SIMULATION OF A HYDRAULIC CIRCUIT FOR A MAGNETIC REFRIGERATOR

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ABSTRACT

The flow distribution system plays a key role in the operation and the overall performance of a magnetic refrigerator, but only a few works in the literature are dedicated to the design and evaluation of it. Therefore, the focus of this work was to evaluate the transient behavior of a flow management system by means of numerical simulations of a simplified hydraulic circuit of the magnetic refrigerator developed at POLO/UFSC using a commercial software package. Water hammers were predicted to occur after switching the fluid flow direction, and their magnitude was proportional to the volumetric flow rate. The performance of the hydraulic system showed a dependence on the valve opening ramp; while fast ramps increased the magnitude of the water hammer, slow ramps led to fluid flow bypassing the AMR. The use of a proportional returning valve upstream of the high-pressure valves is recommended to absorb the impact of the water hammers and make the flow through the regenerator beds smoother.

1. INTRODUCTION

Engineering design can be a valuable tool in the development of more efficient magnetic refrigeration systems. From an engineering system perspective, a magnetic refrigerator can be divided into three main sub-systems, namely the fluid flow management system, the magnetic field generation system and the active magnetic regenerator (AMR). In the open literature, the flow management (or hydraulic) sub-system has been the least investigated of the three. Nevertheless, it can be responsible for a significant fraction of the total losses in magnetic cooling devices [1,2,3]. The present study advances a computational simulation in a commercial software package of the time-dependent behavior of the hydraulic sub-system of the prototype developed by Lozano *et al.* [4]. The focus is to understand the most important characteristics of the hydraulic sub-system that should be considered in the design of new prototypes.

2. COMPUTATIONAL SIMULATION

A simplified hydraulic circuit model of the magnetic refrigerator prototype developed by Lozano *et al.* [4] was carried out in this work. The model was implemented using the Computer-Aided-Engineering (CAE) software package Flowmaster [5].

The prototype developed by Lozano [6] has 16 regenerator beds; however, only 2 regenerator beds are sufficient to describe the basic system dynamics. A schematic diagram of the simplified flow management system with 2 regenerators is shown in Fig. 1. The system layout implemented in Flowmaster is shown in Fig. 2, with the appropriate measurement (reference) points. The most important discussions on the flow behavior are related to Node 1 (upstream the high pressure rotary valve) and Node 5 (downstream the low pressure rotary valve). The numbers makers in Figs. 1 and 2 regard to the same hydraulic nodes.

The purpose of the rotary valves is to control the direction of the fluid flow. While one side (coming from the pump) has a rotating oblong, the other (going to the AMR) has orifices. The rotary valve and the magnet are connected to the same shaft and have the same operating frequency. The opening (or closing) ramp is related to the duration of the opening (or closing) of the rotary valve orifices, and it is expressed as degrees out of one revolution (360º) to describe it independently of the operating frequency. The fluid switching time used

in [6] corresponded to 8º out of 180º. In this time interval, one of the orifices is closing while the other is opening, thus giving the system its opening ramp characteristic. In the computational simulation, the valves were modeled as gate valves in each orifice. In order to model the rotary valves in the software, each one is modeled as a two gate valves with the opening times synchronized.
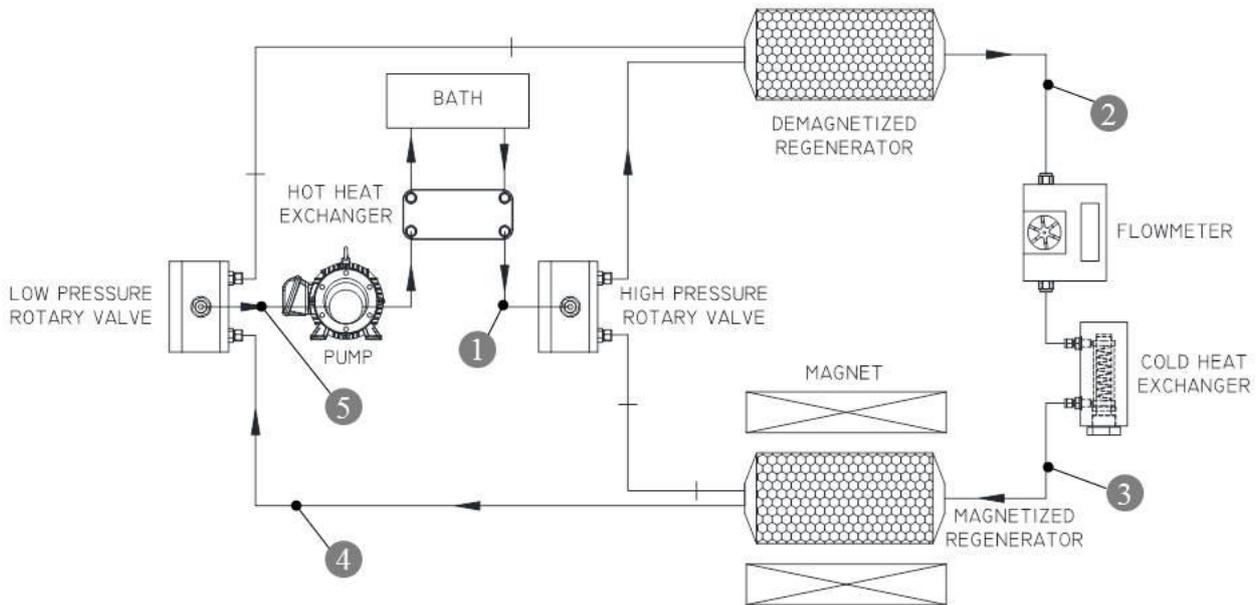

