Study of reversals in Rayleigh-Benard Convection using correlations from temperature measurements

Arnab Dhabal*
Department of Physics, Indian Institute of Technology Kanpur

Experimental verification of flow reversals in Rayleigh-Benard convection for a cylindrical geometry of aspect ratio 1 has been carried out. The top and bottom surfaces are maintained at constant temperatures with a temperature difference ranging from 5 to 25 degrees (to vary the Rayleigh number between 10^8 and 10^9). Thermocouples placed at regular intervals registering temperatures are used to detect the direction of flow, and to study other features of the flow like velocity, turnover time and higher Fourier modes. The same setup will be used to investigate reversals for cuboidal geometries.

Introduction

Rayleigh Benard convection involves heating a fluid sample from below and maintaining it at a lower temperature from above that drives a convective flow. The system is defined by three parameters –Rayleigh number, Prandtl number and the geometry (including the aspect ratio) [1]. Flow reversals for high Rayleigh number fluids have been studied for both cuboidal and cylindrical chambers by independent research groups. In cuboidal geometry (rectangular cross-section), the flow is confined to the diagonal plane [2] and reversals can take place only by cessation, that involves growth of the secondary corner rolls [3][4]. In case of cylindrical cross-sectional chambers, due to azimuthal symmetry, reversals can take place both by flow rotation (through 180 degrees) and by cessation [1].

The reversal detection techniques commonly used are short-time correlations of temperature fluctuations [5][6] and particle image velocimetry (PIV) [3]. The flow visualization technique produces accurate results, but involves complicacies in experimental set-up and substantial processing requirements.

The aim of this project is to experimentally verify reversals and to investigate the dependence of reversals on Rayleigh numbers by temperature measurements only. My collaborator T. V. Raziman would use optical techniques to study the same. We have first tried to emulate the results of Brown and Ahlers [1] for cylindrical chambers. In the paper, only first Fourier mode was examined, while we have looked into the presence of higher modes of flow for the same geometry. Also, since previous research on cuboidal geometries has been largely restricted to quasi-2D experiments, we would extend the research to cuboidal chambers having comparable length, breadth and height dimensions.

Working Fluid

A study of available fluids was carried out in terms of achievable Rayleigh numbers and Prandtl numbers by varying the value of height and temperature differences between the top and bottom plates. The velocity and eddy turnover times depend on these constants by the following parameters [7]:

$$u_{rms} = 0.15\frac{k}{d}\sqrt{Ra * Pr} \quad (1)$$

$$T_{eddy} = 2d/u_{rms} \quad (2)$$

where k is the thermal diffusivity, d is the vertical length of the chamber, Ra and Pr being the Rayleigh number and Prandtl numbers respectively. There is no specific dependence of reversal periods on other parameters, but it is usually 100-1000 times the eddy turnover time. The Rayleigh numbers vary from 10^6 to 10^{10}. Although we are interested in studying low Rayleigh number fluids because of limited research in the regime, most of them like glycerine have a high Prandtl number, which does not support reversals [3]. We also checked the velocity boundary layer and thermal boundary layer values for each fluid. For temperature measurements, the thermocouples' ends should be located outside the thermal boundary layer but within the velocity boundary layer such that it does not affect the flow. A partial list of the fluids studied is given below in Table 1. Taking into account all these parameters, water at room temperature was chosen as the most suitable working fluid. For a height of 240mm, with temperature difference varying from 5°C to 25°C, the attainable Rayleigh numbers are between 1×10^9 and 6×10^9. The Prandtl number has a value of 6. This amounts to an eddy turnover time of 27s to 61s, and thus reversals are expected in periods of the order of 1-2 hours. The minimum velocity boundary layer thickness is 2mm and the maximum thermal boundary layer thickness is 0.5mm, which allows for the thermocouples to be inserted to a nominal depth of 1mm into the fluid.

Fluid	Ra	Pr	T_{eddy}(s)	Velocity BL(mm)	Thermal BL(mm)
Water	3.5×10^9	6.1	35	2.4	0.4
Silicone Oil (1cSt)	3.2×10^{10}	11.7	15	1.6	0.1
Ether	1.3×10^{11}	3.7	13	0.8	0.2
Glycerine	9.8×10^6	10227	24	66.7	<<0.1
Chloroform	7.4×10^{10}	3.8	15	1	0.3
Acetone	1.0×10^{11}	2.8	14	0.8	0.3

Table 1: Selected list of fluid parameters for δT=15°C and d = 240mm

Apparatus - Overview

The setup has an 800mm x 360mm x 36mm bakelite base, with a 12mm air gap in between. The heating element, - a layer of 3mm wide nichrome strips in series is placed above this with mica sheets on either side for uniform heat distribution. A 10mm thick aluminium plate (700mm x 360mm) placed above it conducts the heat on to the cylindrical perspex chamber containing water which is supposed to undergo reversals. The cylinder has an inner diameter of 240mm and a vertical aspect ratio of 1. Above the cylinder, a 2mm thick removable copper plate supports a cooling chamber. Cold water at a specific temperature is channeled through the top chamber, to keep the top copper plate at that temperature. The temperature is maintained using a cooling unit.

