EXPERIMENTAL MEASUREMENTS OF A MAGNETIC REFRIGERATION SYSTEM INTEGRATED IN A BEVERAGE COOLER

*Sergiu LIONTE, Michel RISSER, Jean-Baptiste CHAUDRON, Christian MULLER

Cooltech Applications, 5 Impasse Antoine Imbs, 67810, Holtzheim, France

** Corresponding author: s.lionte@cooltech-applications.com*

Abstract

Magnetic refrigeration technology is a fast-developing cooling technique which is assumed to be capable to replace the traditional vapor-compression technology in terms of efficiency and environmental requirements in the near future. Cooltech has developed a new series of Magnetic Refrigeration Systems (MRS) capable of successfully working into a commercial beverage cooler. For this application, a specific prototype has been implemented in a beverage cooler cabinet. The 500 liters cabinet uses a magnetocaloric system made of NdFeB permanent magnets generating a field of 0.8 T in the air gap and 3 kg of Gd alloys as a magnetocaloric material.

In this paper we present and analyze a set of experimental measurements performed on the entire system. The air inside the cabinet has been regulated at +2°C, with a duty rate of the motor inferior at 50%. Actual measurements demonstrate that magnetic refrigeration is now a technology able to technically respond to the refrigeration market requirements.

In the end, an overview of a high power magnetic refrigeration system will also be presented.

Keywords: Energy efficiency, Integration, Magnetic refrigeration

Introduction

After the Kigali Amendment to the Montreal Protocol in October 2016, the refrigeration market started to use natural refrigerants as alternative solutions considered to be viable and environmentally sustainable. However, they have a series of drawbacks which still require that research has to be done in order to find the best replacements. Ammonia (R717) is poisonous in high concentrations. Carbon dioxide (R744) works with high pressures (around 100 bar at the compressor discharge) therefore the system must be substantial reinforced. Hydrocarbons such as propane (R290) and isobutene (R600a) are flammable, require special certifications and are limited to a low charge of maximum 150 g which restrict the application range [1].

All these continuous regulations and limitations in terms of refrigerants lead to an increased interest towards alternatives to the existing vapor-compression technology. Among all the emerging cooling technologies, magnetic refrigeration (MR) has been identified as the most promising one [2].

Technology overview

Magnetic refrigeration (MR) is an emerging cooling technology that uses the magnetocaloric effect (MCE), a thermal effect present in different magnetic alloys. The MCE consists in an adiabatic temperature change (ΔT_{ad}) of the alloy when being exposed to a variable magnetic field. This effect is maximal at the Curie temperature of the material and is proportional to the applied magnetic field value. These alloys are called magnetocaloric materials (MCM) and currently the most common ones use Gadolinium in their composition as benchmark materials [3]. Due to its availability only in small quantities compared to the significant demand provoked by the market potential and the environmental cost, research is oriented towards other materials with a larger MCE, such as the alloys based on Iron-Silicium-Lantane (FeSiLa).

However, all these alloys present a limited adiabatic temperature change (around 3 to 4 K par Tesla), which is not enough for conventional cooling and refrigeration applications with a magnetic field intensity value that can be obtained in industrial devices (around 1 Tesla). Therefore a thermal regeneration is used to amplify the temperature span, realized with a coupled and synchronized magnetic field change over a reciprocating movement of a heat transfer fluid. The MCM is in fact as a porous matrix which is able to work as a regenerative material and as a refrigerant as well [4]. In this way, the temperature span between the cold end and the hot end of the Active Magnetic Regenerator (AMR) is increased by performing cascaded Brayton cycles in serial in order to technically respond to the refrigeration market requirements in terms of temperature span.

Numerical modelling

In order to choose the proper technical and geometrical dimensions and characteristics as well as the operating parameters of the Magnetic Refrigeration Systems (MRS), a series of numerical simulations have been carried out. We used a multi-physics and multi-scale numerical model that has already been analyzed, discussed and presented by Risser et al. [5]. The numerical model is a time-dependent finite difference-based which accounts for the three major physics taking place inside the AMR. Magnetism is 3D modelled in order to account for the demagnetizing field which depends on the external applied field, the geometry of the MCM sample and the characteristics of the magnet. In the following figure we present a cross section of the magnetic field in the material plate, which values from 0.4 to 0.9 T, depending on the Curie temperature of the material.

