Numerical Modelling and Experimental Validation of a Turbulent Separated Reattached Flow

Florin Popescu, Tănase Panait

Abstract—An experimental study was conducted to analyse the field velocity of a fully developed turbulent incompressible flow behind a backward-facing step with a curved nose shape. The laser Doppler anemometry was used as measurement technique. The Reynolds number, Re, based on the step height, h, and the maximum velocity U0max of the velocity distribution at the inlet, was 84000.

A Fluent simulation of the flow for the same geometrical and flow conditions as the experimental ones was performed.

The resulted velocity fields of the numerical simulation and of the experimental study were compared and analysed.

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— backward-facing step, turbulent separating reattaching flows, laser Doppler anemometry, numerical simulation.

I. 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 flows causes loss of available energy. Thus, understanding the flow separation and reattachment phenomena is important in engineering design. The research has been conducted for different geometric configurations, some of which are shown in figure 1. 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, 1988).

The objective of this report is to present a set of detailed measurements of the flow over a backward step (Fig.1.(a)), 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 = 84000, calculated on the basis of the step height.

Manuscript received Feburary 15, 2007, revised August 12, 2007.

Florin Popescu is PhD, professor at the University Dunărea de Jos of Galați, Faculty of Mechanics, Department of Thermotechnics, 47, Domneasca, str., 800008, Galați, Romania (corresponding author to provide phone: +40-721-233-679, fax: +40-236-314-463; e-mail: florin.popescu@ugal.ro).

Tănase Panait is PhD, professor at the University Dunărea de Jos of Galați, Faculty of Mechanics, Department of Thermotechnics, 47, Domneasca, str., 800008, Galați, Romania (corresponding author to provide phone: +40-723-500-622, fax: +40-236-314-463; e-mail: tanase.panait@ugal.ro).

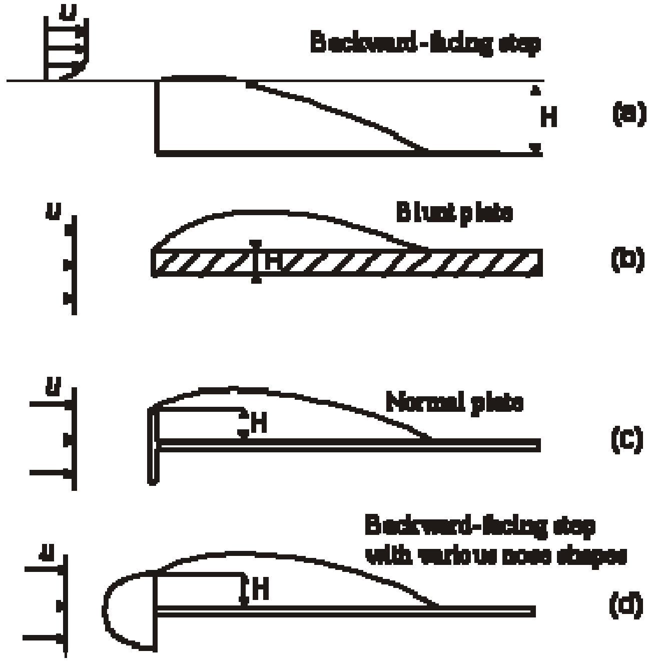

Figure 1 Flow configurations with separation and reattachment

I. 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 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 all. defined a coherent structure on the basis of the second invariant of the term ∇u, quantity which must be positive to have a coherent structure:

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

where Ω_{ij} and S_{ij} represent the antisimetric and simetric parts of of the deformation tensor ∂ui /∂uj. Otherwise, we have:

