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# ON THE INFLUENCE OF ASYMMETRIC CONFIGURATIONS OF A MAGNETIC FIELD IN THE THERMO-MAGNETIC CONVECTION IN A FERROFLUID CAVITY: AN EXPERIMENTAL INVESTIGATION

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***Abstract.*** *This study quantifies the impact of varying vertical asymmetric configurations of a neodymium magnet's steady-state magnetic field relative to a rectangular ferrofluid cavity during its convective phases. Depending on orientation and temperature gradients, the combined magnetic and gravitational fields influence ferrofluid convection differently near the magnet, thereby affecting heat transfer rates in the system. Our closed rectangular cavity, oriented vertically and filled with ferrofluid, is bounded by two plates at different temperatures, creating a nonuniform temperature gradient. Magnetic influence is provided by a characterized neodymium magnet positioned at different points adjacent to the hotter plate's side. Processes are monitored at one-second intervals. We collect an extensive dataset processed using Python code for qualitative and quantitative analysis of heat transfer efficiency changes. Our findings reveal systematic effects based on magnet placement, resulting in either increased or decreased heat transfer rates, depending on whether the magnet is positioned above or below in the vertical asymmetric direction. This suggests that considering this magnetic influence is crucial for managing asymmetry effectively.*

***Keywords:*** *thermomagnetism, thermomagnetic convection, ferrofluid, asymmetric magnetic field*

## 1. INTRODUCTION

The definition of a ferrofluid can be synthesized in a group of monodomain ferromagnetic particles that stay inside a nonmagnetic fluid containing and transporting them. This kind of configuration permits the ferrofluid reacts to magnetic fields that are stronger than gravity, allowing to us control the mobility of the particles to determined applications. It can be detached the applications of ferrofluid in water treatment, energy harvesting, medicinal therapy, medical imaging and others (Oehlsen *et al.*, 2022), and that show us the importance of understand the comportment of this kind of fluid. Going in this direction, others studies have been developed to understand the ferrofluid behavior in different scenarios, searching to quantify and qualify the behavior. We can detach a study published in the IOP Science (Vegera, 2019) that conducted experiments to see the influence of magnetic and electrical fields in the heat transfer process and found the influence of this fields in a flat layer, what indicates to us a possibility to find the influence in closed cavity. An important study with a real application of magnetic fluid and a magnetic field interacting with each other (Nakatsuka *et al.*, 2002) showed better results in the heat transfer with the application of the field, indicating a significative effectivity of this kind of configuration when we use a magnetic fluid, but it is important to evaluate if this improvement suits in every kind of configuration or if asymmetric positioning of the magnetic field could get worse the heat transfer. Furthermore, the study of the natural convection in a closed cavity is in the radar of several studies because it is a very complex and embracing field, that could open a horizon of possibilities and applications. It's no new this kind of study have been developed, but in the recent decades it is standing out due his possibility of applications, including cooling in nuclear power plants (Zheng *et al.*, 2021).With this type of studies and questions, this article is developed, to try to evaluate heat transfer process in a closed cavity, using a ferrofluid as working fluid and using a neodymium magnet to generate a magnetic field around the cavity, to subsequently adapt it for use in a thermoacoustic refrigerator similar to the one proposed by (Bannwart and Arruda, 2009). To achieve this, it is important to try to evaluate the quantitative effects on the process and explore the different types of configurations.

## 2. EXPERIMENTAL PROTOCOL

To study all these phenomena, an experimental workplace has been utilized. It is a test stand located in the Laboratory of Thermoacoustic and Thermomagnetic of the School of Mechanical Engineering/UNICAMP, from previously works (Alegretti, 2023), originally conceived with the objective of studying the influence of the magnetic field in the process of heat transfer along the axial line at the central position of the cavity. Now, it has been adapted to study the same influence of the magnetic field, but in positions out of center, dislocated up and down, to verify that will have some improvement in the process of heat transfer due to asymmetry.

