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The Influence of a Favourable Pressure Gradient on the Growth of a Turbulent Spot

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ABSTRACT

This paper is a preliminary study of the influence of a favourable pressure gradient on the spatial development of a turbulent spot within a laminar boundary layer. The spot spreads at an angle of about 7° in the spanwise direction, compared with about 9° for a zero pressure gradient. The convection velocity of the spot is larger for a favourable pressure gradient than for a zero pressure gradient, the increase being more pronounced at the trailing edge than at the leading edge of the spot.

INTRODUCTION

There has been renewed research interest in the turbulent spot perhaps as a result of the possibility that it may be the building block for a turbulent boundary layer and other turbulent shear flows (e.g. Coles and Barker, 1975; Wygnanski et al, 1976; Cantwell et al, 1978). A recent summary of current knowledge on the spot was given by Riley and Gad-el-Hak (1985). Flow visualisations (e.g. Matsui, 1980; Gad-el-Hak et al, 1981; Perry et al, 1981) and multi-point measurements of either velocity or temperature (Antonia et al, 1981; Wygnanski et al, 1982; Itsweire and Van Atta, 1984) have indicated that a turbulent spot contains several coherent structures within it. It has been suggested (e.g. Perry et al, 1981) that a spot consists of an array of hairpin eddies. These structures have been identified in a turbulent boundary layer (e.g. Head and Bandyopadhyay, 1981) and Bandyopadhyay (1983) has noted at least two features which a turbulent spot and a turbulent boundary layer have in common.

The present work represents part of a more general study - one of the long term goals of which is to obtain more information on the kinematic and dynamic properties of coherent structures in a turbulent boundary layer by subjecting the latter to changes in surface conditions (e.g. wall suction) or external conditions (e.g. pressure gradient). Since the turbulent spot provides a more suitable environment than a turbulent boundary layer for the controlled study of the underlying coherent structures, it seemed desirable to first study the topology of the spot structures and the effect of the pressure gradient on this topology. As a prelude to this study, the influence of the pressure gradient on overall characteristics of a spot such as its three-dimensional rate of growth, was first examined. We present preliminary results for the spanwise rate of spread of the spot and the convection velocities of its boundaries. The determination of the previous quantities is facilitated by the use of temperature as a passive marker of the flow.

EXPERIMENTAL DETAILS

The wind tunnel used for the present investigations has been described in detail by Antonia et al (1985). It is an open circuit, low speed, blower type wind tunnel. Two straight-sided diffuser sections are used for the expansion of flow and screens are inserted before each section. A honeycomb is placed at the inlet of the settling chamber (square cross section 885 × 885 mm). A two-dimensional contraction with a nominal area ratio of 6 : 1 joins the settling chamber to the working section. The dimensions of the working section are 5.4 m long, 0.89 m high and 0.15 m wide when the walls are parallel. The position of one wall is adjustable to permit the pressure gradient to be easily changed. The surface over which the boundary layer develops is vertical and consists of three aluminium plates. Each plate is heated by six Sierracin pads (0.1 m thick, 30 × 30 cm square) which have been bonded to the bottom of the plate. Thermal insulation, 45 mm thick, is used on the back of the plate to reduce the heat loss. The wall was heated to about 10° above the ambient temperature during all the experiments. The surface temperature was continuously monitored at a number of streamwise and spanwise stations with temperature transducers which are made of two terminal integrated circuits (AD590). The transducers are located every 30 cm in the streamwise direction along the centreline of the aluminium plate. At a streamwise separation of 90 cm a number of transducers are located in the spanwise direction with a spacing of 18 cm from each other.

To generate a turbulent spot, we first discharged a spark across a pair of sewing needles. This was the method previously used by Wygnanski et al (1976) and Antonia et al (1981). The two main disadvantages of this arrangement are the interference caused during the generation of the spark on some of the electronic equipment (e.g. the FM tape recorder) and the oxidation of the sewing needles which often resulted in a weak discharge. To avoid these problems, a system similar to that of Itsweire and Van Atta (1984) was used. The spot was triggered by a speaker (high frequency dome tweeter) mounted on the back of the aluminium wall. When a pulse was fed into the speaker, it created an air jet through a 3 mm dia. hole in the aluminium plate at $x \equiv x_s = 0.3$ m where x is measured from the exit of the contraction. The thickness of the laminar boundary layer at this location is about 5 mm. The pulse duration of 62.5 μs produced a well developed spot starting from x = 0.7 m, the interval between spots being equal to one second.

