
RESEARCH NOTE

THE PERTURBATION FLOW FIELD ASSOCIATED WITH PASSAGE OF TURBULENT SPOT

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Abstract The flow field associated with the passage of the turbulent spot in a 3-D duct with streamline divergence under zero pressure gradients was investigated and displayed as contour plots of the velocity perturbation in plan and elevation view of the spot. It suggests that, streamline divergence has no strong effect on the internal structure of the spot and eddies and their propagation in the downstream direction is similar to 2-D flows. The orthographic views are also shown. They are rather similar to contour plots but with different kind of presentation to show velocity excess and deficit as peaks and valleys respectively in the flow field while passage of the spot. This work was a part of detailed investigation of the structure of a distorted turbulent spot in a 3-D constant pressure flow.

Key Words Boundary-Layer, Transitional Flow, Turbulent Spot

چکیده میدان جریان تحت تأثیر عبور لکه متلاطم در یک مجرای سه بعدی با خطوط جریان واگرا و شیب فشار صفر مورد مطالعه قرار گرفته و نمودارهای خطوط ثابت اغتشاشات سرعت نشان داده شده است. مشاهده گردیده، واگرایی خطوط جریان تأثیر چندانی بر ساختار داخلی لکه متلاطم، دنباله‌های آن و نیز نحوه انتشار آن در پایین دست جریان نداشته و رفتاری مشابه جریانهای دوبعدی دارد. نماهای ارتوگرافی نیز نمایش داده شده است. این نماها مشابه نمودارهای خطوط ثابت بوده و نمایانگر مناطق افزایش و یا کاهش سرعت به صورت قله‌ها و یا دامنه‌ها در میدان جریان هنگام عبور لکه متلاطم می‌باشد. این مطالعات بخشی از تحقیقات مشروح نویسنده در خصوص تعیین ساختار لکه متلاطم منحرف شده در یک جریان فشار ثابت سه بعدی است.

1. INTRODUCTION

Quite a few investigators have provided contour plots of the velocity perturbation in different flow fields: Zilberman et al. [1] in a fully turbulent environment, Van Atta and Helland [2] in a heated laminar boundary layer, Antonia et al. [3] in the plane of symmetry of a transitional turbulent spot, Itsweire and Van Atta [2] in a zero pressure gradient laminar boundary layer, Barrow et al. [4] in a Blasius flow, and Sokolov et al. [5] in a two-dimensional duct. The major differences between these earlier works and the present plots are as follows. (1) All of the earlier works were for 2-D flow. (2) Except Itsweire and Van Atta who give a plan view of the contours of constant velocity perturbation, the rest concentrated on the elevation view of these contours. (3) The major distinctive feature of the present contours is that they are drawn for the spots at a fixed (frozen) time, whereas previous

works show contours in time at a fixed space location. This work was a part of detail investigation of the structure of a distorted turbulent spot in 3-D constant pressure flow (see Jahanmiri et al. [6,7]). Here we suffice to explain only the relevant results in connection with the present context.

2. EXPERIMENTAL SET-UP

The experiments were conducted in the low-turbulence wind tunnel at the Dept. of Aerospace Engineering, I.I.Sc., Bangalore (nominal free-stream turbulence 0.03%) which has been modified to obtain a constant pressure divergent flow (Figure 1a). An artificial turbulent spot was generated by a loud speaker exciting the flow at a frequency of 3Hz through 1 mm static hole at 100mm downstream of the flat plate leading edge

