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Transitional intermittency in boundary layers subjected to pressure gradient

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Summary. Results are reported from an extensive series of experiments on boundary layers in which the location of pressure gradient and transition onset could be varied almost independently, by judicious use of tunnel wall liners and transition-fixing devices. The experiments show that the transition zone is sensitive to the pressure gradient especially near onset, and can be significantly asymmetric; no universal similarity appears valid in general. Observed intermittency distributions cannot be explained on the basis of the hypothesis, often made, that the spot propagates at speeds proportional to the local free-stream velocity but is otherwise unaffected by the pressure gradient.

1 Introduction

The key variable in describing a boundary layer during transition from laminar to turbulent flow is the intermittency γ. In constant pressure layers, there is a satisfactory model based on the theory of spots (Emmons 1951) and the hypothesis of concentrated breakdown (Narasimha 1957, Dhawan & Narasimha 1958, Narasimha 1983). In the presence of pressure gradients data available are limited and scattered (Narasimha 1958, Gururani 1972, Devasia 1974, Abu-Ghannam and Shaw 1981); the purpose of this note is to present a consolidated report on experiments conducted at the Indian Institute of Science (IISc) over the years, and to briefly assess available models in the light of the data.

In planning the present series of experiments, it was considered important to be able to study in detail the effect of the location of pressure gradient relative to transition onset, as this had been identified as a key factor in the problem long ago (Narasimha 1958). The two parameters were therefore independently controlled, the pressure gradient by use of movable tunnel wall liners and transition onset by transition-fixing devices. A wide range of combinations could thus be obtained; these offer much insight into the factors likely to be important in determining intermittency distributions, and further constitute good test cases for transition zone models.

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2 Experiments

All IISc experiments cited here were conducted on a flat plate mounted midway in a 0.6 m square boundary layer tunnel (Fig. 1). The plate was polished aluminium, 4.8 mm thick and 2.09 m long; its incidence could be varied over ± 2 deg., to adjust the pressure gradient and to help ensure no separation at the leading edge. The pressure gradients were applied in some experiments by tilting the top wall, but more often by mounting liners on it. By placing such liners at different positions along the wall, the gradients could be applied over different streamwise zones on the plate.

A serious problem with the use of such liners is that under certain conditions they can alter flow direction in the tunnel sufficiently to cause leading edge separation on the plate. This was avoided by a variety of measures. First of all, the leading edge was a super-ellipse, with an index of 3.0 and axis ratio of 6.0; it has been shown (Prasad 1973) that this is a reasonable optimum if one wants to minimize chances of laminar separation. Secondly, the plate could be tilted slightly in both directions, to move the stagnation point towards the top surface of the plate when necessary. Finally a choke could be placed on the top wall towards the rear end of the plate, again helping

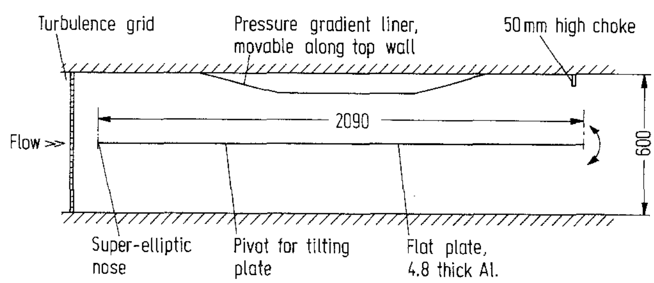

Fig. 1. Schematic diagram of the experimental arrangement. The pressure gradient distribution imposed on the flat plate boundary layer can be altered by use of different liners; furthermore the liners can be moved along the top wall, enabling the region of pressure gradient to be placed at any desired location (all dimensions in mm)

to alter flow directions slightly. With the use of one or more of these methods it was always possible to ensure that no leading edge separation occurred.

With the normal turbulence level in the tunnel (about 0.08%), transition occurred towards the end of the plate even at the highest velocity. In most experiments therefore tansition was forced, by increasing tunnel turbulence level with the help of grids at the beginning of the test section. By suitable choice of grids and tunnel liner position, it was possible to manipulate the locations of transition onset and pressure gradient into almost any desired combination.