Holes are drilled into the 5mm thick perspex cylinder at heights H/4, H/2 and 3H/4, 60 degrees apart azimuthally, for the thermocouple ends to be inserted. These 18 thermocouple readings will allow us to study higher Fourier modes of flow (up to 3 modes azimuthally, and 2 modes vertically). Also they can give an insight into corner flows.

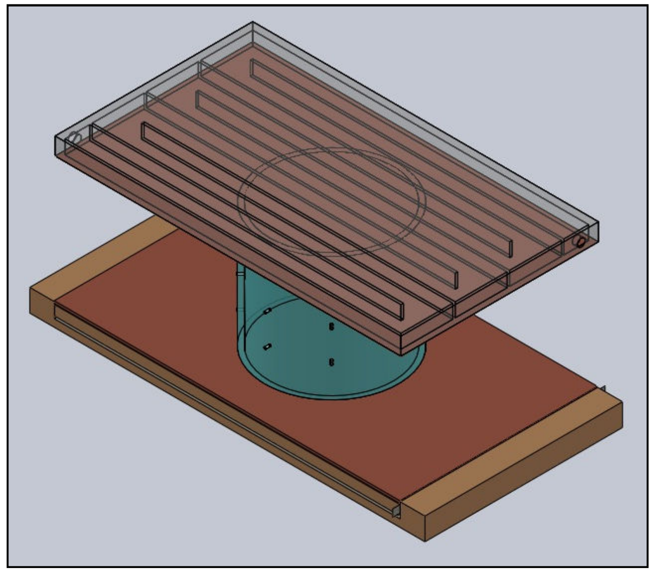


Figure 1: Isometric view of the model made in SolidWorks 2010

After authentication of the setup by comparing results with previous research, the experiment shall be conducted by replacing the cylinder with a cuboidal cells with aspect ratios (h:l:b) of 1:1:1 and 1:2:1 with the smallest side dimensions ranging between 150mm and 400mm. The dimensions were decided from heat flux considerations which shall be discussed in the section below.

Detailed Design Considerations, Fabrication and Experimental Set-up

A large number of design considerations were made in planning and fabricating the set-up. Copper is used as the conduction material for the top plate and Aluminum for the bottom plate because of their high conductivities ($\sigma_{Cu} =$ 400W/m^{-1}K^{-1} and $\sigma_{Al} =$ 237W/m^{-1}K^{-1}), thereby minimizing energy losses. The cylinder material chosen is perspex to ensure that the sidewalls are thermally insulating. The energy requirement for the system is calculated as follows.

In the steady state, the limitation is set by the cooling unit, which can remove heat from the system at 1.5 kW. We constrain ourselves to supplying 1 kW from the strip heaters. The total heat transferred by water for different temperature differences is calculated by $W_{tot} = Nu * W_{cond}$ where Nusselt number $Nu = 0.15Ra^{1/3}$ and $W_{cond} = kA(\delta T)/d$, A being the area of contact and k being the conductivity. For δT lying in the range 5°C to 25°C, the heat transferred by water is between 100W to 900W for cylindrical geometries. A similar analysis for heat dissipation by air gives a maximum value of 32W. Hence it is achievable in practice. The low conductivity of bakelite base ($\sigma = 0.4$ $W/m^{-1}K^{-1}$) along with an air gap ensures that very minimal heat is lost in the downward direction (~10W). Forced convection of the air is disallowed by sealing the air gap from all the 4 sides.

The analysis was repeated for cuboidal geometries, and it was found that for the aspect ratios we are interested in studying, the heat transfer characteristics of 150mm x 300mm x 150mm (h x b x l) cubes will be satisfied in the entire temperature range from 5°C to 25°C. However, for larger dimensions, only a lower temperature difference (up to 15°C) was supported. The heat flux through the fluid for different geometries is given below in Table 2. The achievable Rayleigh numbers lie in the range 3 x 10^8 to 5 x 10^9.

