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A NOVEL MAGNETIC VALVE USING ROOM TEMPERATURE MAGNETOCALORIC MATERIALS

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ABSTRACT

Magnetocaloric materials with near-room-temperature tuneable Curie temperatures have been utilized to develop a novel magnetic valve technology. The temperature dependent attractive force between the materials and a permanent magnet assembly is used to actuate valves as a response to temperature changes. This is made possible by the strong temperature dependence of the magnetization close to the Curie temperature of the magnetocaloric materials. Different compositions of both $La_{0.67}(Ca,Sr)_{0.33}MnO_3$ and $La(Fe,Co,Si)_{13}$ have been considered for use in prototype valves. Based on measured magnetization data a 3D finite element model has been set up to calculate the magnetic force between (graded) blocks of these materials and a permanent magnet assembly. The results have been used to calculate equilibrium points for actuation systems where the magnetic force is balanced by a spring force. On the basis of these calculations two temperature adjustable valve prototypes have been designed, built and tested. Possible applications of near-room-temperature valve actuation based on these materials originally developed for magnetic refrigeration are discussed on the background of the present investigation.

1. INTRODUCTION

The ongoing research in the field of ferromagnetic materials with a near room temperature Curie point has primarily been driven by the desire for utilizing the magnetocaloric effect for magnetic refrigeration purposes. The present investigation considers an alternative use of such materials where it is the strong temperature dependence of the attractive force between a permanent magnet and such materials rather than the magnetocaloric effect itself that is utilized. This gives rise to the possibility of designing autonomous valve systems actuated by temperature changes (Bahl et al., 2011). Furthermore, it even becomes possible to change the temperature of actuation externally by moving the permanent magnet relative to the magnetocaloric material (MCM) which can be graded in such a way that it contains regions with different Curie temperatures. This concept can be utilized to design a broad variety of valves for different applications. In order to design a specific valve, one must first consider the following:

- Should the valve respond to a temperature change in the surroundings or in the flowing medium?
- Should the valve switch state abruptly at a certain temperature (on/off) or should it regulate the flow in a modulating way over a temperature interval?
- Choice of magnet and MCM considering Curie points, corrosion resistance, magnetization, type of transition (1st or 2nd order) etc.
- Understanding the forces between the magnetocaloric materials and permanent magnet as a function of geometry and temperature. Need for material characterization and modeling.
- Biasing forces (for instance spring, gravity or pressure)
- Combining magnetic and biasing forces and relate to fluid flow to obtain valve characteristics.

In this paper we report the design considerations, building and testing of shunt valve prototypes as a relevant application of the basic concepts.

2. SHUNT VALVE CONCEPT

A shunt valve is a device that distributes an incoming flow between two or more outlets. The application of shunt valves is an area of particular relevance for the present technology primarily due to the fact that the active magnetocaloric material is always in thermal contact with the flowing medium, i.e. it becomes possible to regulate a flow directly according to the fluid temperature.