### 2.1 Description and configuration of the test stand

The configuration of the test stand can be observed in Figure 1. It is a cavity composed by two copper plates each side with ferrofluid between them. Each plate is bathed by water in two different temperatures to keep them with a temperature gradient and enable the heat transfer. What guarantee these temperatures are two devices called Warm Bath and Cold Bath, they are water reservoirs that keep water in a specified temperature using an electric resistance to heat and a heat changer to cool. To compare the schematical image, we had the real photo of the test stand in Figure 2.
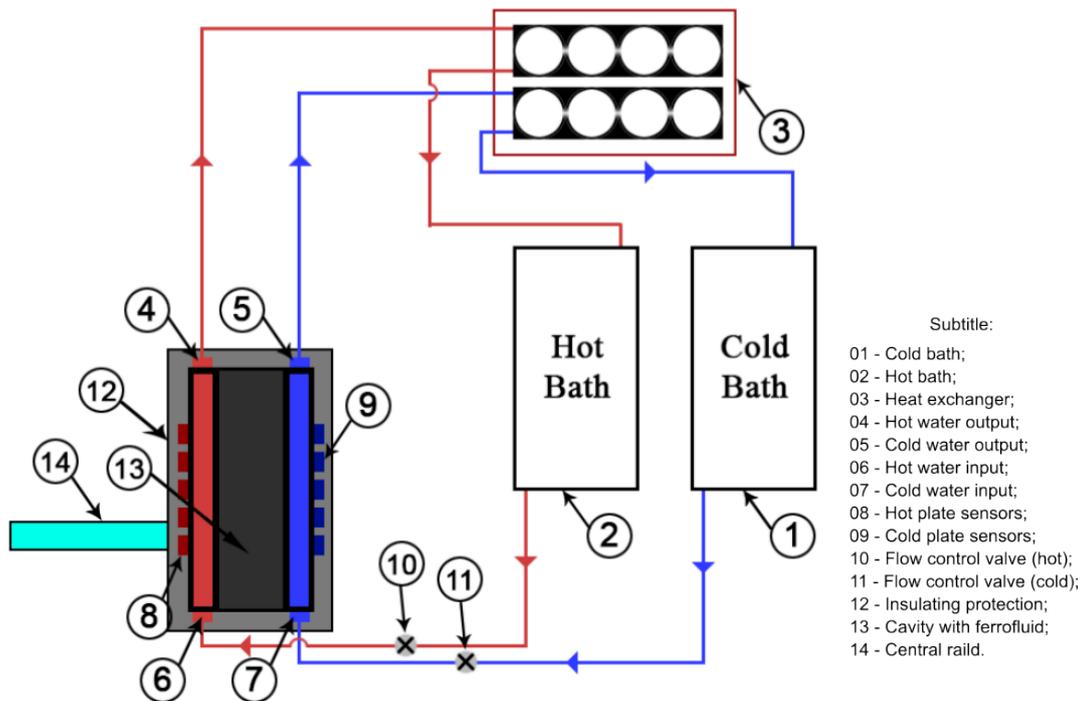


Subtitle:
01 - Cold bath;
02 - Hot bath;
03 - Heat exchanger;
04 - Hot water output;
05 - Cold water output;
06 - Hot water input;
07 - Cold water input;
08 - Hot plate sensors;
09 - Cold plate sensors;
10 - Flow control valve (hot);
11 - Flow control valve (cold);
12 - Insulating protection;
13 - Cavity with ferrofluid;
14 - Central raild.

Figure 1. Schematic diagram of the laboratory test stand.



