Experiment study of Rayleigh-Bernard convection with upper heat plate effects

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Abstract — Natural convection heat transfer appears in a wide range of smaller scales (in pipelines, canals and tanks) to huge scales (atmospheric, molten planet essence) that have been studied for a very long time for their energy importance. Natural convection depends on the geometric relationships and the temperature of the surfaces involved, and determines the type of flow, either laminar or turbulent, which may occur. Normal convection takes place between two parallel plates at different temperatures, and the subject is often studied when the temperature of the lower plate is higher than the temperature of the upper part - a well-known convection case called Rayleigh-Bainard convection. Certain examples of natural convection based on circular plates still restrict flow being unlimited. In engineering practice, this is certainly not the case so that in the proposed research the effect of side walls on the flow is, with no ideal for the process and in the real three-dimensional field.

Natural convection has an undeniable effect on thermal flow processes in engineering practice that are used in most mobile engineering systems, which have a parallel shape. These can contain all types of alcohol, so that the search inside the alcohol, which represents the majority of liquids that can be found in the tanks given. The temperature changes on the thermal flow processes that take place in the given tanks. Results obtained should show closely the actual flow systems in the given tanks as well as their impact on the deposition of solid particles that can be found in the given tanks.

Index Terms — Natural convection, Alcohol, total suspended solid,

I. INTRODUCTION

Energy is the primary concern of all societies. Its development and progress depends entirely on the ease and quantity of its energy. Rising population and rising and growing of demand for energy have resulted in the burning of more and more fossil fuels, resulting in many phenomena, such as global warming, climate change and air pollution [1]-[2]. Energy and the need for fuel have become national concern, as it could cause deterioration in countries’ growth and hurt their national budgets due to volatile oil and gas prices [3]. Therefore, the trend towards renewable energies, especially solar energy, is a promising and excellent alternative to reducing dependence on fossil fuels, especially in the production of electricity and heat [4].

Solar energy can be used to heat water for domestic and office use [5], and can be used to warm the air for comfort [6]. Solar energy can be used to produce electricity directly using PV modules [7], or by heating and concentrating its radiation to generate steam that used to run turbines [8]. In any case, many solar applications such as water heaters [9], Trombe wall [10], air heaters [11], water distillers [12], and PVT systems [13]-[14], in which the heat is transferred from top to bottom that the solar radiation falling from the top turns to heat on the high surface of the device and the penetration of this temperature down to heat the fluid or parts of the solar system [15]. Hence, from here came the importance of studying the effect of convection heat transfer from top to bottom, which we will address in this study.

The simplest case of the fluid flow which is described in fluid mechanics is a laminar flow. Such flow takes place until the flow parameters, such as the Reynolds number, do not reach a critical value [16]. After that, the laminar flow becomes unstable under the influence of small disturbances so that it cannot be maintained as such; so, it turns into a turbulent one, this flow is extremely unstable while its mathematical modelling most often extremely complicated [17].

The stability criterion plays a central role in fluid mechanics, when it comes to the fluids that are exposed to disturbance, given that the instability can cause their transition from the laminar to the turbulent state [18]. The criterion that determines when the fluid flow changes or retains its status is called the stability criterion [19]. The theory of linear stability in fluid mechanics implies predicting the critical Reynolds number at which the fluid flow instability appears [20].

Rayleigh - Bénard convection experimentally explained by the French scientist Henri Bénard (Henri Claude Bénard (1874-1939)) in 1900. Nobel Prize winner for physics, Lord Rayleigh (John William Strutt, 3rd Baron Rayleigh (1842-1919)) in 1918 was the first to lay the theoretical foundations based on the temperature gradient [21]. A special group of these flows occur when the flow is performed between the parallel plates of different temperatures, usually when the temperature of the lower plate is higher than the upper plate temperature [22]. In this approach, the boundary conditions at the top and bottom of the observed domain imply the disappearance of the vertical velocity component [23]. It is not in accordance with the Bénard that have made changes to the model based on surface tension, which brought the model into agreement with the experiment, i.e. physical reality [24].

