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Large eddy and direct numerical simulations of a turbulent water-filled differentially heated cavity of aspect ratio 5

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ABSTRACT

Natural convection in a differentially heated cavity is characterized by different phenomena such as laminar to turbulent flow transition in the boundary layer, turbulent mixing, and thermal stratification in the core of the cavity. In order to predict the thermal and fluid dynamic behavior of the flow in these cavities, the location of transition to turbulence should be accurately determined. In this work, the performance of three subgrid-scale (SGS) models is submitted to investigation in a water-filled cavity of aspect ratio 5 at Rayleigh number $Ra = 3 \times 10^{11}$. To do so, the models are compared with the solution obtained by means of direct numerical simulation. The models tested are: (i) the wall-adapting local-eddy viscosity (WALE) model, (ii) the QR model, (iii) the WALE model within a variational multiscale framework (VMS-WALE). It has been shown that the VMS-WALE and WALE models perform better in estimating the location of transition to turbulence, and thus their overall behavior is more accurate than the QR model. The results have also revealed that the use of SGS models is justified in this flow as the transition location and consequently the flow structure cannot be captured properly if no model is used for the tested spatial resolution.

1. Introduction

The flow in a differentially heated cavity (DHC) has been studied extensively in the literature, due to its relevance to model many applications of industrial interest, like air flow in buildings, heat transfer in solar collectors, or cooling of electronic devices. The flow is characterized by a thermal gradient which is orthogonal to the gravitational field. In accordance with the available computing power, first efforts mainly addressed steady laminar two-dimensional flows (see for instance [1]). In the last two decades, more demanding two- and three-dimensional transitional and turbulent flows appeared in the literature thanks to the increasing computational resources, which allowed dealing with different scales of motion present in such flows at moderate and high Rayleigh numbers (Ra) [2–5]. Although the geometry is rather simple, different regimes coexist when the Rayleigh number is increased beyond a critical value: (i) laminar flow in the upstream part of the vertical boundary layers and in the core of the cavity, (ii) transitional and turbulent flow at some location where the downstream traveling waves grow sufficiently to disrupt the vertical boundary layer and eject large unsteady eddies. In the core of the cavity, a thermally stratified zone is expected. Even though at relatively smaller velocities compared with the vertical boundary layer, the core is in motion, as the isotherms oscillate around a mean horizontal profile, which can be attributed to the internal gravity waves. Although conducting direct numerical simulation (DNS) in real-scale engineering problems is not feasible yet, the present configuration, being a canonical case, has been subject of DNS studies on moderate Rayleigh numbers [6–8]. These works have contributed to understand the physical phenomena of turbulence and provided useful data.

The vast majority of the performed studies consider air-filled cavities (Prandtl number $Pr \approx 0.7$). However, the working fluid is water for many buoyancy-driven applications. In the case of a water-filled cavity, i.e. greater Prandtl number compared with air, obtaining solutions for the governing equations gets more complicated since the thermal boundary layer becomes thinner for the same Rayleigh number [9]. Therefore, finer grids are required to capture the smallest scales of the flow. This may be one of the reasons explaining that numerical studies of water-filled DHC are quite scarce when compared with air-filled ones and are generally limited to a two-dimensional domain [10–12]. Alternatively, large eddy simulations (LES) are an encouraging alternative for the resolution of turbulent natural convection in these cavities as they model the smallest scales of flow while the large scales are solved. The selection of an appropriate subgrid-scale (SGS) stresses model for describing the complex flow behavior is crucial in this

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cavity flow, where the overall performance of the model is dependent on the accurate prediction of the transition to turbulence phenomenon.

With regard to the use of LES models in DHC flows, several authors published relevant contributions for the air-filled cavities. Peng and Davidson [13] studied a flow with a low level of turbulence ($Ra = 1.58 \times 10^9$) in a cubical cavity. They obtained good results in the main flow quantities by using approximately 0.6 million control volumes (CV). On the other hand, second-order turbulent statistics showed discrepancies with the reference experimental work, due mainly to the lower resolution of the grid in the outer shear layer and the spanwise direction.

In the recent years, different studies of LES on a DHC configuration of aspect ratio 5 appeared in the literature. Barhaghi and Davidson [14] studied a turbulent DHC of aspect ratio 5 at $Ra = 4.028 \times 10^8$ (based on the cavity width) by means of the Smagorinsky [15], the dynamic eddy-viscosity [16], and the wall-adapting local-eddy viscosity (WALE) [17] models. The finest mesh they employed had approximately 2.5 million CVs. The tested SGS models gave substantially different results in capturing the location of transition in the vertical boundary layer, with the dynamic eddy viscosity model the most accurate one. They performed a full analysis of turbulent statistics in both transitional and turbulent regions of the cavity. They indicated that the results in the transition region showed considerable differences between the coarse and fine meshes, while in the fully turbulent region the grid dependency was no longer important.