Subtitle:
01 - Cold bath;
02 - Hot bath;
03 - Hot water output;
04 - Cold water output;
05 - Entry of hot plate sensors;
06 - Entry of cold plate sensors;
07 - Cavity with insulating protection;
08 - Central rail;
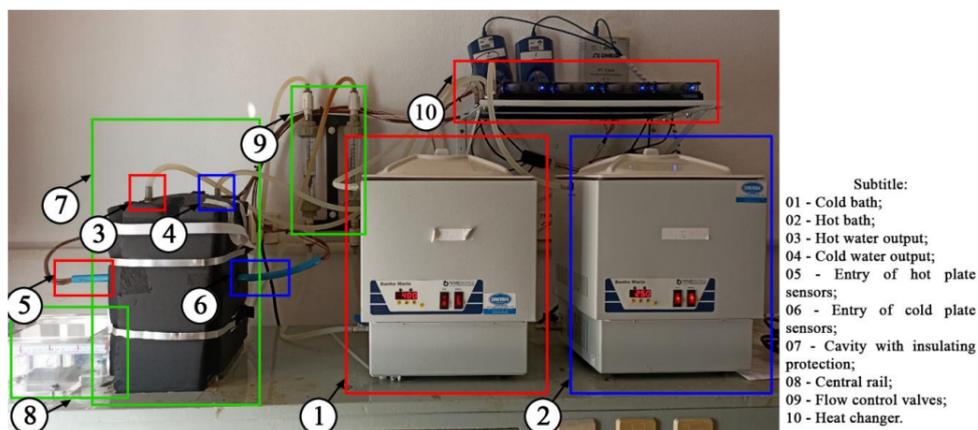09 - Flow control valves;
10 - Heat changer.

Figure 2. Real picture of the laboratory test stand.

It is important to detach the control method used in this test stand. We had a group of five thermocouples T type in each plate, symmetric separated to monitor the temperature of them. Furthermore, we had a PT100 probe in hot and cold water input and output to monitor these temperatures and estimate the heat exchange between plate and water. In the calculations, it is necessary the flow of water entering the region of contact with the plates and for it, it is utilized two volumetric flow valves to control these inputs. And to finish all the controls that we had in the test stand, there is a sensor to monitor the room temperature.

## 2.2 Data gathering method

With all these sensors, it is possible to create a big database using a computer do control and register this data. It is utilized a software PicoLog, offered by Pico Technology company for free in its site. This software enables us to control the monitoring and register of the temperatures in each second with a previous programing, including a preset timer to register these temperatures in a predetermined window of time.

This register is exported in a CSV file, where we had 16 columns of data with the preset number of lines that corresponds the seconds of measuring choose. These columns include the second measured, temperature of hot water input and output, temperature of cold-water input and output, temperature of five sensors in hot plate, temperature of five sensors in cold plate and the room temperature, respectively.

## 2.3 Data processing method

The code and processing method of analysis of this data was developed in Python in a Doctoral Thesis for Alegretti (2023) using this test stand. The method of processing consists in the measurement of two variable of the flow, the Temperature and the Volumetric Flow. The simpler one is the volumetric flow that is measured utilizing a rotameter coupled in each line of water, hot and cold, that enables the control of the flow, defined for all measurements in 0.000017 m³/s. The second variable of control that is the temperature, has a more complicated way of analysis. It is collected the temperature in 5 points of the plate, separated by 5 centimeters each, aiming to monitor the temperature of each copper plate. With these measures, the code process them to define a spatial average that is used in the posterior calculations. Another important temperature is the temperature of water in the input and output enters of the cavity, that can be observed in the Figure 1 in the 4 to 7 items. With them, it is possible to find the thermal flow, showed in the Equation 1,

$$q'' = \frac{\dot{m}_i c_{pi}(T_{in} - T_{out})}{A_i},$$ (1)

where $\dot{m}_i$ is the mass flow of the fluid, $c_{pi}$ is the specific heat capacity of the fluid in the average temperature, $T_{in}$ is the input temperature of the fluid in the region in contact with plate, $T_{out}$ is the output temperature of the fluid and $A_i$ is the area of this plate. (Bergman, 2011) With this information, it is possible to evaluate the thermal flow in each side of cavity, Hot and Cold, and consequently find the thermal flow of the cavity, Equation (2),

$$q''_{cav} = \frac{q''_H - q''_C}{2},$$ (2)

where $q''_{cav}$ is the convective flux of cavity, $q''_H$ and $q''_C$ are the heat flux in hot plate and the cold plate, respectively. After this, it is necessary to evaluate the convection heat transfer coefficient utilizing the Newton's law of cooling that was adapted for our case. With it, we obtain the Equation (3),

$$h = \frac{q''_{cav}}{\overline{T}_H - \overline{T}_C},$$ (3)

