REVISTA BRASILEIRA DE ENERGIAS RENOVÁVEIS

EXPERIMENTAL ANALYSIS OF A SINGLE-PHASE PASSIVE COOLING SYSTEM[1]

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Abstract: The Fukushima Daiichi Accident highlighted the need for new sustainable technologies with high reliability for removing thermal load, in the thermal power area, with focus on nuclear power plants. This technology is designed for heat transfer from a hot source to a cold source by natural convection, without the need of active components, such as pumps or ventilators, reducing costs and improving reliability. In order to analyze the system parameters of such passive systems, with focus on its thermo-hydraulic stability, an experimental campaign was performed using a reduced model built at State University of Rio de Janeiro – UERJ – with a Single-phase Passive Cooling System. Thus, the objective of this work is the experimental characterization of such systems for the analysis of the physical phenomena that drives the flow to unstable regimes and also to validate a 1D numerical model developed within this research project to simulate this kind of systems.

Keywords: Natural Convection, Thermal Energy, Nuclear systems.

ANÁLISE EXPERIMENTAL DE UM SISTEMA DE REFRIGERAÇÃO PASSIVO ÚNICO

Resumo: O Acidente Nuclear de Fukushima Daiichi trouxe à tona a necessidade de novas tecnologias sustentáveis com alta confiabilidade agregada na remoção de carga térmica em sistemas de potência térmica, principalmente em usinas nucleares. Essa tecnologia é uma solução da engenharia que tem como objetivo a transferência de calor de fontes quentes para fontes frias por meio do fenômeno de convecção natural, dispensando a necessidade de componentes ativos, tais como bombas ou ventiladores, reduzindo custos e agregando confiabilidade à usina.No intuito de analisar os parâmetros desse sistema, sobretudo no que se refere à estabilidade termo-hidráulica, uma capanha experimental foi realizada utilizando um modelo reduzido na Universidade do Estado do Rio de Janeiro – UERJ – com um Sistema Passivo de Resfriamento Monofásico. Nesse sentido, este trabalho tem como objetivo a caracterização experimental desses sistemas para análise dos fenômenos físicos que aportam instabilidades ao escoamento e para validação de um modelo numérico 1D para simulação desses sistemas, desenvolvida no âmbito deste projeto.

Palavras-chave: Convecção Natural, Energia térmica, Sistemas Nucleares.

Introduction

Passive Cooling Systems are engineering solutions designed to transfer heat from a hot source to a cold source by natural convection. These systems have been used as emergency cooling systems in nuclear power plants and other thermal power systems.

They incorporate high operational reliability to a process plant, avoiding pumps and other flow machines, reducing costs, thus becoming more sustainable. Although these systems have many advantages over active cooling devices, they are subject to thermo-hydraulic instabilities.

The Passive Cooling Systems which are composed by a natural convection loop can be classified into two main categories in terms of phase change: single-phase and two-phase systems. Two-phase systems are more effective in the task of heat removal, but are much more susceptible to instabilities than single-phase systems, which presents an inverse tradeoff between heat transfer and thermos-hydraulic stability.

The classical paper of Bouré et al. 1973, provided a pioneering classification of the types of instabilities encountered in two-phase natural convection loops. Two decades later, March-Leuba et al. 1993 published a new review on the instabilities associated to the coupling of thermo-hydraulics to neutronics in Boiling Water Reactors (BWRs), therefore compound instabilities. Authors were motivated by a series of instability events in operating BWRs, like the case in Caorso, Italy, 1984, and in LaSalle, US, 1988. The authors listed three main types instabilities viz. (i) control system instability, (ii) channel thermo-hydraulic instability and (iii) coupled neutronic-thermo-hydraulic instability, which is also called reactivity instability and is considered by the authors the most relevant type for BWR operation. More recently, Durga-Prasad et al. 2007 identified the types studied by Bouré et al. 1973 as thermo-hydraulic instabilities, and added two other groups aside this: the instabilities associated to control systems and the ones associated to neutron kinetics.