More recently, two works for very similar Rayleigh numbers were carried out using the same aspect ratio. Lau et al. [18] tested different SGS models in an air-filled DHC of aspect ratio 5 at $Ra = 4.56 \times 10^{10}$ using approximately 2.1 million CVs. The comparison with the available experimental data demonstrated that the transition to turbulence cannot be well captured if the models are too dissipative, thus leading to important discrepancies with the reference data. Trias et al. [19] studied a turbulent DHC flow of aspect ratio 5 by means of DNS and regularization modeling for $Ra = 4.5 \times 10^{10}$. For the modeling of turbulence they used a novel class of regularization that restrain the convective production of small scales of motion in an unconditionally stable manner. The comparison of the results showed that the method was able to capture the general patterns of flow even for very coarse meshes, illustrating the potential of the regularization method to deal with complex flows.

Ghaisas et al. [20] tested different SGS models for weakly turbulent flow in a DHC of aspect ratio 4 for two different Rayleigh numbers, obtaining good agreement with the available DNS data for $Ra = 6.4 \times 10^8$, although higher mesh resolution was shown to be needed when the Rayleigh number was raised to 2.0×10^9.

Sergent et al. [21] recently used LES to show that the discrepancies between the numerical and experimental stratification values in the center of the air-filled DHC is due to the contribution of the front and rear end walls in heat transfer and fluid flow.

The conducted studies so far showed that the accurate assessment of the transition location is essential in predicting flow configuration in a turbulent DHC flow. As a result, the performance of the SGS models are primarily dependent on their capability to capture this location. Considering this, the present work aims at testing the performance of three SGS models for the turbulent natural convection flow in a water-filled DHC of aspect ratio 5 at $Ra = 3 \times 10^{11}$. The tested models are: (i) the WALE model [17], (ii) the QR model [22], and (iii) the WALE model within a variational multiscale framework [23] (VMS-WALE). In the literature, for the DHC configuration, the numerical investigations of LES are concentrated on the air-filled cavities. Thus, the current study is intended to fill a gap, providing DNS and LES results for moderate-to-high Rayleigh numbers in three-dimensional water-filled cavities. Moreover, to the best knowledge of the authors, this is the first study to test the QR model in a DHC configuration.

The remainder of the present paper is organized as follows. In the next section, the description of the case is presented. Then, Section 3 is devoted to the DNS: the numerical methodology used is outlined and the details of the verification studies are explained. In Section 4, the LES models tested in the study are briefly described. In Section 5, the performance of the LES models is assessed by comparison with the DNS results. The discussion is focused on the prediction of the transition to turbulence location and its influence on the flow structure and heat transfer. Finally, concluding remarks are given in Section 6.

2. Description of the case

The turbulent natural convection in a three dimensional DHC of height H, width W, and depth D is submitted to investigation (see Fig. 1). The aspect ratio is $H/W = 5$. This aspect ratio was studied previously by different authors [14,18,19,24]. The cavity is subjected to heating along the left vertical wall, and cooling along the right vertical wall by means of isothermal confining walls at T_h and T_c, respectively. The cavity height based Rayleigh number ($Ra = g\beta(T_h - T_c)H^3 Pr/\nu^2$) is 3×10^{11}, where g is the gravity, β is the thermal expansion coefficient, and ν is the kinematic viscosity. The Prandtl number ($Pr = \nu/\alpha$) in this water-filled DHC is 4.31, which corresponds to water at 40 °C, where α is the thermal diffusivity. The confining walls at the top and bottom of the cavity are adiabatic. No-slip velocity condition is imposed on these four boundaries in x- and y-directions, whereas periodic boundary conditions are imposed in the z-direction for all the variables.

3. DNS

3.1. Governing equations

Considering an incompressible viscous Newtonian fluid, assuming the Oberbeck–Boussinesq (OB) approximation, and neglecting thermal radiation, the governing equations read,

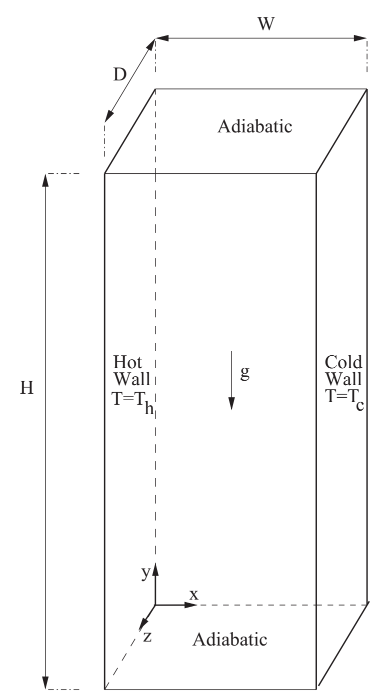

Fig. 1. Schema of the three-dimensional DHC.