where $h$ is the convection heat transfer coefficient of cavity, $\overline{T}_H$ is the spatial average of temperatures of hot plate and $\overline{T}_C$ is the spatial average of temperatures of cold plate. And to finish the first step of heat transfer analysis, it is necessary to use another empirical formula that relation the convection heat transfer coefficient with the Nusselt number, that will be used here to verify the heat transfer efficiency and compare the results in the different positions, and the gravitational Rayleigh, that will be used to verify the influences of the magnetic field. These relations are showed in Equation (4) and Equation (5),

$$Nu = \frac{h\delta}{k_w},$$ (4)

where $Nu$ is the number of Nusselt, $\delta$ is the spacing between the copper plates and $k_w$ is the thermal conductivity coefficient of the fluid,

$$Ra_H = \frac{g\beta H^3 (T_1 - T_2)}{\vartheta \alpha}, \tag{5}$$

where $Ra_H$ is the gravitational Rayleigh number, $g$ is the gravity, $\beta$ is the volumetric expansion coefficient, $H$ is the height of cavity, $T_1$ and $T_2$ are the temperatures of each side of flow, $\vartheta$ is kinematic viscosity of the fluid and $\alpha$ is the thermal diffusivity coefficient.

It is important to detach that the heating process of water is made by an electrical resistance, so we had a little range of temperature oscillations that this resistance surrounds. Here, we defined a minimal number of seconds to characterize a temperature window to bypass this instrumental issue and it was effectively observing the standard deviation of the results.

## 2.4 Configuration without magnet

The first configuration that was defined for the test stand was the one without the magnet, just the cavity and the heat changes in the copper plates was evaluated. Here, it was defined a series of temperatures differences between the plates to observe just the development of the flux and define a better range to operate the test stand. Besides, it was used this configuration to try to define the type of flux, laminar or turbulent, and see how the heat change in these configurations behaves. Another point observed in this part of study was the behavior of the sensors and the electrical resistance and if it was a scenario that we avoid the interference of these uncertainties or at least, minimize them. So, the battery of tests of this part was divided following the configuration of Table 1.

Table 1. Configuration of the test stand for measurements without the magnet.

| Number of of the set | Temperature of cold plate [°C] | Temperature of hot plate [°C] | Difference of temperatures [°C] | Measurement time [s] |
|---|---|---|---|---|
| 1 | 25.0 | 27.5 | 2.5 | 172800 |
| 2 | 25.0 | 30.0 | 5.0 | 172800 |
| 3 | 25.0 | 32.5 | 7.5 | 172800 |
| 4 | 25.0 | 35.0 | 10.0 | 172800 |
| 5 | 25.0 | 40.0 | 15.0 | 172800 |
| 6 | 25.0 | 55.0 | 20.0 | 172800 |
| 7 | 25.0 | 60.0 | 35.0 | 172800 |
| 8 | 25.0 | 65.0[1] | 40.0 | 172800 |

[1] Limits of the test stand with some irregularities to maintain the temperature.

## 2.5 Configuration in symmetric and asymmetric position of the magnet

The second configuration that was defined for the test stand was the positioning of the magnet in the lateral of the cavity in the side of the hot plate. The magnet was positioned with the center line of the cavity coinciding with the center line of the magnet utilizing the central rail, showed in Figure 2. From this central position, it was created other twos positions of measurements with asymmetric positioning regarding the central position, but symmetric between themselves. This configuration can be seen in Figure 3, where it is showed these three positions called: Central, Upper and Bottom Position.

The distances between them were defined as 8.5cm, first reason was the limitation of the Bottom Position, that is limited by the table, and the second reason was the need to the upper line of magnet stay inside the limitation of the upper line of cavity in the Upper Position, and the bottom line stay inside the limitation of the bottom line of cavity in the Bottom Position.

Table 2. Configuration of the test stand for measurements with the magnet.