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

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

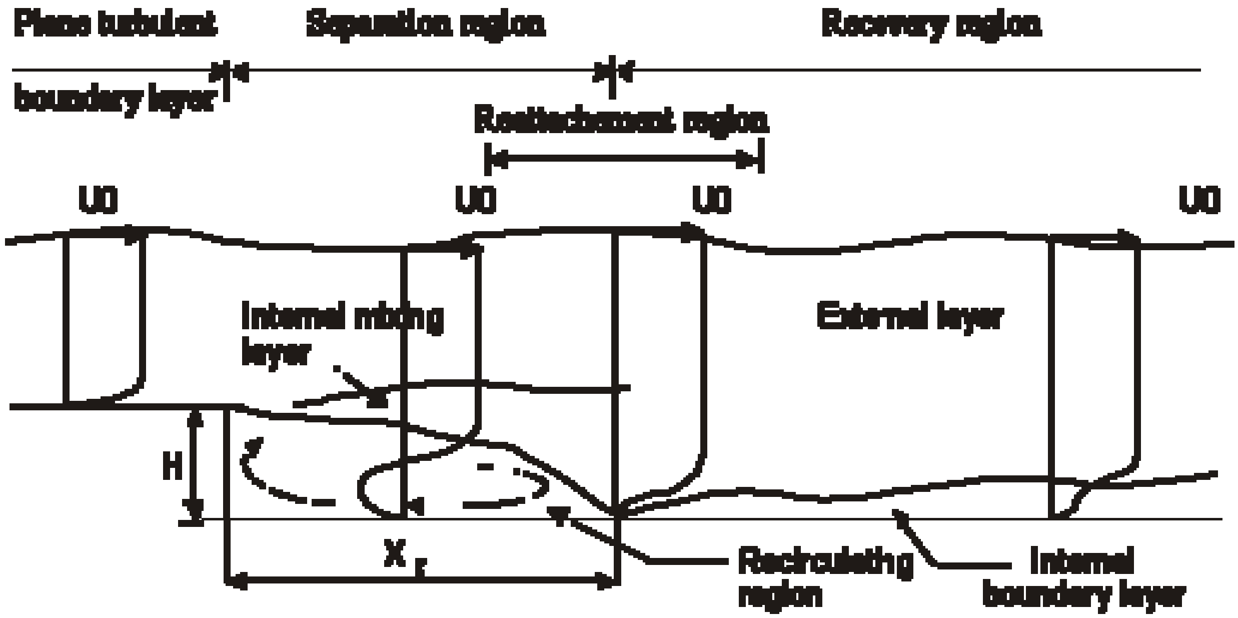

Figure 2 Flow configuration

I. EXPERIMENTAL STUDY AND FLUENT SIMULATION OF THE FLOW OVER A BACKWARD FACING 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. The measurements domain and the velocity distribution at the inlet are illustrated in figures 3 and 4.. We used the laser Doppler anemometry method to measure the velocity field.

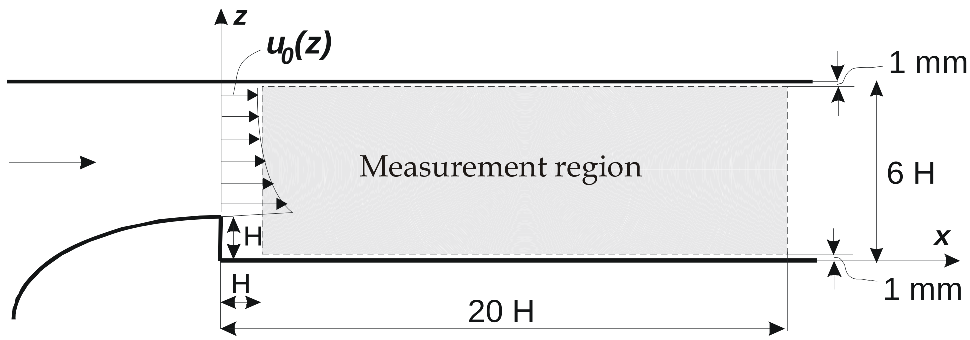

Figure 3. The measurements domain (H=10mm)