The intermittency was measured using 5 μm dia. Pt-Rh hot wires sensing the longitudinal velocity fluctuation, processed mostly through constant current electronics. The probe was located sufficiently close to the surface so that the reading was unaffected by the variation with normal distance characteristic of "edge" intermittency (Dhawan and Narasimha 1958, Narasimha 1983). Sampling time was always taken long enough to ensure that the measured intermittency did not change with record length; this requires long records for very low and very high intermittencies. A more serious problem was the setting of the discrimination level, especially at low γ; in one experiment, for example, the value of γ inferred varied from 0.053 to 0.073 depending on the discriminator setting. This uncertainty is less important at higher γ, and must be borne in mind in interpreting the results.

Pitot profiles were measured with a 0.5 mm tube.

All probes could be mounted on a traverse which enabled their movement in all three directions – along, across and normal to the plate. Longitudinal movement was obtained by a lead screw (with a travel of 860 mm), lateral by a turntable, and normal by a micrometer.

Table 1 lists the experimental conditions in the flows reported.

3 Results

Figure 2 shows two sets of intermittency data obtained in zero pressure gradient flow. It will be seen that there is very satisfactory agreement with the theoretical universal

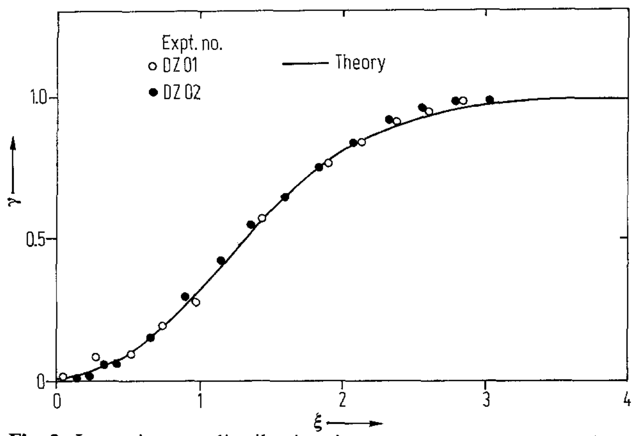

Fig. 2. Intermittency distribution in two constant-pressure flows, showing excellent agreement with the theory of Narasimha (1957)

Table 1. List of flows investigated

Flow code	Pres. grad.	U_0 (m/s)	Transition agent	Reference	Remarks
NFD 1	F	–	Cylinder wake	Narasimha (1958)	Pressure gradient by tilting top wall
NFU 1	F	–			
GZ 02	0	12.9	0.25 mm × 20 mm tape 120 mm from leading edge	Gururani (1972)	Pressure gradient by convergent liner, moved progressively from 493–752 mm in GF02 to 615–874 mm in GF05
GF 02	F	14.2			
GF 03		14.2			
GF 04		14.2			
GF 05		14.2			
DZ 01	0	10.0	1/8 grid	Devasia (1974)	
DZ 02	0	12.0	1/16 grid		
DFU 1	F	13.65	1/4 grid		Pressure gradient by movable liners of shape illustrated in text
DFU 2	F	9.8	3/4 grid		
DFU 3	F	12.0	1/16 grid		
DFD 1	F	12.5	1/4 grid		
DFD 2	F	12.95	3/4 grid		
DAU 1	A	13.4	1/16 grid		Flow DAU 1 has slight favourable gradient near onset; see text

F = favourable; A = adverse. U_0 = reference velocity, measured upstream of plate (hence also of pressure gradient). Flow code is constructed as follows: first character indicates reference, second sign of pressure gradient, third (if letter) upstream or downstream location of pressure gradient relative to onset of transition, last serial number. Grid numbers give mesh size in inches distribution based on the hypothesis of concentrated breakdown (Narasimha 1957),

$$\gamma(x) = 1 - \exp(-0.412\,\xi^2), \quad \xi = (x - x_t)/\lambda\,, \tag{1}$$

where

$$\lambda = x\,(\gamma = 0.75) - x\,(\gamma = 0.25)$$

is a measure of the extent of the transition zone, and x_t is the effective location of the beginning or onset of transition.