Geometry	δT(°C)	Flux(W)
Cylinder (h = 240mm; d = 240mm)	5	105
	25	891
	30	1135
Cuboid (150mm x 300mm x 150mm)	5	97
	25	825
Cuboid (250mm x 500mm x 250mm)	10	656
	15	1125
Cuboid (300mm x 600mm x 300mm)	10	939
Cube (400mm x 400mm x 400mm)	10	831
Cube (200mm x 200mm x 200mm)	5	83
	25	706

Table 2: Steady state heat flux for different geometries and temperature differences using water as the working fluid

The heat is to be provided by NiCr 80/20 strips of 3mm width and 0.3mm thickness, running along the 700mm length, and connected in series. The arrangement is inspired from the design used by Andallib Tariq for his PhD thesis [8]. The strips are laid by punching 2 mm holes and mechanically fixing them to the Bakelite sheet at the two ends by using screws. They are placed as close to each other as possible without short circuiting. 70 strips are laid with a gap of 2mm between each strip. The total resistance was measured to be 68Ω and hence, to supply 1kW power, current and voltage requirements are 3.8 A and 260V respectively. On laying the strips it was found that the possibility of a short circuit wasn't yet eliminated. A heat conducting, electrically insulating and pliable material was required. Asbestos threads were used for the purpose. Nine threads were woven alternately above and below the nichrome strips to ensure that they do not make contacts except at the ends.

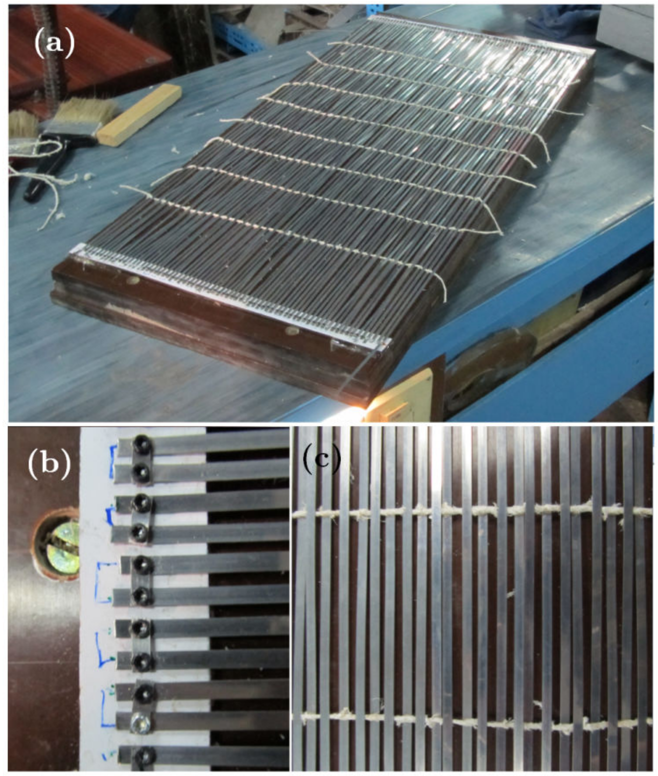


Figure 2: Heating assembly - (a) The series of nichrome strips on the Bakelite base (b) The fixing and contacts at the strip ends (c) Alternate looping of the asbestos thread around the strips

A layer of mica is used on the lower side so that the bakelite does not start burning by direct heating, and a layer of uniform thickness above, along with thermal tape ensures that the Aluminium plate receives uniform heat throughout. The plate itself is kept much larger than the area of actual heating, to reduce edge effects.

The cylinder for the working fluid was available only in specific dimensions. The one that was closest to our initial design had 240mm inner diameter and 250mm outer diameter. The height was cut to 240mm to make the aspect ratio 1, and the two ends of the cylinder were made smooth using sand paper. However on close observation, it was found that there was a tilt of 0.5 degrees. To ensure that neither of the two directions of flow is favoured, the tilt was reduced further using a precision cutting technique available at the 4-I lab.

The top chamber is assembled on the thin copper plate. It comprises of 7 channels, each of 45mm width separated by 4mm plastic walls. The outer wall is made of perspex and is 10mm thick. The first and the last channels have holes for inlet and outlet. This arrangement ensures that the water continuously flows over the entire area of the plate, thereby causing uniform cooling.