All measurements were conducted at a reference free stream velocity of 4.8 m/s measured at the exit of the contraction (x = 0). The hot wire probe (5 μm dia., Pt-10% Rh, 1.5 mm length) used for the velocity measurements was operated with a DISA 55M10 constant temperature anemometer at an overheat ratio of 0.8. For the temperature measurements a single cold wire probe (0.6 μm dia., Pt-10% Rh, 1.0 mm length) was used with in-house constant current (0.1 mA) circuits. The initial distance between the probe and the wall was determined optically by viewing the wire and its reflection in the polished aluminium surface through a theodolite (least count 0.01 mm). The square wave pulse and the cold wire signals were directly digitised at a sampling frequency of 3200 Hz and recorded into a PDP 11/34 digital computer. Processing of the data was carried out on a VAX 11/780.

LAMINAR VELOCITY AND TEMPERATURE PROFILES

Velocity and temperature profiles were measured at several streamwise stations to verify the behaviour of the laminar boundary layer for zero and favourable pressure gradients. The pressure gradient dP/dx is related to the exponent m in the free stream velocity variation $U_\infty(x) = Kx^m$ by $m = -(x/\rho U_\infty^2)\, dP/dx$. For the favourable pressure gradient considered here, m is 0.05. Mean velocity profiles were measured at x = 0.4, 1.0 and 1.9 m and presented in Figure 1 in the form of U/U_∞ vs η, where $\eta = y\sqrt{U_\infty/\nu x}$. For m = 0, they are in reasonable agreement with the Blasius distribution. There is also reasonable

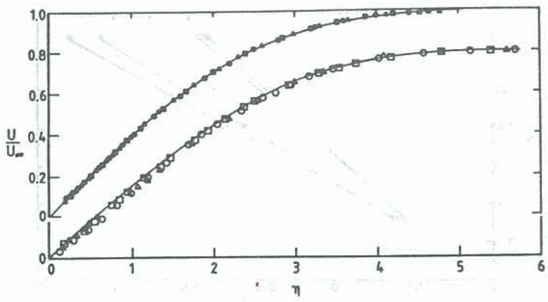

Figure 1 Velocity profiles for m = 0 and m = 0.05.
m = 0: ○, x = 0.4 m; □, 1.0; △, 1.9.
m = 0.05: ●, x = 0.4 m; ■, 1.0; ▲, 1.9.

agreement, for m = 0.05, between the measured profiles and the corresponding Falkner-Skan distribution. Temperature profiles, measured at x = 0.7, 1.0 and 1.3 m for both m = 0 and m = 0.05, are presented in Figure 2. Here, the non-dimensional temperature $\theta = T-T_\infty/T_w-T_\infty$ (T_w and T_∞ are the wall and free stream temperatures respectively) is plotted as a function of η. They are in adequate agreement with the theoretical Pohlhausen distributions calculated, using a numerical procedure outlined by Browne and Antonia (1982), for m = 0 and m = 0.05. A value of 0.8 is used for the molecular Prandtl number.

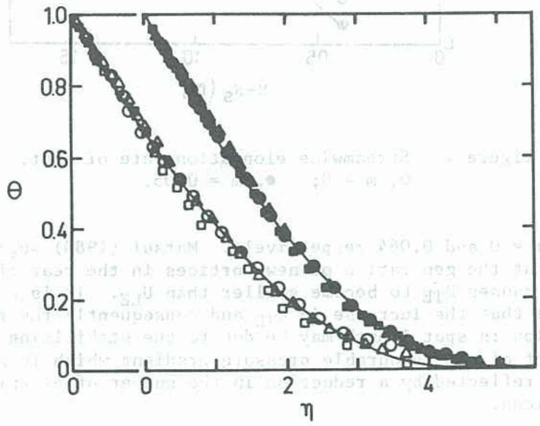

Figure 2 Temperature profiles for m = 0 and m = 0.05.
m = 0: ○, x = 0.7 m; □, 1.0; △, 1.3.
m = 0.05: ●, x = 0.7 m; ■, 1.0; ▲, 1.3.