In single-phase systems, instabilities are related to density waves produced by a perturbation in a process parameter. In a work published on 1975, Creveling et al. 1975 state that, in previous works, instabilities in single-phase natural circulation loops were only reported for systems operating at conditions close to the pseudo-critical point. They mention, however, analytical results published between 1966 and 1967 which concluded that there are conditions under which subcritical single-phase systems present instabilities. Motivated by this evidence, Creveling et al. 1975 were the first work to show experimental results with unstable behavior in a conventional (subcritical) single-phase natural circulation loop. Today there is a wide knowledge about instabilities in single-phase systems. For example, Vijayan et al. 2005 state that stability in such systems depends on the

- Grashof and Stanton numbers;
- flow regime;
- heater and cooler orientation;
- length scales of the loop (height, total length, heater and cooler lengths etc.).

Active cooling devices are subject to failure in cases of lack of electricity supply, which can occur as a consequence of a natural disaster, such as tsunamis and earthquakes. That was precisely the cause of the nuclear event on March 2011 in Fukushima Daiichi, Japan: the loss of cooling capacity generated by the huge tsunami that hit the nuclear station drove the reactor vessel to a meltdown[1]. Motivated by this event, studies on Passive Cooling Systems, which were already being increasingly employed in new nuclear system designs, have gained major importance along the past five years. This can be seen in the project carried out by Eletrobras Eletronuclear for the Nuclear Power Station of Angra dos Reis, where a completely passive system to the Spent Fuel Pool was considered.

The objective of the present work is to study the main parameters associated to thermo-hydraulic instabilities in single-phase passive cooling systems, by means of an experimental model, evaluating the performance of the system against the thermal load and parameters of stability. Therefore, an experimental campaign was performed using a reduced model built at State University of Rio de Janeiro - UERJ. The model consisted of a rectangular loop with a heater and a cooler, both in horizontal positions, and an Arduino platform system that acquire data through four sensors located at the inlet and outlet of the heater and cooler. The Arduino platform also controls the system-operating envelope, limiting operating parameters in the range that results in safe and acceptable equipment performance. An overview of the experimental setup is presented in the figure 1.

Other research groups have also constructed experimental natural convection loops, such as Angelo et al. 2012, with vertical heater with power input inside the circuit and Vijayan 2002, employing different orientations of heater and cooler. Literature also has numerical works done on single-phase natural convection loops, among which the papers, Ambrosini et al. 2004; Ambrosini and Ferreri 2003; Basu et al. 2013, worth to be cited.

[1] It should be highlighted that the same earthquake and tsunami hit the nuclear station of Fukushima Daini, which is located 12 km to the south of Fukushima Daiichi. None of the four nuclear reactors in Fukushima Daini underwent any cooling limitation, because the backup diesel generators were installed at a higher elevation than those of Fukushima Daiichi and could withstand the tsunami.

Figure 1: Passive Cooling System built for the project.

Materials and methods

The passive cooling system built and commissioned for operation consisted of a rectangular PVC loop with an inner diameter of 22 mm, isolated by an elastomeric foam tube. The designed model follows the scale suggested by Vijayan and Austregesilo (1994).

At the bottom of the circuit, there was a heater with a length of 400 mm horizontally positioned, composed by copper tube enveloped by three resistors of 72.57 ohms each. These resistors were responsible for thermal load injection to the natural convection circuit, which it was driven by the AC voltage transformer (Variac). The Variac had a voltage regulator that delivers the voltage desired by the circuit operator to the system. The heater was insulated by glass wool.

The heat load injected in the system is removed by a 400 mm long shell and tube heat exchanger, located at the top of the circuit. The cooler, positioned horizontally, had its heat removed through an active secondary cooling system, composed by a pump and a fan-coil unit. In order to perform the acquisition of temperature data, four sensors of the model DS18B20 were arranged at the inlets and outlets of the cooler and the heater.