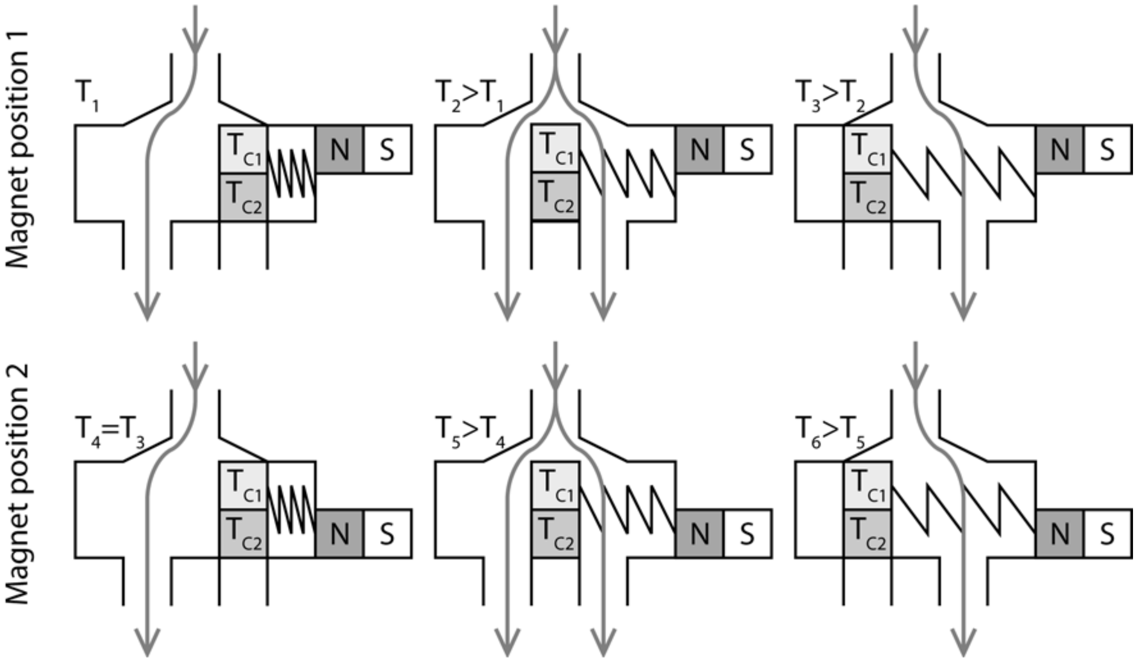

Figure 1. Schematic illustration of working principle for shunt valve. The graded MCM contains two regions with $T_{C1}<T_{C2}$.

The basic concept of our design is shown in Figure 1. The magnetic force on the MCM is balanced by a biasing force from a compression spring. The equilibrium position of the MCM is changing with temperature around the Curie temperature as a result of the changes in the magnetic force between the permanent magnet and the MCM. By moving the magnet to another part of the MCM with a different Curie temperature, the change of the magnetic force is shifted to a different temperature.

3. MODELLING

In order to be able to design and dimension actual shunt valves it is necessary to know the expected forces as a function of geometry and temperature. For this purpose a 3-D finite element model has been set up using the commercially available software tool “Comsol Multiphysics” (Comsol). The model calculates the attractive force of a NdFeB permanent magnet with a remanence of 1.3T on a block of MCM. The magnetization data used in these calculations were measured using a LakeShore 7407 Vibrating Sample Magnetometer. As illustrated in Figure 2, the magnetic forces are calculated as a function of displacement for a number of temperatures around the Curie temperature of the MCM. A set of equilibrium points are also evaluated and plotted on this figure where the magnetic force is biased by a linear spring force corresponding to a compression spring pushing the block of MCM away from the magnet. Finally, based on the assumption of a linear valve characteristic, an expected flow distribution for a shunt valve containing the modeled magnet-MCM system is plotted as a function of temperature. An important design element in this system is the spring. The spring characteristic can be altered by choosing a different spring stiffness and preload. The lower the spring stiffness the more narrow the switching temperature interval will be. A sufficiently high spring force with a low spring stiffness can be obtained by preloading the spring. If a broader switching interval is desired, a lower spring stiffness should be chosen.