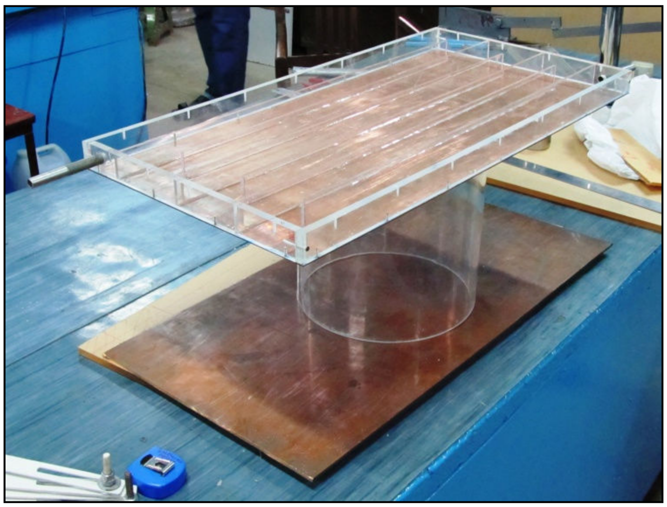


Figure 3: Top chamber assembly

T-type (Copper- Constantan) thermocouples have been used for making the temperature probes, because their operating temperature range is relatively small (-200°C to 350°C) compared to other thermocouples, thereby giving better accuracy (~0.1°C after calibration). The reaction time for registering temperature is inversely related to the wire thickness, but the fluctuations increase simultaneously. Since our application requires accuracy over fast reaction times, a nominal thickness of 1.25mm is used. The thermocouple wires were cut in various lengths (between 40cm and 60cm) and arc-welded.

These thermocouples were calibrated by using a water bath, a thermometer and a NI-Data Acquisition device (Chassis: NI-SCXI-1102C and Connected Accessory: NI-SCXI-1303). For each temperature value, readings were taken at 200Hz for 10 seconds and averaged over. The data was used to confirm that the thermocouples were accurate with all temperature readings at a particular time having 0.25°C variation on an average. Even these variations are to be largely attributed to inhomogeneities of the water, since at room temperature (when the temperature is most uniform), the variation was least at 0.1°C.

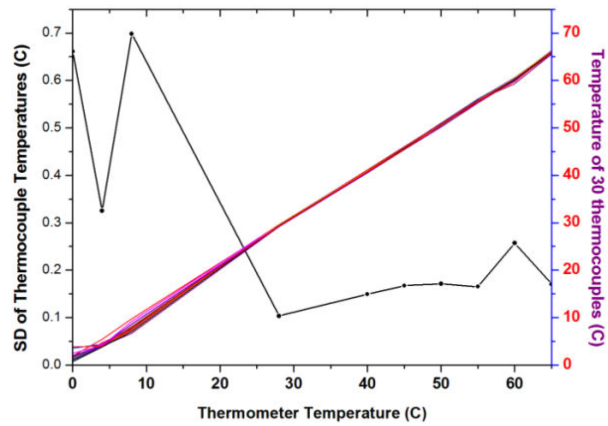


Figure 4: Thermocouple calibration data

18 of these thermocouples were inserted into 2mm holes drilled on to the sides of the cylinder. The insertion depth was as per boundary layer calculations. They were fixed and the holes were sealed using an industrial grade epoxy compound.

The cylinder was then fixed to the Aluminium base plate using the same epoxy compound and Silicon sealant. The cylinder was filled with water and heated up to 62 degree Celsius temperature to check for leaks up to maximum operating temperature. At the same time uniformity of the bottom plate was also checked by using thermocouples in the water with their tips 1mm above the bottom surface.

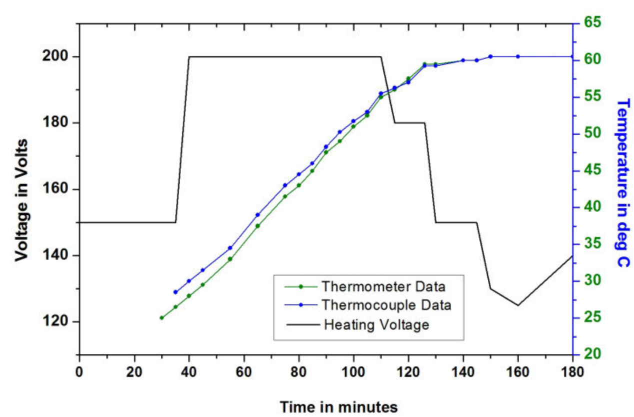


Figure 5: Bottom plate temperature uniformity

Both temporal and spatial temperature uniformity were confirmed using thermocouple data for the bottom plate. The plot (Figure 5) shows that it takes about two hours from the start of the heating process to get to uniformity, by constant temperature monitoring and adjusting the variac appropriately. It also shows once stabilized, minor variations in heating do not cause substantial change in the bottom plate temperature.

