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EXPERIMENTAL STUDY RAYLEIGH–BÉNARD CONVECTION IN A RECTANGULAR MOTOR OIL TANK

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Abstract: Measurements of temperature distribution were performed in a rectangular tank with aspect ratios 4x2x1, using motor oil as a working fluid. The experimental setup was adjusted to be as close to real fuel tanks exposed to solar radiation, as in airplane wings. The measurements were taken at fifteen different positions on the faces of the tank. Probes used are PT100 elements. In order to obtain as uniform temperature as possible, double bottom was used, with water as medium for obtaining the constant surface temperature. The results are compared with those obtained by IR camera. This paper is part of the research done within the National Program of Integral and interdisciplinary Investigations, project number: III42008, funded by the Government of Republic of Serbia.
Keywords: Rayleigh–Bénard convection, temperature profile, PT100, motor oil

1. INTRODUCTION

The Rayleigh–Bénard experiment is a commonly used as a model for the study of turbulence and heat transport in thermal convection. Rayleigh–Bénard convection occurs in a fluid between a lower heated plate with the temperature T_t and an upper cooled plate with the temperature T_h. The temperature difference $\Delta T = T_t - T_h$ between the plates drives the flow. The convection cell is adiabatic at the side walls and has isothermal top and bottom plates. In reality, it is not unknown for the heated and the cooled plate to switch sides, as is common for tanks, which are heated from the Sun.

This kind of convection can be fully described by the Rayleigh number (Ra), the Prandtl number (Pr), the Nusselt number (Nu) and two aspect ratios Γ_x and Γ_y. The Rayleigh and Prandtl numbers are given by:

$$Ra = \frac{\beta g \Delta T h^3}{\nu a} \quad (1)$$

$$Pr = \frac{\nu}{a} \quad (2)$$

the aspect ratios are defined as

$$\Gamma_x = \frac{l}{h} \text{ and } \Gamma_y = \frac{w}{h} \quad (3)$$

and the Nusselt number is defined as

$$Nu = \left.\frac{\partial T}{\partial z}\right|_{z=h} \cdot \frac{h}{\Delta T} \quad (4)$$

where β is the coefficient of thermal expansion, g – gravity acceleration, height between the heating and cooling plate, l – length of the cell, w – width of the cell, ν – kinematic viscosity, a – thermal diffusivity and $\partial T/\partial z|_{z=h}$ – temperature gradient at the heated wall.

The transition to the turbulent regime in air occurs for $Ra \sim 10^6$. In the focus of this investigation, Ra range was $2.58\times10^7 < Ra < 5.59\times10^7$, so, it can be assumed that the regime was turbulent for all experiments.

It is important to mention that there were two sets of experiments: with heated plate on the bottom, or classic Rayleigh–Bénard convection – RBC, and with heated plate on the top, for simulation of the insolation and influence of the atmosphere on the fuel tanks, which are being heated mostly from above – RRBC.

2. EXPERIMENTAL SETUP

The tank used for this experiment is shown in the figure 1. The dimensions are 500×250×125mm, in x, y and z axis, respectively. The distance between the hated and the cooled plate is represented in z-direction. For obtaining of constant surface temperatures, another tank was added on the heating plate side. This tank volume of about half of the experimental tank, and its dimensions are 500×250×60mm. Electric heater is used for obtaining of the desired temperature as shown in the figure 1, and a mixer is added into the water tank, in order to maintain the constant water temperature. Mixer iz placed from the opposite side of the heater, in order to ensure the most uniform water temperature in the tank.

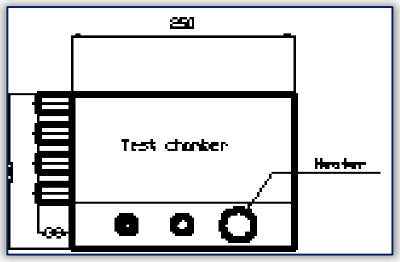


Figure 1. Front side of the tank, with the heater position

Temperature probes are PT100 elements, with precision of 0.1^{0}C, manufactured by the firm Nigos – Niš. Fifteen measuring locations are measuring temperature distribution in the chamber, one is measuring the temperature in the heating water tank and one is measuring the air temperature below the chamber. The cooling plate is air cooled, in order to observe the atmospheric influences on the tank, as is happening in the reality.

For comparing of the results, the lateral sides of the tank are made of plexiglass, as shown in the figure 2.