SPATIAL GROWTH OF THE SPOT

Ensemble averages of the instantaneous temperature signal were obtained by first determining the position of the leading edge of the spot. For the identification of this leading edge, we used the criterion

$$\left| T(n) - \frac{1}{d} \sum_{j=n+1}^{n+d} T(j) \right| > K ,$$

where T(n) represents the n^{th} sample of the digital time series for the instantaneous temperature, d is the number of samples over which the signal is averaged and K is a threshold. The values of K and d were carefully chosen, after examining individual spot realisations, to eliminate noise effects creating spurious spots. For the present experiments K = 0.45 and d = 10. Averaging was carried out for an ensemble of 120 realisations, after aligning the spots relative to the leading edge. The instantaneous temperature T can be decomposed as follows:

$$T = T_L + \tilde{T} + T_f ,$$

where the subscript L refers to the laminar flow value and $\tilde{T}$ is the ensemble averages value of $T-T_L$, i.e.

$$\tilde{T} = \langle T\rangle - T_L$$

angular brackets denoting ensemble averaging. By definition, $\langle T_f\rangle = 0$.

Contours, in the (z,t) plane, of constant $\tilde{T}/\Delta T$, were calculated at x = 0.7, 1.0, 1.3 and 1.9 m. Contours at x = 1.3 m are shown in Figure 3 for m = 0 and m = 0.05. These contours are generally similar to the velocity perturbation contours obtained by Itsweire and Van Atta (1984) in the (z,t) plane for m = 0. They indicate that

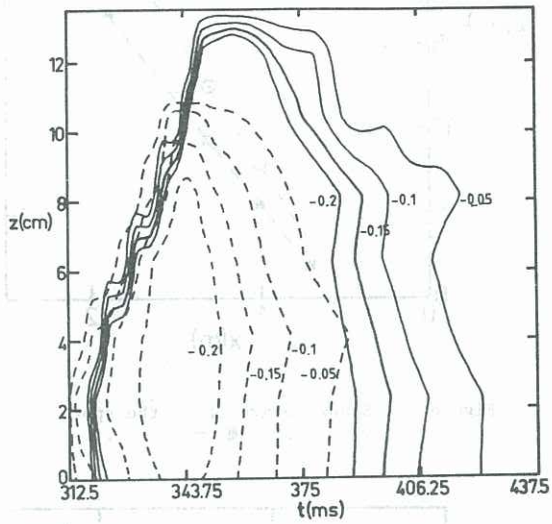

Figure 3 Temperature disturbance contours, $\tilde{T}/\Delta T$, in the (z,t) plane for m = 0 and m = 0.05 at x = 1.3 m and y = 3.0 mm.
——, m = 0; ---, m = 0.05.

the pressure gradient reduces the extent of the spot significantly in both the spanwise and streamwise directions. This may reflect the stabilising influence of the favourable pressure gradient. In this context, Corrsin and Kistler (1955) had noted that the destabilisation of the rotational flow adjacent to the spot should affect the spanwise growth of the spot.

The lateral extent of the spot was obtained from the constant $\tilde{T}/\Delta T$ contours in the (z,t) plane. The width of the spot, determined using the contour $\tilde{T}/\Delta T = 0.01$, is plotted in Figure 4 as a function of x, the constant slope of the line is proportional to the semi-angle of the spot. For m = 0 and m = 0.05, the angles are approximately 9° and 7.3° respectively (Figure 4). By comparison, Wygnanski et al (1982) reported a minimum value of 9.2° for m = 0 while Wygnanski (1981) obtained 5° for m ≃ 0.064.

The turbulent wedge of a wall roughness element in a laminar boundary layer grows in a manner similar to that of a turbulent spot (e.g. Charters, 1943). The spread rate associated with a disturbance produced by a pin (3 mm height, 2 mm dia., located at x = 0.3 m) was measured for m = 0 and m = 0.05. The width of the spot at a given x was arbitrarily defined as the value of z corresponding to $u'/U_\infty = 0.04$ (u' is the longitudinal turbulent intensity). The slopes indicated by the linear variation in Figure 5 are in agreement with those inferred from Figure 4. This result is consistent with the assumption that the pin disturbance consists of a continuous train of spots.