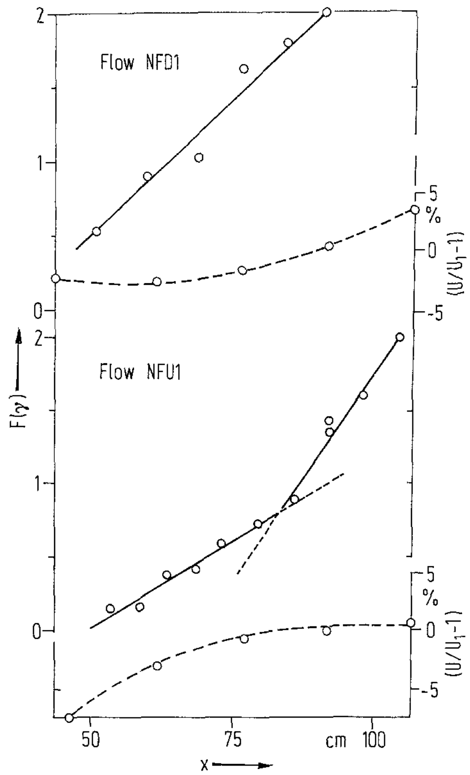

Fig. 3. Data from two favourable pressure gradient flows studied by Narasimha (1958), plotted in variables that should exhibit a linear relationship if the intermittency distribution (1) is obeyed. Note the break in the curve in flow NFU 1

Figure 3 reproduces the results of two experiments reported by Narasimha (1958), on the effect of a favourable pressure gradient on γ-distributions. The results are displayed in an $F(\gamma)$ plot, where

$$F(\gamma) = [-\ln(1-\gamma)]^{1/2}\,; \tag{2}$$

if the distribution (1) is obeyed, $F(\gamma)$ will be linear in x. Such linearity is indeed observed in flow NFD1, where the pressure gradient is imposed over the downstream half of the transition zone. On the other hand in flow NFU1, where the pressure gradient occurs over the onset region, the $F(\gamma)$ plot is no longer linear, and in fact possesses an unmistakable kink. From these data Narasimha concluded that γ would obey the distribution (1) if the pressure gradient were present in the downstream part of the transition zone, but not if it were in the upstream part.

Figure 4, from Gururani (1972), gives an overall impression of the way the intermittency distribution changes as a favourable pressure gradient is moved downstream, without any change in the free-streem turbulence level; onset of transition was fixed in these experiments by a 20 mm wide adhesive tape of 0.25 mm thickness, stuck across the plate about 120 mm from the leading edge. In flow GF02 onset is delayed, and the transition zone is longer, relative to the constant pressure flow GZ02. As the pressure gradient liner is moved further downstream, however, the effects are not monotonic: in GF03 onset is at about the same location as in GF02, or possibly slightly earlier: the transition zone is also slightly shorter. This is perhaps not very surprising, however: the occurrence of the pressure gradient further aft means that the stabilization of the flow near the onset is less, which promotes earlier transition, and hence also a shorter zone.

We now look at the results of a series of careful experiments made by Devasia (1974). The free-stream velocity and intermittency distributions in these experiments are shown in Fig. 5 to 8. The data in Fig. 5 come from two flows with the same free-stream turbulence level. In both flows, the free stream velocity varies from

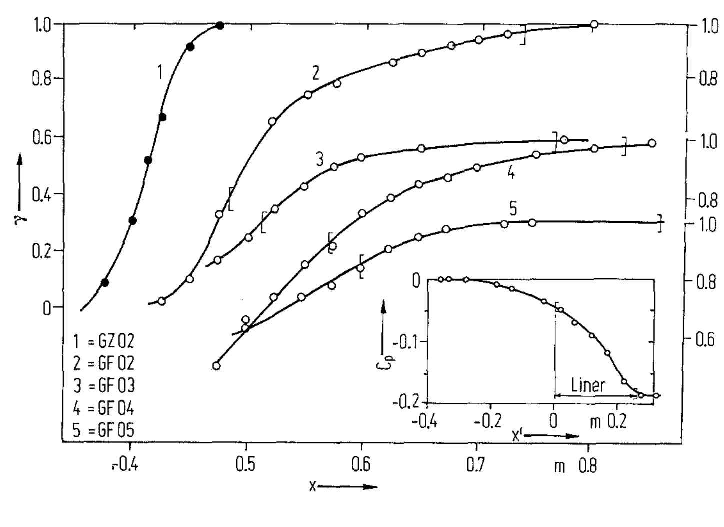

Fig. 4. Results from the G-series of experiments, showing changes in γ-distribution as a favourable pressure gradient region is moved downstream along the plate, at fixed upstream velocity and free-stream disturbance level. Square brackets on each curve show position of tunnel wall liner; the associated pressure gradient is shown in the inset. Curve 1 shows γ in the absence of pressure gradient