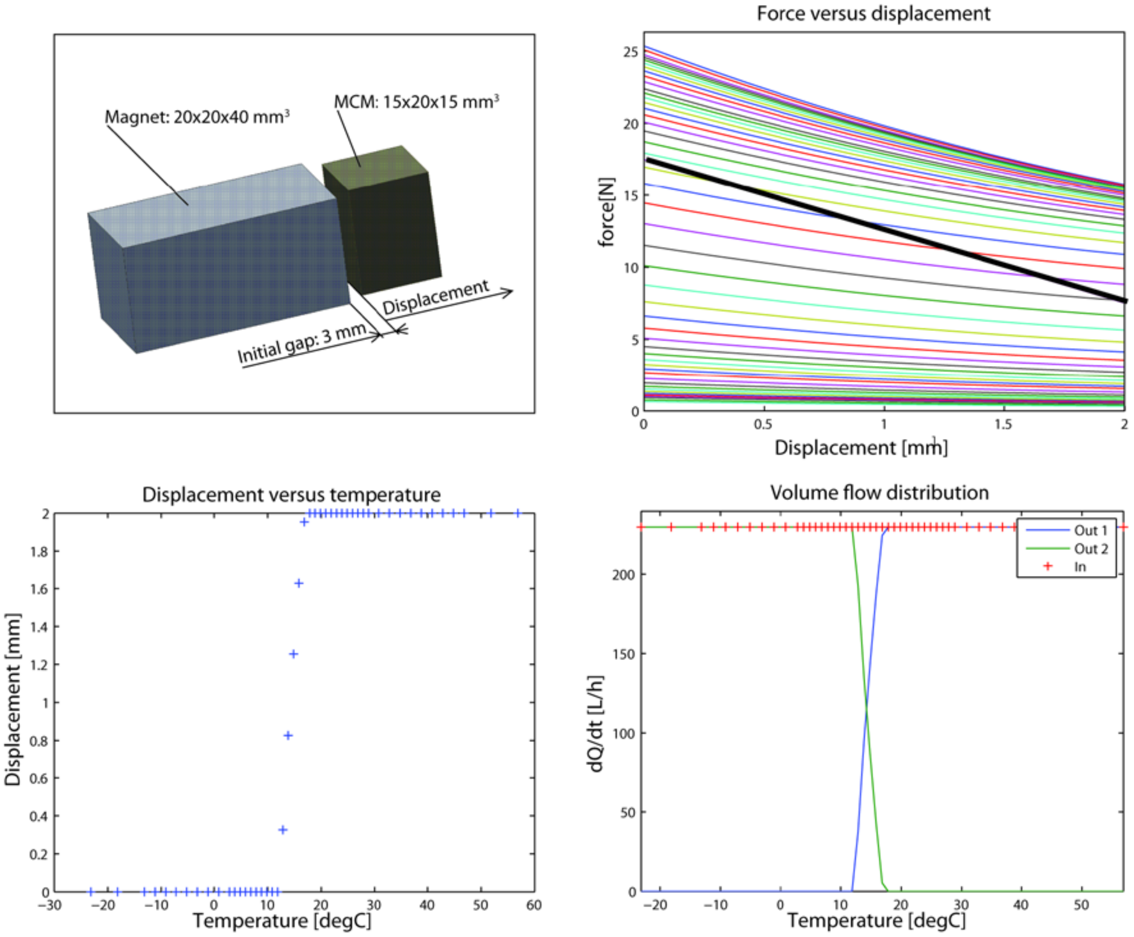

Figure 2. Modeling as a design tool. 3D model geometry of permanent magnet and displaceable MCM (top left), result of magnetic force calculations (each curve representing a certain temperature with a resolution of 1^{o}C close to the Curie temperature) together with linear spring force from a compression spring (top right), Equilibrium points at different temperatures (bottom left) and expected flow distribution (bottom right).

4. PROTOTYPE DESIGN

On the basis of the modeling results, two generations of shunt valve prototypes have been designed and built. They have been designed for conditions similar to domestic water or central heating applications. The flowing medium is chosen to be water at a flow rate of up to 250 L/h. The magnetocaloric materials tested in the valves are made from different compositions of $La_{0.67}(Ca,Sr)_{0.33}MnO_3$ (Dinesen *et al.*, 2005) and $La(Fe,Co,Si)_{13}$ (Katter *et al.*, 2008). Whereas the former materials are non-corroding ceramics, a thin polymer coating was applied to the latter to avoid corrosion in water. The valve housings were made of polyamide using selective laser sintering rapid prototyping (SLS).

4.1. Linear shunt valve

A first generation prototype relying on the linear motion of a bar containing three blocks of different magnetocaloric materials and two compression springs was designed and built, see Figure 3. Rather than using a single graded block of MCM, three different blocks were placed with sufficient spacing between them to ensure that only one of them will be active at a time. During operation, the incoming flow at the top is distributed over the entire bar ensuring temperature equilibrium with the MCM. A two millimeter sideways travel of the bar gradually distributes the fluid between two outlet chambers at the bottom of the valve according to the present temperature determined equilibrium position between magnetic force and spring forces. The permanent magnet was made from four blocks of commercial grade NdFeB magnet.