The top chamber was sealed and distilled water passed through it from the chiller-cum-pump through flexible pipes. The pressure developed inside the cooling chamber was too large to keep it leak-proof in spite of using sealant. To reduce the pressure, the flow rate was reduced using a valve.

After the apparatus was certified leak-proof, it was moved to an air-conditioned room and kept on a desk that can damp vibrations efficiently. Minor leveling adjustments were made. The cylinder was filled with distilled water and the cooling chamber mounted on it accurately and sealed. The thermocouples were connected to the NI-DAQmx device. A Labview program was run on a computer to acquire, log and display the data during run-time. An additional thermocouple was connected for checking plate, room and chiller temperature.

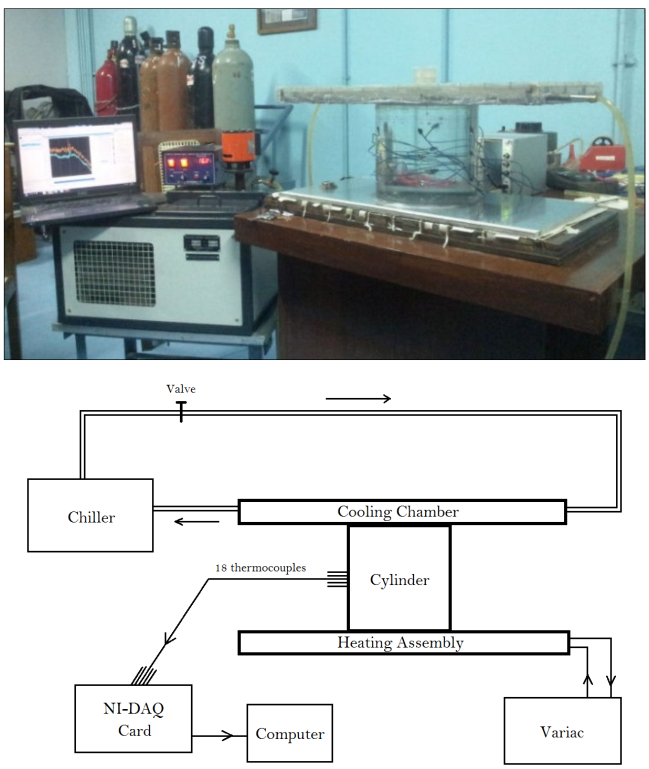


Figure 6: (above) Apparatus in running state (below) Schematic of the apparatus

Experimental Conditions and Data Analysis

After a few short runs taking the apparatus through a few heating/cooling cycles, long runs of up to 14 hours were planned. Three experiments whose results are reported here were run at:

(i) $T_{top} = 20°C$; $T_{bottom} = 48°C$; $Ra = 7.45 \times 10^9$
(ii) $T_{top} = 25°C$; $T_{bottom} = 50°C$; $Ra = 6.65 \times 10^9$
(iii) $T_{top} = 5°C$; $T_{bottom} = 27°C$; $Ra = 5.85 \times 10^9$

In all three cases the room temperature was maintained at 27°C. Thermocouples were used for measuring the temperatures because of higher accuracy, and since all other temperature measurements related to flow pattern are based on other thermocouples. Thermometers and in-built temperature readings were used only for rough estimates.

The 18 thermocouples used are numbered as 0-5 (upper layer at 3H/4), 13-18 (middle layer at H/2), 26-31 (lower layer at H/4). Readings were taken and recorded at a sampling rate of 5 seconds. They were simultaneously monitored and analyzed on the computer to check for temperature stabilization, and reversal events.

Initially when the heating and cooling process was just started, the thermocouples exhibited very less temperature variations ($\sigma = 0.1°$, range $< 0.4°$). This is again indicative of the accuracy of the thermocouples. Depending on the average temperature between the top and bottom plates, the mean temperature as displayed by the thermocouples increased or decreased from the initial starting temperature. The variation continued to be low until at a certain point, it was found that the readings of different thermocouples separated out and a flow pattern emerged with the variation increasing to beyond 0.75° (range ~3.5°). Also it was noted that simultaneously readings of multiple thermocouples separated out.

