RAYLEIGH NUMBER DEPENDENCE OF THE ARCHIMEDES NUMBER DEPENDENT LARGE-SCALE FLOW STRUCTURE FORMATION IN MIXED CONVECTION

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Abstract We report on the experimental investigations of large-scale flow structure formation in mixed convection. We characterize the flow field by measuring the velocity fields within a rectangular model room using 2D2C PIV. The control parameters are the Reynolds number Re, the Rayleigh number Ra and the Prandtl number Pr. All parameters are linked through the Archimedes number *Ar*. In $6.4\times10^{-2} \leq Ar \leq 1.39\times10^{1}$, $4.2\times10^{3} \leq Re \leq 6.35\times10^{4}$ and $Ra = 3.1\times10^{7}$, $Ra = 1.8\times10^{8}$ and $Pr = 0.713$ we found flow 3 different flow structures. While keeping *Ra* and *Pr* constant and varying *Ar* through *Re* variations, we found an *Ar* dependence of the large-scale flow structure formation within $6.4\times10^{-2} \leq Ar \leq 1.39\times10^{1}$. Furthermore, we found a *Ra* dependence of the structure formation, which shifts the transition points between the structures to higher Archimedes numbers and reduces the mean velocities within the investigated domain.

INTRODUCTION

Mixed convection is defined as the temporal and spatial superposition of natural and forced convection and is driven by inlet velocity u_{in} and a temperature gradient ΔT within a gravity field. In most applications, e.g. indoor airflows, this flow is turbulent and its temperature and velocity field is dominated by the formation of large-scale flow structures, as comprehensively studied in Rayleigh-Benard-Convection (RBC) (review of RBC see e.g. [1]). These structures verifiable have a high impact on matter and heat transport properties in the considered domain [2, 3]. The control parameters uin and ΔT can be expressed by the Reynolds number *Re*, the Rayleigh number *Ra* the Prandtl number *Pr* (see [4] for definitions). The relation between them is defined as Archimedes number *Ar*, which seems to be the main control parameter for the interaction of forced and natural convection ($Ar < 0.1$ … forced convection; $Ar \approx 1$… mixed convection; $Ar >>1$ natural convection). Beyond the found large-scale flow structures, we aim to show that the Archimedes dependent structure formation also depends on the Rayleigh number *Ra*. This might have a strong impact on the predictability of the large-scale flow structures.

EXPERIMENTAL SETUP

Figure 1a shows the model room in Cartesian coordinates *x*, *y*, *z*, which are subsequently normalized to *L*, *H*, *D*, respectively. The room has a rectangular shape with aspect ratios $\Gamma_{xy} = L/H = 1.33$ and $\Gamma_{xz} = D/H = 1.66$ and a height of $H = 0.3$m. The cross-section shown in Fig. 1a is constant along the depth of the room. The global temperature difference ΔT if defined as difference of the mean temperature of the four electrical heated obstacles at the bottom and the mean temperature of the air inlets at the top of the side walls. The air inlets and outlets at top and bottom of the side walls are generating the inlet velocity u_{in}. For more details on room and boundary conditions, please refer to [4, 5].