Steady State Experiments were conducted following the concept of Steady-State used by Nayak et al. (2009), according to which there were no qualitative variations of temperature over time. The experiments have pre-operation steps, such as: In order to eliminate dissolved gases in water, which releases bubbles in the operation, a preheating of 1,2 Liters of Milli-Q type water at a temperature of 80°C for 20 minutes was performed. After the heating, the water was added to the system and it was cooled to ambient temperature naturally. For operation of the circuit, the secondary cooling system pump, the data acquisition system and the Variac were activated. The experiments began with the activation of the desired voltage in the Variac that deliver thermal load to the circuit. All the experiments starts at constant temperature in the loop and end when the steady-state was reached. The Steady State was achieved when the following conditions are satisfied: Input power was constant; External temperature was constant; Mass flow rate was constant; Maximum temperature measured was below 75 °C. A temperature gauge measured the ambient temperature and the experimental data of temperature was saved for future numerical treatment.

The transient experiments had started from a low power at steady-state of operation in the Passive Cooling System. These experiments were performed by means of an almost instantaneous variation in the voltage delivered by the Variac, through a sudden change in the Variac selector, starting from the steady state voltage to the desired higher voltage. The operation was monitored until the new steady state at the higher voltage was reached, and the experiment finalizes with the shut off the system. As in the steady-state experiments, the temperature data obtained through the sensors was stored for future analysis and comparison with numerical simulations.

Results and discussion

Steady State Experiments were carried out at the powers of 44,08 W, 99,18 W, 176,31 W, 275,48 W. Typical experimental data of temperature as a function of time from these experiments were plotted in Fig. 1-4, for the different power levels. These figures show the time evolution of temperatures of cooler inlet and outlet (represented by Tleftc and Trightc), and the temperatures of heater inlet and outlet (represented by Tlefth and Trighth), from the beginning of the experiment until the steady state condition is reached.

The experiments also showed that for higher thermal loads the system may undergo instabilities due to localized vapor bubbles formation in the heater, which was defined by Nayak et al (2009).

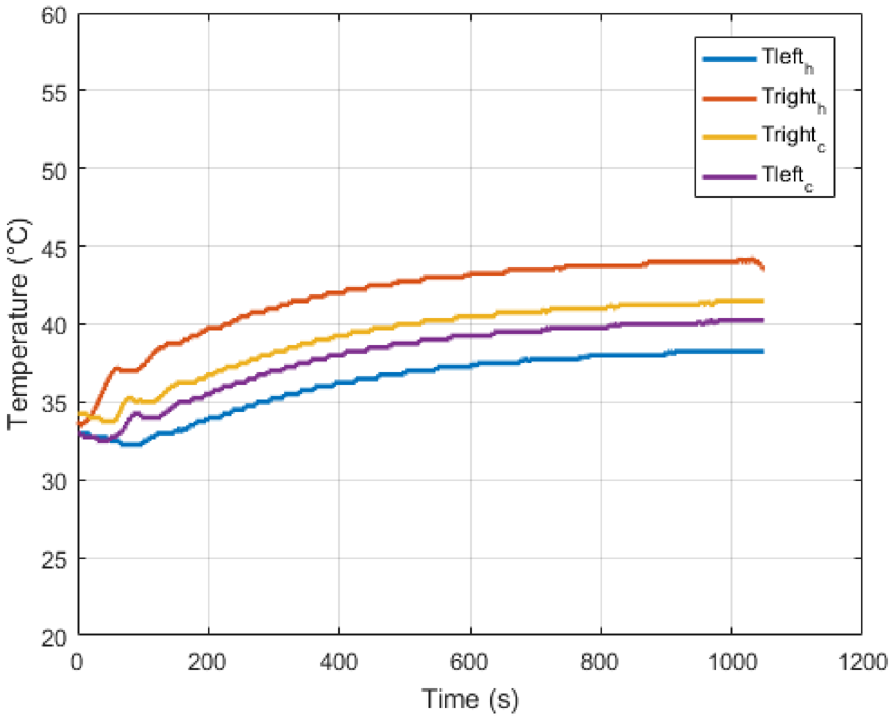

Figure 2: Temperature over time graphic for 44,08W experiment.

