism for the ejections and inflows resides within the boundary layer rather than within the individual cavity. It is very likely that the interaction between the cavity and the outer layer is a result of the passage of quasi-streamwise vortices. Spanwise views (Figure 5) obtained with the light sheet in the (*x-z*) plane indicate the presence of low-speed streaks very similar in appearance to those over a smooth wall. In Figure 5 the light sheet plane is about 6 wall units above the wall. Low-speed streaks on a d-type rough wall were first established using flow visualization by Liu et al. (1966). If the low-speed streaks are formed by the quasi-streamwise vortices, it is possible that these vortices trigger the ejections. The presence of a pressure minimum at the core of these vortices should account for the fluid being pumped out of the cavity. Evidence for this was obtained by locally injecting a solution of rhodamine into a cavity (at a distance of 6*w* downstream of the main dye injection slot) through a 0.5mm hole (indicated as DH in Fig.1). The rhodamine, when excited by the laser light sheet, appears orange because its light emission wavelength is in the orange region of the spectrum ($\approx$560 nm). In Figure 5a, the locally injected rhodamine, indicated by arrow, appears as a faint orange patch (because it is below the plane of the light sheet), seemingly undisturbed by the outer flow. As a streak passes over this location, there is an ejection from the cavity which is made visible by the rhodamine (bright orange) moving into the plane of the streak (Figures 5b and 5c). This is then convected along the streamwise direction (Figures 5d-5f). Further support for this was obtained by viewing in a plane at 135^0 to positive *x*-direction (Figure 6). The mushroom-like structure, which is presumably a cross-section of the streak in the plane of viewing, appears to be a characteristic signature of the quasi-streamwise vortices (also see Head and Bandyopadhyay, 1981; Hooshmand et al., 1983). The rhodamine is seen to be pumped out of the cavity (indicated by arrow) by this structure. These views (Fig.5 and 6) also suggests that the ejections occur over regions which could be some what extended along the *x* but narrow in *z* which is inconsistent with Townsend's (1976) description of spatially coherent ejections over an area comparable to the flow width. Evidences are obtained by viewing the flow with two light sheets in *x-y* plane separated by 45mm in *z* direction (Fig.7).

CONCLUSION

Flow visualization over transverse square cavities reveal strong interactions between the cavity and boundary layer flows. Earlier observations of a strong circulation inside the cavity, frequent ejections from the cavity and existence of low-speed streaks are confirmed in this study. Ejections are followed by inflows into the cavity. These ejections occur over regions which are elongated in the x-direction but narrow in the z-direction. There is evidence to suggest that the low-speed streaks are formed by quasi-streamwise vortices which are responsible for the ejection of fluid out of the cavities.

ACKNOWLEDGMENTS

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