Figure 1. Schematic diagram of the simplified flow management system of a magnetic refrigerator [6].
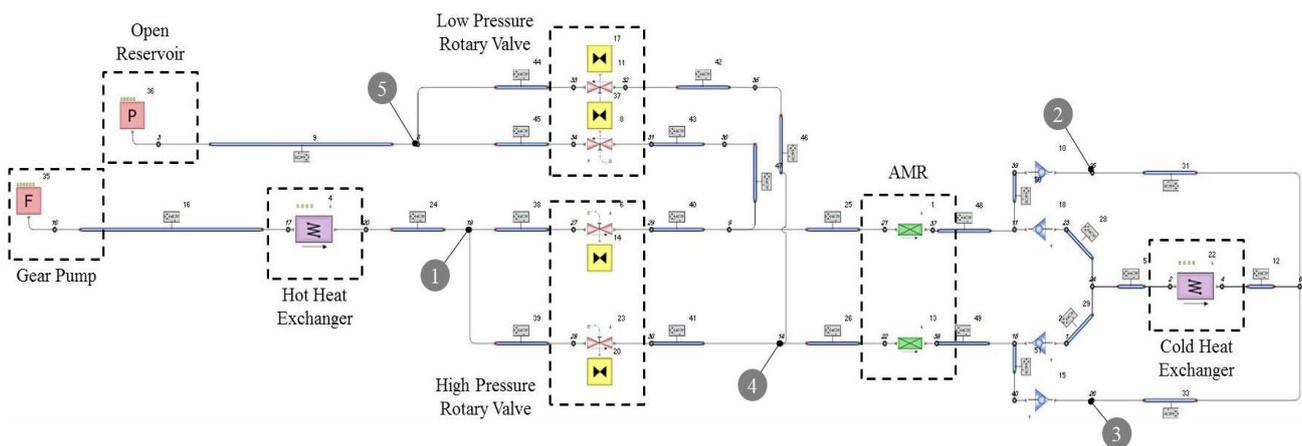

Figure 2. System layout implemented in the software Flowmaster [5].

Assuming water as the working fluid, the connecting hoses have been modeled as flexible, with an internal diameter of 6 mm and a wall thickness of 2.4 mm. The regenerators were modeled as packed-sphere beds, for which the pressure drop can be determined by the Ergun correlation [7]. For practical reasons, the system has not been considered a closed circuit. Rather, a fixed inlet mass flow rate was assumed. This approach facilitates focusing on the dynamic response of the fluid switching device. On the other hand, a fixed pressure boundary condition was used as the exit, which resembles the use of a reservoir open to atmospheric pressure.

3. RESULTS

The model has been evaluated at different operating conditions in order to better understand the behavior of the hydraulic circuit and its key characteristics. The analysis has been carried out for different mass flow rates and opening ramps.