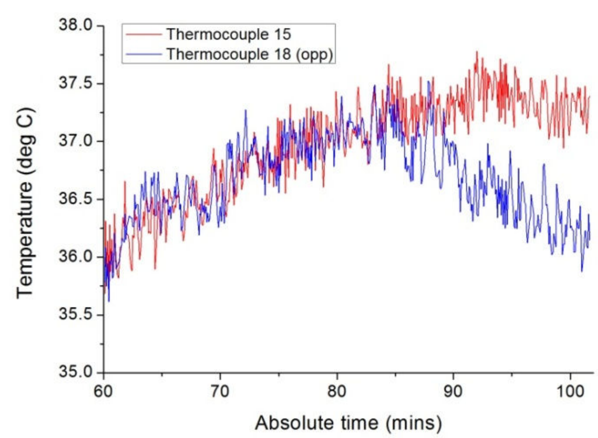


Figure 7: Readings of oppositely placed thermocouples in the middle layer showing flow separation into cold and hot plumes

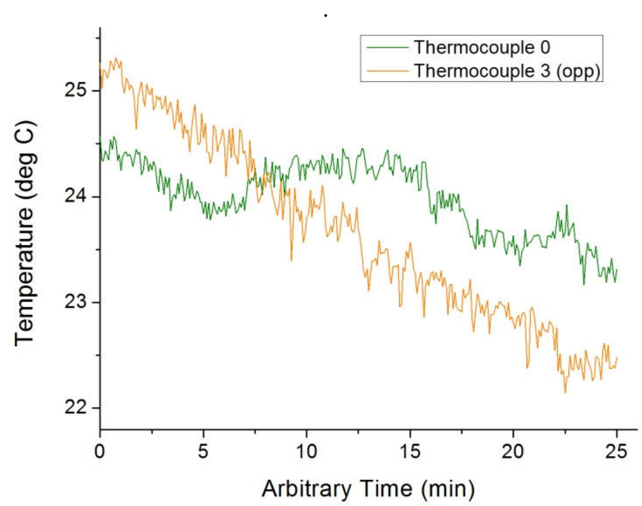


Figure 8: Readings of oppositely placed thermocouples in the upper layer showing switching of plume position (cessation type pseudo-reversal)

In one of the experiments (iii), a flow pattern was already present when the temperature was reduced to a different range. It was found that while the temperature was reducing, the hot and cold plume positions got interchanged, i.e. a cessation-type reversal was observed (Fig 8). However, this cannot be reported as a proper reversal since the flow was in an unsteady state and the temperatures were rapidly reducing– 1°C/5 min.

It took about 3-4 hours for the flow to stabilize. The mean and variation in water temperature for one of the experiments changing with time has been shown in the figure below.

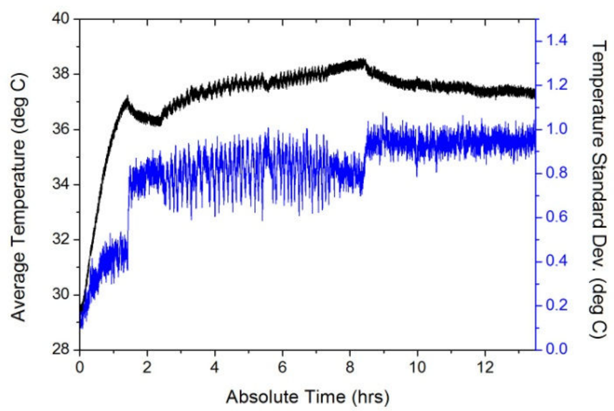


Figure 9: Plot of mean temperature (black) and temperature variation (blue) with time

The pattern was analyzed from data taken in the stabilized region. Since the temperatures of the same thermocouple showed some fluctuations with time in consecutive readings, due to local variations in the large scale flow, an average of the readings is taken for every 5 minutes to compare with other sets and conclude whether the flow has stabilized (Variation in mean temperature < 0.2°/5 minutes).

In the preliminary study, secondary structures (higher Fourier modes) are not taken into account. A sinusoidal flow pattern is assumed as in Brown and Ahlers (2006) [1] with higher temperatures being recorded at the parts where the hot plumes move upwards and vice versa. Each of the 3 layers of the thermocouple data of 6 azimuthal points are plotted against θ and fitted with the empirical function

$$T = T_0 + \delta T sin\left(\pi \frac{\theta - \theta_0}{180}\right)$$, where θ is in degrees,

for averaged data sets each of 5 minutes interval. Here T_0 is the mean temperature of the large scale circulation, δT is the measure of the amplitude and θ_0 gives the flow orientation in the azimuthal plane.

Results and further experiments

It was found that the sinusoidal approximation could be applied only to the lower set of thermocouple temperatures (with the orientation error ~ 10° as compared to >30° values for the two other thermocouple layers). Thus, curve fitting data only from the lower layer of thermocouples is used for determining the orientation, which is plotted with time in figure 10.