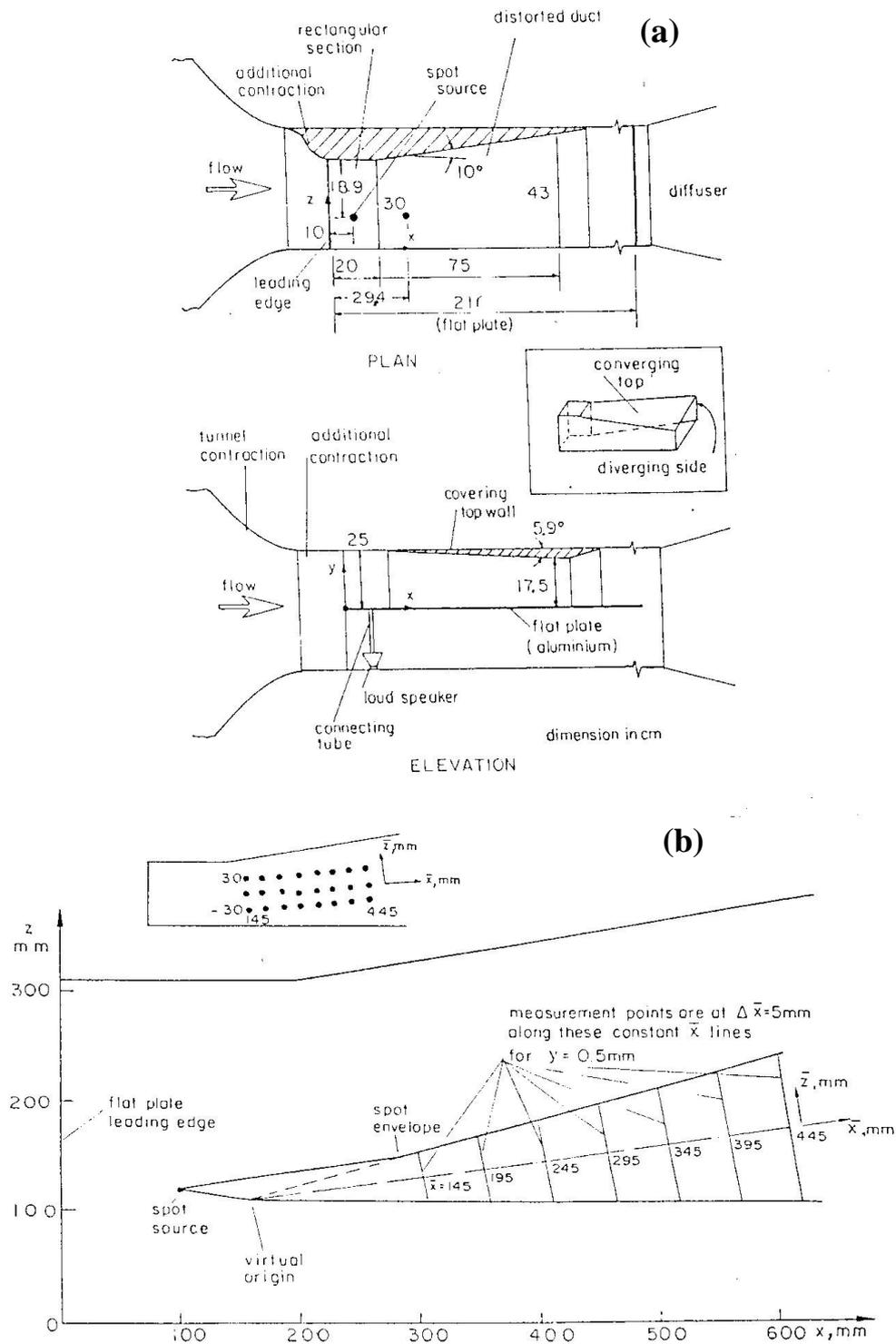


Figure 1. (a) Schematic view of the experimental set-up and (b) Coordinates and measurement locations.

Measurements were made using a constant-temperature hot-wire anemometer. A new

technique was developed to identify turbulent and non-turbulent regions (Jahanmiri et al.[8]),

