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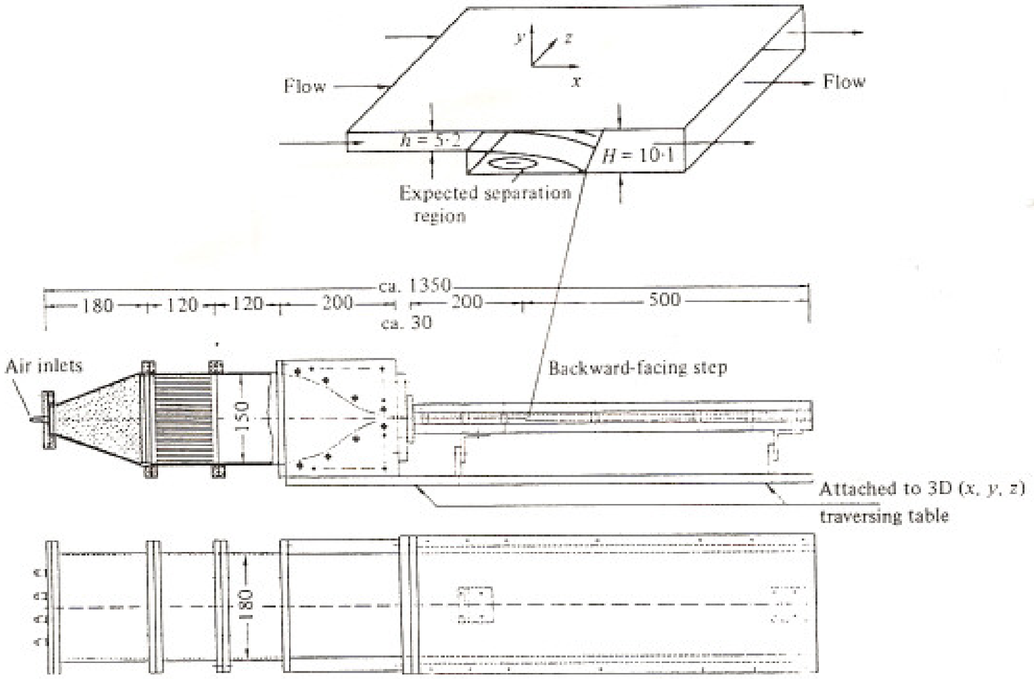

FIGURE 1. Schematic of air tunnel and test section (dimensions in mm).

2. Experimental investigation

2.1. *Apparatus and experimental procedures*

The open air-driven flow channel that was used for this study is shown schematically in figure 1. It incorporated a two-dimensional backward-facing step that provided an expansion ratio of 1:1·94. The larger channel, downstream of this step, had a height of 1·01 cm and an aspect ratio of 18:1. The tunnel and the test section were constructed from aluminium and all parts were machined to very close tolerances regarding parallelity of walls, surface roughness, manufacturing of step corners, etc. The two sidewalls were made of glass of 1 cm thickness to support the rigidity of the test section and also to facilitate laser-Doppler measurement with forward-scattered light. The air flow into the channel contained scattering particles of 2 μm mean diameter provided by a silicone-oil particle generator described by Cherdron, Durst & Whitelaw (1978). The air flow with particles was passed through a large settling chamber and was fed through five, 6 mm diameter, bored tubes into the first part of the flow channel. This part consisted of an expansion section packed with steel wool to smoothen the flow and to prevent input disturbances from affecting the measurements. The flow was then passed through a section with flow straighteners and was afterwards guided into a smooth contracting nozzle with an inlet-to-outlet area ratio of 30:1. The outlet of the nozzle was connected to the inlet of the channel test section, which was 0·52 cm in height and 20 cm in length up to the backward-facing step. These dimensions ensured a two-dimensional fully developed flow at the cross-section where the step was located for the entire Reynolds-number range studied by the authors. The upper and the lower part of the test section and the glass sidewalls were held parallel together by machine screws and were attached to the nozzle exit by location pins. The assembly of channel and inlet section was placed on the top of a three-dimensional traversing table which allowed the measuring

