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Influence of flow tree-dimensionality on the heat transfer of a narrow channel backward facing step flows

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ABSTRACT

This manuscript studies the forced-mixed convective flow on a three-dimensional backward facing step with low aspect ratio (AR = 4) and expansion ratio ER = 2 for Reynolds number in the laminar and beginning of transitional regime (Re 100–1200). The analysis is performed using large eddy simulations, with the main objective assessing the effect of sidewalls on heat transfer characteristics on bottom wall in narrow channels with sudden expansion. The numerical model has been validated with experimental and numerical results from the literature and qualitatively with the experimental results obtained through Moiré deflectometry. The bottom surface was kept at constant temperature greater than the flow inlet temperature, while the other walls are considered to be adiabatic. To decouple the three-dimensional flow features due to the sidewalls and the intrinsic three-dimensional instabilities of the separated flow, two different boundary conditions on lateral walls, slip and non-slip, have been used. The results obtained show that when slip sidewalls are considered, the three-dimensional intrinsic structures begging to appear for Re equal to 1200. These structures enhance the heat transfer in the bottom wall. On the contrary, with non-slip sidewalls, the strong three-dimensional structures caused by the sidewalls represented by the upper side recirculation bubble and the wall jets mask the intrinsic three-dimensional instability, decreasing the heat transfer in the lower wall downstream of the step. As a consequence, the surface averaged Nusselt for all Reynolds numbers corresponding to the beginning of the transitional flow is lower for the case of non-slip sidewalls than for the case of slip sidewalls. Thus, the study concludes that sidewalls have a negative effect on heat transfer in narrow channels for flow Reynolds numbers in the early transitional regime.

1. Introduction

Flow separation, with a recirculation region and subsequent reattachment is a common feature encountered in many engineering flows, such as atmospheric flows in contact with the ground surface, ducts with a sudden change in area, airfoils at high angles of attack, and many types of fluid systems used in thermal devices such as turbine blade cooling [1,2], combustion chambers [3,4] and many other applications in all engineering disciplines.

The study presented in this paper is performed on the flow over a backward-facing step (BFS) geometry. This approach is followed for the sake of geometrical simplicity, but keeping the complexity in terms of flow structure and heating transfer features encountered in actual geometries. The fluid flow over a BFS geometry is a well-established case for benchmarking flows with sudden expansions, as the ones of interest in this paper, and it has been the subject of numerous numerical and some experimental studies over the last decades.

Several publications on BFS are focused on laminar, transitional and turbulent adiabatic flows over two-dimensional or three-dimensional geometries with a considerably large aspect ratio, defined as channel width to height ratio upstream of the step, and mainly devoted to characterize the flow structure, reattachment conditions, and other flow features. Some examples can be found in the studies from the literature [5–8].

Following these classical studies, a large number of investigations has been dedicated to improve the understanding the three-dimensional aspects of this flow in the laminar, transitional and turbulent regimes, characterizing the flow behaviour, and mainly focusing on two different phenomena: the effect of the sidewalls on the flow and the three-dimensional stability of the flow over a backward-facing step.

Kaiktsis et al. [9,10], Barkley et al. [11], Beaudoin et al. [12] amongst others, have carried out detailed analysis on the flow stability from two-dimensional laminar flow to three dimensional flow, obtaining the intrinsically unstable three-dimensional modes, and

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revealing characteristics such as bifurcation conditions (critical Reynolds number), unsteadiness caused by convective instabilities, or the wavelength of the instabilities.

Concerning the former topic, several investigators have devoted substantial efforts to study the sidewall induced three-dimensionalities in the flow. Williams and Baker [13], Chiang and Sheu [14] and Biswas et al. [15] performed numerical simulations on a BFS with the same aspect ratio used by Armaly et al. [6] for a range of Reynolds numbers in the laminar and near the transitional regimes. The results show the appearance of complex secondary flow patterns near the sidewalls and the development of longitudinal vortices along the channel.

Nie and Armaly [16,17] and Armaly et al. [18] conducted numerical and experimental studies on three-dimensional BFS geometries with sidewalls a range of expansion ratios (ER) and different Reynolds numbers on a model with an aspect ratio (AR) of 8. The flow features found, include: the development of wall-jets or jet-like flow located downstream of the step near the sidewalls and pointing towards the channel mid-plane, a thinner upper wall recirculation zone modifying the two-dimensional configuration of the flow, and a spanwise distribution of the primary reattachment line with a maximum reattachment length at the sidewall and a minimum reattachment length close to the wall (increasing then again when moving towards the mid-plane).

Rani et al. [19,20] and Sheu and Rani [21] performed simulation of the flow behaviour on a geometry analogous to the one used by Armaly et al. [18] with AR = 8 and ER = 2, and at laminar and transitional regimes. The studies assessed the effect of sidewalls on the flow and the shed vortical structures downstream the BFS. A detailed description of the flow downstream of the BFS was obtained, and the three-dimensionality of the flow is associated with Kelvin-Helmholtz instabilities and Taylor-Gortler-like vortices.