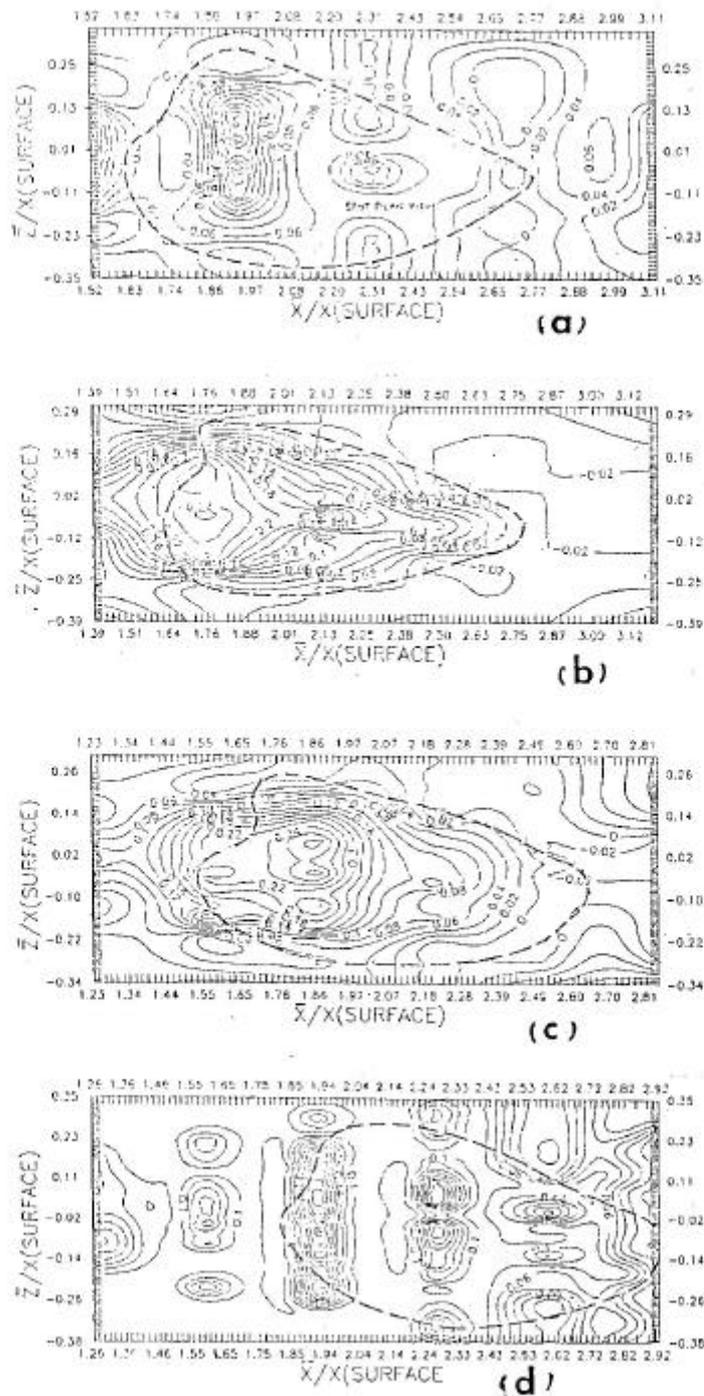


Figure 2. Contour plot of perturbed velocity field at (a) 42 ms, (b) 46 ms, (c) 50 ms and (d) 56 ms for $y = 0.5$ mm.

based on the sensitization of the signal by squaring its double derivative.

The present measurements map the spot in fixed phase time as it propagates downstream (for the