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2.2. *Experimental results*

2.2.1. *Longitudinal flow structure.* Measurements of the reattachment length and velocity distribution were performed for a Reynolds-number range between 70 and 8000, which covered the laminar, transitional and part of the turbulent regime of the two-dimensional backward-facing step flow. The definition of the Reynolds number which is used in this study is given by

$$Re = \frac{VD}{\nu},$$

where V is two-thirds of the measured maximum inlet velocity, which corresponds in the laminar case to the average inlet velocity, D is the hydraulic diameter of the inlet (small) channel and is equivalent to twice its height, $D = 2h$, and ν is the kinematic viscosity. In all of the cases that are reported here the average velocity was determined from measurements of velocity at the centre of the inlet channel at about 1 cm upstream of the step. Reynolds numbers used in step-flow studies such as the one based on centre velocity and/or step height can be easily deduced from the stated definition and from the 'inlet' mean-velocity profile measurement for each Reynolds number.

The attempted two-dimensionality of the flow in the inlet channel was confirmed by measurements. The flow in the plane of the sudden expansion in the inlet channel was symmetric and two-dimensional over the centre 150 mm of its width to within 1 %, as shown in figure 3. In the laminar range, the velocity field was close to that of a fully developed channel flow with a slight deviation from a parabolic profile. This was caused by the pressure change downstream of the sudden expansion. The section length downstream of the step was sufficiently long to permit the flow to redevelop into a fully developed channel flow, i.e. $\partial U/\partial x = 0$. As expected, with increasing Reynolds number, the length of flow development downstream of the step increased. At the outlet of the test section, a fully parabolic profile was established for the small Reynolds numbers, but small deviations were present for the higher ones.

Measurements of reattachment length x_1 are shown in figure 4 as a function of Reynolds number. From the shape of this curve one can clearly identify the laminar ($Re < 1200$), the transitional ($1200 < Re < 6600$) and the turbulent ($Re > 6600$) regimes of the flow. To the authors' knowledge this is the first detailed measurement, via a laser-Doppler anemometer, of reattachment-length variation with Reynolds number that covers the three different regimes of flow and defines them on the basis of actual velocity measurements. Previous studies of this property have been carried out by means of flow-visualization techniques or were performed on the basis of heat- and mass-transfer measurements (e.g. see Back & Roschke 1972; Filetti & Kays 1967; Sparrow & Kaljes 1977; Kottke *et al.* 1977). The laminar regime of the flow is characterized by a reattachment length that increases with Reynolds number. The increase is, however, not linear as suggested for reattachment-length variations in axisymmetric sudden pipe expansions (see Macagno & Hung 1967). This fact has also been demonstrated by Denham & Patrick (1974), who reported on a laminar-flow study in a geometry similar to the present one but with an expansion ratio of 3:2. However, they had velocity profiles at the step that strongly deviated from the laminar nearly parabolic profile set up in the present case.

The regime of transitional flow ($1200 < Re < 6600$) is characterized by first a sharp decrease in the reattachment length x_1, a continued gradual, but irregular decrease to a minimum value at a Reynolds number of approximately 5500, then an increase

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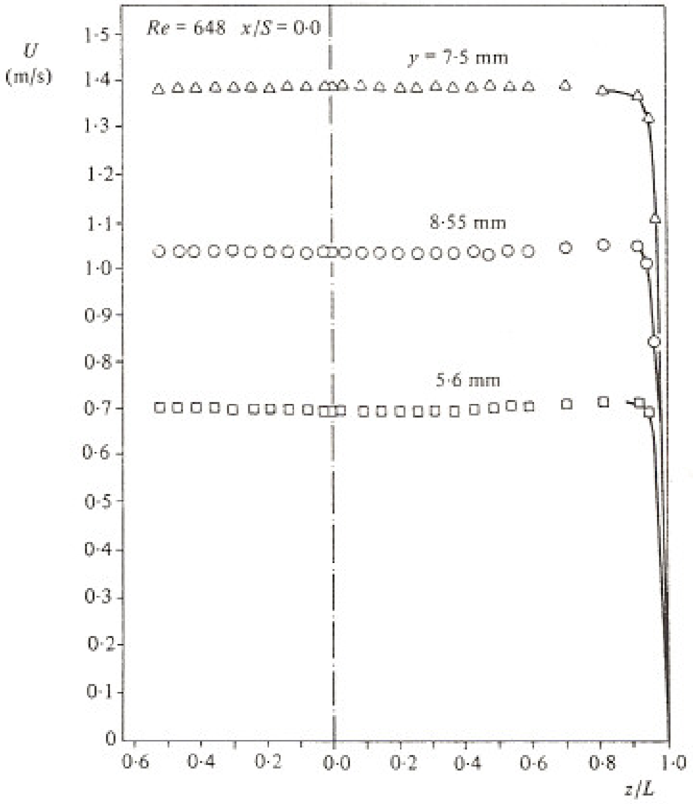