The arrival times of the leading edge and trailing edge are measured from the time at which the speaker trigger pulse is fired. Figure 6 is a plot of leading edge and trailing edge arrival times at various streamwise stations measured from the pulse. The slopes of the lines represent the convection velocities of the leading edge and trailing edge respectively. For m = 0, the convection velocity U_{LE} is found to be $0.74U_\infty$, which is identical with the value reported by Antonia et al (1981). For m = 0.05, both U_{LE} and U_{TE} appear to be constant, even though U_∞ increases by about 4% between x = 0 and x =

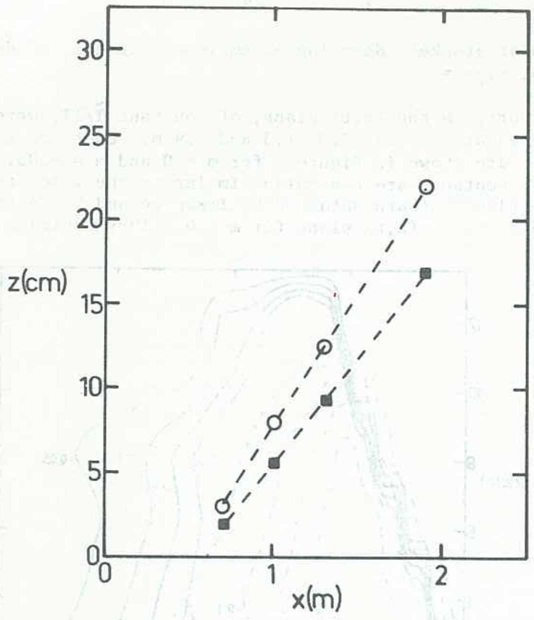

Figure 4 Spanwise growth of the spot. ○, m = 0; ■, m = 0.05.

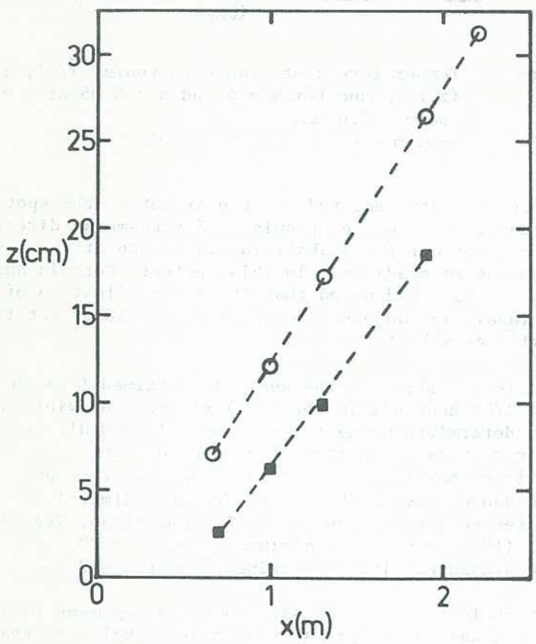

Figure 5 Spanwise growth of the disturbance caused by a small cylindrical pin on the wall (x = 0.3 m). ○, m = 0; ■, m = 0.05.

1.9 m. Relative to m = 0, U_{LE} increases by only 5% whereas U_{TE} increases by about 13%. For the present experiments, the ratio of U_{LE}/U_{TE} is about 1.47 for m = 0.05 and about 1.6 for m = 0. Wygnanski (1981) obtained a value of U_{LE}/U_{TE} = 1.43 for m ≃ 0.064. It appears that the influence of the pressure gradient is more pronounced on the trailing edge than on the leading edge of the spot.