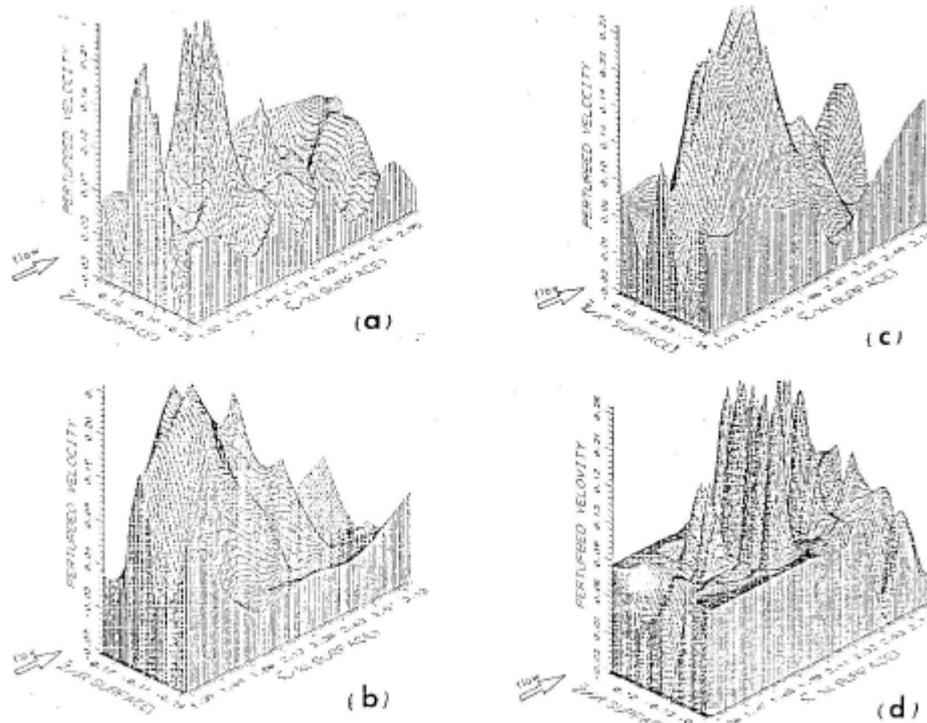


Figure 3. 3-D view of perturbed velocity field at (a) 42 ms, (b) 46 ms, (c) 50 ms and (d) 56 ms for $y = 0.5$ mm.

first time in turbulent spot studies), this is done by triggering the spot periodically and taking ensemble averages for 100 spots (with respect to constant phase from the leading edge of the spot) over 7 stream wise and 3 span wise stations as shown in figure 1b, involving a total of 210 measuring points, and a grid of 144 points at a fixed height of 0.5 mm above the surface.

3 RESULTS & DISCUSSION

The perturbation velocity is defined as follows:

$$U_{\text{pert}} = \langle U \rangle - U_L$$

where U_L is the steady longitudinal velocity of the unperturbed laminar boundary layer, and $\langle U \rangle$ is the ensemble-averaged velocity obtained as explained by Jahanmiri et al. [7]. Hence U_{pert} represents the ensemble mean disturbance produced by spot passage.

Figures 2, 4, 6 and 8 show contours of constant perturbation velocity in the normalized $\bar{x} - \bar{z}$ and

$\bar{x} - \bar{y}$ planes at different instants of time. The \bar{x}, \bar{z} coordinates are normalized with respect to the length of the spot at the surface at that instant of time, whereas the y -coordinate is non-dimensionalized with respect to spot height at the corresponding time instant. All the perturbation velocity values are in percentage of free stream velocity.

Figure 2 (a, b, c, d) shows results at $y = 0.5$ mm, with a superimposed plan view of the spot. It can be seen that the region of velocity excess is concentrated close to the centre of the trailing edge and the intensity decreases towards the edge boundary of the spot. The heart of these velocity fields is represented by two vortices (as shown in these figures), and the whole structure is consistent with the picture of a horseshoe vortex that entrains fluid from the outer laminar zone. Coles and Barker [9] propose that the spot structure is a large U-shaped vortex which moves down the plate with its ends slipping along the surface. Arakeri and Coles [10] in their synthetic boundary layer conclude that the spot like eddy appears to be