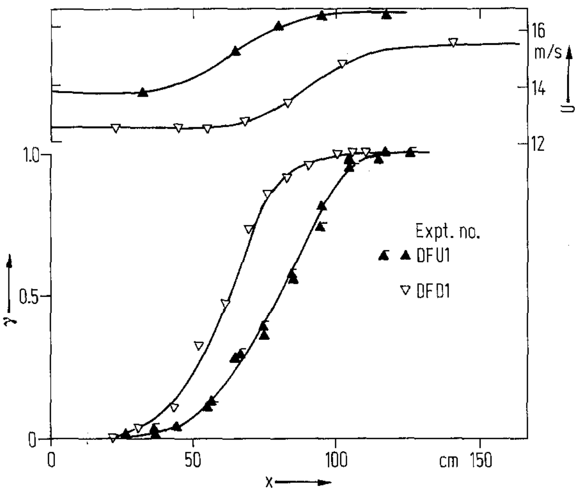

Fig. 5. Data from two flows showing the movement of transition upstream when the pressure gradient is displaced downstream. Flagged points are repeats in the same flow

one constant value U_1 up-stream to a different constant values U_2 downstream. Note first the good repeatability of the data, as illustrated by measurements made on different days in flow DFU 1. When the pressure gradient is shifted downstream (flow DFD 1) it is clearly seen that transition moves slightly upstream, in spite of the lower free-stream velocity – which may be attributed (as before) to a loss of stabilization at onset.

Further, the shapes of the γ-distributions in the two flows are rather different; DFU 1 is spread out more near onset, and DFD 1 near completion: in both cases, the favourable pressure gradient appears to have the effect of lengthening the transition zone over the gradient region. The two γ-distributions are clearly not quite similar in shape.

Results of two other experiments with a different tunnel wall liner and free stream disturbance level are shown in Fig. 6. In DFD 2, transition is effectively complete while the pressure gradient is still large; in DFU 2, on the other hand, the transition zone is longer than the pressure gradient region. These experiments emphasize how large changes in intermittency can occur for relatively slight changes in the position of the pressure gradient relative to onset of transition.

Flow DFU 3 (Fig. 7) shows more clearly, in a milder pressure gradient, how stabilization near onset can significantly widen the early transition zone, and result in a highly asymmetric γ-distribution. Flow DAU 1 (Fig. 8) also displays a strong skewness, aided now by an adverse gradient over the aft half of the transition zone, which hastens completion of transition.

Figures 9 and 10 show respectively the momentum thickness Reynolds number and the shape factor in the different flows. Note in particular how, in flow DFU 3, the intervention of the favourable pressure gradient suppresses boundary layer growth. The rapid growth seen further downstream in this flow, as well as in DFU 1, is of course characteristic of fully turbulent flow.

Figure 10 shows that in all the flows reported the shape factor drops relatively smoothly from a value near 2.6, characteristic of the laminar Blasius solution, to values slightly less than 1.5, as may be expected in fully turbulent flow. There is evidence of small "bumps" in the curves, especially in the flows DFD 1, DFU 1 and DFU 3, but these are less pronounced than in Fig. 9.

4 Discussion

There are two models in use for describing γ-distributions in pressure-gradient flows. The first uses a transformation to reduce the problem to that of constant pressure flow (Chen & Thyson 1971), and the second assumes the existence of similarity (Abu-Ghannam and Shaw 1980).

We have already pointed out how the γ-distributions obtained here show qualitative differences; it follows that they cannot in general be similar in variables that take no account of the pressure gradient, unless of course the pressure gradient is very mild.

