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EXPERIMENTAL & NUMERICAL STUDY OF BACKWARD-FACING STEP FLOW

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ABSTRACT

Flow over a backward-facing step in a horizontal rectangular channel is studied by measuring the instantaneous wall shear rate along the channel centreline, using an electro-diffusion technique. A *3D* numerical simulation is also conducted and the computational results are validated with the experimental ones. The flow rates examined correspond to the laminar, transitional and beginning of turbulent flow regime. The numerical results concerning wall shear stress profiles behind the step and the position of the reattachment point are in good agreement with the experimental data.

INTRODUCTION

Separated-reattached flow due to a backward-facing step is involved in various heat and mass transfer processes. Momentum and thermal transport in the reattaching flow region and inside the reverse flow regions varies greatly and affects significantly the performance of heat exchanging equipment; e.g. the minimum wall shear stress and the maximum heat transfer rate occur in the neighbourhood of the reattaching flow region on a stepped wall [1]. Recent studies of this type of flow point out that the flow structure is three-dimensional even for relatively low Reynolds numbers [1, 2, 3]. Although the flow over a step belongs to the fundamental problems in fluid mechanics and is an established benchmark in Computational Fluid Dynamics (*CFD*) [4], the simulations reported in the literature are limited mainly to the study of the laminar flow case [3, 5].

The scope of this work is the experimental and numerical study of this flow configuration for a range of Reynolds numbers covering the laminar, transitional and the beginning of the turbulent regime, with the intension to investigate the effect of the operating conditions on the *reattachment length* (i.e. the length of the primary recirculation zone). This parameter is considered an important feature of this type of flow and it depends primarily on the initial boundary layer, the specific geometry of the channel and the fluid Reynolds number [2].

EXPERIMENTAL SETUP AND PROCEDURES

Experiments are conducted in a rectangular Plexiglas® channel (0.25m in width, 0.02m in height and 2m in length). The step is formed by inserting into the channel (*Figure 1*) a movable Plexiglas® block having a thickness (*s*) of 0.01m (expansion ratio, *ER*=2). The channel upstream section is long enough (1m) to ensure the developed flow conditions at the step. A two-segment electrodiffusion probe is mounted flush in the stream-wise centreline of the channel bottom wall, to measure the wall shear rates and define the direction of the near-wall flow. Due to the moving ability of the step block, the distance between the step and the probe can be gradually changed permitting the shear rate measurements at various distances from the step. The electro-diffusion method [6], based on the measurement of the limiting diffusion current of the ferricyanide ions reduction at a small working electrode, is used for the wall shear rate mapping. For a single strip segment the current-signal, I, can be related to the instantaneous value of wall shear rate, s_w, through the formula:

$$I = 0.807\, z\, F\, c_0\, w\, l^{2/3} D^{2/3} s_w^{2/3} \tag{1}$$

where z is the number of electrons involved in the electrochemical reaction, F is the Faraday constant, l is the length of the strip in the mean flow direction, w is its width, c_0 is the bulk concentration of the ions used, and D is their diffusivity in the solution. The method is described in detail elsewhere [2, 6]. The fluid used is water containing equimolar 0.025 M potassium ferro-ferricyanide and 0.057 M potassium sulphate as a supporting electrolyte. Experiments are conducted for a Reynolds number range of 30 to 1800, where $Re = Us/\nu$ is based on the step height (s) and the mean upstream velocity (U).

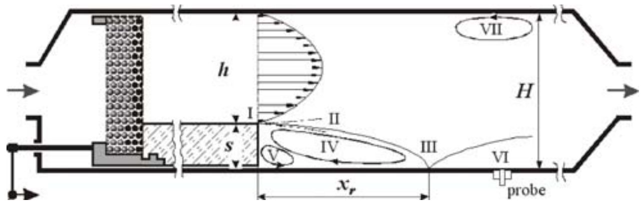

Figure 1. The backward-facing step apparatus.