As can be seen on the figure 2, the measuring positions are ensuring the monitoring of the vertical temperature profile at the left and right sides (eight probes) and in the center (3 probes, on the opposite side) of the largest tank side (x-z plane). Longitudinal temperature distribution in x-axis is measured with 5 probes.

In order to ensure minimal heat loss to the sides of the tank, it was insulated with 2 cm sponge (to disable the air flow between the tank and the insulation) and 5 cm styrofoam. Water tank was also insulated, in order to minimize heat loses, and improve the system response. Insulation is kept in place with elastic bandages. Insulation is adapted to be removable on either side, in order to make access for the IR camera.

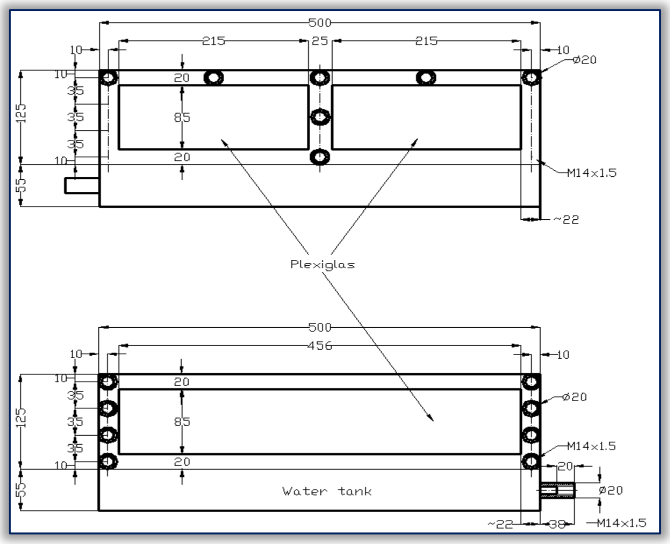


Figure 2. Disposition of the measuring points on the lateral sides of the tank

The cooler plate is free to the atmosphere, and was cooled by the air in the test room. The air temperature was measured below the chamber.

In order to enable the free air flow at the cooled plate, the tank was equiped with 50mm feet both from the heated, as from the cooled side, thus allowing for the heated and cooled plates to change positions.

3. MEASUREMENTS RESULTS

Measurements were performed for about five days each (RBC and RRBC), with different temperature levels. On the figure 3, 5 day continous measurements and representative stable hourly measurements for RBC are presented. The curve TS01 represents the heating tank temperature, which can be assumed to be the temperature of the heated plate, due to the low thermal resistance of the tank. One can notice that daily temperature change is between 2 and 4^{0}C, with the largest hourly change of 0.2^{0}C, which is at the level of the probes precision. The daily change of the test room temperature is varying between 4 and 7^{0}C (up to 0.2^{0}C per hour, curve TS16), which is at the level of the possibility of commercial control systems to maintain the room temperature per hour.

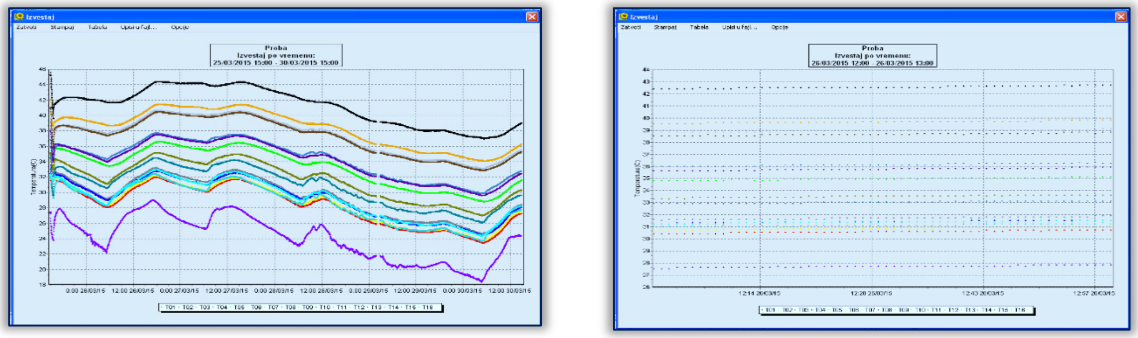


Figure 3. Long term and selected stable hourly measurements for case of RBC

On the figure 4, 4 day continous and stable hourly measurements for RRBC are presented. The curves TS01 and TS16 represents the heating tank and the test room temperature, respectively. Daily temperature change of the heating tank is 1 to 4°C, with the hourly change up to 0.2°C. The daily change of the test room temperature is 4 to 6°C, up to 0.2°C per hour.