The given examples of natural convection are still based on the generalization of the plates between which the flow takes place being unlimited [25]. In engineering practice,
this is not the case, so that this research will define the influence of the side walls to the flow, without idealization and within the real three-dimensional domain [26].

Despite the complex mathematical model, under certain conditions, we can predict how the instability is affecting the structure of the turbulent flow [27]. A typical example is the Rayleigh - Bénard convection in which a thin layer of fluid, limited by two parallel plates is heated from below and upper [28]. Due to the temperature differences in the fluid layers, the flow under the impact of the buoyancy forces occurs in the fluid. Depending on the flow parameters, different cell structures are formed in the temperature, velocity and vortices fields [29]. In the case of 3D flow, so-called rolls are formed. Therefore, the Rayleigh-Bénard's problem in its simplest form and in the way it was treated in its earliest study [30]. It is the case of the so-called infinite layer. In such a case, the fluid layer is limited by two infinite horizontal plates. The surface is heated from below, i.e. it is at a higher temperature than the upper plate. The upward heating has a negative temperature gradient since the fluid is denser on the top than on the bottom; such a formation, with the denser fluid at the top, is potentially unstable [31]. When the temperature gradient is below a certain value, the natural tendency of a fluid to be moving due to the buoyancy forces will be disrupted due to the viscosity of the fluid, and heat dissipation [32]. Thermal instability occurs when the negative temperature gradient exceeds a certain critical value [33].

The thermal convection phenomenon caused by the negative thermal gradient is known as the Rayleigh-Bénard convection [34]. As for the physicality of the phenomenon, however, combining both names into a single expression adds confusion in understanding of the convection mechanism, which is still not fully resolved [35]. Bénard observed phenomenon in which instability due to the temperature dependence on the surface tension coefficient played an important part, while Rayleigh studied the convection caused by other types of instability, namely by non-uniformity of temperature (and density) of the fluid layer [36]. The term Rayleigh-Bénard convection is usually attributed to the convection resulting from the Rayleigh mechanism, while the term Bénard-Marangoni convection refers to thermo-capillary convection [37].

Cell formation is a characteristic of the systems which are far from equilibrium. They can be thrown out of balance by different physical mechanisms [38]. Some of them are: temperature difference in the fluid, electrical potential difference or chemical reactions [39]. For each of the driving forces there is a dissipation mechanism, such as viscosity, which opposes the unbalancing of the system [40]. The balance between the driving force and the dissipation mechanism results in the cell formation that can have different shapes (circular, square, hexagonal, spiral, stripes...) [41].

In addition to the importance of this system for various branches of technology and physics, the Rayleigh-Bénard system is also investigated for purely theoretical and fundamental reasons. The classic "standard" mathematical model of this problem consists of a series of non-linear combined partial differential equations that are impossible to solve by the classical mathematical apparatus [42]. This model serves as a paradigm of non-linear system which, if properly researched, can provide a clearer insight into nonlinear systems [43]. It is now generally recognized that the time dependence of the Rayleigh-Bénard system indicates the transition from the laminar to the turbulent flow. It is worth noting that, in general, the phenomenon of transition is geometry-independent and is more of a feature of the flow [44]. For example, proper selection of dimensions gives the same Reynolds number for the case of flow over a flat plate and in pipes. As for another similar question, the Rayleigh-Bénard system is the most carefully studied case of non-linear systems that shows self-organization of the system model forming Experimental studies have been carried out extensively in chambers of different shapes, such as parallelepiped, cylindrical, trapezoidal, spherical [45]. For various fluids (Newtonian) the Rayleigh-Bénard convection, it can be considered as "the forefather of the canonical examples that were used for the study of model forming and behaviour in extended systems in space." It provides excellent opportunities for the study of the spontaneous ordering in space and at the same time raises the question of the feasibility of a special shape and size of flow, or the selection of the desirable shapes and proportions [46].