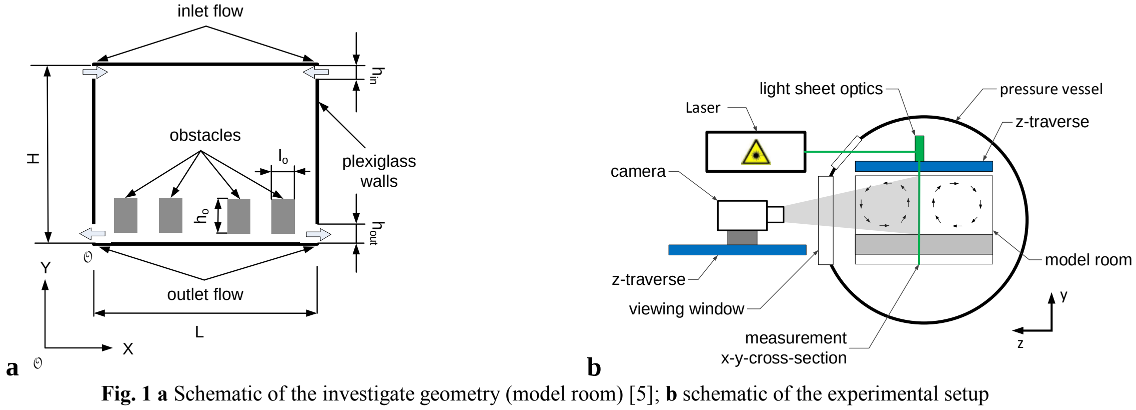

Fig. 1 a Schematic of the investigate geometry (model room) [5]; **b** schematic of the experimental setup

Two Rayleigh numbers have been investigated $Ra = 3.1\times10^{7}$ and $Ra = 1.8\times10^{8}$ at constant Prandtl number $Pr = 0.713$ and $\Delta T = 10$K. The Rayleigh numbers have been achieved by using compressed air at pressures $p = 1.0\times10^{5}$Pa and $p = 2.51\times10^{5}$Pa. Thus, the experiments are carried out in a pressure vessel, as shown in Fig. 1b. In order to achieve an Archimedes number variation in the range of $6.4\times10^{-2} \leq Ar \leq 1.39\times10^{1}$, the Reynolds numbers are varied between $6.82\times10^{3} \leq Re \leq 2.05\times10^{4}$ and $4.22\times10^{3} \leq Re \leq 6.35\times10^{4}$ for the lower and the higher Rayleigh number, respectively. The velocity fields are measured using a 2D2C PIV system, as depicted in Fig. 1b. The PIV System comprises a PCO

SensiCam camera (1280x768pixel, 12bit) and a Continuum Minilite PIV Laser (E = 30mJ/pulse) connected with an ILA Synchronizer. The measurements are carried out at f = 2Hz, a measurement time of t = 900s and at z = 0.5. DEHS particle are used for seeding. All measured velocities are normalized to the inlet velocity u_{in}.

RESULTS & DISCUSSION

Figure 2 depicts the found flow structures within $6.4\times10^{-2} \leq Ar \leq 1.39\times10^{1}$ using the vertical and horizontal velocity component u and v averaged both over time and x and y, respectively. The red dots represents the averaged horizontal velocity component $u(y)$ and the blue dots the averaged vertical component $v(x)$. The dash black line shows a simple model on how the structures should look like. In Figure 2a the flow structure is dominated by forced convection, which is why $v(x{\approx}0.5) < 0$ and $u(x) \approx 0$. This can be explained by two counter-rotating large eddies as described in [5]. Figure 2b and 2c represents a symmetry break, where one large eddy dominates full domain as described in [4], whereas $v(x{=}0.5) \approx 0$. In Figure 2d the thermal convection is dominant, i.e. the mean flow points upwards. In a two dimensional case the flow structure would be the opposite of 2a. But in the present case one large eddy evolves, which rotates around x. However, at this case $v(x{=}0.5) > 0$. So there are 3 different structures within the investigated Ar range.

