JOURNAL OF ENGINEERING
annals OF
FACULTY OF ENGINEERING HUNEDOARA

APPLICATION OF MAGNETOCALORIC EFFECT IN THE DESIGN OF EFFICIENT REFRIGERATION SYSTEM

S. P. VENDAN, D. DINESH, A. GIRISH

Department of Mechanical Engineering, PSG College of Technology, Coimbatore, INDIA

ABSTRACT:
In order to demonstrate the potential of magnetic refrigeration which can provide cooling effects without affecting the environment, an experimental setup was built, in which a rotating regenerative gadolinium beds of 350 g were used. Water was used as a heat transfer fluid, and a magnetic field of 1.5 T was applied using permanent magnets. With this setup, the influence of the heat transfer fluid, the temperature drop was studied systematically. The analytical solution for entropy change as a function of enthalpy and temperature were obtained in MATLAB and compared with the experimental results. The thermodynamic properties of gadolinium were studied to find out the appropriate temperature drop and entropy change in the refrigeration process. The flow over the gadolinium were analysed in STAR CCM+. The results in this analysis provide useful data for efficient design and development of room temperature magnetic refrigerators for commercial purposes.

KEYWORDS:
Gadolinium, Magnetic field, Entropy change, rotary wheel, Permanent magnet, temperature drop, Numerical modelling, Magnetic refrigerator.

1. INTRODUCTION

Refrigeration systems find its application in our day to day activities. With the increasing demand in most of the developing countries for the refrigeration systems, there is greater need to design a most efficient system. Although vapour compression refrigeration has been improved, it is mature, with only incremental energy efficiency improvements anticipated in the future. Furthermore, conventional refrigeration systems use ozone depleting and global warming gases leading to undesirable environmental impacts. Although the global refrigeration and air conditioning industry are eliminating the use of ozone depleting chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants with more environmentally benign hydrofluorocarbon (HFC) and hydrocarbon (HC) refrigerants, these replacement refrigerants are of growing concern due to their global warming potential as well as safety concerns in some applications. There is less scope for the further improvement of the existing systems [8]. The conventional refrigerants are now being replaced by more eco friendly refrigerants such as CO_2 and NH_3 [3]. Besides, efforts are being directed to develop other types of refrigeration technologies e.g., adsorption refrigeration, magnetic refrigeration and thermoelectric refrigeration which will be more eco-friendly, cost effective, efficient, simple in design, convenient and reliable. Some of the eco-friendly refrigeration technologies are Magnetic refrigeration, thermoelectric refrigeration, Thermoacoustic refrigeration [3].

The main principle of magnetic refrigeration is the Magnetocaloric Effect (MCE), discovered by Warburg in 1881. Specifically, the MCE is "the response of a Magnetic material to a varying magnetic field is evident from its temperature change" [4]. When a magnetic field is applied to a magnetic material, the unpaired spins partially comprising the material's magnetic moment are aligned parallel to the magnetic field. This spin ordering lowers the entropy of the system since disorder has decreased [20]. To compensate for the aligned spins, the atoms of the material begin to vibrate so as to randomize the spins and lower the entropy of the system again [6]. In doing so, the temperature of the material increases. Conversely, outside the presence of a field, the spins can return to their more chaotic, higher entropy states, and there is the decrease in the material's temperature. The warming and cooling process is analogous to a standard refrigerator which implements compressing and expanding gases for variations in heat exchangers and surrounding temperature [9].