This study aims to investigate mathematically and experimentally the external parameters that influence real tank behaviour. Temperature is the primary parameter; the source of temperature gradient depends on the insolation. The convection intensity and the speed of its advance occur as a direct relationship between the differences in the temperature of different surfaces. The largest temperature variations that occur on the respective surfaces are also taken into consideration.

In this expression, while the Rayleigh number \( Ra \), is the ratio of the buoyancy and the viscous forces, that is

\[
Ra = \frac{\alpha \beta \Delta T L^3}{\nu a}
\]

Further interest is to determine the stability limit of the Rayleigh-Bénard convection, and the effect of the disturbance, or perturbation on the fluid state. In the linear analysis, the disturbance is represented as a function in the form

II. MATERIALS AND METHODS

The main objective of the research in this paper is to determine the real flow parameters in the real tanks exposed to external influences. As the temperature gradient is the main cause of a given flow, temperature measurements were obtained in a real temperature range occurring at the location where the experiment was be performed, i.e. in the laboratory of the Faculty of Mechanical Engineering, Niš. The temperature gradient source is insolation; since it is clear that the convection intensity, or the occurring velocities, are in direct proportion to the given temperature difference, what is to be taken into account are the greatest temperature differences occurring at respective surfaces.
Since it is known that the intensities of the velocities that occur at such convection are quite low, the study is based on the numerical experiment. For the purpose of validation of the numerical experiment, an experimental installation is formed with respective dimensions H×W×L of 1×2×4 (500×250×125mm, in x, y and z directions, respectively) [19]. The experiment comprised the measurement of the temperature profiles in several sections, both vertical and horizontal.

As there are many types of hydraulic fluids we can find in real tanks, the real as well as the experiments were carried out with five different working fluids - water, diesel fuel, motor oil, alcohol and air (the case of an "empty" tank). One can, with sufficient accuracy, assume that the chosen fluids faithfully represent the majority of fluids that can be found in the real tanks.

Since the impacts of the Rayleigh-Bénard convection on real tanks are not extensively explored in the available literature, the aim of this study is to show the real thermal processes in the case of the aforementioned parallelepiped tank. Better knowledge of these processes can increase the safety and reliability of the whole systems of which they are component parts, which is of exceptional importance, especially for tanks in various hydraulic systems of an aircraft.

![Fig. 1. Scheme of experimental installation](image)

In order to confirm the results of the experiment, in the premises of the Laboratory for Thermal Engineering, the experimental installation was formed in which the temperature was measured at 16 points in the chamber, in several sections, both vertical and horizontal, using a special construction of PT100 temperature sensors that enabled chamber sealing in respective positions. The chamber is insulated on the sides by sponge and Styrofoam. Additional check-up of the results is done by thermal imaging camera.

As can be seen in the diagram of Fig. 1., above the chamber there is alcohol area, 50mm high, in which there is a heater, which is through the variable resistor (Variac) can accurately heat the water. In this chamber there is a mixer, for equalization of the temperature of the water, and thus the hot plate, which is located on the opposite side of the heater. The chamber is equipped with the trestles which enable its turning so that the hot plate can be either at the top or the bottom of the chamber. External influences are simulated by heating the upper plate (insolation). The following Fig. shows the temperature field at the appropriate layers of insulation, obtained by thermal imaging camera Flir E30.
The measurement system was developed in cooperation with firm Nigos, Nis. It consists of two eight-channel data loggers for collecting data on temperatures in respective chamber locations (Fig. 1.). This approach gives temperature profiles in three vertical sections, on either side of the chamber, in order to determine the temperature deviation from...
the "front" (sunny) and "rear" side of the chamber. In order to determine the uniformity of temperature distribution of hot plate, close to it a set of 5 temperature sensors was located at one lateral side and two on the other.