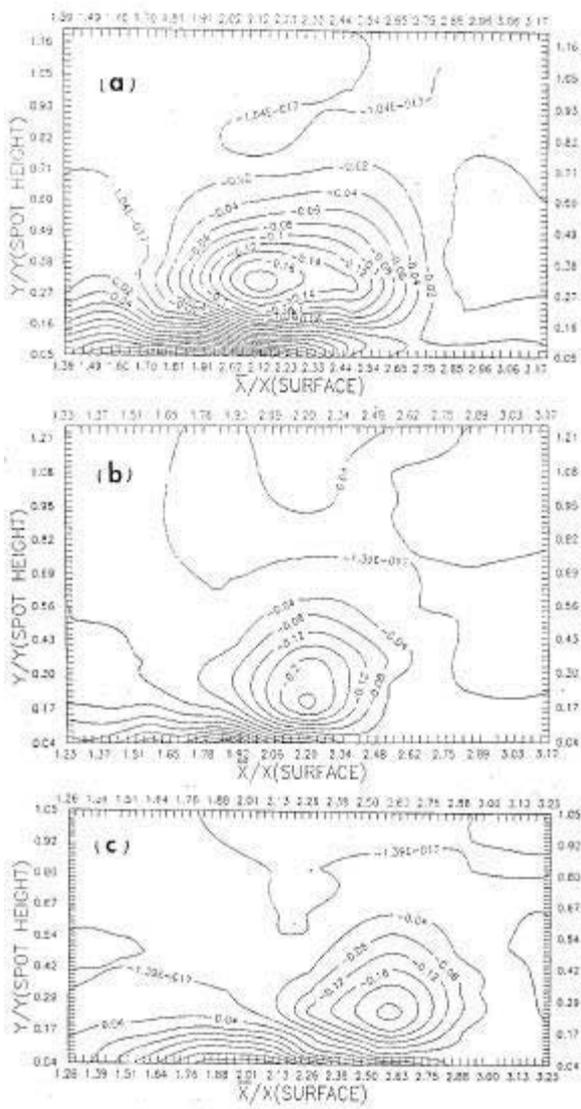


Figure 4. Contour plot of perturbed velocity field at (a) 46 ms, (b) 50 ms, and (c) 56 ms for $\bar{Z} = 0$.

composed of a pair of counter-rotating vortices, which is consistent with the present findings; these vortices are close to each other and farther from the wall at the downstream end and may represent the two legs of a horse-shoe vortex.

By comparing with the contours of Arakeri and Coles (Figure 5) and of Itsweire and Van Atta (Figure 6), it is speculated that the streamline divergence has negligible effect on the inner structure of the spot, and that the eddy pattern and

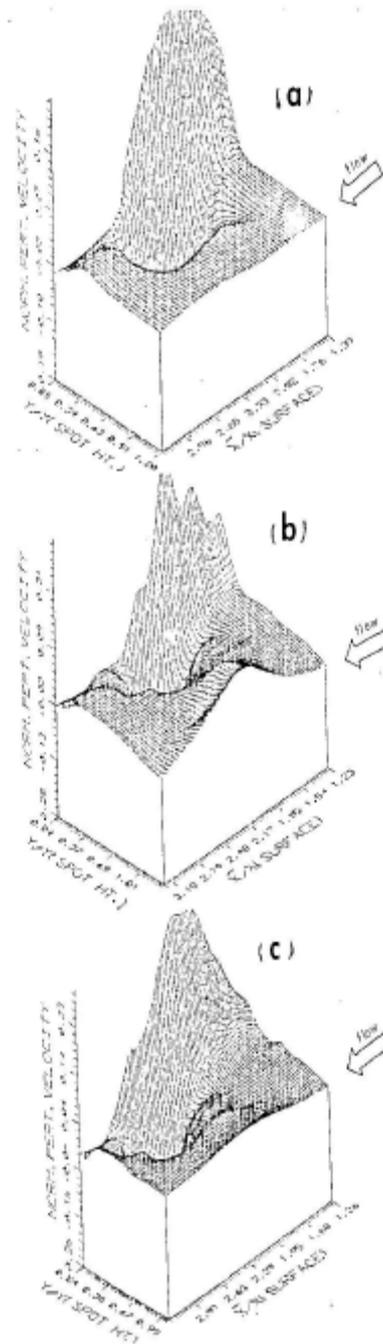


Figure 5. 3-D view of perturbed velocity field at (a) 46 ms, (b) 50 ms, and (c) 56 ms for $\bar{Z} = 0$.

its propagation downstream are very similar to that in 2-D flows.