I. initial boundary layer
II. separated free layer
III. reattachment zone
IV. recirculation region
V. corner eddy
VI. redeveloping boundary layer
VII. roof eddy

NUMERICAL CALCULATIONS

A commercial CFD code (*CFX® 5.7*) is employed to simulate the flow corresponding to the conditions studied experimentally. The problem is solved in a *3D* computational domain which corresponds to the experimental apparatus, since recent studies [3] have proved that the phenomenon is three-dimensional, especially for moderate and higher Reynolds numbers and for channel geometries with aspect ratio, *AR,* less than 50. A vertical symmetry plane is placed along the channel flow axis. A fully developed velocity profile is imposed as boundary condition at the channel entrance and no-slip condition (i.e. zero streamwise velocity) is employed on the channel walls. A laminar flow model is used for the laminar flow regime, whereas a k-ω based turbulence model, i.e. the Shear-Stress Transport (*SST*) model, recommended for high accuracy boundary layer simulations [7], was employed for the turbulent case. Computational domains, consisting of hexahedral cells with various refinement levels, are used at different *Re* numbers. The optimum number of cells is selected by conducting a grid dependence study. The calculations are performed on a *PC* cluster for parallel processing with six 64bit *CPU* and 6GB *RAM*.

RESULTS

The wall shear rate, s_w, is normalized with respect to the wall shear rate for developed channel flow, $s_{w,fd}$, while the distance from the step along the flow direction, x, is normalized with respect to the reattachment length, x_r. The universal wall shear rate profile for $Re<250$ (laminar region) is presented in *Figure 2.* The experimental profile exhibits a strong negative peak corresponding to the reverse flow inside the primary recirculation zone followed by a rapid boundary layer recovery. As *Re* increases, the absolute value of the minimum wall shear rate in the recirculation zone tends to be equal to the value of the wall shear rate for the developed flow. This peak is located near the middle of the recirculation zone and moves closer to the reattachment point as the flow rate increases.

The dependence of the reattachment length (normalized with respect to the step height) on *Re* is shown in *Figure 3*. It is apparent that the ratio x_r/s increases almost linearly with *Re*, reaches a peak value (~17) at transitional flow conditions, then decreases irregularly and finally reaches a constant value (~7) in the turbulent regime. The experimental results are in good agreement with available published data [8, 9].

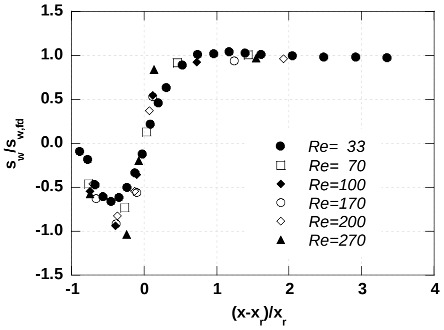

Figure 2. Normalized wall shear rate vs. the normalized distance in the laminar regime.

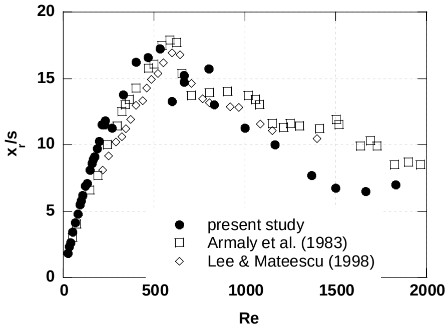

Figure 3. Dependence of the reattachment length x_r on *Re*; comparison with literature.

The time-averaged wall shear rate distribution and its *rms* values are calculated from the experimental data and are presented in *Figure 4* for typical *Re* corresponding to the various flow regimes. At transitional flow conditions (i.e. *Re*>300), the wall shear rate fluctuations are already considerable and the wall shear rate profile becomes less regular (*Figures 4b & 4c*) compared to the laminar one (*Figure 4a*). It is flat just after the channel expansion, becomes steeper close to the reattachment point, and thus the profile minimum is shifted towards the reattachment point. A secondary recirculation region is even observed around a location of *x/s*~19 in *Figure 4b*. According to Tihon et al. [2], the positive wall shear rate values identified just behind the step (for *x/s*<2) at the turbulent flow regime (*Figure 4d*) can be attributed to the presence of a significant corner eddy. A relative movement of the fluctuating wall shear rate peak value position with respect to the reattachment point is also noticeable in *Figure 4*.