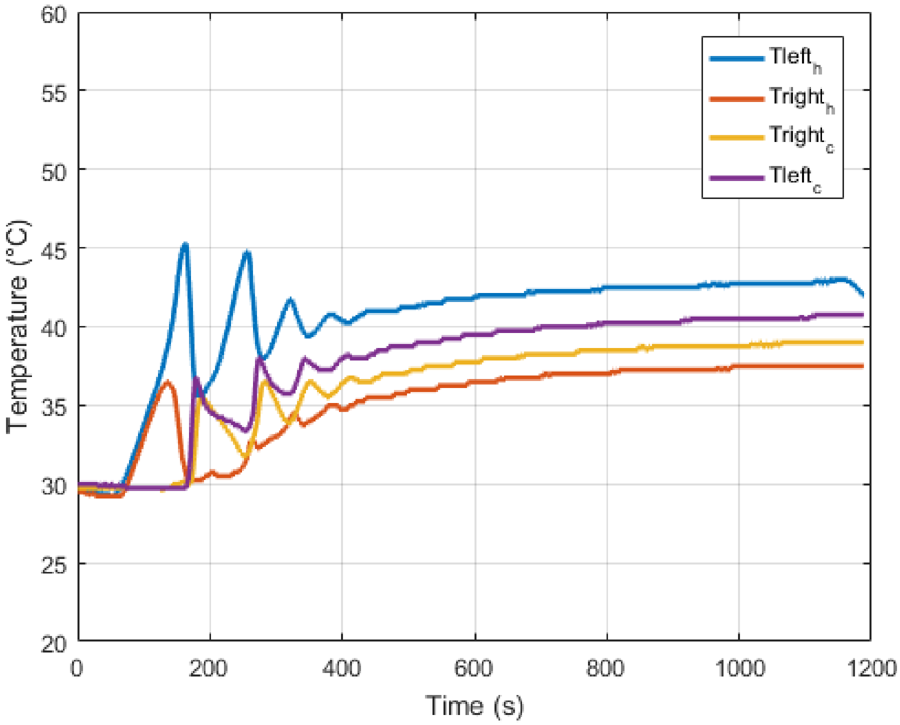

Figure 3: Temperature over time graphic for 99,18W experiment.

Figures 2, 4 and 5 show typical temperature differences due to a counterclockwise flow, while in Fig. 3 the temperature differences are reversed (left and right) as is typical in a clockwise flow.

The system is shown to be stable to perturbations such as the initial sudden change in power input, showing dumped oscillations in temperature with a period p ~ 70 s (see Fig. 3).

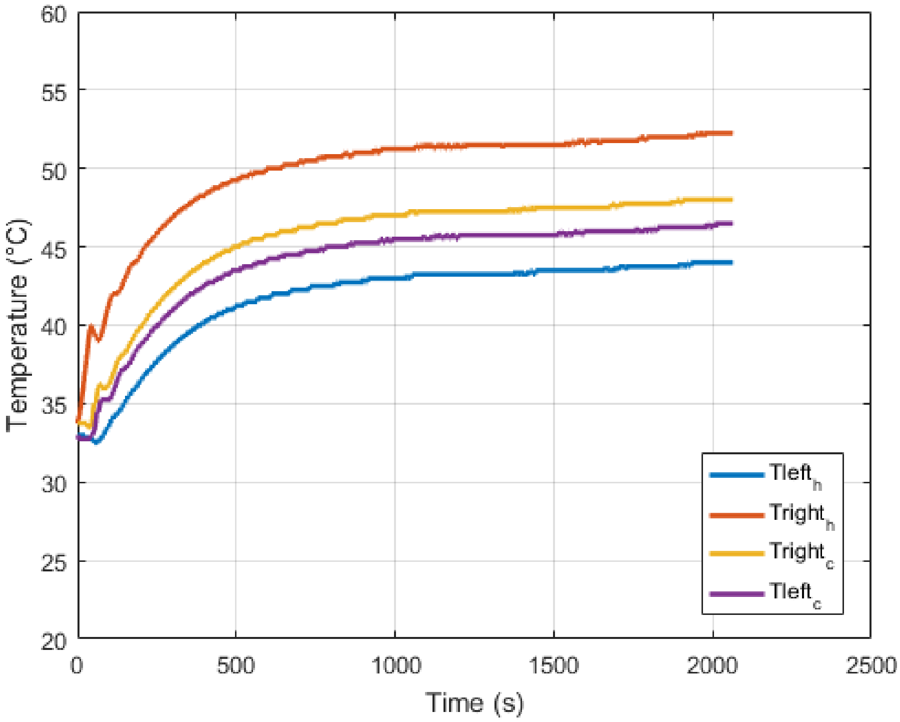

Figure 4: Temperature over time graphic for 176,31W experiment.