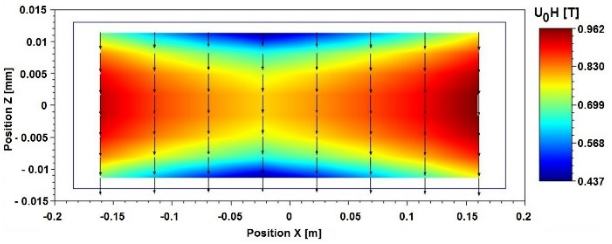

Figure 1: Cross section representation of the magnetic field value in the material plate

Fluidics is 2D modelled using the Navier-Stokes equations for the fluid flow in the micro channels between the solid plates of MCM. In the following figure we can observe the velocity profile which is completely developed since the beginning of the liquid movement over one half cycle.

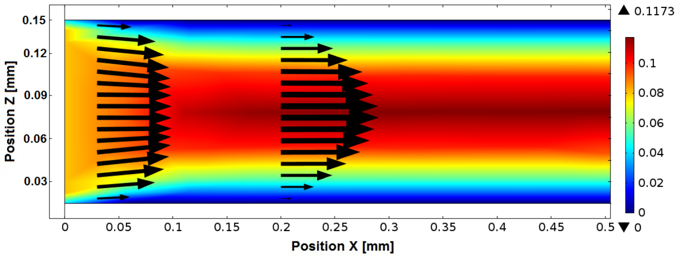

Figure 2: Velocity profile of the heat transfer fluid over the micro channel

The heat transfer is also 2D modeled and accounts for the transfer of heat between the hot heat exchanger (HHEX) and the cold heat exchanger (CHEX). The heat transfer is actively done at each half cycle to and from the MCM though the heat transfer fluid towards both heat exchangers. In the following figure one can see the thermal gradient over the complete length of the regenerator, both for solid material (upper figure) and for the heat transfer fluid (bottom figure).

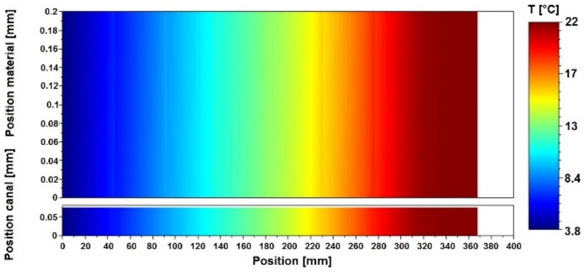

Figure 3: Thermal gradient over the complete length of the regenerator, both for solid material (upper figure) and for the heat transfer fluid (bottom figure)

A relatively large campaign of numerical simulations has been carried out (around 3000 points) and several geometrical dimensions and operating points have been identified. Multiple parameters have been varied such as the magnetic field intensity, thickness of the material plates, mini channel thickness, magnetocaloric frequency, flow rate, etc. in order to identify the most adapted combination of parameters. Choosing the best parameters can be a complex task because they involve a large number of entities in multi-physics interactions which are responsible of complex and emergent behaviors. The selection of the most adapted parameters could be made via an evolutionary algorithm combined with Deep Learning Artificial Intelligence (AI) and has already been associated with massively parallelized computing capabilities.

Experimental procedures

After the numerical validation of the chosen geometrical and operating parameters of the MRS, a series of experimental measurements have been carried out in order to confirm the results and to support the solution. All the measurements have been realized on a specific prototype that was specially designed to fit all the requirements imposed by this cooling solution in terms of dimensions, weight limitation and noise limits [6].

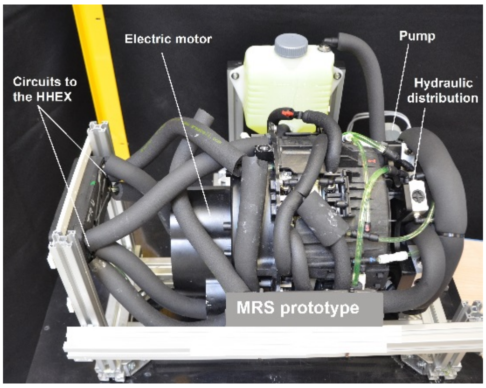

Figure 4: The main components of the MRS used for the integration in the beverage cooler

