PERIODIC AND QUASIPERIODIC TEMPERATURE OSCILLATIONS IN MIXED CONVECTION

Daniel Schmeling [a)], Johannes Bosbach, Claus Wagner
German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology
Bunsenstraße 10, 37073 Göttingen, Germany

Summary We report on temperature oscillations which we observed during experiments in turbulent mixed convection at $Ra = 2.0 \times 10^8$ in a rectangular enclosure with a length of $L = 2500\,\mathrm{mm}$ and aspect ratios of $\Gamma_{xz} = L/H = 5$ and $\Gamma_{yz} = W/H = 1$, heated from below and cooled from above. The measurements were conducted using an arrangement of PT-100 temperature sensors. Depending on the Reynolds number of the flow entering the cell, and thus the Archimedes number, we detected stable flow conditions as well as quasiperiodic and periodic oscillations in the temperature field. Comparison with smoke visualisations allowed us to ascribe the respective temperature distribution to a certain number and arrangement of large scale circulations (LSCs) in the flow. We interpret the temperature oscillations, which reach the highest frequency $f = 2.0 \times 10^{-3}\,\mathrm{s}^{-1}$ at $Ar = 1.8$, as motions of the LSCs in longitudinal cell direction.

INTRODUCTION

Mixed convection (MC) comprises of forced convection, caused by inertia forces, and thermal convection, initiated by buoyancy forces, being of the same order of magnitude. In MC the Archimedes number $Ar = Ra \times Re^{-2} \times Pr^{-1}$ serves as a measure for the ratio between thermal and inertia forces. Here, Ra denotes the Rayleigh number with the height of the cell H and the temperature difference between bottom and ceiling (ΔT) as characteristic length and temperature difference, respectively. For the Reynolds number Re, the mean inflow velocity (u) and again the height of the cell serve as characteristic values while the Prandtl number Pr merely depends on the fluid material properties.

Previous investigations in the observed rectangular convection cell addressed structure formation, heat transport and low-frequency oscillations ([3], [4] and [6]). Thereby, temperature oscillations in the outflowing air, the arrangement of large scale circulations (LSCs) and oscillations in Proper Orthogonal Decomposition modes of the velocity field were investigated. The details of the underlying dynamics of the LSCs, which govern these effects, however, are still open issues. Numerically, Sergent and Le Quéré [5] and Kaczorowski and Wagner [2] investigated pure Rayleigh-Bénard convection (RBC) by means of Large Eddy Simulations (LES) and Direct Numerical Simulations (DNS), respectively, in a rectangular enclosure similar to ours. While there are numerous studies on LSC dynamics in RBC [1], little is known about the effects in systems where thermally induced LSCs are interacting with externally driven shear flows. We present results of analysis of temperature time series in MC in a range of $1.1 < Ar < 2.7$ at constant $Ra = 2.0 \times 10^8$ under variation of the inflow velocity u (i.e. $1.0 \times 10^4 < Re < 1.6 \times 10^4$).

EXPERIMENTAL SET-UP

The investigations were conducted in a rectangular convection cell with a length of $L = 2500\,\mathrm{mm}$ and aspect ratios of $\Gamma_{xz} = L/H = 5$ and $\Gamma_{yz} = W/H = 1$ (for details see Figure 1). All side walls consist of double glazing polycarbonate plates with a $5\,\mathrm{mm}$ air gap and an additional $100\,\mathrm{mm}$ polystyrene insulation, in order to minimise heat losses through the side walls. The working fluid is air at ambient pressure ($Pr = 0.71$). The measurements were conducted using 35 PT-100 temperature sensors placed within the cell and another 86 PT-100 sensors for control reasons, e.g. in the cooling plate or the heating plate. The scanning rate of the temperature sensors amounted to $0.1\,\mathrm{Hz}$, while the typical duration of a complete measurement was of the order of one day for each case.

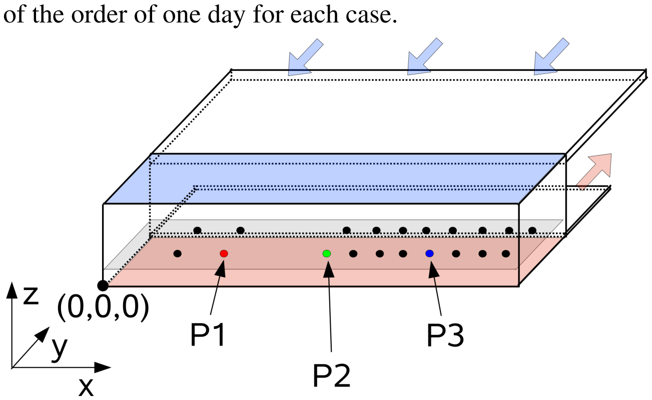

Figure 1. Sketch of the convection cell. The bottom plate of the cell is heated (red) while the ceiling is kept at ambient temperature (blue). Inflow and outflow channel are located at the same side and span the whole length of the cell. Black dots mark the positions of the PT-100 sensors in the layer $Z/H = 0.2$ within the cell.