FIGURE 3. Examples of velocity traverses to check two-dimensionality of the inlet flow.

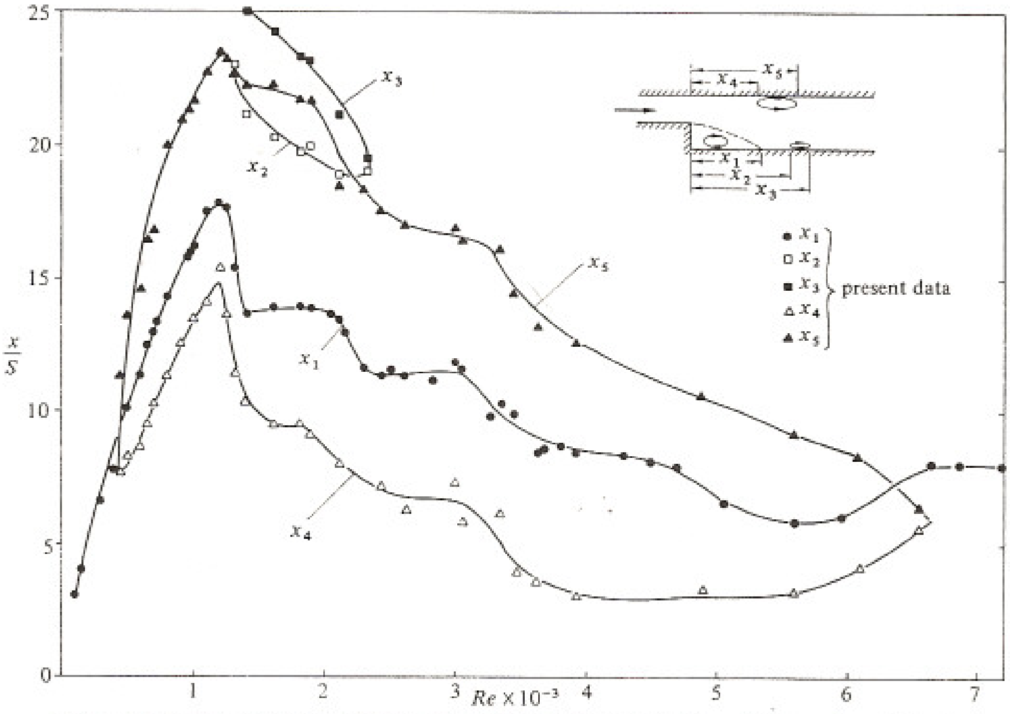

FIGURE 4. Location of detachment and reattachment of the flow at the centre of the test section; variation of locations with Reynolds number.

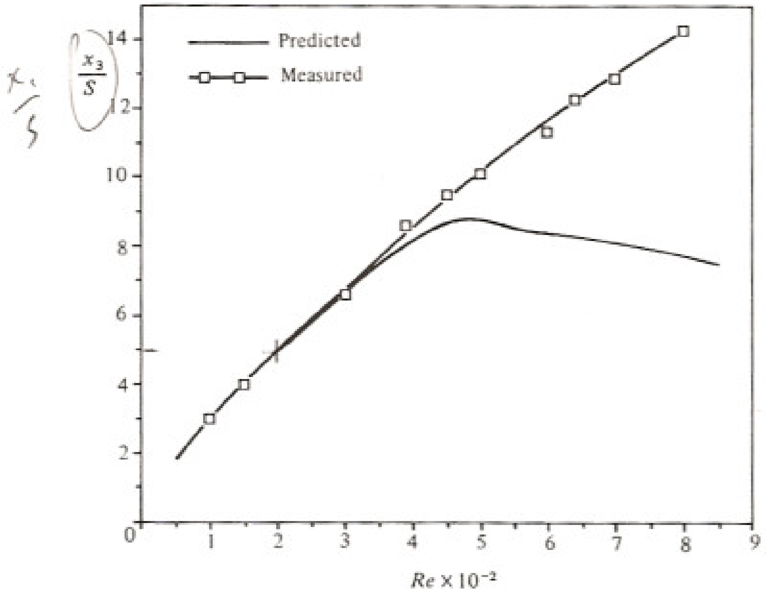

FIGURE 14. Comparison of experimental and theoretical results for the reattachment length up to $Re = 800$.