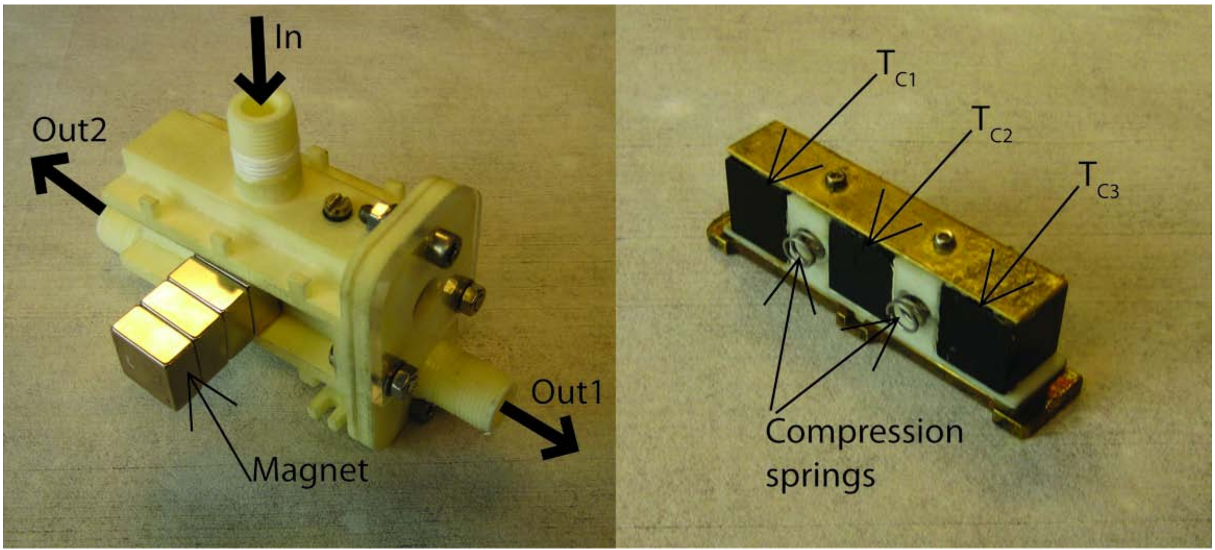

Figure 3. First prototype. Linear motion from side to side distributes incoming flow between two outlet chambers.

The performance of the first prototype shows a fair agreement with modeling results. However, when the valve is fully closed in one side, the MCM is in contact with the housing wall in that side, which creates a temperature gradient in the MCM rather than a thermal equilibrium with the fluid. This implies some alternation of the expected valve characteristic and a longer response time to a fluid temperature change. Furthermore, the valve characteristic is influenced by significant friction forces between the sliding parts.

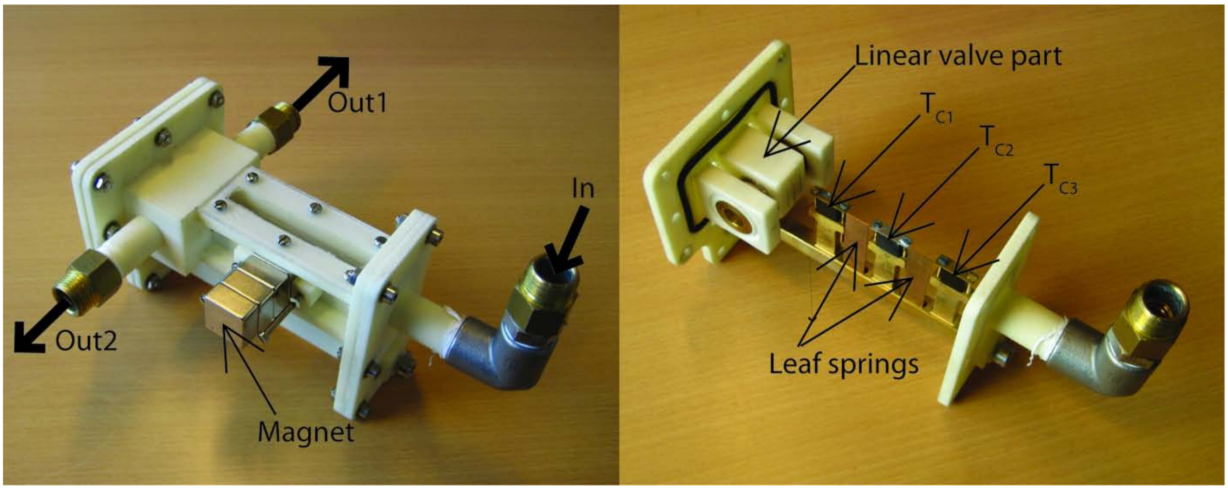

Figure 4. Second prototype. The angular motion of the actuator is transferred to a linear valve part with two outlets.

