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Large Eddy simulation of turbulent mixed convection in a 3D ventilated cavity: Comparison with existing data

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ABSTRACT

We consider in this study the mixed convection airflow encountered in a 3D anisothermal cavity ventilated with supply and exhaust slots under stable thermal stratification. The flow in this cavity has been experimentally studied in the past (S. Mergui, Caractérisation expérimentale des écoulements d'air de convection naturelle et mixte dans une cavité fermée, thèse de l'Université de Poitiers, France, 1993) and was subject to a jet deflection and to a sudden change in the flow pattern between a general clockwise rotation and a counter-clockwise rotation when varying the inlet jet velocity. This phenomenon also exhibits a hysteresis effect depending on the way the velocity is changed, which made us to think that this flow bifurcation is of subcritical nature. Numerical studies have been yet devoted to this configuration, using RANS simulations or Large Eddy Simulation (LES), but this phenomenon has not been reported. So, we chose to numerically study this challenging flow with an LES approach associated with a subgrid diffusivity model previously developed for natural convection airflows. The comparison with the available experimental data and with other LES results using a classical dynamic model proves that the present LES not only correctly predicts the mean characteristics of the flow but is also able to correctly reproduce the flow bifurcation and the hysterisis effect.

1. Introduction

We are interested in this paper with numerical simulations of indoor airflows under mixed convection situations. Because air distribution inside a room results from buoyancy effects due to temperature differences (natural convection), momentum differences due to mechanical ventilation system (forced convection) or external pressure differences on the facades of the room, many indoor situations experience mixed convection flows. As a wide variety of flow structures can be encountered depending on the local and instantaneous equilibrium between inertial and buoyancy forces, combining as an example laminar to turbulent transition, relaminarisation, detached or recirculating flow regions, mixed convection is a very challenging field of research for Computational Fluid Dynamics on the one hand, and for engineering and economical purposes such as building ventilation systems design, energy saving or comfort improvement on the other hand.

From a computational point of view, indoor airflows have been investigated extensively in the past decades, particularly for turbulence modelling. Nevertheless, most of the work is devoted to forced convection flows in isothermal ventilated enclosures such as the one experimentally studied during Annex 20 of the International Energy Agency by Nielsen [1] which constitutes a benchmark exercise for numerous turbulence model adjustments (see as an example Refs. [2–5]).

On the other hand, mixed convective flows have received comparatively less numerical attention. We will focus in this study on the case of a non-isothermal ventilated cavity experimentally investigated by Mergui during her Ph.D. thesis [6]. Despite this cavity is a reduced scale model rather than a real size room, it is very challenging. First, the airflow in this 1 m^3 cavity is representative of flow features encountered in real rooms and second the flow exhibits a singular behaviour when varying the inlet jet velocity, with a bifurcation between two turbulent clockwise and anti-clockwise airflow regimes associated to a hysteresis phenomenon.

Moreover, this cavity has been numerically studied by several authors using RANS or LES approaches [4,5,7–9]. Particularly, Chen and co-workers [4,5,9], commonly use this cavity as a test case for

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Nomenclature

Ar	Archimede number
Ax, Ay	aspect ratios of the cavity
C	constant of the subgrid model
D	depth of the cavity, m
Fr	Froude number
g	gravitational acceleration, m s^{-2}
G	filter function, m^{-1}
h_i	subgrid heat flux per unit of thermal mass ρc_p, K m s^{-1}
H	height of the cavity, m
Φ_{sm}	subgrid thermal energy per unit of thermal mass ρc_p, K m s^{-1}
h	height of the inlet slot, m
k	non-dimensional turbulent kinetic energy
l	height of the exhaust slot, m
P	modified pressure, m s^{-2}
Pr	Prandtl number
Ra	Rayleigh number
S_{ij}	strain-rate tensor, s^{-1}
Re	Reynolds number
t	time, s
T, ΔT	temperature and temperature difference, K
T_{ij}	subgrid thermal tensor, K m^{-1} s^{-1}
U	non-dimensional horizontal velocity
U_{inj}	mean flow rate velocity at injection, m s^{-1}
W	cavity width or non-dimensional vertical velocity, m or –
x, y, z	non-dimensional Cartesian coordinates
y^+	wall units coordinate

