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## THE STUDY OF A SEPARATING AND REATTACHING FLOW TOPOLOGY

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**Abstract:** An experimental and a numerical simulation were conducted to analyze the field velocity of a fully developed turbulent incompressible flow behind a descending step. The laser Doppler anemometry was used as measurement technique. The Reynolds number of the flow was 62000. A Fluent simulation of the flow for the same geometrical and flow conditions as the experimental ones was performed. The results of the numerical simulation were validated by the experiment. Both the numerical and experimental results shows the existence of four interacting zones: separated free shear layer, the recirculating region under the shear layer, the reattachment region and the attached/recovery region.

**Keywords:** turbulent flow, experimental study, numerical simulation

### 1. INTRODUCTION

The separation and reattachment of turbulent flows occur in many practical engineering applications, both in internal flow systems such as diffusers, combustors and channels with sudden expansions, and in external flows like flows around airfoils and buildings. In these situations, the flows experiences an adverse pressure gradient, i.e., the pressure increases in the direction of the flow, which causes the boundary layer to separate from the solid surface. The flow subsequently reattaches downstream forming a recirculation bubble.

In some applications such as combustors, the presence of the recirculation and turbulence due to separation can help enhance the mixing of fuel and air. On the other hand, separation in pipe and duct flow causes loss of available energy. Thus, understanding the flow separation and reattachment phenomena is important in engineering design. Among the flow geometries used for the studies of separated flows, the most frequently used is the backward-facing step, the normal flat plate with a splitter plate and the blunt flat plate; in all these cases the separation line is straight and fixed by the geometry. Considerable work has been carried out on the flow over a backward-facing step due to its geometrical simplicity. The separation point is fixed at the step; thus one can avoid the difficulty resulting from the oscillation of the separation point. Furthermore, unlike flow over an obstacle, the backward-facing step produces only one separation bubble; and the streamlines approaching the step are nearly parallel to the wall. Finally, from the computational view point, the rectangular domain of the backward-facing step allows for simple grid structure.

In spite of the large amount of experimental work on the backward-facing step flows, the physics of the reattachment is still not fully understood. The reason, as pointed out by Eaton and Johnson (1981), lies partially on the inadequacy of cross-wire hot-wire probes in highly turbulent flows used in early studies. Even with the advent of the laser anemometer and the pulsed-wire anemometer, velocity measurements, particularly in the separated flow region where instantaneous flow reversal occur, may still be the subject to errors caused by velocity bias (Adams & Eaton, 1998).

The objective of this report is to present a set of detailed measurements of the flow over a backward step, the results obtained with a Fluent simulation and to perform an analysis of the data.

The experiment and the Fluent simulation have been both conducted for the same geometry and for  $Re = 62000$ , calculated on the basis of the step height.

### 2. THE FLOW TOPOLOGY AND THE IDENTIFICATION OF COHERENT STRUCTURES

A separating/reattaching flow can be divided into four interacting zones (see figure 2). The zones are: the separated free shear layer, the recirculating region under the shear layer, the reattaching region and the

attached/recovery region. Each flow region bears some similarities to well-studied flow cases such as mixing layers and boundary layers, while the reattaching and recirculating regions are unique to separated flows. There are more criteria used to identify the coherent structures in turbulent flows: criteria based on the vorticity or on the pressure. It seems that for the flow over a backward-facing step, the most efficient criterion is the Hunt criterion of identification of the coherent structures (1988) or the  $Q$  criterion. We consider that this criterion might be an element that could be developed in the future by the Fluent development team.

Hunt et al. defined a coherent structure on the basis of the second invariant of the term  $\nabla u$ , quantity which must be positive to have a coherent structure:

$$Q = F \frac{1}{2} (\Omega_{ij} \Omega_{ij} - S_{ij} S_{ij}) \quad (1)$$

where  $\Omega_{ij}$  and  $S_{ij}$  represent the antisymmetric and symmetric parts of the deformation tensor  $\partial u_i / \partial x_j$ . Otherwise, we have:

$$\Omega_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right), S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (2)$$

Physically, the regions where the  $Q$  is positive are regions where the vorticity is superior to the shear stress.