4.2. Excentric shunt valve

Based on the experience described in the previous section a second generation prototype relying on a different mechanical concept was designed and built, see Figure 4. The MCM blocks are placed on a holder which can perform an angular motion around an axis near the bottom of the valve. This acts as a gearing to minimize the ratio between the torque from the friction force to that resulting from the magnet/spring actuation forces. This makes it possible to reduce the volume of each MCM block, which in this prototype is 10x10x5 mm^3, and still have sufficient force to actuate the valve. The angular motion is transferred to a linear motion of a more traditional low friction valve part with a cone and seat at each outlet. The relatively tall and narrow geometry of the actuating part of the valve supports the use of leaf springs. To introduce extra degrees of freedom in experimental tests of the valve, the two leaf springs were equipped with adjustment screws. This makes it possible to adjust the preloading of the springs from the outside. The relatively low volume and thickness of the MCM blocks which are at no point touching the valve housing implies a short time for equilibrating the MCM to the fluid temperature which ensures a short response time for the valve.

5. PROTOTYPE TESTS

A test rig for measuring corresponding values of flow rates through inlet and outlets as well as temperatures and pressure was set up, see Figure 5. The flow circuit consists of a temperature bath with the capability of controlling the water temperature, a pump for circulation, a bypass valve for controlling the flow rate, the flow meters and the actual shunt valve prototype.

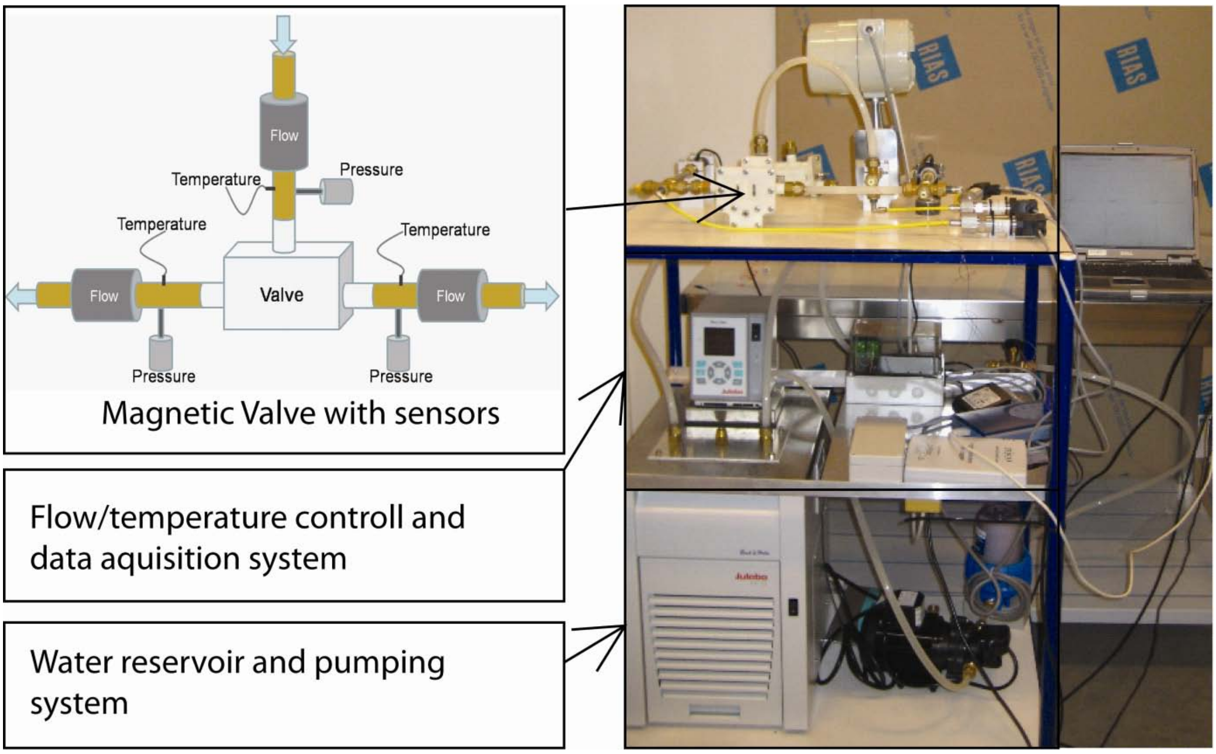

Figure 5. Test rig for evaluating shunt valve prototype performance.