Chen and Thyson (1971) treat the pressure gradient by making the hypothesis that the spot propagation velocity at any point x is proportional to the local free-stream velocity $U(x)$; the transverse growth of the spot across streamlines is assumed to be unaffected. This amounts to saying that the spot propagation cone, defined in $x\,y\,t$ space by Emmons (1951), has straight generators if the

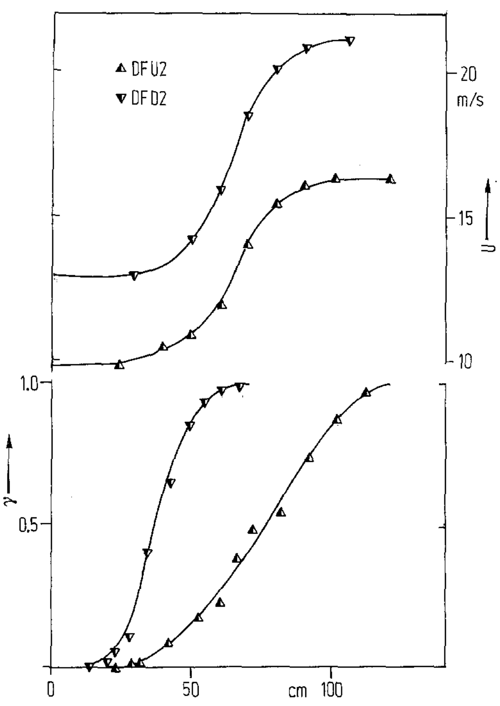

Fig. 6. Results from two experiments showing large changes in γ with small changes in pressure-gradient location

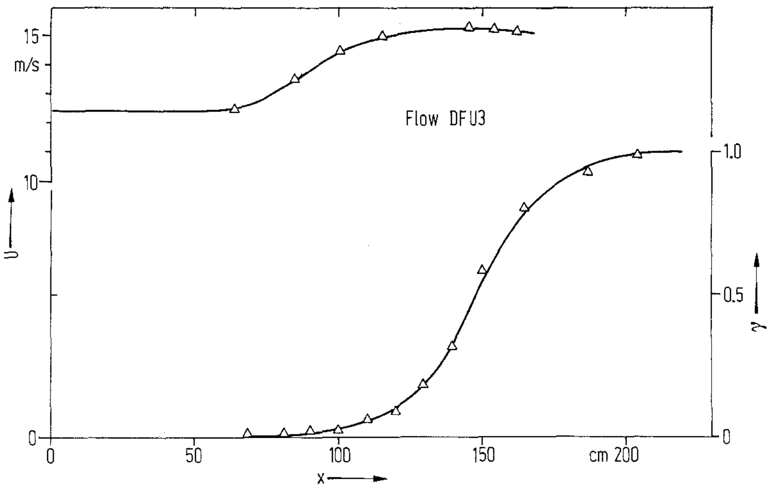

Fig. 7. Results from flow DFU 3, showing how a relatively mild pressure gradient at onset can lengthen the transition zone significantly

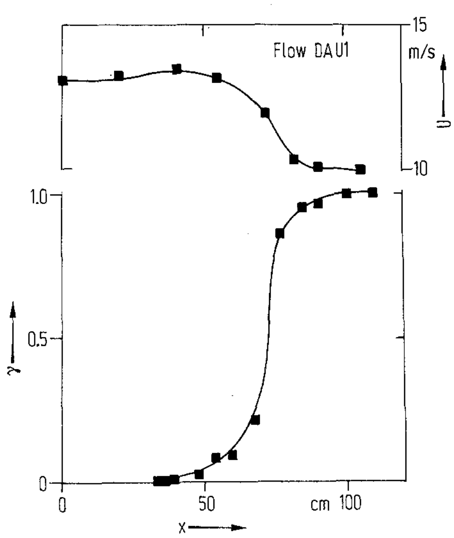

Fig. 8. Intermittency in a flow where a mild favourable gradient is followed by a stronger adverse gradient. Notice the skewness in the resulting intermittency distribution