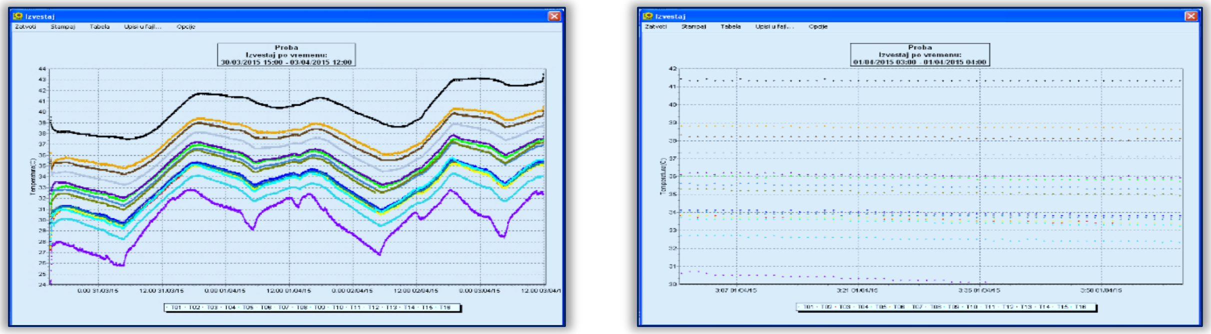


Figure 4. Long term and selected stable hourly measurements for case of RRBC

On the figure 5, the temperature profile in the left, middle and right vertical cross-section of the chamber with oil in case of RBC (a,b,c), for temperatures of the heated TS01=41.3°C and cooled plate TS16=30.3°C, and RRBC (d,e,f) for temperatures TS01=42.5°C and TS16=27.6°C are presented. One can notice the more uniform temperature profiles for RRBC case, especially on the left profile (a, d). The difference is expected as the velocities are higher for the RBC case, resulting in better mixing of the oil in the chamber.

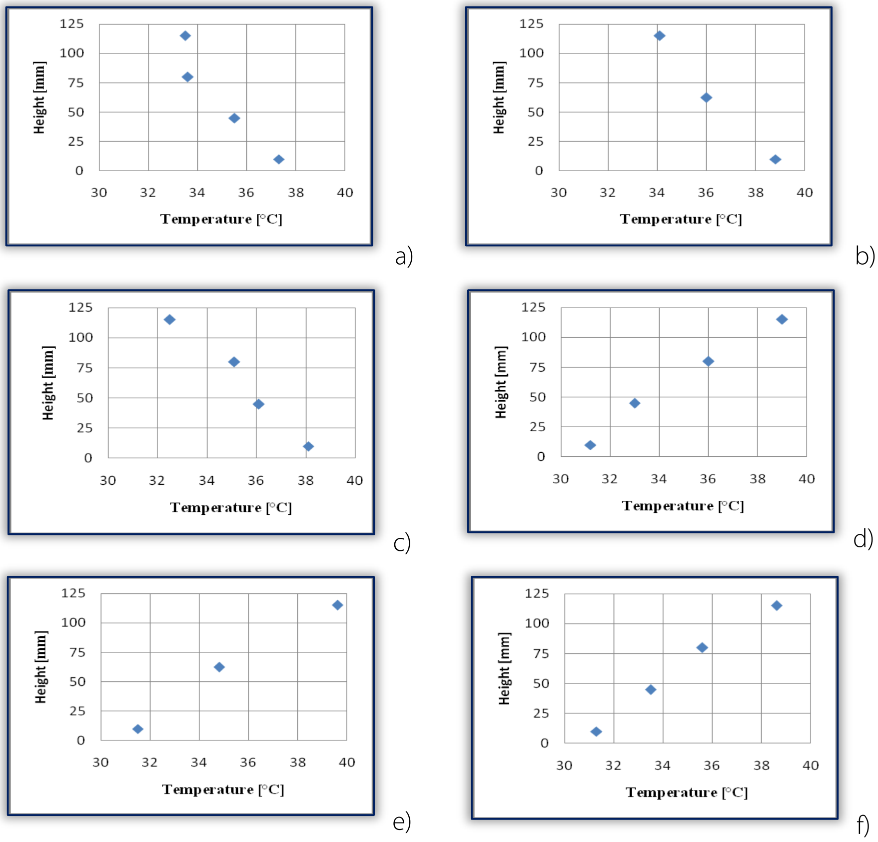


Figure 5. The temperature profile in the left, middle and right vertical cross-section of the chamber with oil in case of RBC (a,b,c) for temperatures TS01=41.3°C and TS16=30.3°C and RRBC (d,e,f) for temperatures TS01=42.5°C and TS16=27.6°C