From the first plot of figure 10, it is seen that the flow orientation was initially fluctuating in the order of 15°C, which is comparable to the error. Around the 8.5hr-9hr period there is a non-negligible rotation of the orientation by about 25° which can be considered a *rotation-type reversal*. This corresponded to a similar change of the order of 20-25 degrees at the same time in the flow visualization data which was being run simultaneously. A higher angle rotation would have been a more convincing result, but for that the experiment needs to be run for longer periods. The chances of cessation are an order of magnitude lower than the chances of a rotation [1]. After the orientation change, by the end of the 8^{th} hour, the fluctuation in orientation reduced.

The second plot has even lesser fluctuations and no reversals were recorded in the 7-hour period, although the flow pattern was reverse to that of experiment (ii). The flow had changed direction by about 180 degrees during the unsteady phase (as discussed in connection to figure 8), and hence cannot

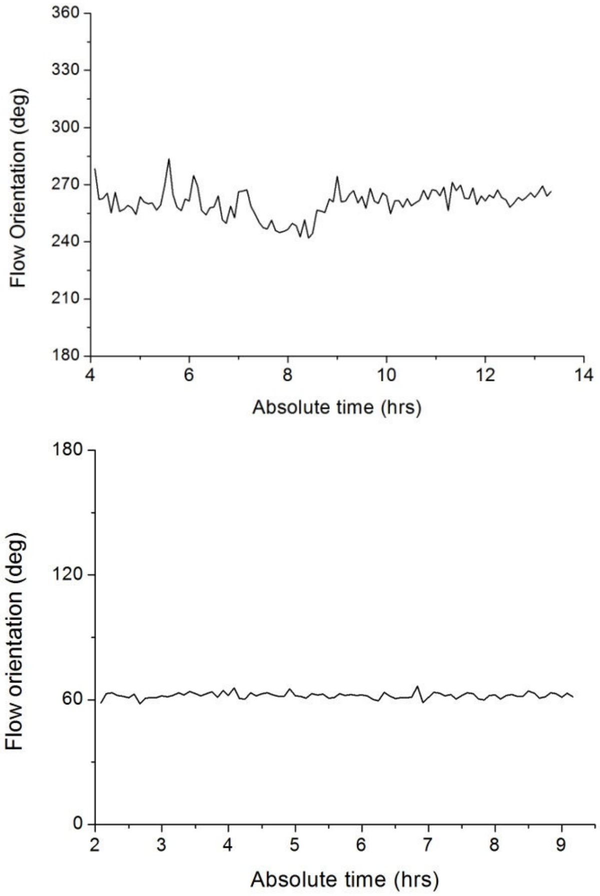
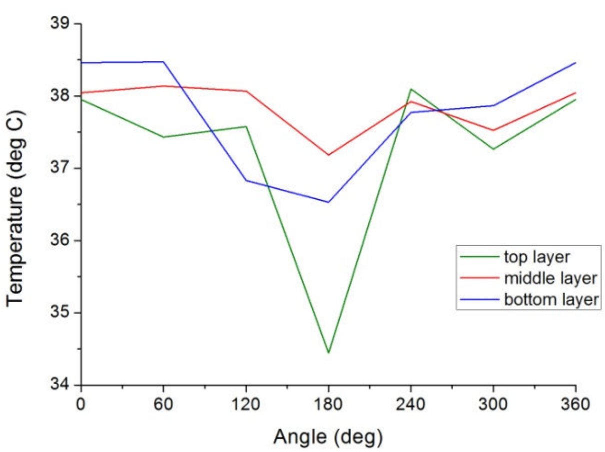


Figure 10: Plot of θ_0 (flow orientation) with time for experiments (ii) and (iii) respectively

be regarded as a reversal in Rayleigh-Benard convection. The amplitude values for the bottom layer of thermocouples were around 0.9°C with an average error of 20%.

An example each, of the flow patterns in experiments (ii) and (iii) is given below at some arbitrary time of steady flow.