Tylli et al. [22] and more recently Malamataris [23] present results of experimental and numerical simulations over a three-dimensional BFS with an AR = 40 and ER = 2 for laminar flow (low Re). The effect of lateral walls on the primary and upper wall recirculation zones was demonstrated. The studies relate the onset of unsteadiness with the presence of sidewalls and propose that the transition to three-dimensional flows is due to the growing penetration of the wall-jet from the sidewall to the central symmetry plane.

The studies on BFS geometry have been extended with the inclusion of the heat transfer through the chamber walls. When heat transfer is present, the mixing process of high and low energy flows occurs in the reattachment region impacting significantly the mechanism of heat transfer and the flow behaviour.

Many works have been devoted to investigate heat transfer characteristics of BFS flow, on laminar and near the transitional regimes in two-dimensional [24,25] and three-dimensional geometries [16,26–28] and on turbulent regime [29].

Iwai et al. [26] investigate the effect of channel aspect ratio for a Reynolds number equal to 250 and including heat transfer through the bottom wall. They show contours of Nusselt number (Nu) and friction coefficient on the bottom wall and found the maximum Nu near the lateral wall and that the value of this maximum increases with the aspect ratio. Nie et al. [16] present results of numerical simulations for low Reynolds number (100–400) on a BFS with AR = 8. The peak in the Nusselt number increases with the step height and appears in the same region where the reattachment length is minimum. In the manuscript, the authors propose that the impingement of the wall-jet flow on the step wall is the cause. Xu et al. [28] investigate the fluid flow and heat transfer characteristics for a 3D backward facing step with aspect ratio 16 in the range of Re 200–1200. The authors use air as fluid, assuming constant properties, including density. For Re = 1000, they show K-H instabilities in the central plane of the channel. However, these results disagree with the study carried out by Xie [25] for a two-dimensional BFS, in which the vortex appear for a Re (based on the step height s) greater than 500, that is, a Re based on 2s greater than 1000. Also, several studies can be found in the literature on BFS with heat transfer enhancement by local forcing with suction and blowing or pulsating flow [30,31,32]. Those studies are focused on two-dimensional geometries.

However, few studies have addressed backward-facing step flow on three-dimensional geometry in narrow channels, i.e., at aspect ratios smaller than 8, such as those found in actual geometries of internal flows systems used in heat transfer applications, such as turbine blade cooling channels with ribs, in which the effect of the sidewalls on the topology of the flow is more relevant. The previously cited work from Iwai et al. [26] investigate the thermal flow over BFS with AR = 4 for Re = 250. Barbosa et al. [33] study the effect of Richardson number in a BFS flow with AR = 4 and for a single Reynolds number (Re = 200).

Due to this lack of studies in narrow channels, the authors [34] recently published a numerical and experimental study of the adiabatic flow of an ideal gas over a BFS with aspect ratio ranging between 4 and 8 to provide deeper insight into the three-dimensionality occurring in the separated flow inside a narrow channel, focusing on the secondary recirculation bubble formed at the upper wall of the channel and its effect on the development of different three-dimensional flows, and the corresponding hydrodynamic action. The simulations were validated with experimental results obtained from flow visualization techniques.

To the authors' knowledge the thermo-convective airflow over a narrow BFS channel (with low aspect ratio) for the range of Reynolds number 100–1200 has not been investigated yet and this gap in the literature demonstrated in the foregoing review has motivated the present study. Therefore, the aim of the present work is to assess the effect of the side-walls on heat transfer features of the backward facing step in a narrow channel at laminar and early transitional regimes. The study is presented like natural extension of the studies performed by the authors [34] without heat transfer, and it is performed by means of Large Eddy Simulations using two different wall boundary conditions (slip and non-slip) to separate the wall induced phenomena from the inherent 3D flow structures.

The paper is organized as follows. Section 2 presents the description of the problem and the numerical model used in the study. Section 3 evaluates the accuracy of the mesh through a mesh independence analysis. The computational code used in the present work and the numerical model for adiabatic walls was already validated in the previous work, for this reason in Section 4, the effect of heat transfer is validated against data published for Re = 400 and AR = 8. The authors have developed an experiment to provide a qualitative insight of the flow behaviour. The experiment consists in the use of Moiré interferometry technique in the same investigated geometry. Section 5 discusses the results obtained from the simulations analysing the effect of sidewalls on heat transfer phenomena. Finally, Section 6 summarizes the main conclusions of the study.

2. Problem formulation and numerical model

The numerical procedure used in the present work is the extension of a previous study by the authors [34] to a heat transfer problem. The problem studied is the three-dimensional convective airflow in a rectangular channel with a backward facing step. The flow is modeled by time-dependent Navier-Stokes equations combined with an equation of state for the flow, which in the case of air is the ideal gas law, defined as follows:

$$\rho = \frac{p_{OP} + p}{R_g T} \tag{1}$$

Where p is the predicted local relative pressure and p_{OP} the operating pressure. The range of flows studied includes laminar and early transitional flow regimes (100 ≤ Re ≤ 1200). The distinction between the different flow regimes is not obvious and depends on the flow configuration. In such flows, the unsteady Reynolds-averaged Navier-Stokes