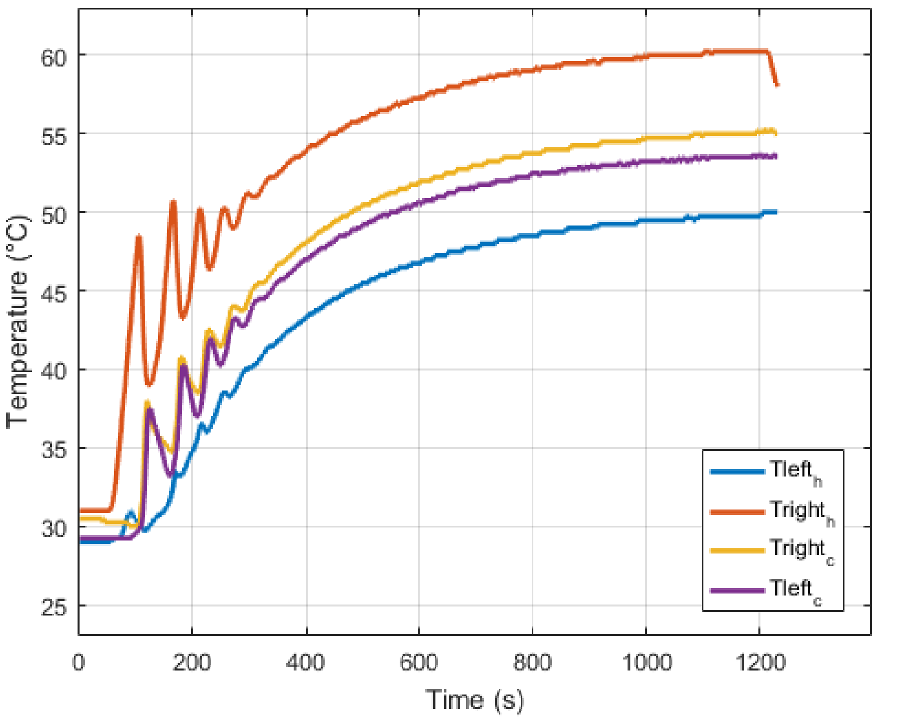

Figure 5: Temperature over time graphic for 275,48W experiment.

The experiments were performed up to the maximum power of 275,48W, due to the presence of bubbles in higher powers.

The table 1 presents the statistical data of experiments, such as average experimental powers (w), temperature variation in the cooler (DTcooler), standard deviation of temperature variation in the cooler (SdevC) and these coefficient of variation (cv).

Table 1: Statistical data of cooler temperature variation.

Power (w)	*DTcooler (°C)*	*SdevC*	*Cv (%)*
44,08	1,13	0,3953	35,14
99,17	1,30	0,1180	9,08
176,31	1,63	0,1738	10,88
275,48	1,75	0,3536	20,20

Through these results, the figure 6 demonstrates the power input in terms of the temperature variation in the cooler, the linear fitting line with the least square coefficient and its equation.

