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[1.] Sadun AYED, [2.] Miloš JOVANOVIĆ, [3.] Gradimir ILIĆ, [4.] Predrag ŽIVKOVIĆ, [5.] Mića VUKIĆ, [6.] Mirko DOBRNJAC, [7.] Suzana KLJEČANIN

EXPERIMENTAL STUDY OF TEMPERATURE DISTRIBUTION FOR TURBULENT RAYLEIGH–BÉNARD CONVECTION IN A RECTANGULAR TANK

[1-5.] University of Niš, Faculty of Mechanical Engineering, Niš, SERBIA
[6.] University of Banjaluka, Faculty of Mechanical Engineering, Banjaluka, BOSNIA & HERZEGOVINA
[7.] The Public Institution Institute for materials and and construction testing of Republic of Srpska, Banjaluka, BOSNIA & HERZEGOVINA

Abstract: Measurements of temperature distribution were performed in a rectangular tank with aspect ratios 4x2x1, using different working fluids. 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. As to obtain as uniform temperature as possible, double bottom was used, with water as medium for obtaining of the constant surface temperature. The results are compared with the those obtained by IR camera. This paper is concerned by the National Program of Integral and interdisciplinar Investigations, project number: III42008, funded by the Government of Republic of Serbia.
Keywords: Rayleigh–Bénard convection, temperature profile, PT100, IC camera

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:

$$Ra = \frac{\beta g \Delta T h^3}{\nu a}; \ \Pr = \frac{\nu}{a}$$

The aspect ratios are defined as

$$\Gamma_x = \frac{l}{h} \text{ and } \Gamma_y = \frac{w}{h}.$$

and the Nusselt number is defined as

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

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 $\partial T/\partial z\big|_{z=h}$ – temperature gradient at the heated wall.

The transition to the turbulent regime in air occurs for Ra~10^6. In the focus of this investigation, Ra range was $3.3\times10^6<Ra<5\times10^6$, so, it can be assumed that the regime was turbulent for all experiments.

It is important to mention that in this experiment heated plate was on the top, as the idea was to simulate the insolation and influence of the atmosphere on the fuel tanks, which are being heated mostly from above.

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.

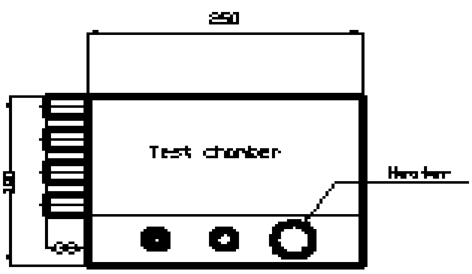


Figure 1. Front side of the tank, with the heater position

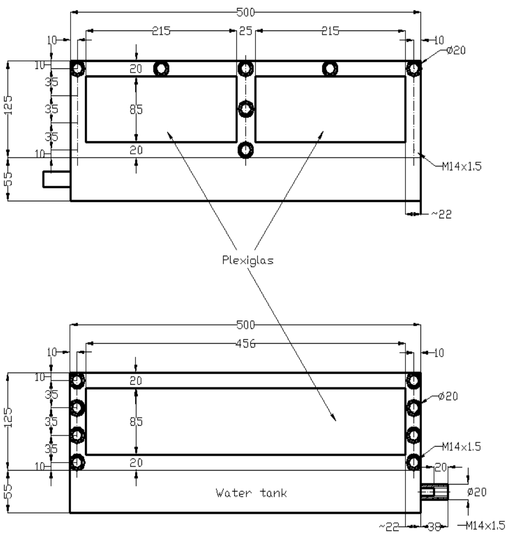


Figure 2. Disposition of the measuring points on the lateral sides of the tank

Temperature probes are PT100 elements, with precision of 0.1ºC, 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 sides (eight probes) and in the middle (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 2cm sponge (to disable the air flow between the tank and the insulation) and 5cm styropor. 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.

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 a month, with different temperature levels. On the following figure, 5 day continous measurements 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 3 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 7 and 8^{0}C (up to 0.2^{0}C per hour), which is at the level of the possibility of commercial control systems to maintain the room temperature per hour.