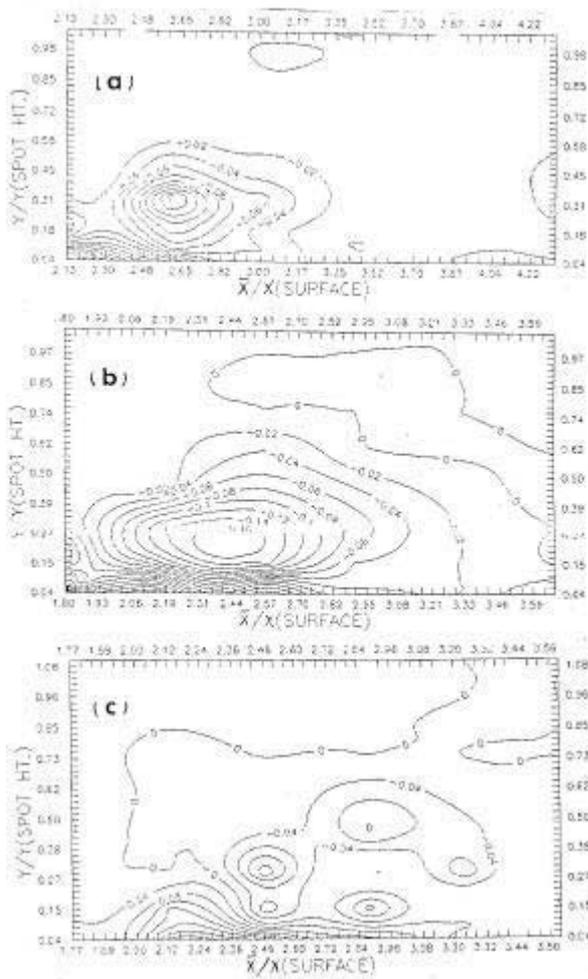


Figure 6. Contour plot of perturbed velocity field at (a) 46 ms, (b) 50 ms, and (c) 56 ms for $Z = -30$ mm.

Figure 3 shows the same constant perturbation velocity contours in an orthographic view. These views show graphically the presence of peaks and valleys in the central region of the spot, along with the appearance of Tollmien–Schlichting waves at the wing tips ($\bar{z}/x_{surf} = \pm 0.35$) of the spot at 42ms (see Figure 3a).

The Tollmien–Schlichting waves trailing a spot, first observed by Wagnanski et al. [11], are playing important role in formation of a new turbulent spot at later stages of transition process (Dey et al. [12]). This fact could be verified by careful examination of the span wise evolution of the perturbation velocity at later times (see Figures 3b, c and d). The T–S wave finally gets merged