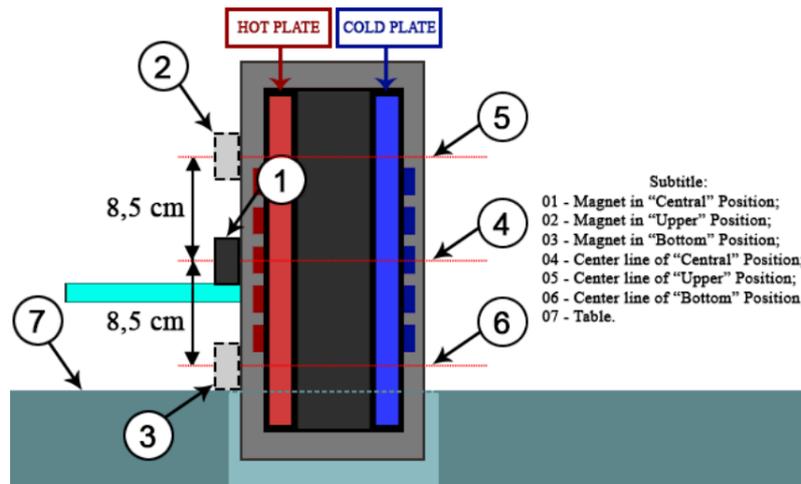| Number of of the set | Temperature of cold plate [°C] | Temperature of hot plate [°C] | Difference of temperatures [°C] | Measurement time [s] | Position | Vertical distance between center of magnet and cavity [cm] |
|---|---|---|---|---|---|---|
| 1 | 25.0 | 40.0 | 15.0 | 7.200 | Central | 0.0 |
| 2 | 25.0 | 40.0 | 15.0 | 7.200 | Upper | 8.5 |
| 3 | 25.0 | 40.0 | 15.0 | 7.200 | Bottom | -8.5 |

Figure 3. Schematic diagram of the position of the magnet.

## 3. RESULTS

The results of these series of measurements were consolidated in graphics relating the heat flux in cavity found and the time of development of the flux in the first part of experiments. In the second part was observed the Number of Nusselt and the Gravitational Rayleigh Number to see the influence of the magnet in the flux

### 3.1 Results of laminar and turbulent flux

The first part of experiments was dedicated to define the better range of temperatures to conduct the experiments and to try to define what kind of flux was occurring inside the cavity. So, it was initiated with the lowest difference of temperature, 2.5 °C until the maximum difference, 40 °C and the results can be observed in the Figures 4 and 4, where we had the numbers 1 to 8 related to the batteries previously presented. With this, it was possible to choose the better configuration of temperatures, that was selected in 40 °C and 25 °C because it is where the flux stays more constant in the measurements. The results are shown in Table 3.

Table 3. Validation of better flux range.

| Number of of the set | Difference of temperatures [°C] | Average flux rate [W/m$^2$] | Variation [%] |
|---|---|---|---|
| 1 | 2.5 | 435.14 ± 1.1 | 0.24 |
| 2 | 5.0 | 591.87 ± 0.9 | 0.15 |
| 3 | 7.5 | 701.38 ± 0.5 | 0.06 |
| 4 | 10.0 | 818.17 ± 0.7 | 0.09 |
| 5 | 15.0 | 1419.52 ± 1.0 | 0.07 |
| 6 | 20.0 | 1945.45 ± 10.0 | 0.51 |
| 7 | 35.0 | 2123.70 ± 13.5 | 0.64 |
| 8 | 40.0 | 2319.79 ± 9.6 | 0.41 |