A.1. Temperature measuring device

Fig. 3. VT-08 is microprocessor device that measures and displays the current temperature values from 8 measuring points

The temperature measurement and acquisition were done by 2 eight-channel loggers VT08 (Fig. 3) and 16 PT100 probes type TS05, 0.1°C accuracy, enabling the necessary chamber sealing (Fig. 4). Calibration of PT100 probes using a reference thermocouple (TP) is shown in the following Fig.

Fig. 4. Structure and parameters of temperature probes TS-05 with PT100 temperature sensor

Fig. 5. Calibration of PT100 probes

Microprocessor logger VT08, in addition to temperature measurement is comparing the measured values with the set limit values. If some measured value of the measuring point exceeds the permitted limit, one of the relay outputs, serving as alarms, is activated. The limit values are widely adjustable. There is a possibility of adjusting the temperature offset for each input. The upper display shows the measured current value of the temperature measuring points, and the bottom shows the number of the measuring point.

Changing the display can be automatic or manual. In automatic change, the display for a limited time alternates measured points for which the measured temperature values are displayed. In the case of manual changes, permanent display of the desired measuring point can be set.

<table>
<thead>
<tr>
<th>General data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Tube length L1</td>
</tr>
<tr>
<td>Tube diameter</td>
</tr>
<tr>
<td>Cable Length L2</td>
</tr>
<tr>
<td>Probe connectors</td>
</tr>
<tr>
<td>Sensor type</td>
</tr>
<tr>
<td>Material</td>
</tr>
</tbody>
</table>

Table 1. LOGGERA VT08 Data
### General data

- **Power supply**: 90 – 250 Vac; 40 – 400 Hz; 4VA max
- **No. of inputs**: 8
- **No. of outputs**: 3
- **Display**: Double, 4-cipher × 7 segments LED, 13mm, red
- **Signalization of output**: 3 × LED diode, 3mm, red (OUT1, OUT2, OUT3)
- **Working conditions**: T: 0 – 50 ºC; RH: 5 – 90%
- **Storage**: T: -40 – 85 ºC; RH: 5 – 90%
- **Dimensions / fitting opening (W×H×L) / (W×H)**: DIN 1/4: 96 × 96 × 145 / 91 × 91 (mm)
- **Mass**: 550g

### Input

- **Thermocouple**
  - **Type**: J, K, L, R, S, B
  - **Thermocouples must be galvanically isolated**
- **Resistant sensor**
  - **Type**: Pt100, 2-wire; KTY10, 2-wire
- **Linear input**
  - **Current signal**: 0 – 20mA
  - **Voltage signal**: 0 – 1V
- **Measurement**
  - **Total error**: < 0.5% ± 1 digit
  - **Input filter**: 1 – 128
  - **Sampling rate**: 8 samples / sec

### Input

- **Relay**
  - **Data**: 2-pin (SPST); 8A / 250Vac, permanent 3A for resistive loads
  - **Application**: Alarm

### Communication

- **Digital Communication standard**: EIA 485
- **Protocol**: EI - BISYNC

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### B. System for data acquisition – NIGOS Manager Acquisition Software

NIGOS Manager is a PC application that enables monitoring and management of all the measuring and control devices that have embedded communication interface [65]. The application allows communication with devices over a serial or USB port and the appropriate adapter. It is possible to work and in a LAN network using a communication server to remote computers.
The user with administrator access rights defines the network of devices the application communicates with. He has the ability to choose the parameters of the device monitored (diagram with current values is generated) and archive them in a database. Based on the data collected, reports can be generated afterwards in a graphical or table form (Fig. 10), or the data can be exported to a file for processing in other applications for table calculations such as Excel, Calc, etc.

![Diagram with current values](image)

**Fig. 8.** Reports that can be obtained in the software NIGOS Manager
(a) Table, (b) Colour diagram and (c) Black-and-white diagram

The report is generated as a diagram on one sheet of A4 paper.

There is also the possibility of entry of data from the report to a file. Data is written to the .csv (comma-separated values) format. This file can be opened in any text editor, as in Microsoft Office Excel.