On the figure 6, the paralel measurements with the IR camera are presented. The IR camera measurement lasted for 4 minutes. There is no significant temperature change on the probes due to removing of the insulation (largest near the cooled plate, about 0.4°C, so it can be assumed that the temperature change is due to the increased convection, as result of the higher air speed in the room, from opening of the door, moving of people during measurements, removing and returning of the insulation, etc.

The results are shown for the RRBC case (heated upper plate), as this case is more likely to occur in the atmosphere. For the RRBC case, the fluid can not be completely mixed (like in the RBC case) as the gravity and the boyancy forces are in the same direction. The viscous forces are working against the flow, so fluid velocities are an order of magnitude smaller than in the RBC case.

4. CONCLUSIONS

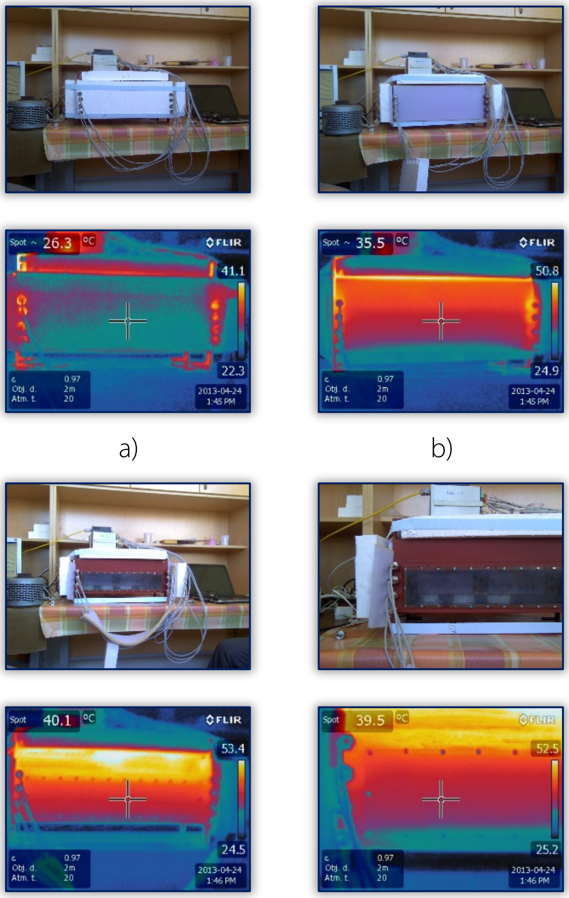
The chamber used for this experiment shows high flexibility in the work. The probes are positioned in the adequate locations, and can be used for various fluids, at diferent temperatures and changeable positions of the heated and the cooled plate.

The experiment showed that the influence of the changeable environment is transfering to the entire chamber, as the heating power was kept constant. The measuring system showed high sensibility and flexibility to the atmospheric changes.

Measurements with the IR camera confirmed that the heat loses are low enough, but could be further reduced, especially on the probe locations, for both RBC and RRBC case.

Measured results shows the existence of the innert upper zone, for the RRBC case. The height of the of the Rayleigh-Benard structures is lower for the RBC case. The fluid mixing is even less intense in this case, which can be noted on the figure 5.

In both RBC and RRBC case, no significant depositions were observed. This is result of the high purity of the oil used, as well as the clean surfaces of the chamber. Further research is to be done on the particle deposition in fuel and oil tanks.



a) b) c) d)

Figure 6. Temperature distribution measured with IR camera with or without insulation

Note

This paper is based on the paper presented at 13th International Conference on Accomplishments in Mechanical and Industrial Engineering – DEMI 2017, organized by University of Banja Luka, Faculty of Mechanical Engineering, in Banja Luka, BOSNIA & HERZEGOVINA, 26 - 27 May 2017.

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