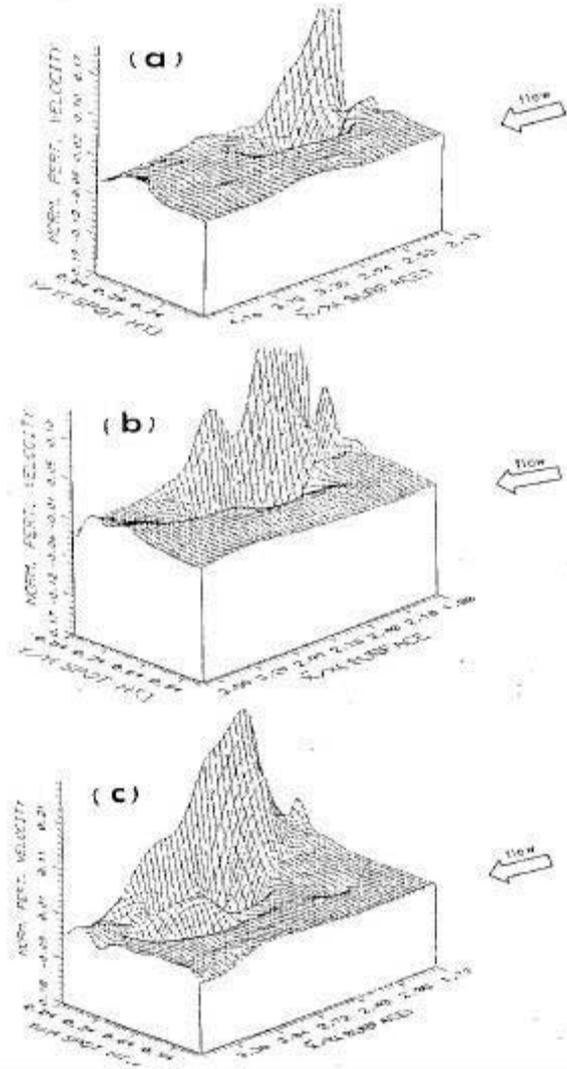


Figure 7. 3-D view of perturbed velocity field at (a) 46 ms, (b) 50 ms, and (c) 56 ms for $Z = -30$ mm.

into the main structure of the spot at 56ms.

The elevation views of the perturbation velocity field are shown in Figures 4 to 9. For the spot at different time instants the corresponding height and length at the surface are used for non-dimensionalizing the y and x coordinates respectively. Here again, as in the plan views, the values of velocity perturbation are indicated as a percentage of free stream velocity. Figures 4, 6 and 8 provide contour plots of the perturbation velocity at different span wise stations for various instants of time.

In these figures the spot is represented by a

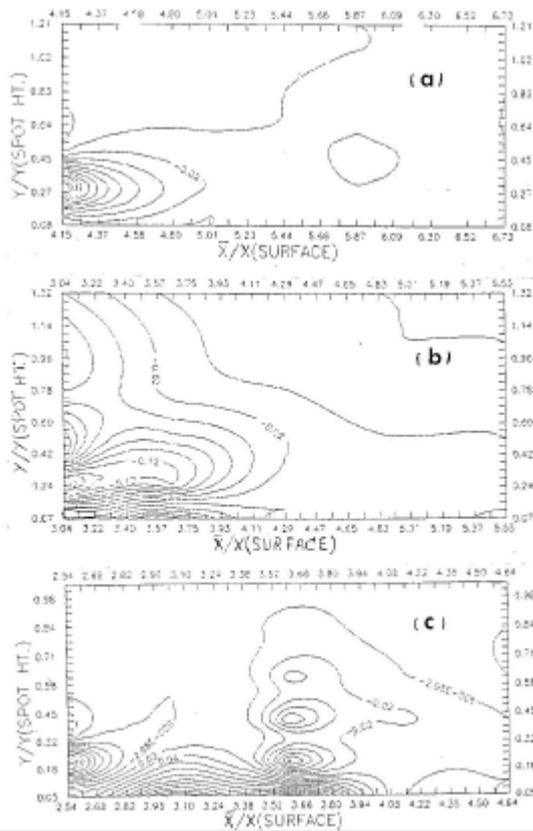


Figure 8. Contour plot of perturbed velocity field at (a) 46 ms, (b) 50 ms, and (c) 56ms for $\bar{z} = 30$ mm.

closed loop of velocity defect extending outward from $y/\text{spot height} = 0.1$, riding above the contours representing excess velocity, which also trail behind the turbulent region. Since the excess velocity decays rather slowly behind the spot, the trailing interface near the wall does not follow any contour of constant velocity perturbation.

The widely separated contours in these figures (e.g. Figure 6b) above or ahead of the active turbulent region, representing a slight velocity defect, may be related to the calm region left behind by the preceding spot.

These contours are quite similar to those of Zilberman et al. [1], Antonia et al. [3] and Itsweire and Van Atta [13] except that due to the streamline divergence the present contours are distorted and the conventional overhang and slanted trailing edge shapes are sometimes difficult to distinguish.