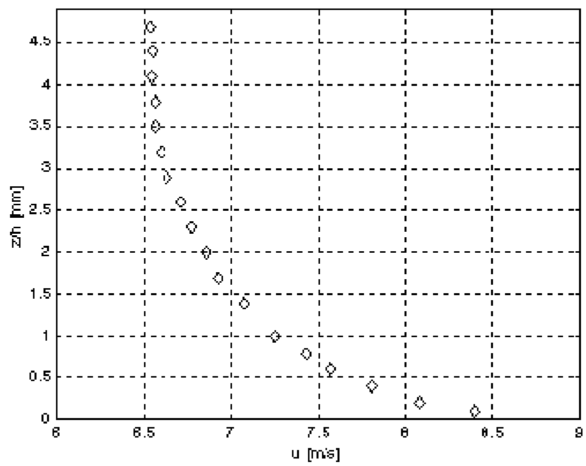

Figure 4. The velocity distribution at the inlet (H=10mm)

The Fluent simulation was performed for the same geometry and flow properties as the experimental ones. The flow model was k-ε.

Figures 5a, 5b, 5c illustrates both the experimental and the numerical results for the mean velocities Ux at different distances from the step. The profiles are represented for all the three regions of the flow.

Figures 6a and 6b illustrate the contours of the mean velocities Ux for the experimental data and the Fluent simulation while figure 7 illustrates the contours of Urms velocities but only for the experimental data.