5.1. Steady state valve charateristics

The main objective of the conducted experiments was to measure steady state characteristics of the valves at different magnet and spring configurations. An example of the results of such tests can be seen in Figure 6. The two plots represent test results together with model predictions for the second prototype with two different positions of the external magnet. In the experimental results represented by Figure 6 (left) the temperature of the flowing water was initially above the switching point. Then the temperature was incrementally lowered and kept constant until steady state conditions were achieved. This was repeated several times, until the temperature was well below the switching point. The temperature was then increased again in the same manner. Then the magnet position was changed and the experiment repeated, however this time with an initial temperature below the new switching point (Figure 6, right). It is clear from the plots that there is in general a good agreement between experimental results and model predictions. However, there is a minor internal leak between the valve cone and seat at one of the outlets which means that the valve is not completely closed in that side when the actual temperature is higher than the switching temperature. Furthermore, a minor “opening” of the measurement curves is observed when the temperature is incrementally changed across the switching point and back again. This is most likely due to a static friction force that has to be overcome every time the moveable parts inside the valve have to change position due to a temperature change.

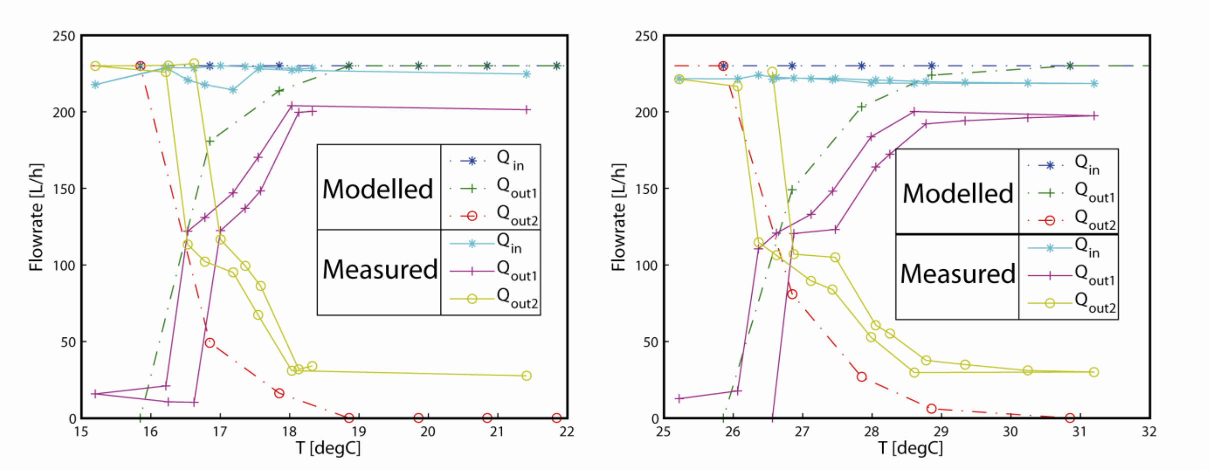

Figure 6. Steady state tests for two different magnet positions. The MCM’s are made from two different compositions of $La(Fe,Co,Si)_{13}$.