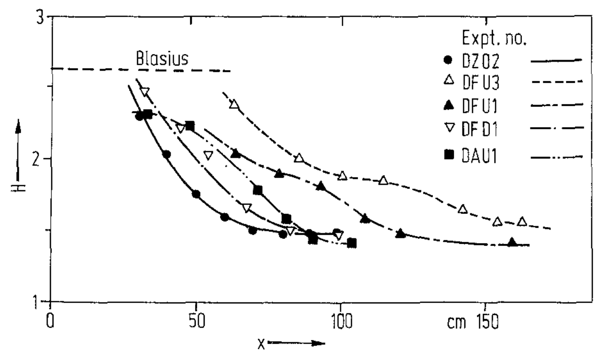

Fig. 10. Shape factor variation in the various flows reported here

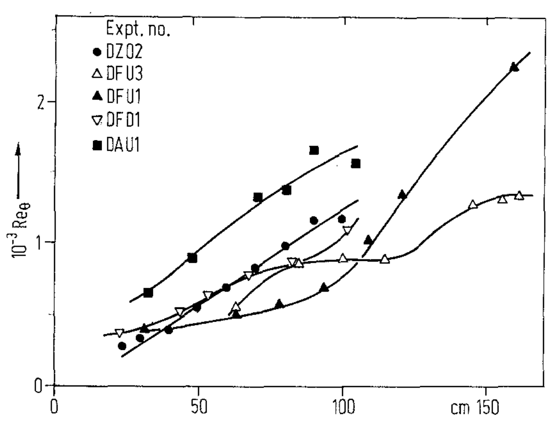

Fig. 9. Momentum thickness Reynolds number in the various flows reported here

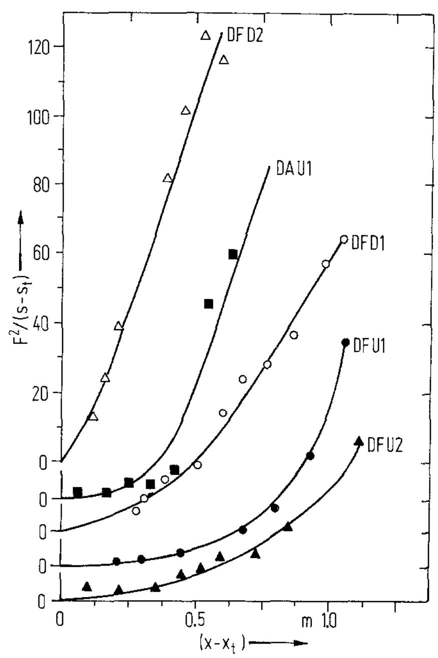

Fig. 11. Intermittency data from various flows reported here, replotted in transformed variables. These should exhibit a linear relationship if the hypothesis were valid that spot propagation is linear in the time-of-flight variable s

time t is replaced by the time-of-flight for fluid particles in the free stream,

$$s = \int^{x} \mathrm{d}x / U(x). \tag{3}$$

Using this variable, and retaining the hypothesis of concentrated breakdown (Narasimha 1957), the γ-distribution in plane flows subjected to pressure gradient becomes

$$\gamma(x) = 1 - \exp\left[-A(s - s_t)(x - x_t)\right] \tag{4}$$

where A is a constant. If this were valid, it follows that the quantity

$$F^2(\gamma)/(s - s_t), \tag{5}$$

where F is defined by (2), must be linear in x.

Figure 11 shows the results from the D-series of present experiments plotted in the variable so suggested. It is clear that the proposed straight line relationship is in general not obeyed. It remains to add that there is independent evidence (Narasimha 1983) that the assumptions underlying (4) are in general not valid.

5 Conclusions

From a series of experiments conducted in two-dimensional transitional boundary layers in pressure gradient, it is found that:

(i) the effect of pressure gradients on the intermittency distribution depends strongly on their location relative to the onset of transition;

(ii) a favourable gradient tends to lengthen the transition zone, especially when it occurs near onset;

(iii) consequently, γ-distributions can under certain conditions be highly asymmetric or skew;

(iv) for the kind of pressure gradients investigated here, significant departures from constant-pressure similarity laws are observed; and

(v) the hypothesis that the spot propagation cone has straight generators in the free-stream time-of-flight variable does not explain observed intermittency distributions.

An alternative model for describing such transitional flows will be proposed separately.

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