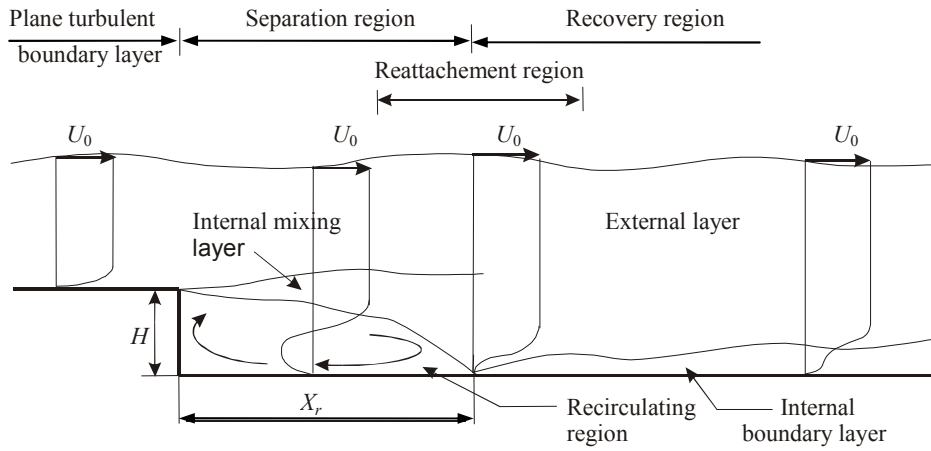


Figure 1: Flow configuration.

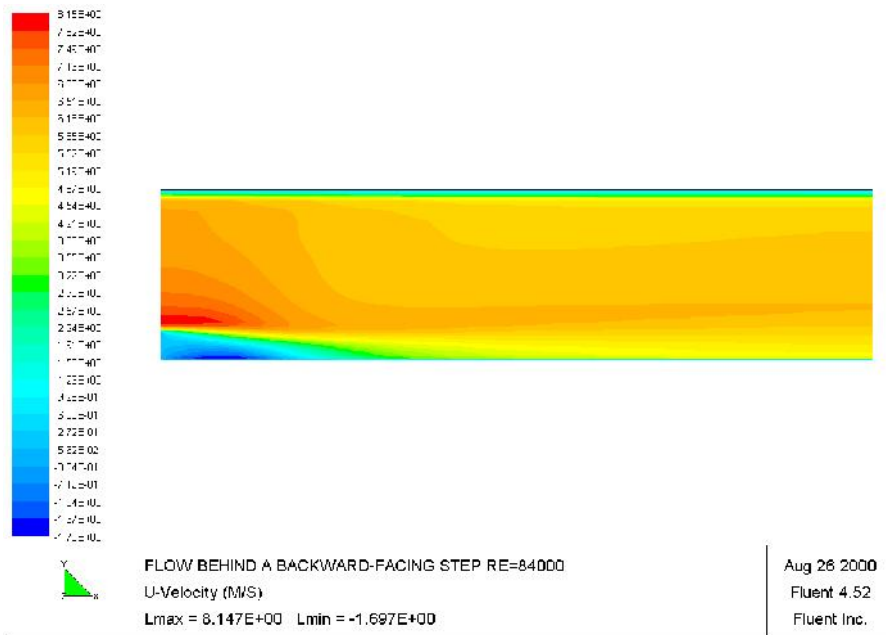
### 3. EXPERIMENTAL STUDY AND FLUENT SIMULATION OF THE FLOW BEHIND THE DESCENDING STEP

The experiment was conducted on the hydrodynamic tunnel from the Laboratory of Geophysical and Industrial Flows – “Ecole Nationale Polytechnique de Hydraulique et Mecanique” from Grenoble. We used the laser Doppler anemometry method to measure the velocity field.