[a)] Corresponding author. E-mail: daniel.schmeling@dlr.de

RESULTS

Figure 2 shows temperature time series at three selected sensor positions (see Figure 1) at $Ar = 1.8$ over a time period of one hour, revealing periodic oscillations of the temperature signals with a frequency of $f = 2.0 \times 10^{-3}\,\mathrm{s}^{-1}$. The observed oscillation is stable over the whole measurement time and reproducible. Further analysis of the signals of all temperature sensors in the layer $Z/H = 0.2$ shows that four systematically different temperature distributions occur. Combined with smoke visualisations we can ascribe these temperature fields to four different LSC configurations. Two configurations with three convection rolls and two with four convection rolls are occurring during one oscillation period. The temporal evolution is illustrated in Figure 4. A dynamic process of convection roll formation at $X/L \approx 0$ (left side wall) and break down at $X/L \approx 1$ (right side wall) was detected, resulting in a periodic change between LSC configurations with three and four rolls.

Figure 3 shows the dependency of the oscillation frequencies as a function of Ar as determined by Fourier analysis. Obviously, there are no oscillations (within our measurement time) for very low and very high Ar, as in these cases either the buoyancy or the inertia forces dominate the flow and thus stabilise the LSC configuration. In the intermediate region, i.e. $1.3 < Ar < 2.3$, temperature changes occur. Thereby, periodic oscillations were found for $1.6 < Ar < 2.0$, whereas in the other Ar regions we observed spontaneous oscillations or "jumps" and the given frequency is a result of the number of events divided by the total measuring time, which is of the order of one day. At $Ar = 1.8$ the frequency reaches its maximum value of $f = 2.0 \times 10^{-3}\,\mathrm{s}^{-1}$.

We ascribe the periodic oscillations to the interaction between the warm upwelling fluid of the LSCs with the forced convective inflow. If neither buoyancy nor inertia forces are dominant, this interaction destabilises the flow with fixed positions of the upwelling warm fluid. As a result, the number of buoyancy induced convection rolls changes between three and four while new rolls are formed on the left side of the cell and other rolls break down on the right side. The exact processes of roll formation and break down, however, is still an open question and the subject of further investigations.

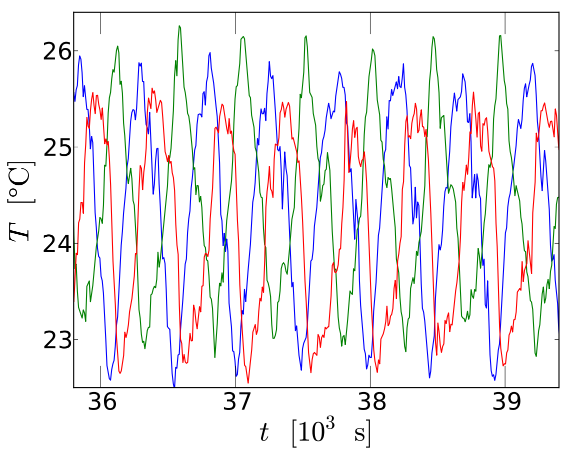

Figure 2. Temperature time series at $Ar = 1.8$ at three selected sensor positions for constant $Y/W = 0.25$ and $Z/H = 0.20$: — $X/L = 0.25$, — $X/L = 0.50$ and — $X/L = 0.75$.

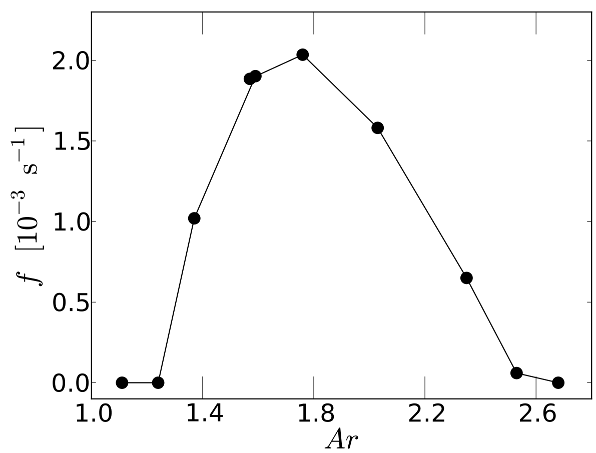

Figure 3. Observed oscillation frequency as a function of Ar.

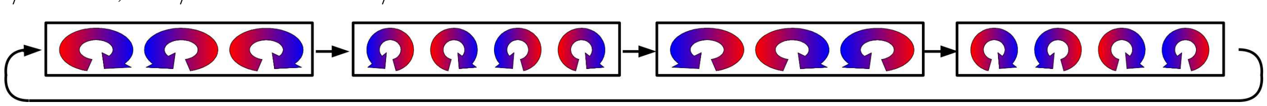

Figure 4. Sketch of the dynamics of the convection rolls.

CONCLUSIONS

Temperature oscillations were found in mixed convection for a certain range in Ar at a constant $Ra = 2.0 \times 10^8$. We ascribe the occurrence of the oscillations to the interaction between the superimposed shear forces of the forced convective flow and the buoyancy driven flow. The frequency of the oscillations depends on Ar and reaches a maximum value of $f = 2.0 \times 10^{-3}\,\mathrm{s}^{-1}$ at $Ar = 1.8$ ($Re = 1.3 \times 10^4$).

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