### 3.2 Results of asymmetric magnet placement

So, the second part of the experiment wanted to show the influence of magnetic field in the heat change inside the cavity. An initial experiment of this effect was conducted in a Final Paper of a student of School of Mechanical Engineering that shows a very interest relation between the position of the magnet and the heat change inside the cavity, where it was conclude that it had a significant worsening of efficiency of the heat flux when the magnet is put upper the center line of cavity, reaching in 12% of worsening. The bottom position didn't present a very significant improvement of the heat change, reaching in 1.5% of improvement compared with the central position. This study was a preliminary investigation that occupied a little part of the paper because it wasn't the initial focus, but enabled a motivation to study this influence deeper. Here, the objective of the experiments was repeat these initial measurements and try to quantify it, with a larger sample space of collects and a symmetric configuration of the position between themselves. Here, it was defined a group of 20 measurements in the 3 positions showed previously to complete a round, totalizing 120 hours of measurements per
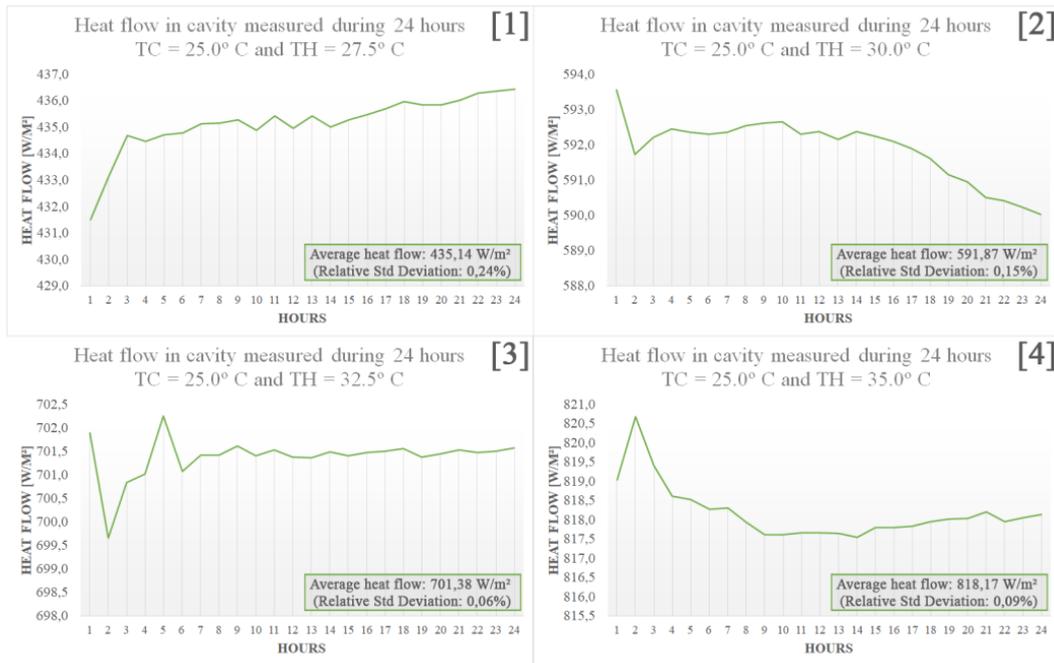
Figure 4. Results of first part of experiment - Graphics 1 to 4.
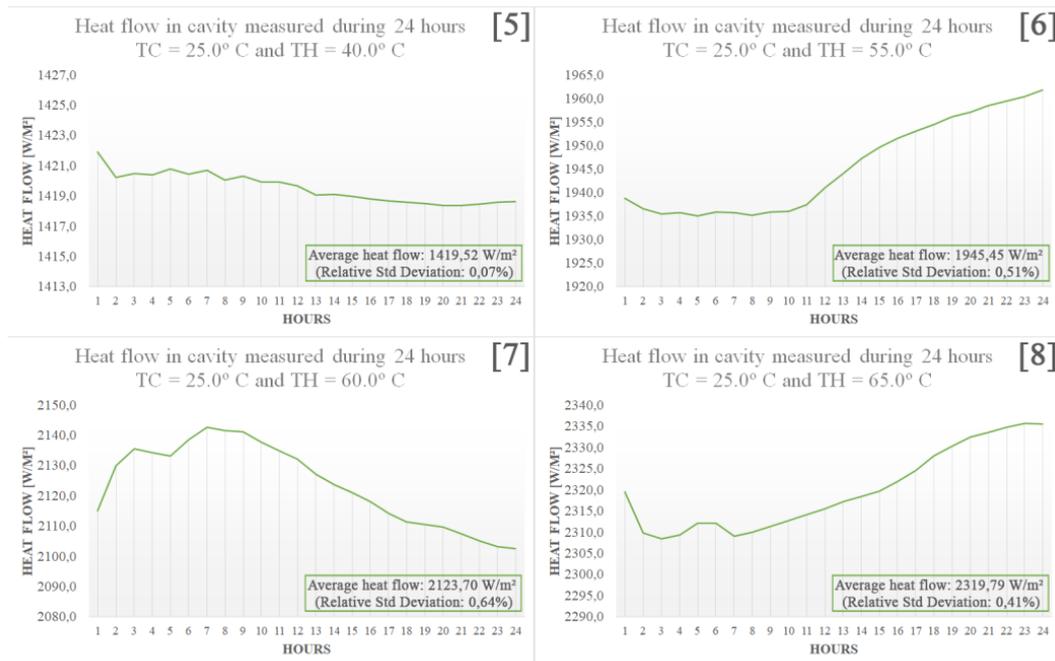