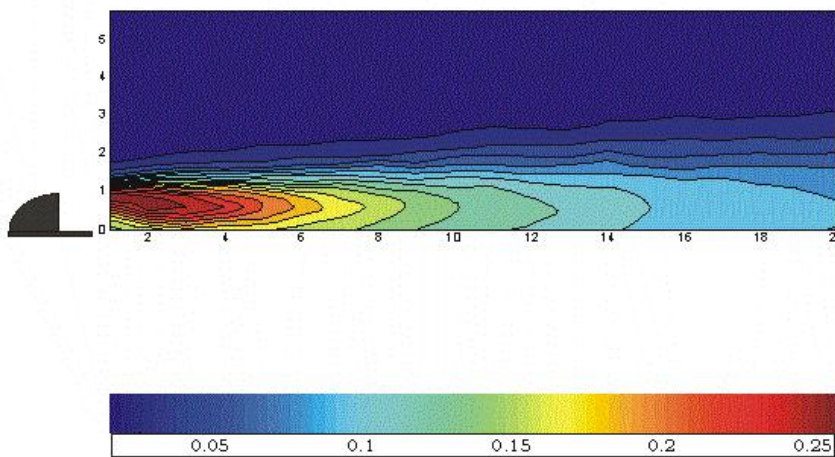
The Fluent simulation was performed for the same geometry and flow properties as the experimental ones. The turbulence model was  $k-\epsilon$ .

Figures 2a and 2b illustrate the contours of the mean velocities  $U_x$  for the experimental data and the Fluent simulation while figure 3 illustrates the contours of  $U_{rms}$  velocities but only for the experimental data.

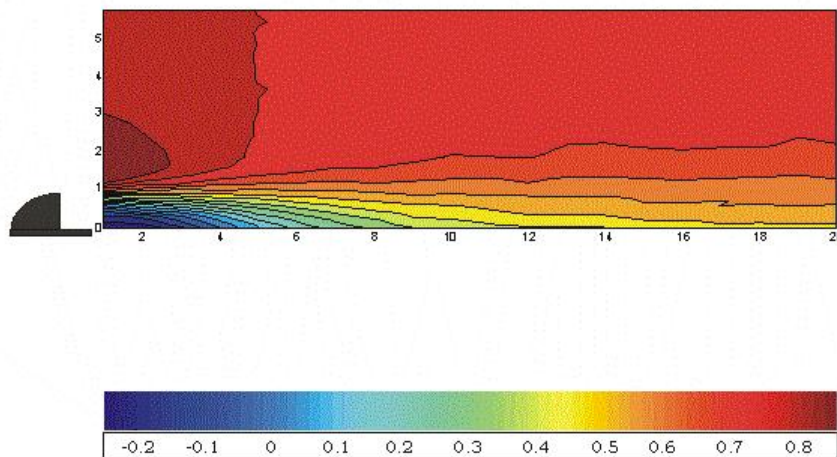
We observe an inflection point on the profile of the velocity at the outlet. It results that even at this distance from the step we can not find a classical profile of a boundary layer. A well known characteristic of the flow over a backward-facing step is the slow velocity of refit of the flow after the reattaching region. An analysis of  $U_{rms}$  velocities data reveals the existence of a maximum immediately after the step and the tendency of this quantity to a constant value as we advance. This structure is practically the proof of the redevelopment of a classical boundary layer after the step.



**Figure 2a:** The profiles of the axial mean velocity  $U_x$  (Fluent simulation).



**Figure 2b:** The profiles of the axial mean velocity  $U_x$  (experimental data).



**Figure 3:** The profiles of the velocity fluctuations  $U_{rms}$  (experimental data).

### 3. CONCLUSIONS

The results shows that an internal shear layer, imbedded in the inner part of the original boundary layer, emanates immediately from the step edge. This shear layer has many similarities with a plane mixing layer, but does not resemble exactly.

The no-slip conditions imposed on the flow in the reattaching region limit further growth of the mixing-layer-like flow, promoting a new internal boundary layer developing on the wall down-stream of reattaching. The data show that the structure of the internal layer attains quasi-equilibrium, with production and dissipation of turbulent kinetic energy approximately equal, by  $20H$  from the step.

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