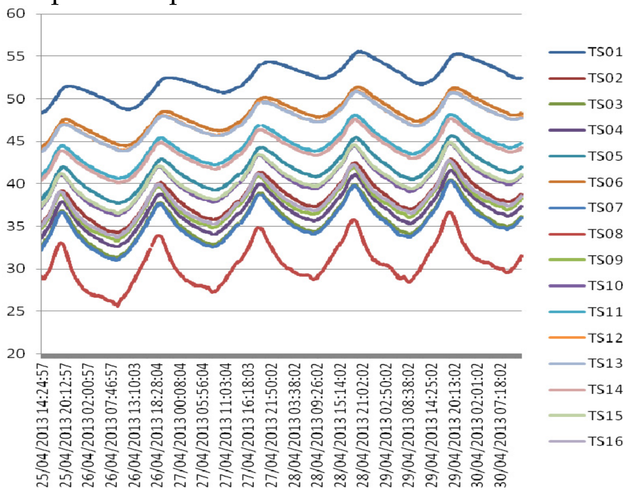


Figure 3. Temperature change over 5 day period

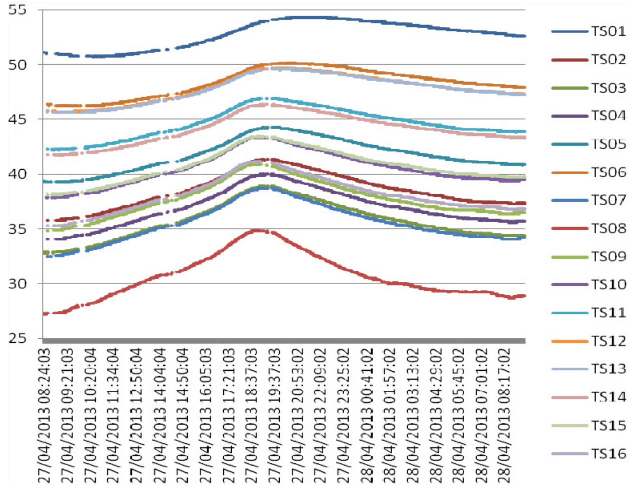


Figure 4. Typical daily temperature change

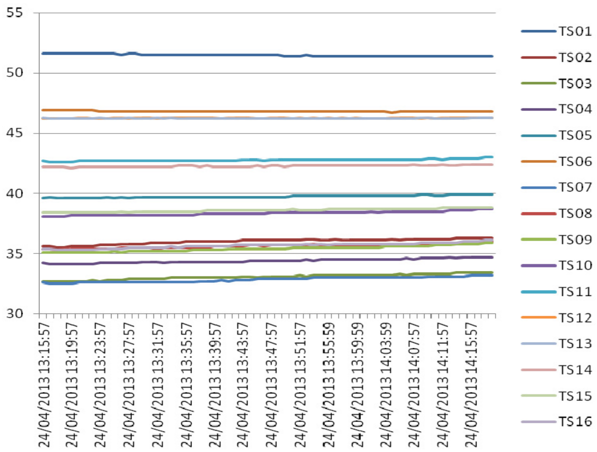
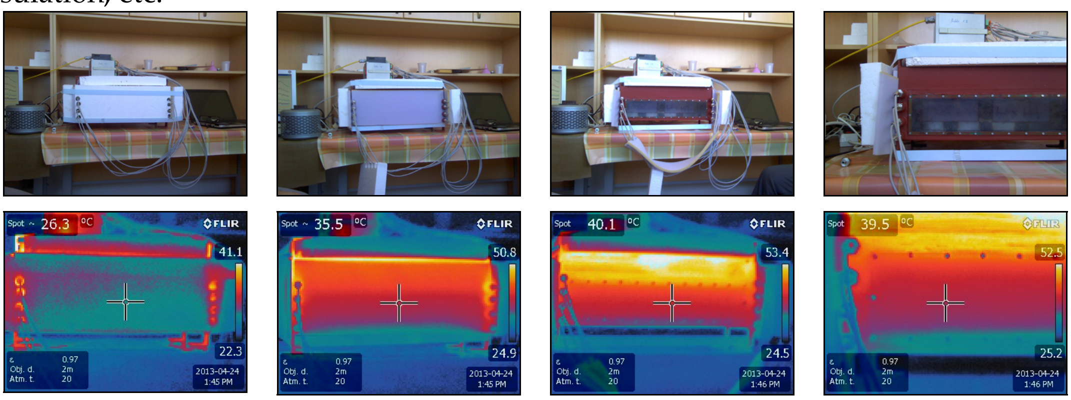


Figure 5. Hourly temperature change while measured with IR camera

On the following figure, the typical daily temperature change is presented. One can notice that all temperature probes are showing the similar behaviour to the temperature change.

On the following figure, the hourly temperature change during the paralel measurements with the IR camera are presented. The period presented is 30 minutes before and after measuring with IR camera, which lasted for 4 minutes itself. The period when the insulation was remowed is in the middle of the presented data. As there is no significant temperature changes on the probes (except the ones closest to the cooled plate, which is only slightly larger than usual, it can be assumed that this 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.



a) b) c) d)

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

On the figure 6, temperature distributions are presented, measured with IR camera. The temperature of the heating tank appears to be 1^0C higher than measured with the PT100 probe, but it can be assumed to be dye to the camera being calibrated to plexiglass. Figure 6 shows temperatures of the outer insulation (~26^0C, 6.a), inner insulation (~36^0C, 6.b), temperature in the middle of the chamber (~40^0C, 6.c), and the temperature near to the side wall (6.d). The room temperature was 26.5^0C.

One can notice, especially on the figure 6.d, that there is slightly higher temperature in the upper zone. It is due to the conductive heat transfer in the upper zone, which causes the lower height of the Rayleigh-Bénard structures, which can not be formed over the entire height of the chamber, as in the case when the heated plate is on the bottom. This shows that the experiment is in good agreement with the reality of the process.

The fluid can not be completely mixed, as when the heated plate is on the bottom, as the gravity and the boyancy forces are in the same direction. The viscous forces are working against the flow, so there are even less movement in the chamber.

4. CONCLUSION

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 other fluids, and diferent temperatures and positions of the heated and the cooled plate.

The experiment showed that the influence of the steady environment is allowing for the cooler plate to be directly exposed to the atmosphere. From the other hand, the influence of the air flow over the cooling plate should and will be investigated in much more details, in order to include the influence of the wind to the tank surfaces.

The measuring system is showing appropriate response to the outer disturbances, thus allowing extensing of the experiment.

Measurements with the IR camera shows that the heat loses are low enough, but could be further reduced, especially on the probe locations.

The probe sockets are increasing the innertia of the probes, which causes longer time for steadying of the process, but allows the paralel measurement with the IR camera.

Measured results shows the existence of the innert upper zone, for the case when the heated plate is on the upper side. The height of the of the Rayleigh-Benard structures is lower than of ones in the case of the lower heated plate. The fluid mixing is even less intense in this case.

The results obtained in this experiment gives valuable contribution to the investigation of the processes of natural convection and heat transfer in the closed tanks.

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