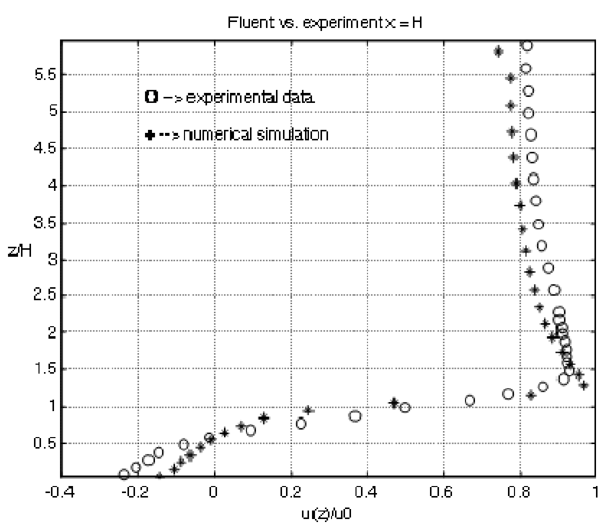

Figure 5a Mean velocity profile x = H

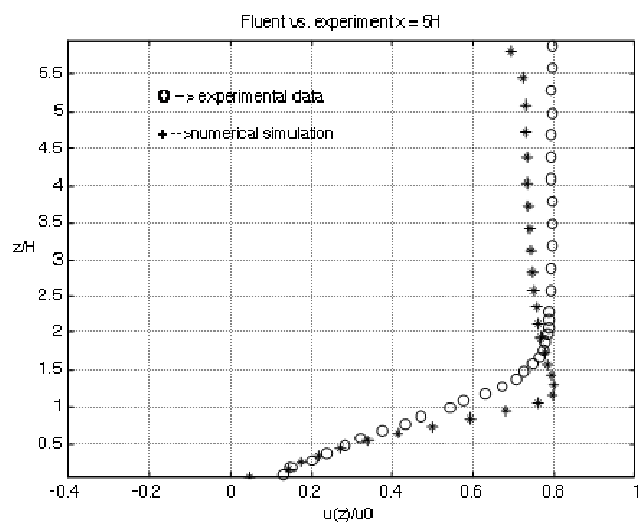

Figure 5b Mean velocity profile x = 5H

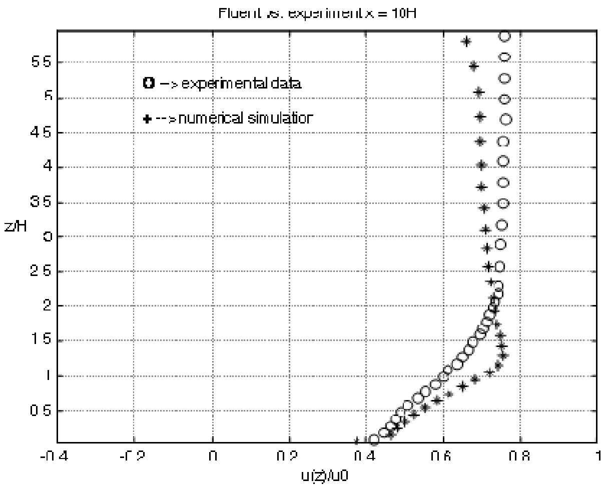

Figure 5c Mean velocity profile x = 10H

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 Urms 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.

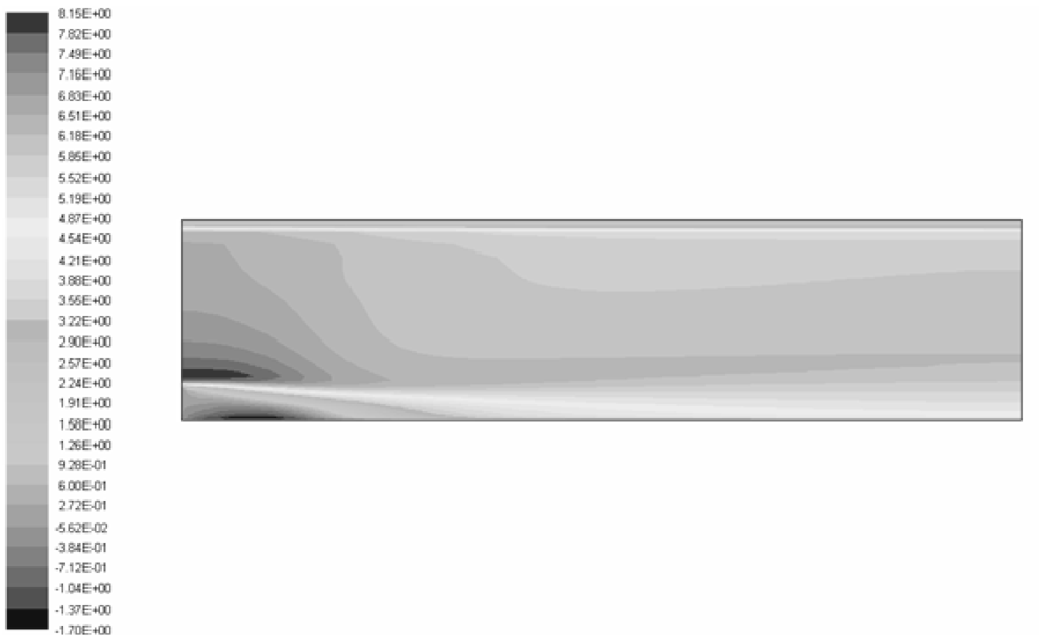

Figure 6a The profiles of the axial mean velocity Ux (Fluent simulation)