Greek letters

ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
θ, $\Delta\theta$	non-dimensional temperature and temperature difference
κ	thermal diffusivity m^2 s^{-1}
τ_{ij}	subgrid stress tensor, m^2 s^{-2}
$\varDelta$	filter width, m

Subscripts

air	relative to air properties
h	relative to the inlet slot
H	relative to the height of the cavity
mol	relative to non-dimensional molecular quantities
sm	relative to subgrid quantities

Superscripts

$\overline{x}$	implicit filtered variables
$\widetilde{x}, \widehat{x}$	explicit filtered variables

different versions of RANS or LES models. In this way, Xu and Chen [9] using a 2D RANS approach with a modified two-layer model observed a good agreement with the experimental data for the clockwise flow pattern. They also observed the anti-clockwise pattern, but this case was not well documented. Previously, Zhang and Chen [4] investigated the flow in this cavity with two LES models, a classical Smagorinsky model, and a Filtered Dynamic Scale Model. However, their results, obtained on a coarse $62 \times 12 \times 62$ grid were not really convincing. Recently, Zhang et al. [5] revisited this problem performing a comparison not only between various RANS models but also between LES and DES, and obtained a satisfactorily comparison between LES and the experimental data for the mean and turbulent clockwise fields, using a $60 \times 30 \times 60$ spatial grid.

Nevertheless, none of these numerical studies report the hysteresis cycle associated to the flow bifurcation, so we chose to numerically explore this cavity with an original LES approach. LES is preferred here because it avoids DNS spatial requirements, and contrarily to RANS modelling, LES is a naturally unsteady description which allows to access not only the statistic quantities but also the instantaneous pictures of the flow as can be obtained during a real experiment.

Various viscosity subgrid-scale models have been developed for LES in the last 40 years, the first and simple one being the Smagorinsky model [10] and the currently more popular one being the dynamic Germano–Lilly model [11, 12]. In this paper, we use an original subgrid diffusivity model based on the thermal characteristics of the flow, which avoids to consider a subgrid Reynolds analogy generally encountered in LES studies of natural convection flows. This original "Mixed Scales Diffusivity Model" proved to be efficient when applied to pure natural convection problems at high Rayleigh numbers [13–15] and we investigate here its capability to deal with mixed convection flows in cavities.

First, we briefly present the description of the LES approach and the subgrid-scale modelling, followed by the description of the numerical procedure. Afterwards, the physical problem is presented and a description of the observed airflow behaviour in the experimental cavity is given.

The numerical results obtained with the Mixed Scale Diffusivity Model associated to a dynamic procedure are then compared with the experimental data available in Refs. [6–8] and also with the recent LES results of Zhang et al. [5], as this later paper probably provides the actually best available LES results for this cavity.

Finally, the numerical investigation of the flow bifurcation associated to the hysteresis effect is presented and discussed.

2. LES approach

The LES separates small-eddies from large-eddies with a spatial convolution filtering. For one-dimensional flow, the filtered velocity is:

$$\overline{u}_i = \int G(x,x')u_i(x')\mathrm{d}x' \tag{1}$$

where $G(x,x')$ is a filter function. The filter function value is large only when $(x-x')$ is less than the filter width, a length scale over which averaging is performed. The eddies larger than the filter width are called the "large-eddies", and the eddies smaller than the filter width are the "small-eddies". In the physical spaces, a box filter is usually used, i.e.:

$$G(x_i) = \begin{cases} 1/\varDelta_i & (|x_i| \le \varDelta_i/2) \\ 0 & (|x_i| > \varDelta_i/2) \end{cases} \tag{2}$$

When performing finite-volume method, it seems natural to define the filter width, $\varDelta_i$, as an average over a grid volume. For a three-dimensional flow, the filter width is generally defined as $\Delta = (\Delta x \Delta y \Delta z)^{1/3}$, where Δx, Δy and Δz are, respectively, the sizes of the control volume in the X, Y and Z directions.

When dealing with non-isothermal flows in ventilated cavities, application of the filtering technique to the equations of motion