Figure 5. Results of first part of experiment - Graphics 5 to 8.

round. The results were showed in Table 4. About the Figures 4, 5 and 6 it was possible observe the influence of the magnetic field in the different positions and compare them, what show us an important constatation, the negative influence of a positioning of the magnet upper to the center line of cavity and the question that appears was the reason for this effect. When we think about the behavior of the ferrofluid inside the cavity, it is possible to assume that a vortex is formed inside, with the fluid moving up in direction of the hot plate and going down in direction of the cold plate. That way, when we put a magnetic field besides the cavity, an alteration in this vortex is expected and consequently a change in the process of heat transfer too. The significant modification occurred when the magnet was put in the Upper position, closer to the hot plate, region where the fluid was going to and it could be caused because this magnetic field, added to the movement of fluid due to the temperature gradient, could cause a turbulent flux inside the cavity, harming the heat change process.

Table 4. Results of the flux hate in cavity with magnet.

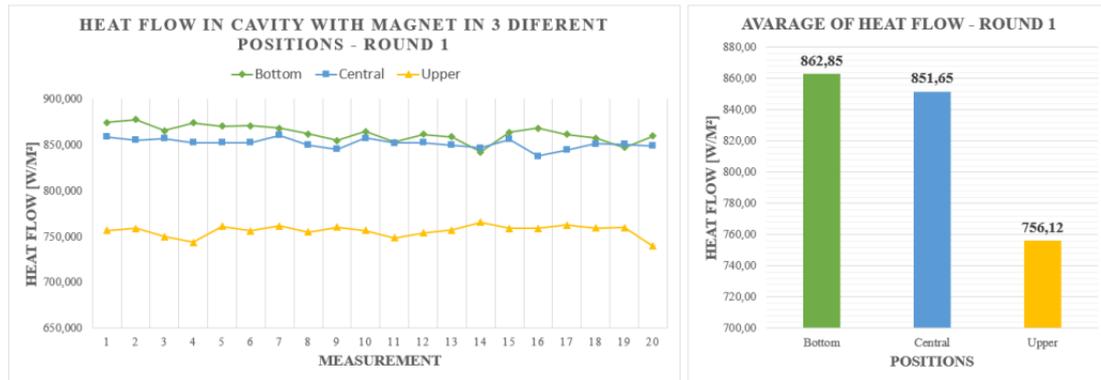| Number of of the set | Difference of temperatures [°C] | Average flux rate [W/m$^2$] | Variation [%] |
|---|---|---|---|
| 1 | Upper | 756.12 ± 6.4 | -11.22 |
| | Central | 851.65 ± 5.4 | Base |
| | Bottom | 862.85 ± 9.1 | +1.31 |



Figure 6. Results of heat flux in cavity with magnet – Round 1.

## 4. CONCLUSIONS

This study potentially enables us to find the best scenario of operation of our experimental investigation since we have obtained an significant amount of data focused in find this configuration and methodology, and consequently more stable and trustful data.

Relying on this methodology developed to operate the test stand, other asymmetric configurations can be envisaged in order to better investigate the magnetic field influence. The first one and more interesting we think of is the configuration with the magnets being placed next to the cold plate so that to compare its results with the ones of this article, and also to possibly reveal the effects of the magnetic field close to region where the fluid is going down in the convective vortex. Furthermore, an investigation with the cavity being positioned horizontal may lead to new findings.

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