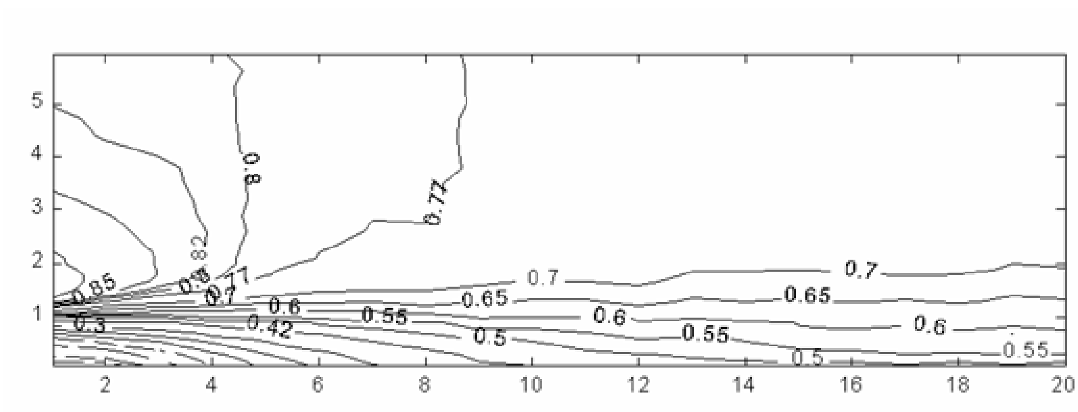

Figure 6b The profiles of the axial mean velocity Ux (experimental data)

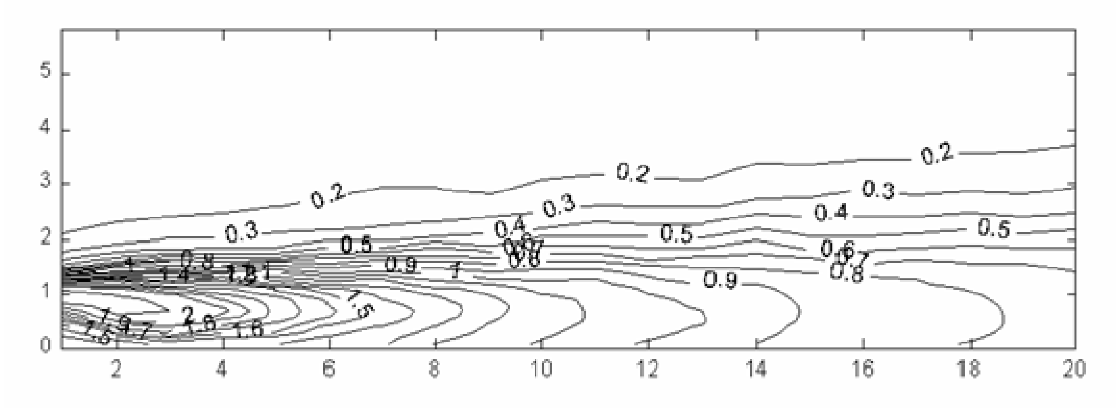

Figure 7. The profiles of the velocity fluctuations Urms (experimental data)

I. 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.

REFERENCES

[1] E.W. Adams, & J.K. Eaton, “An LDA study of the backward-facing step flow, including the effects of the velocity bias”, J. of Fluids Eng., 110, pp.275-282, 1988

[2] F. Delcayre, “Etude par simulation des grandes échelles d’un écoulement décollé : la marche descendante.” Thése - l’Institut Polytechnique de Grenoble, 1999,

[3] J.K. Eaton & J.P. Johnston, “A Review of research on subsonic turbulent flow reattachment”, AIAA J, 19, pp1093-1100, 1981.

[4] Hung Le & Parviz Moin “Direct Numerical Simulation of Turbulent Flow Over a Backward-Facing Step”, Report No. TF-58, Stanford University, 1994.

[5] S. Jovic “An Experimental Study of a Separated/Reattached Flow Behind a Backward-Facing Step. Reh=37000”. NASA Technical Memorandum 110384, 1996.

[6] M. Kiya & K. Sasaki, “Structure of a turbulent separation bubble. Journal of Fluid Mechanics”, 137, 83-113, 1983.

[7] F. Popescu, “Contributii la studiul miscarii fluidelor în jurul corpurilor profilate”, PhD Thesis, 2000.

[8] F., Popescu, T. Panait “Experimental Study of the Separating-Reattaching Flow over a Backward-Facing Step”, 5th WSEAS Int Conf on Fluid Mechanics (FLUID’08), Acapulco, Mexico, January 25-27, 2008.