The MRS has 3 thermal loops that work in parallel and a common fluid distribution system with an external pump, as shown in the Figure 4. It has a regenerator made from a serial layering of several thin parallel plates of Gd-based magnetocaloric alloys with Curie temperature from 5 to 20 °C. It uses a magnetic system of NdFeB with an intensity value of 0.8 Tesla in the air gap which we consider to be the optimum economic value. As a heat transfer fluid the MRS uses a non-toxic, environmentally friendly water-based liquid which is actually a mixture of water and glycol with a low working pressure of maximum 2 bar. The operating parameters are variable from 3 to 6 l/min for the total flow rate of the fluid and from 0.5 to 2 Hz for the magnetocaloric frequency which represents 125 to 250 rpm.

The cabinet is a commercial available 500 liters volume with a double side glass door. It has the dimensions according to the Figure 5. The MRS compartment is situated in the bottom side and is 650 x 790 x 370 mm. The hot heat exchanger is an air-liquid type placed in the bottom part and connected to a ventilator to evacuate the residual heat. The cold heat exchanger is placed inside the cabinet and uses forced convection to distribute the cold air.

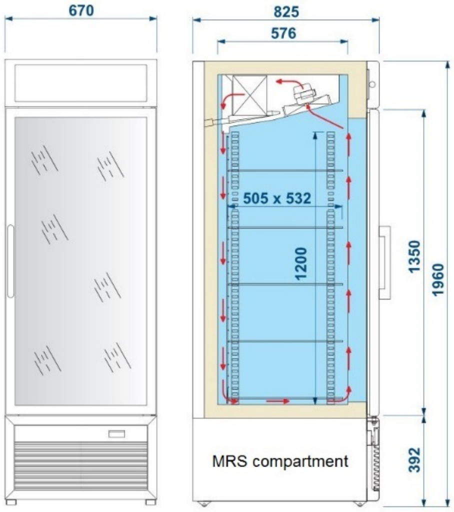

Figure 5: Technical scheme with dimensions of the beverage cooler cabinet

All the measurements have been performed with a 30 kg load of cans of beverage in the cabinet in a climatic chamber with a controlled temperature from 18 to 25 °C. The air temperature inside the cabinet has been regulated at 2 °C. The regulation mode uses a simple scheme with an on-off schedule with a hysteresis value of 4 °C (it turns on at 6 °C and turns off at 2 °C).

Results and discussions

The following results shows the case of the cabinet working into an environment at 20 °C with the liquid temperature at 2.5 °C when returning to the MRS and 0°C when entering the cabinet, for the cold heat exchanger. The liquid temperature on the hot heat exchanger leaves the MRS at 24°C and re-enters at 22 °C, which correspond to an ambient temperature of 20 °C.

In the Figure 6 we can see the temperature scheme issued from the numerical simulations. It shows the temperature variation of the heat transfer fluid at each half cycle, as well as the source temperature fixed at 2.5°C and 22 °C.

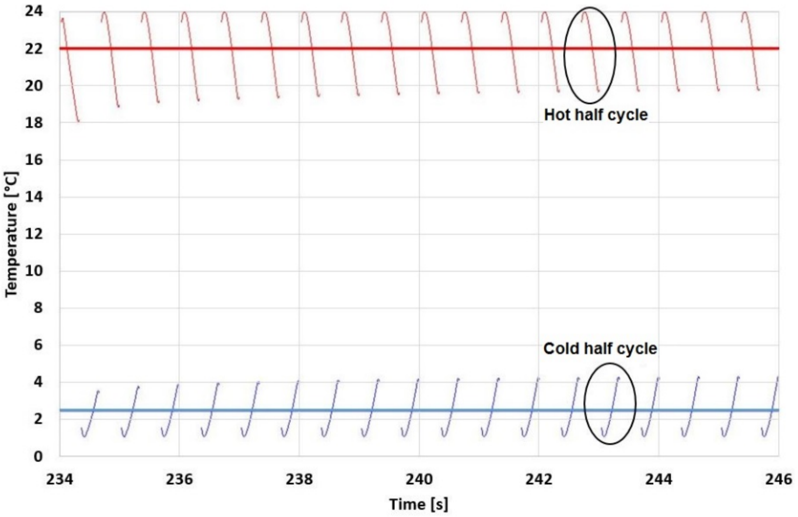

Figure 6: Representation of the temperature variation for each half cycle both for the cold and hot side of the MRS. Result issued from the numerical simulations

We can observe that the steady-state is reached in 246 seconds, due to the ideal conditions from the simulation case which do not take into account the thermal inertia of the load in the cabinet.