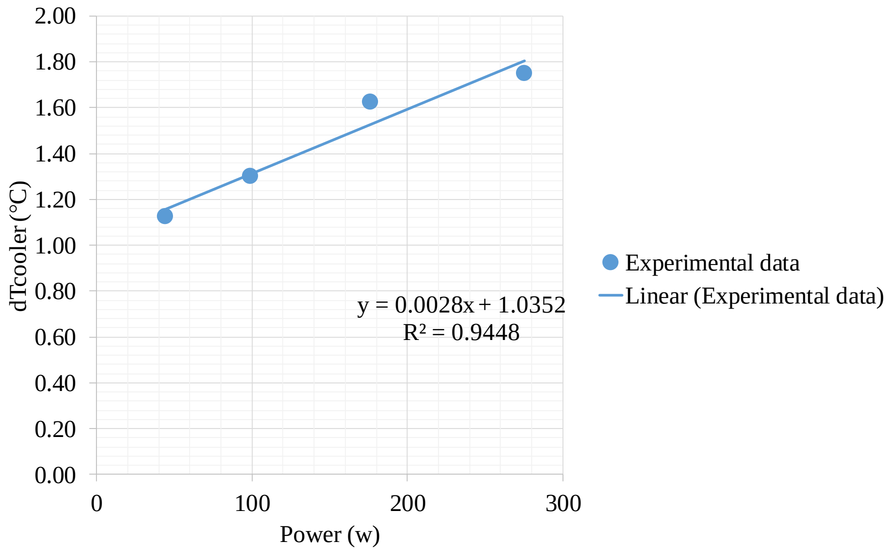

Figure 6: Temperature variation in the cooler by means of operation powers.

The Steady-State Experiments results allow to evaluate indirectly the flow mass rate through the system from power input and the measured temperature differences data, using the expression.

$$w = \frac{P}{C_p * \Delta T_h} \tag{1}$$

where C_p is the specific heat of water at constant pressure in kj/kg*°C, P is the power input in watts and ΔT_h is the heater temperature variation in °C. The table 2 presents the statistical data of experiments, such as average experimental powers (w), flow mass rate (fmr), standard deviation of flow mass rate (Sdevfmr) and coefficient of variation of flow mass rate (Cvfmr).

Table 2: Statistical data of flow mass rate.

Power (w)	*Flow mass rate (g/s)*	*Sdevfmr*	*Cvfmr (%)*
44,08	35,59	1,86	5,24
99,17	130,49	4,19	3,21
176,31	353,25	7,46	2,11
275,48	700,23	11,65	1,66

The figure 7 shows the increase of the flow mass rate as the thermal power injected into the system is increased. In addition, the figure 7 shows the linear fitting of experimental results, least squares coefficient and the linear fitting equation.

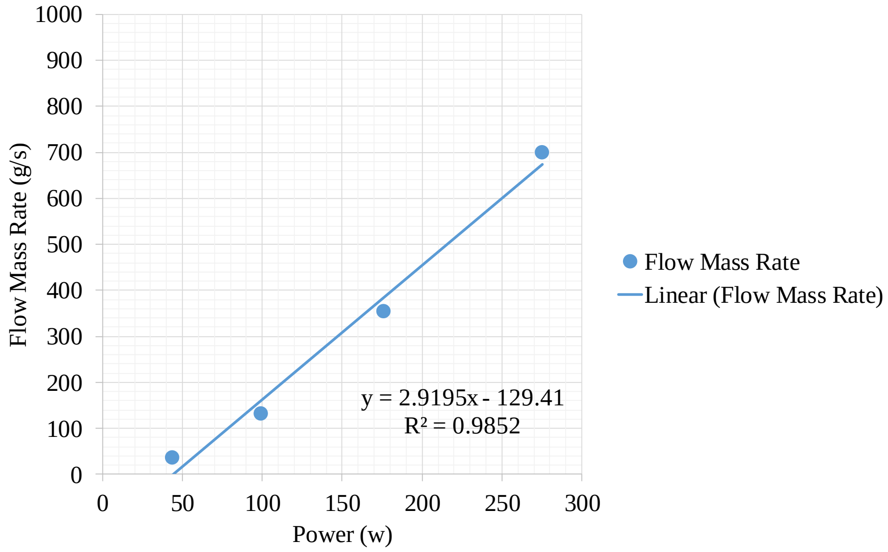

Figure 7: Variation of the flow mass rate in terms of thermal power injected.