with the occurrence of more than one separated flow region, the flow in the experiments becomes three-dimensional in the region downstream of the step, and this prevents direct comparison between the experimental and theoretical results. Nevertheless, it is still interesting to make the comparison between the computed and measured separation lengths x_3/S. This information is provided in figure 14.

Figure 15 shows, for a Reynolds number $Re = 100$, comparisons of measured and predicted mean-longitudinal-velocity profiles. These numerical results were obtained for a 45×45 grid for which grid independence was demonstrated for higher Reynolds numbers. Up to $Re \approx 400$ the experimental and numerical results did not yield any additional regions of separaton apart from the primary one attached to the step. Good agreement between experiments and predictions is obtained under these conditions.

For a Reynolds number $Re = 389$, figure 16 shows, for the first sixteen x-stations, the measured U-velocity profiles and the corresponding predictions. At x-stations between 7 and 12 step heights downstream of the step, small deviations are indicated between the experimentally obtained velocity profiles and those deduced from two-dimensional numerical predictions. Although experimentally and numerically no additional region of separated flow is found on the channel side opposite to the step, the flow inside the experimental test rig showed small deviations from two-dimensionality. At higher Reynolds numbers at which multiple regions of separated flow are found experimentally and numerically, the experimental flow loses its two-dimensionality completely. This explains the discrepancies between experimental and numerical results indicated in figure 17.

In the published literature only a few velocity and/or reattachment length measurements exist for internal flow downstream of a single two-dimensional backward-facing step. The measurements reported by Abbot & Kline (1962) were obtained for turbulent flow and in a test-section geometry similar to the one employed in this study. Their measurements of reattachment length agree very well with the authors' data for high Reynolds number, where $x_R/S \approx 8$ was found for $Re \approx 6000$.

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Experimental and theoretical investigation of backward-facing step flow

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Laser-Doppler measurements of velocity distribution and reattachment length are reported downstream of a single backward-facing step mounted in a two-dimensional channel. Results are presented for laminar, transitional and turbulent flow of air in a Reynolds-number range of $70 < Re < 8000$. The experimental results show that the various flow regimes are characterized by typical variations of the separation length with Reynolds number. The reported laser-Doppler measurements do not only yield the expected primary zone of recirculating flow attached to the backward-facing step but also show additional regions of flow separation downstream of the step and on both sides of the channel test section. These additional separation regions have not been previously reported in the literature.

Although the high aspect ratio of the test section (1:36) ensured that the oncoming flow was fully developed and two-dimensional, the experiments showed that the flow downstream of the step only remained two-dimensional at low and high Reynolds numbers.

The present study also included numerical predictions of backward-facing step flow. The two-dimensional steady differential equations for conservation of mass and momentum were solved. Results are reported and are compared with experiments for those Reynolds numbers for which the flow maintained its two-dimensionality in the experiments. Under these circumstances, good agreement between experimental and numerical results is obtained.

1. Introduction

The phenomena of flow separation of internal flows caused by sudden changes in test-section geometries is well known. The importance of such flows to engineering equipment has been stressed in many publications (e.g. see Abbot & Kline 1962; Seban 1964; Goldstein *et al.* 1970), and attempts have been made to develop advanced experimental and theoretical techniques in order to study carefully flows with separation regions (e.g. see Durst & Whitelaw 1971; Gosman & Pun 1974; Kumar & Yajnik 1980). However, it is only recently that these techniques have reached the required state of development so that they can be of immediate use in fluid-mechanical studies of internal flows with regions of recirculation. In the past, most experimental studies relied on flow-visualization techniques and/or heat- and mass-transfer

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