In the Figure 7 we present the variation of the main temperatures inside the beverage cooler cabinet, syncronised with the on-off working cycles of the machine.

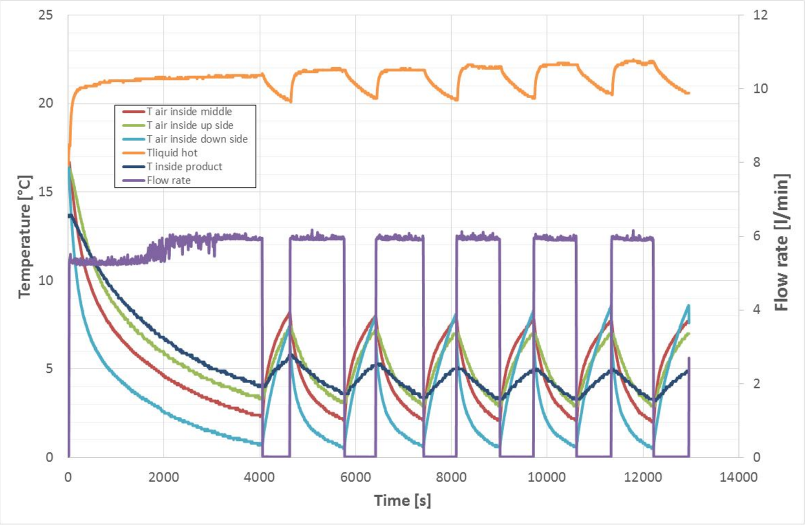

Figure 7: Temperature variation of the interior air inside the beverage cooler cabinet as well as in the product (can of soda) during the working cycles of the MRS (on-off cycles)

Due to the fact that the cabinet is filled with 30 kg load of beverage, the steady-state is reached later, in approximate 4000 seconds due to the thermal inertia. We can observe that once the steady-state is reached, the MRS enters in the regulation mode, with the on-off cycle periods that regulates over the time.

The Figure 8 shows in detail the variation of the temperature inside the cabinet over the working cycles of the MRS. We can see the variation amplitude of the air inside the cabinet in the upper part, middle part and bottom part, with values from 0.7 to 8°C. Also we can observe the temperature variation of the product (can of soda) with values from 3.3 to 5°C.

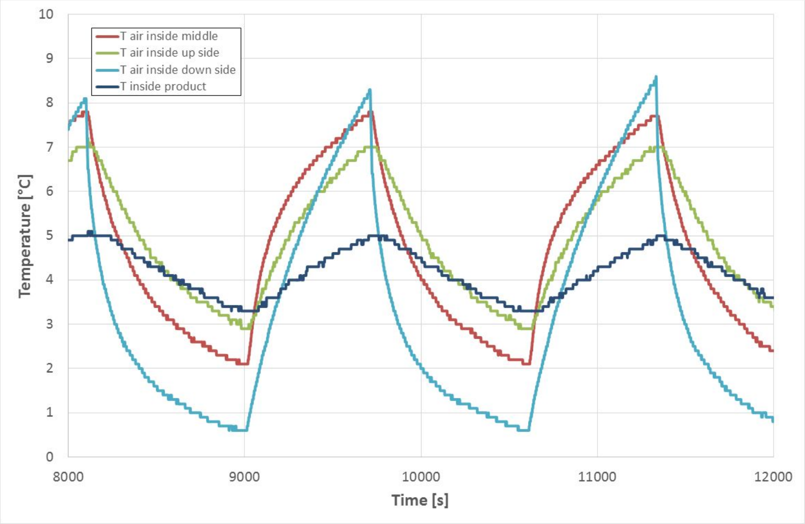

Figure 8: Zoom on the temperature variation of the air inside the cabinet and in the product (can of soda) during the working cycles of the MRS (on-off cycles)

The working cycles of the MRS can be easily observed in the Figure 9 where the temperature variation in the product (can of soda) is related to the flow rate of the MRS by the on-off regulation. In this figure we present the last cycles of the complete process from the Figure 7 which are in steady-state. The duty rate of the machine is 45 % with a temperature variation inside the product of 1.7 °C, which is largely acceptable by the refrigeration industry.