Figure 3 shows the behavior of the time-dependent absolute pressure behavior at Node 1 for an AMR frequency of 1.0 Hz (which corresponds to the valves operating with blow durations of 0.5 second), an

opening ramp of 8° and volumetric flow rates of 50, 120, 170 and 200 L/h. A sharp decrease in pressure is observed at Node 1, followed by severe oscillations when the rotary valves switch direction – when the blow changes its direction, switching the orifices of the rotary valves. It can be inferred that the absolute pressures at Nodes 1 and 5 tend to equalize while switching the direction of the blow. In addition, the fluid finds less resistance to bypass the regenerators when both valves on the same line are opened for flow. During this period, inside the regenerators, the fluid decelerates and is rapidly forced to flow in the opposite direction. Once one of the high pressure valves is totally closed for flow (Node 1), a water hammer occurs within the circuit. The simulated maximum pressure is more than twice the operating system high pressure for different flow rates. This causes the many pressure oscillations which may propagate and harm the hydraulic system or the device structure. As can be seen, the higher the mass flow rate the greater the intensity of the water hammer and its effects.
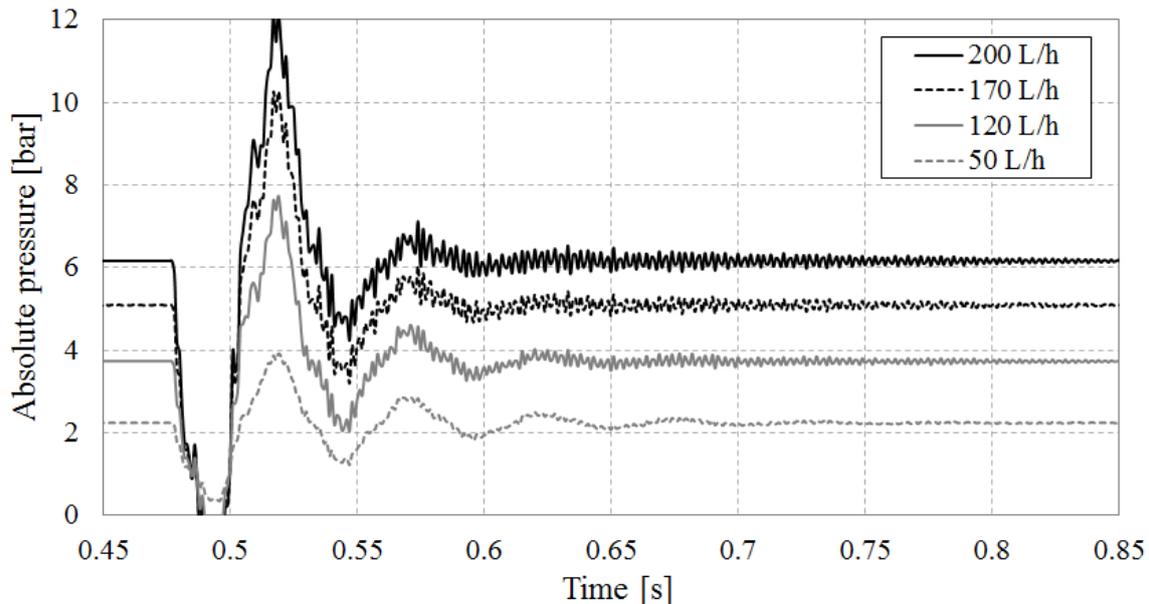

Figure 3. Transient absolute pressure at Node 1 for different volumetric flow rates.

The duration of the opening ramp has been demonstrated to be a key parameter in the behavior of the hydraulic system. Therefore, different scenarios have been evaluated. For a constant volumetric flow rate of 120 L/h and an operating frequency of 1.0 Hz, the pressure behavior at Node 1 has been quantified for different ramp durations of 2°, 4°, 8°, 15° and 45°. Due to space restrictions, the results are not shown here. However, it was inferred that the shortest opening ramps result in a quick drop in pressure and a severe water hammer, whereas for the longer opening ramps the pressure in the high-pressure line drops during longer times and the water hammer is less strong. Opening ramps shorter than 8° (roughly 2% of an AMR cycle) tend to have greater influence on the severe water hammers on the circuit. On the other hand, for opening ramps larger than 15° (roughly 4.2% of an AMR cycle) the fluid finds less resistance to bypass the regenerators during the switching time, which reduces the water hammer effect but acts toward reducing the system cooling capacity because it is not flowing through the regenerators. Based on the different scenarios evaluated, the best overall performance was found for opening ramps between 8° and 15°.