Report generation can be a time-consuming operation, depending on the number of data to be displayed (depending on the time period for the report and the period of entry in the database). For faster generation a shorter period should be chosen or lower frequency of entries in the database.

NIGOS Manager can be used to adjust the device, because through communication interface can access their parameters. Current setting can be saved to a file (setting all parameters). It is possible to enter previously recorded settings to other devices of the same type.

C. **Thermal imaging camera Flir E30**

For comparison of data measured on the PT100 temperature probes, parallel periodical measuring of the temperature field is executed with thermal camera Flir E30 [66]. Cameras specifications are given in Table 4.1. The camera data shows that the reading accuracy of temperature field is ±2°C or ±2% of reading, however, since the temperature was up to a level of 50°C, it follows that the accuracy level is ±1°C, which is an order of magnitude smaller than the accuracy of the used probe PT100. The use of thermal camera was limited to a comparison with the measured temperature fields and visualization, but not really measuring. However, the obtained results are consistent with the measured, and as comparative values they can be taken into account within the specified accuracy.

![Thermal imaging camera Flir E30](image)

**Fig. 9.** Thermal imaging camera Flir E30

III. **RESULTS AND DISCUSSION**

Figure 10 shows the temperature profile in the left, middle and right vertical cross-section of the chamber with alcohol in case of RBC for temperatures TS01=40°C and TS16=20°C. In the ordinary case, the temperature reduces with height, which represents the Rayleigh-Bernard convection. But As Figure 11 reveals the temperature profile in the left, middle and right
vertical cross-section of the chamber with alcohol in case of RRBC for temperatures TS01=41, 8°C and TS16=28°C. The heating source in this case was in the upper place, which made the temperatures of the lower plates less than the upper ones. The revised Rayleigh-Bernard convection exists with very slow moving rate compared to natural convection heat transfer. The Alcohol particles in the ordinary natural convection are moved upward faster than the case of heating the upper plate. In which the revised Rayleigh-Bernard convection, the alcohol particles motion become slower.

TABLE 4 THERMAL IMAGING CAMERA FLIR E30 TECHNICAL DATA

<table>
<thead>
<tr>
<th>Model</th>
<th>FLIR E30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical performance</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>160 × 120 pixels</td>
</tr>
<tr>
<td>Global resolution</td>
<td>19,200 pixels</td>
</tr>
<tr>
<td>Temperature sensitivity</td>
<td>&lt; 0.10°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±2°C or ±2% reading</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-4°F to 662°F (-20°C to 350°C)</td>
</tr>
<tr>
<td>Video camera w/lamp</td>
<td>2.0 MP</td>
</tr>
<tr>
<td>Video output</td>
<td>Composite</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>60 Hz</td>
</tr>
</tbody>
</table>

Fig.10. The temperature profile in the left, middle and right vertical cross-section of the chamber with alcohol in case of RBC for temperatures TS01=40°C and TS16=20°C

Fig.11. The temperature profile in the left, middle and right vertical cross-section of the chamber with alcohol in case of RRBC for temperatures TS01=41, 8°C and TS16=28°C
All the research results can be summarized in the form of several characteristic findings:

- The experimental results have indicated that the relative stability of the surrounding air allows the cooler plate to be directly exposed to external conditions.
- The chamber used in the experiment has shown great flexibility. The probes are placed at appropriate locations so that there are 3 or 4 probes that measure the temperatures in 3 different vertical cross sections. This arrangement allows measurement with various alcohols with different temperature regimes and warm and cool plate positions.
- Measuring system showed an appropriate response to external conditions, enabling a variety of experiments. Probes carriers have somewhat increased measurement inertia, but allowed the control measuring with the thermal camera. Thermal camera measurements showed no significant loss of heat on the insulated part of the chamber.

This chamber construction, through transparent openings, enables the use of non-contact methods for temperature and velocity field measurement, such as laser-Doppler anemometry, various optical methods.

IV. REFERENCES


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