5.2. Transient behaviour

Experiments have been conducted addressing the issue of response time of the prototype valves. Figure 7 shows the result of such a test of the second prototype with a configuration corresponding to the steady state test from Figure 6 (right). The steady state switching point is defined as the temperature at which the two outlet flow rates are equal, which in this case happens at approximately 26.5 °C. The transient test was initiated while the temperature of the water filled valve was 25.5 °C. At $t = 0$ s the pump was turned on, thereby pumping water at approximately 32 °C from the temperature bath towards the valve inlet. It can be seen from Figure 7 (right) that during the first 2-3 s the flow builds up from the valve inlet and out through the open outlet 2. As the propagating hot temperature front starts to reach the valve around $t \approx 5$ s, the outlet flow rates immediately change correspondingly. The valve reaches the switching point at $t \approx 5.8$ s corresponding to a switching point of $T \approx 26$ °C. In fact, the flow rate change with temperature occurs more sharply and closer to the model prediction in the transient test than in the steady state test, which might again be explained by static friction forces in the steady state experiment. It should however be stressed that significant uncertainties are present, especially due to the fact that the transient measurements were only sampled at a rate of 1 Hz. If the transient behavior and response time due to heat transfer from fluid to MCM has to be captured and thoroughly investigated, a much higher sampling rate and an experimental setup with a more accurate parameter control must be used.

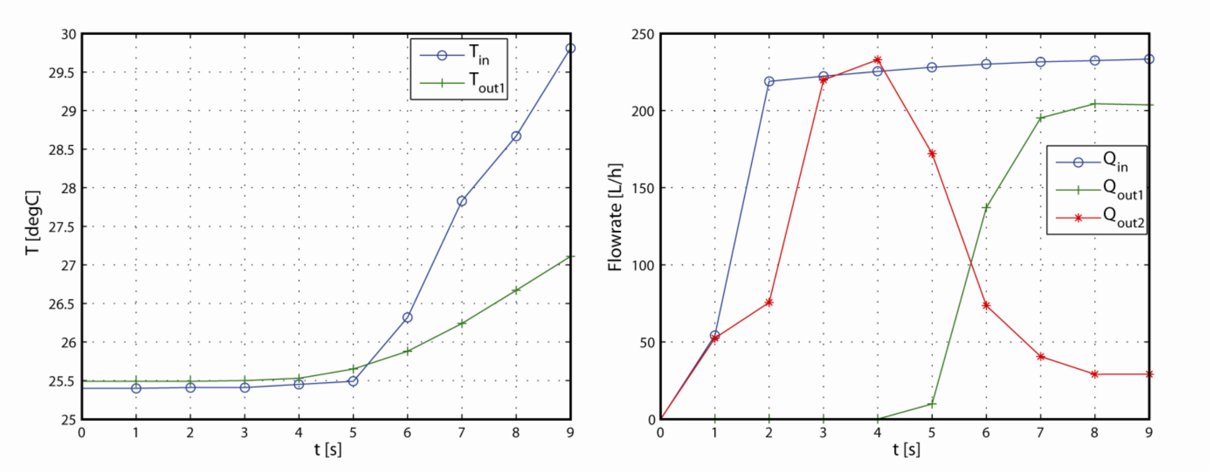

Figure 7. Corresponding plots of temperature and flowrate for the transient test.

6. DISCUSSION

The novel valve technology presented here for use in shunt valves opens many other possible applications where one can utilize the basic concept of temperature dependent magnetic forces between a permanent magnet and a (graded) MCM. The technology could act as a substitute for conventional temperature regulating valves based on, e.g., thermal expansion of wax. It might even extend the temperature range of these applications – this only requires a choice of MCM with the right Curie temperature. The technology could also be useful in applications where it is desired to change the valve set point without penetration of the valve housing with a potential risk of leakage. If oxide MCM’s are used, corrosion resistance will also be a main advantage for many applications for example in the chemical industry. Furthermore, as the valve can function autonomously, remote applications with no power available are obvious possibilities. The short response times also make safety applications such as fire extinguishing or scalding protection attractive possibilities.

7. CONCLUSION

Based on materials with tunable Curie temperatures made from different compositions of $La_{0.67}(Ca,Sr)_{0.33}MnO_3$ and $La(Fe,Co,Si)_{13}$, two prototype shunt valves have been successfully designed, built and tested. A calculation procedure based on 3-D finite element modelling of the magnetic system has been developed and used in the process of designing the valves. Good agreement between model predictions and experimental results are demonstrated. Furthermore a short response time is achieved. It is shown that it is possible to alter the valve switching temperature by moving an external magnet without using a penetration of the valve housing. The developed modelling, calculation and test procedures make it possible to design valves for different applications in the future.

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