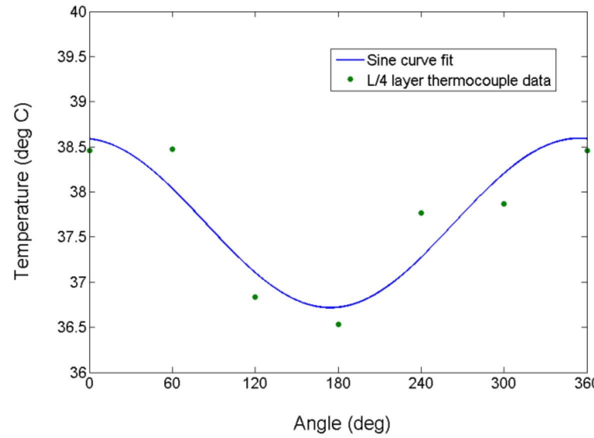


Figure 11: (above) An example of flow pattern in all the three planes at an arbitrary time during steady flow (665th minute for experiment (ii)) (below) Sinusoidal curve fitting at the same time for the bottom layer

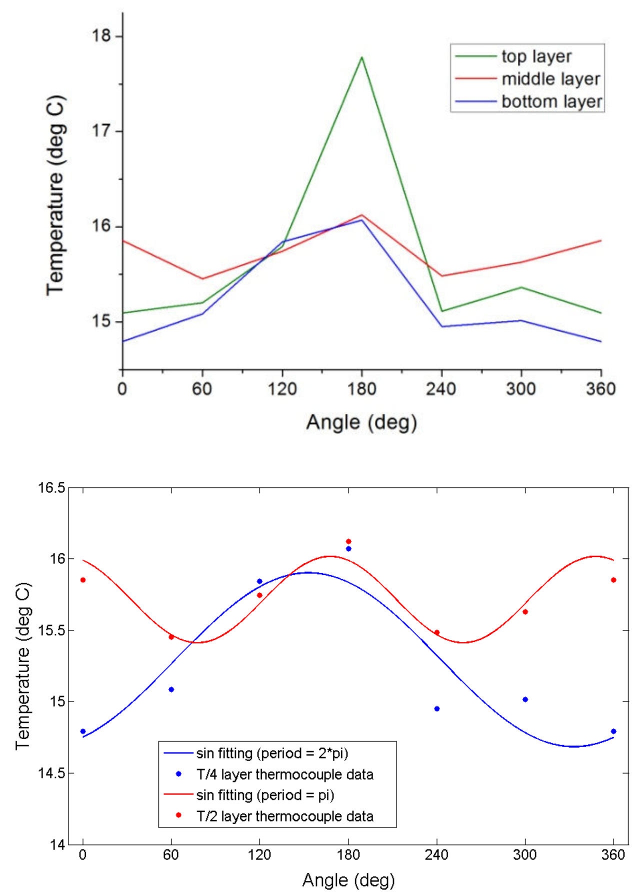


Figure 12: (above) An example of flow pattern in all the three planes at an arbitrary time during steady flow (460th minute for experiment (iii)) (below) Sinusoidal curve fitting at the same time for the bottom layer and middle layer

It was found that for most of the duration of experiment (iii), a higher Fourier mode structure was present in the middle layer. The fitting parameters for a half period roll were found to have errors less than 10%. Thus in the middle layer the roll was rising at two places and coming down at two points azimuthally, although in the lower layer, the data points can be fitted with a primary roll with reasonable accuracy. The top layer data points at any time could not be fit into any sinusoidal function for any of the experiments. This could be because of the presence of trapped bubbles resulting in an improper boundary layer or due to the presence of the flow visualization apparatus, which could be modifying the local flow.

Although one reversal event is reported from the experiments performed so far, further studies need to be carried out on the apparatus for longer periods and different Rayleigh numbers in different temperature ranges for getting to more conclusive results. Since circulations of different orientations could be seen in the apparatus, it is evident that the system is not biased in any particular direction. This means that the system can be considered azimuthally symmetric, thereby increasing chances of reversal.

To study higher Fourier modes which become more important during reversal events, the temperature values shall be expressed in terms of their Fourier transform [6], from which the amplitude for all the Fourier modes shall be calculated. Such an analysis would be useful in studying the mechanism of the reversals.

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*Electronic address: adhabal@iitk.ac.in

[1] E. Brown and G. Ahlers, J. Fluid. Mech, Vol. 568 (2006).

[2] Ke-Qing Xia, Chao Sun, and Sheng-Qi Zhou, Physical Review E 68, 066303, (2003).

[3] Kazuyasu Sugiyama et al, PRL 105, 034503 (2010).

[4] M. Chandra and M. K. Verma, Phys. Rev. E 83, 067303 (2011).

[5] J. J. Niemela et al, J. Fluid Mech. (2001), vol. 449.

[6] Pankaj Kumar Mishra, Arnab De, Mahendra K. Verma, V. Eswaran. J. Fluid Mech, 668 , pp 480-499 (2011).

[7] K. R. Sreenivasan, A. Bershadski, and J. Niemela, Phys. Rev. E 65, 056306 (2002).

[8] A. Tariq, PhD Thesis, IIT Kanpur (2004).