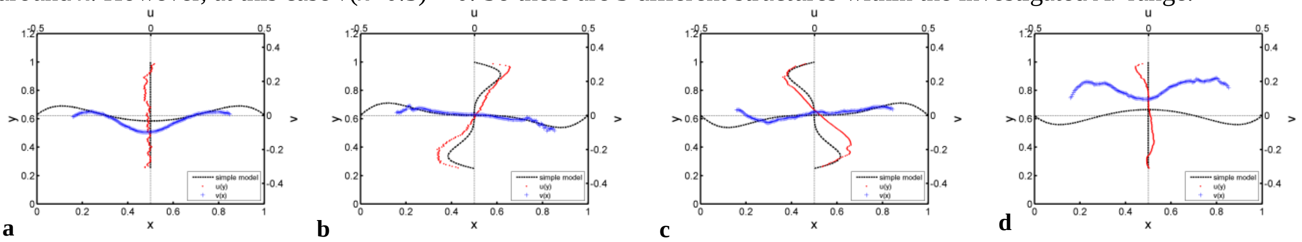

Fig. 2 Three different flow structures are found within $6.4\times10^{-2} \leq Ar \leq 1.39\times10^{1}$, $4.22\times10^{3} \leq Re \leq 6.35\times10^{4}$ and $Ra = 3.1\times10^{7}$ and $Ra = 1.8\times10^{8}$; **a** structure 1; **b**,**c** structure 2; **d** structure 3 (blue dots: $v(x)$; red dots: $u(y)$; black dashed line: simple model of flow structures)

Figure 3 shows $v(x{=}0.5)$ within $6.4\times10^{-2} \leq Ar \leq 1.39\times10^{1}$ and $Ra = 3.1\times10^{7}$ (empty symbols) and $Ra = 1.8\times10^{8}$ (filled symbols). The downward pointing triangles represent the structure 1(Fig. 2a). The upward pointing triangles represent the structure 3 (Fig. 2d) and the diamonds represent the structure 2(Fig. 2b,c). The diagram shows a distinct Archimedes number dependency. But, which is more important, there is also a strong dependency regarding the Rayleigh number. Here, the values of $v(x{=}0.5)$ at $Ra = 1.8\times10^{8}$ are lower than the ones for $Ra = 3.1\times10^{7}$. A reason for this might be the increased turbulence. Furthermore, the transitions between the structures are shifted to higher Ar values. So, the flow structures might become more stable with increasing Ra. However, the main conclusion from these findings is that the Archimedes number Ar is not the main parameter for the formation of the large-scale flow structures.

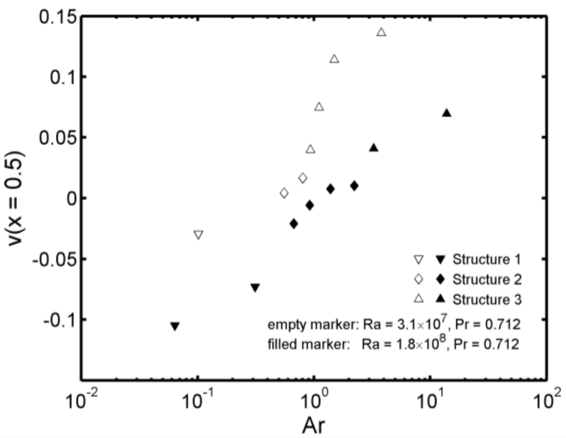

Fig. 3 Archimedes number dependency of the formation of the large-scale flow structure for Rayleigh numbers $Ra = 3.1\times10^{7}$ and $Ra = 1.8\times10^{8}$ (structure 1 = Fig. 2a; structure 2 = Fig. 2b,c; structure 3 = Fig. 2d)

References

[1] F. Chillà, J. Schumacher, New perspectives in turbulent Rayleigh-Bénard convection *The European Physical Journal E: Soft Matter and Biological Physics* **35.7**: 1-25, 2012

[2] J. Bailon-Cuba, M. S. Emran, J. Schumacher, Aspect ratio dependence of heat transfer and large-scale flow in turbulent convection, *Journal Fluid Mech* **655**: 152-173, 2010

[3] E. P., van der Poel, R. J., Stevens, D. Lohse, Connecting flow structures and heat flux in turbulent Rayleigh-Bénard convection, *Physical Review E*, **84(4)** 045303, 2011

[4] M. Körner, An Experimental Method for the Investigation of Indoor Airflows in a Reduced Scale Model Room: Development and Application, Ph.D. Thesis, TU Ilmenau, Ilmenau, Germany, 2014

[5] M. Körner, O. Shishkina, C. Wagner, A. Thess, Properties of large-scale flow structures in an isothermal ventilated room, Build Environ, **59**: 563-574, 2013