The structure of the spot is well explained by Coles and Barker [9], who propose that the spot is a large hairy vortex. The turbulent part up in front

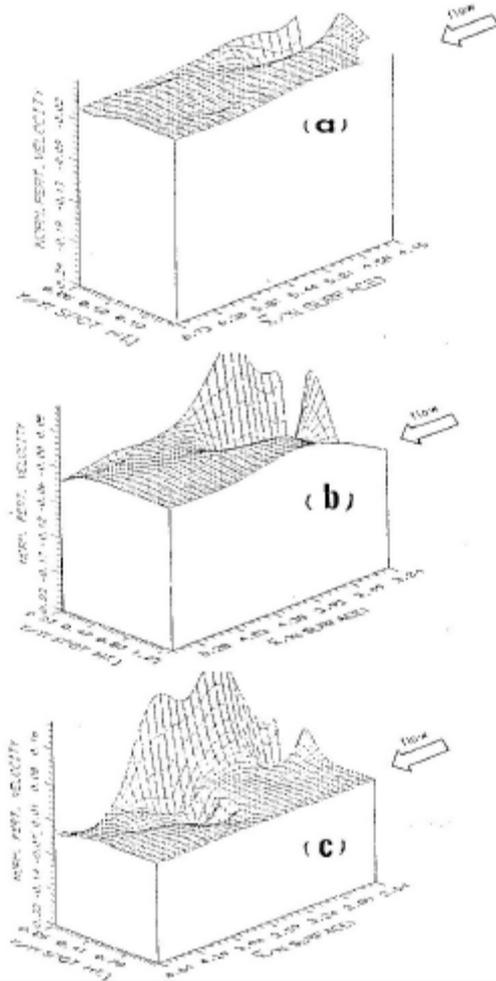


Figure 9. 3-D view of perturbed velocity field at (a) 46 ms, (b) 50 ms, and (c) 56 ms for $\bar{z} = 30$ mm.

is more or less like spray being torn off a wave by wind. One streamline, which comes in at the front near the wall, goes around the vortex, and goes out of the front again. This streamline would probably wrap into the vortex, and this process feeds the spot. The spot overruns the laminar flow and sweeps up vorticity-bearing fluid like a vacuum pump. Moreover, the transport of fluid away from the surface inside the vortex loop, induced by the vortex, may be related to the “bursting phenomenon”.

Notice that the closed loop patterns are better defined for $\bar{z} = 0$ and $\bar{z} = -30$ mm (Figures 4 and 6) as compared to the contours for $\bar{z} = 30$ mm (Figure 8, near the divergent wall). It appears as if the streamlines pushed towards the straight wall (outer side of the bend), the contribution of transfer of

energy and hence entrainment of outer flow to the turbulent spot is more pronounced near the centre and outer side of the turbulent wedge.

Figures 5, 7 and 9 show the elevation view of velocity perturbation values in an orthographic view (similar to Figures 4, 6, and 8). In these views velocity excess appears as peaks and velocity deficit as valleys. The process of formation of these peaks and valleys through the evolution of “^” shaped vortices to form the turbulent spot are elaborately explained by Perry et al. [14]. Since the evolution of spot formation is slower on the inside of the bend ($\bar{z}=30\text{mm}$), it may be said to lag behind the development process in the regions of $\bar{z}=0$ and -30 mm (see Figures 5 and 7); hence the characteristics of the evolution process seem more completely defined at $\bar{z}=30\text{mm}$ (Figure 9). From this point of view, Figure 9 might be showing the early stages of the appearance of side folds as well as the region of fully developed peaks representing the turbulent spot.

4. CONCLUSION

The flow fields associated with the passage of the spot, displayed as contour plots of the velocity perturbation suggest that, streamline divergence has no strong effect on the internal structure of the spot, and that the eddies and their propagation in the downstream direction are similar to 2-D flows. In plan view, the inner spot structure shows a region of velocity excess somewhere close to the centre of the trailing edge and the velocity intensity decreases outward. The observations are consistent with a pair of counter-rotating vortices, which entrain fluid from the surrounding laminar flow. These vortices are close to each other and probably represent the two legs of a horse-shoe vortex as found by Arakeri & Coles [10]. In elevation view the spot is represented by a closed loop of velocity defect extending outward from 0.1 times of the spot height, which rides above contours representing excess velocity. These contours are quite similar to those of Zilberman et al. [1] or Antonia et al. [3].

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