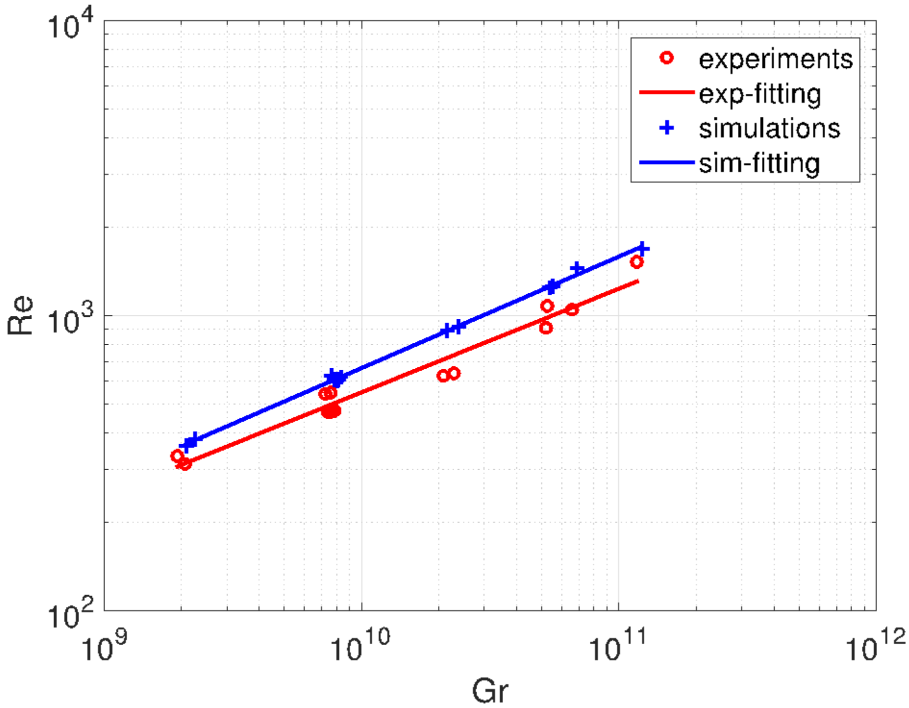

Figure 8: Variation of Grashof number in terms of Reynolds number for numerical and experimental results (in a log-log scale).

Figure 8 shows a linear relation (in a log-log scale) between Reynolds number and Grashof number (in a log-log scale) of numerical simulations and the experimental data results. The relation presented has least square coefficients 0,9599 for experimental line(red line) and 0,9982 for simulation line (blue line). The numerical simulations employed the model described in Lima et al (2016). The numerical relation between Reynolds number and Grashof number follows the scaling laws defined by Vijayan and Austregesilo (1994). The Grashof and Reynolds numbers (actually a modified version of them) were defined by Vijayan and Austregesilo (1994), and are given by

$$Gr = \frac{D^3 * \rho^2 * \beta * g * Q * H}{C_p * \mu^3 * A} \tag{2}$$

$$Re = \frac{D * Q}{A * \mu} \tag{3}$$

where D is the inner pipe diameter in meters, ρ is the water density in kg/m³, β is the coefficient of thermal expansion in 1/°C, g is the gravity in m/s², Q is the power in Watts, H is the loop height in meters, μ is the dynamic viscosity in N*s/m² and A the inner tube area in m².

Conclusions

A scale model of Passive Cooling System was constructed to study the performance of single-phase natural convection systems in thermal power applications. The experimental setup met the operational expectations, showing to be an efficient system in the removal of thermal loads.

In the steady state, the system showed a linear relation (in a log-log scale) between Reynolds and Grashof numbers, as observed by Vijayan and Austregesilo (1994). Figure 8 illustrates this conclusion. It also shows a comparison between numerical simulations using the model described in Lima et al (2016) and the experimental results. It can be seen that the straight line constructed from the numerical simulations are approximately parallel to the one of the experiments, but shifted by a value, which is an effect of the friction model used in the numerical code.

From the point of view of stability, the time series shown in figs. 2 to 5 present an oscillating regime in the phase of temperature rise, which are damped as the system evolves to the steady state. This observation brings the conclusion that, although the system is stable for the designed operation point, startup operations may undergo oscillating regimes which have to be taken into account in the design of a passive cooling system. It also highlights the importance of a mathematical model capable of simulating the startup of a Natural Convection Loop.

Next steps in the project are (i) the construction of a pool to be attached to the circuit, where heat will be transferred to the water in the pool and then to the loop through the heater, and (ii) the improvement of the mathematical model, incorporating thermal inertia in the circuit walls and temperature diffusion, which enables the code to simulate startup from rest.

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