The CFD results concerning wall shear rate profiles behind the step at the channel bottom and the position of the reattachment point are in very good agreement with experimental data for the laminar region (*Figure 4a*). Predictions corresponding to the beginning of the turbulent flow regime (*Figure 4d*) seem to be in reasonable good agreement with the experimental data. The first attempts to simulate the behaviour in the transitional regime (performed for *Re*=600) were unsuccessful but work in this area is still in progress.

CONCLUDING REMARKS

The experimental investigation of the flow over a three-dimensional backward-facing step, using the electro-diffusion technique, provided valuable information on the wall shear rate profiles behind the step at the channel bottom and on the reattachment length. The various recirculation zones downstream of the step were experimentally identified and the *Re* dependence of the reattachment length was obtained. The centreline position of the reattachment point was found to be sensitive to the presence of channel sidewalls and the *3D* flow character was confirmed even for low Reynolds numbers. A *3D* numerical simulation was also conducted and the predictions agree well with the measurements in the laminar flow regime and reasonably well with those in the beginning of the turbulent flow regime.

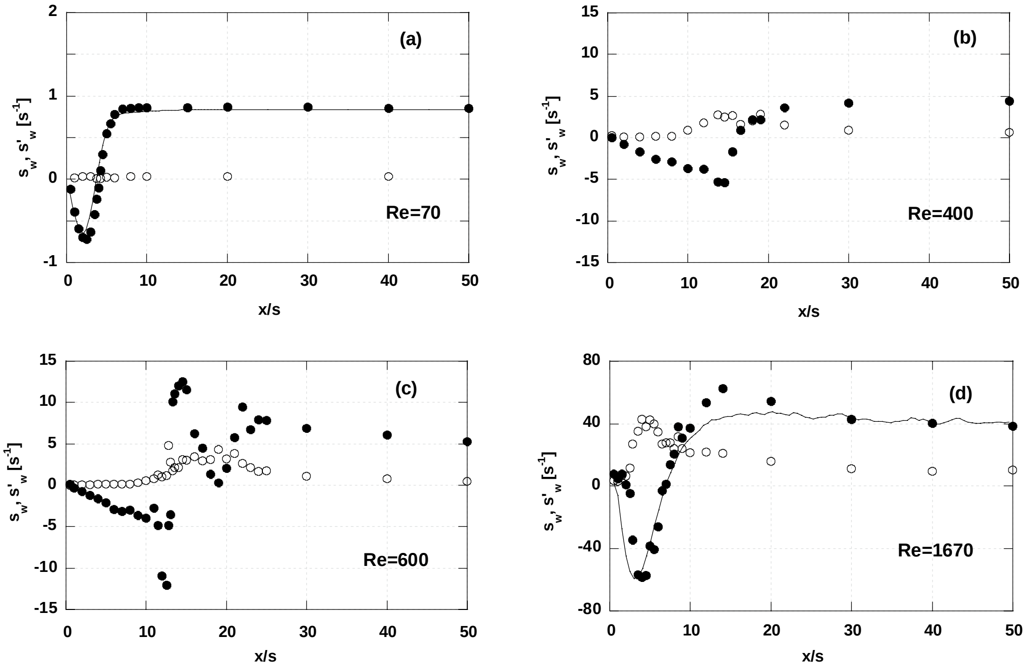

Figure 4. Typical wall shear rate profiles for various *Re*.
● time-averaged values and ○ *r.m.s.* values —— CFD predictions for the bottom wall shear rate.

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