Severe water hammering and oscillations in the hydraulic circuit are undesirable not only from a structural reliability point of view, but also because they may reduce the thermal effectiveness and increase the fluid pumping losses through the AMR. Therefore, to improve the hydraulic performance of the system, the use of a proportional return valve with a low trigger pressure (4.0 bar, based on the working pressures for different flow rates) is proposed. Additional simulations indicated that this device modifies the dynamic behavior of the circuit, absorbing transient effects. Figure 4 shows the comparison between the transient absolute pressures associated with the original and newly proposed layout. One benefit of the new layout is that it makes the flow through the regenerator beds more stable, having a more well-behaved fluid flow profile. The drawback is that the new layout demands a higher pumping power because it requires a higher flow rate at the pump to maintain the same flow rate through the regenerator beds.
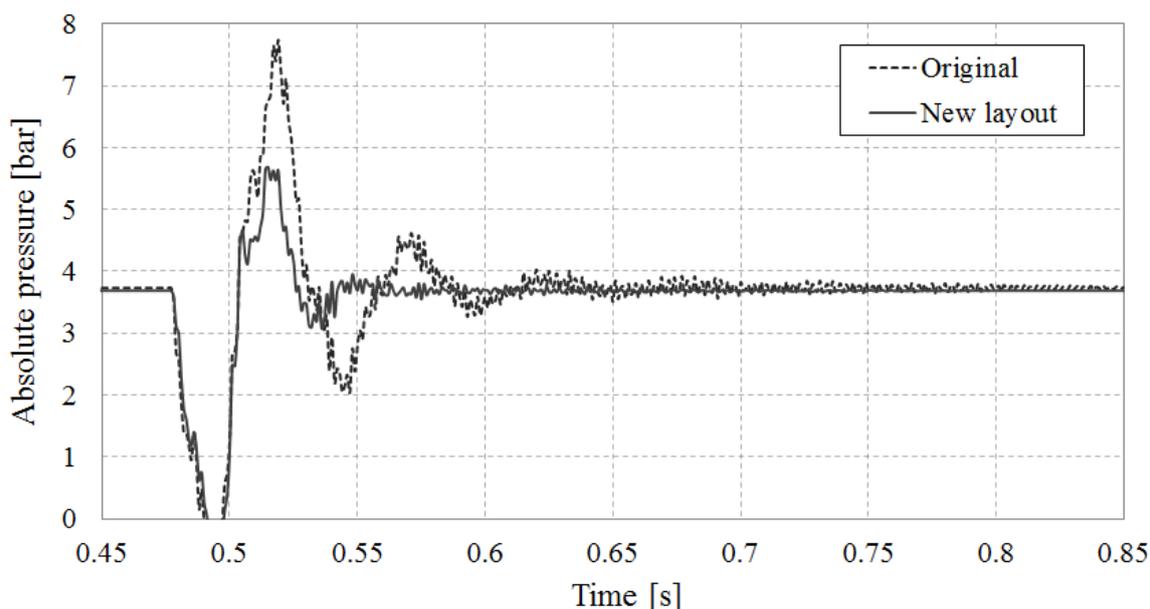
Figure 4. Comparison between the pressure at Node 1 for the original circuit and the proposed new layout.

4. CONCLUSIONS

A commercial CAE software package was used to simulate different operating scenarios of the fluid flow management system of the prototype developed by Lozano [6] in order to better understand its dynamic behavior. Different flow rates and valve opening ramps were evaluated. The magnitude of the water hammer effects was proportional to the mass flow rate. In addition, the duration of the opening ramps played a key role in the hydraulic circuit behavior: for opening ramps shorter than 8º, the circuit tends to have great influence of the water hammer effect. On the other hand, for opening ramps larger than 15º the fluid finds less resistance to bypass the regenerators when switching the fluid flow direction. The best overall performance was found for opening ramps between 8º and 15º. A new layout of the hydraulic circuit was proposed to improve the performance of the refrigeration system. Based on the obtained results, a proportional returning valve before the high pressure valves and after the low pressure valves is proposed. Such a device could absorb the impact of the water hammer effects and make the flow through the regenerators beds smoother. However, since it increases the pumping power, the overall impact of this modification on the system performance needs to be evaluated in further studies.

ACKNOWLEDGMENTS

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