The growth of the spot in the longitudinal direction is a direct consequence of the difference between U_{LE} and U_{TE}. The rate of streamwise elongation of the spot may be defined as dL/dx, where L is the length of the spot. Figure 7 shows the length of the spot (L) as a function of $(x-x_s)$, the distance from the disturbance location. For m = 0, dL/dx is 0.38 whereas dL/dx is 0.32 for m = 0.05. Wygnanski (1981) obtained values of 0.48 and 0.29

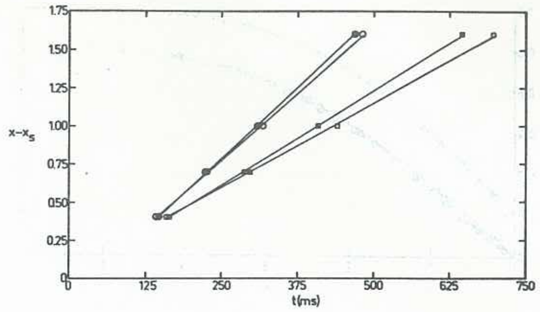

Figure 6 Arrival times of leading and trailing edges of spot.
m = 0: ○, leading edge; □, trailing edge.
m = 0.05: ●, leading edge; ■, trailing edge.

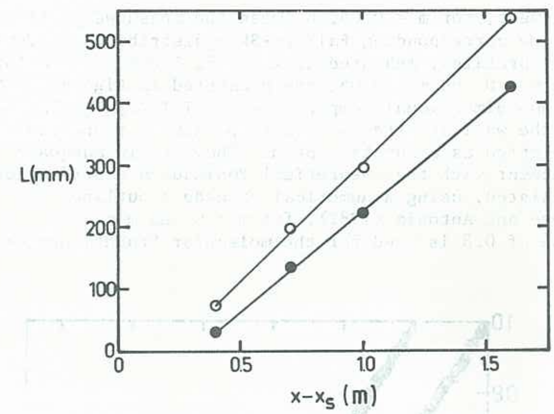

Figure 7 Streamwise elongation rate of spot. ○, m = 0; ●, m = 0.05.

for m = 0 and 0.064 respectively. Matsui (1980) suggested that the generation of new vortices in the rear of the spot causes U_{TE} to become smaller than U_{LE}. It is possible that the increase in U_{TE} and consequently the reduction in spot length may be due to the stabilising effect of the favourable pressure gradient which is perhaps reflected by a reduction in the number of hairpin vortices.

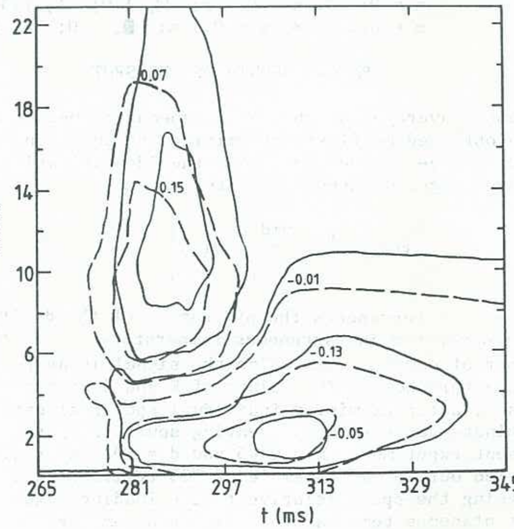

Figure 8 Temperature disturbance contours in the (y,t) plane for m = 0 and m = 0.05. x = 1.3 m, z = 0. ——, m = 0; ---, m = 0.05.

Contours of $\tilde{T}/\Delta T$ (Figure 8) have also been obtained in the (y,t) plane for m = 0 and m = 0.05 at only one x location. They exhibit all the characteristics previously discussed by Van Atta and Helland (1980) and Antonia et al (1981). The positive perturbation contours away from the wall reflect the arrival of warmer fluid from the wall region whereas the negative perturbation contours reflect the arrival near the wall of colder fluid from larger values of y. The vertical extents of both warm and cold regions are reduced by the favourable pressure gradient.

It would be useful to compare the spatial evolution of the spot for favourable and zero pressure gradient conditions within the framework of conical similarity (e.g. Cantwell et al, 1978) or by using the modified conical similarity variables proposed by Sokolov et al (1980). This comparison is currently under investigation.

CONCLUSION

The application of a favourable pressure gradient reduces the rate of growth of a turbulent spot in all three spatial directions. In particular, the convection velocity of the trailing edge is increased more appreciably than that of the leading edge, when the favourable pressure gradient is applied.

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