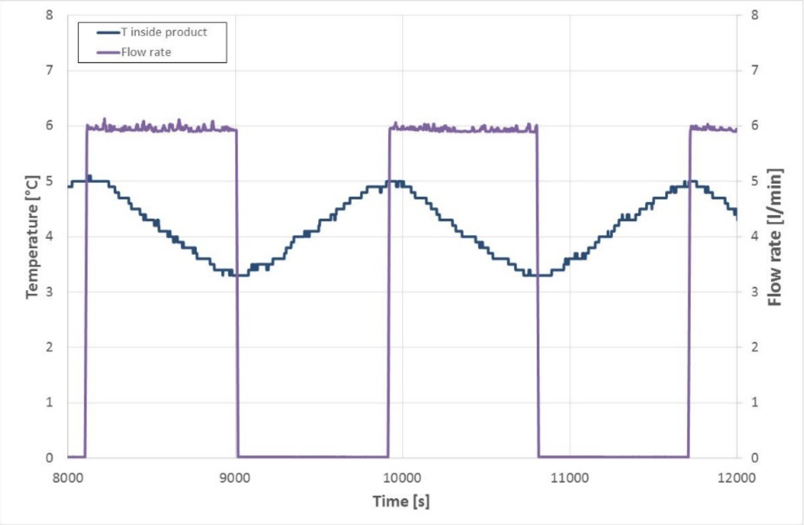

Figure 9: Temperature variation of the product (can of soda) during the working cycles of the MRS (on-off cycles) synchronized with the flow rate values (on-off regulation)

Also, the temperature variation is linked to the frequency of the working cycles of the MRS which, for this operating parameters is around 20 minutes off and 15 minutes on.

Conclusions

A series of numerical simulations have been performed in order to identify the most adapted parameters for a Magnetic Refrigeration System (MRS) to work on a beverage cooler cabinet. The numerical model is a multi-scale and multi-physics which accounts for magnetism, fluidics and heat transfer. The selection of the most adapted parameters in numerical simulation could be made via an evolutionary algorithm and has already been associated with massively parallelized computing capabilities. The simulations results show a good correlation in terms of temperature evolution when comparing to experimental results.

The beverage cooler cabinet is a commercially available 500 liters volume with a thermal load of 30 kg of beverage (cans of soda). The experimental results show a duty rate of the machine of 45 % and a limited temperature variation inside the product (can of soda) from 3.3 to 5°C. This shows that the technology is able to technically respond to the refrigeration market requirements.

Acknowledgements

The authors would like to express their gratitude to the National Research Agency from France (*Agence Nationale de la Recherche*), this study being supported by the project CoolMagEvo, code ANR-17-CE05-0036.

References

[1] C. Davenport, "Nations, fighting powerful refrigerant that warms planet ", Reports on climate change, www.nytimes.com/2016/10/15/world.africa/kigali-deal-hfc-air-con.html, 2016

[2] S. Qian et al., Not-in-kind cooling technologies: a quantitative comparison of refrigerants and system performance, International J. Refrig. 62, 177-192, http://dex.doi.org/10.1016/j, 2016

[3] K.A. Gschneidner et al., Rare earths and magnetic refrigeration, J. Rare Earths 24, 641-647, https://doi.org/10.1016/S1002-0721 (07)60001-5, 2006

[4] M. Risser et al., Improvement and application of a numerical model for optimization the design of magnetocaloric refrigerators, International J. Refrig. 36, 950-957, http://doi.org/10.1016/jirefrig.2012.10.012, 2016

[5] P. Oliverira et al., A 2D hybrid model of the fluid flow and heat transfer in a reciprocating active magnetic regenerator, Int. J. Refrig. 35, 98-114

[6] Lionte et al., Adapting an active magnetic regenerator to a continuous fluid flow application, Int. J. Refrig. 85, 303-313, https://doi.org/10.1016/j.irefrig.2017.10.009 , 2018