2. LITERATURE SURVEY

Magnetocaloric effect based research is going on throughout the world. The current issue in the research is to produce refrigeration effect using permanent magnetic fields. Some of the important research papers and their findings:

Chunfang Tanga *et al.* compared the various number of the eco-friendly refrigeration systems available and compared with the conventional refrigeration and there advantages and drawbacks were clearly discussed. Fisher S *et al.* had evaluated the various models and tools for assessing the magnetocaloric effect for space conditioning and refrigeration applications. He stated that the magnetic heat pump could have a COP as high as 2.80 to 3.75 which can be efficiently used for aerospace applications. Kamiya K *et al.* used the principle of the Magnetocaloric effect for the purpose of the hydrogen liquefaction and other natural gas purification process. They used ceramic materials which show higher Magnetocaloric Effect for the minimum field range in the system. Steyert W stated that magnetic Carnot cycle refrigerators should be capable of pumping heat efficiently and inexpensively from liquid helium temperatures to liquid hydrogen temperatures. Four magnetic refrigerators had been built, but no economically viable unit was in operation. However, fundamental consideration indicates that magnetic refrigerators should eventually replace gas refrigerators, at least below about 80 K where lattice specific heats can be kept small.

Tang Y. B. *et al.* 2004 analysed that the cooling effect depends on the strength of the magnetic field and Magnetocaloric Effect (MCE) of the material used. A PMA (permanent magnetic array) had been designed for an air gap of 5.8mm, and 3T field. Allab F *et al.* 2005 developed a 1-D time dependent model of active magnetic regenerator. This model is used to study about the transient and steady state behaviour of active magnetic refrigerator to know about ambient conditions to achieve highest temperature drop. Kim S. *et al.* 2007 developed a prototype where he used a porous Magnetocaloric element. The cooling tests were conducted at the temperature range of 258 to 280 K using a magnetic field of 1.2 T. A solution of water and ethylene glycol was used as a coolant and the temperature drop of 9K was attained for a silicon material. Bohigas X *et al.* 2000 states that the magnetic refrigerator has been developed based on adiabatic magnetic refrigeration. A temperature drop of 1.6 K is obtained with a magnetic field of 0.3 T. The working temperature range of 70 K to 300 K was used to achieve a temperature drop of 5K. Rowe, Andrew *et al.* developed an active magnetic regenerator (AMR) at 0.65 Hz and 2 T magnetic fields. The possibility of using permanent magnet for cooling purposes at low temperature range was examined by analysing temperature spans of combinations of materials like Gd and some of its alloys.

Manh-Huong Phan *et al.* states that the effective magnetic refrigeration can be achieved in a wide range of temperatures varying from 5 K to room temperature. However, the high cooling efficiency can be achieved only in high magnetic fields of 5T which severely limits the household application of magnetic refrigeration. Therefore searching for new magnetic materials displaying large MCEs in a wide temperature range with which magnetic refrigerators can operate effectively will be a major concern. Zhang Zheng *et al.* have worked on the technology of room temperature magnetic refrigeration. He researched and discussed the theory of the magnetic refrigeration and the value in study. On the other hand, a set of new device was designed through analyzing and investigating the technology of domestic situation. Lastly, the key point of this technology and several technical problems which exist to deal with recently was brought forward and discussed.

On going through the various research works across the world, most prototypes were built based on this effect. Many working on the development of the cheap and effective magnetocaloric materials which include ceramics. There is less analysis about the orientation and the size of the permanent magnet to produce the field. There has always been a constant rpm and flow velocity is being used in the prototype which can be studied in detail by experimenting. Most of the prototypes were developed using valves and other hydraulic system which are costlier. Large number research is done on the magnetic refrigeration performance and improving it by varying the materials. All the prototypes built so far were more complex and not economical. Hence the feasibility for developing a magnetic refrigerator with less complexity and more economical is carried out in this work.

3. PROBLEM DEFINITION

The main reason for introducing magnetocaloric effect over the normal conventional refrigeration systems are due to the following:

With increase in demand for power there is a need for conserving energy. So, designing systems which consumes reduced power is the need of the hour. The compressor used in the conventional systems has maximum efficiency of only 85% and it consumes the maximum energy supplied to the refrigeration system. The alternative system to replace the existing compressor must be designed. The conventional vapour compression refrigeration cycles uses hazardous refrigerants like Freon 134 which liberates harmful CFC, HCFC and other harmful gases which depletes the ozone layer and allows harmful radiations to enter into the earth's surface. This poses a serious threat to the environment causing skin cancers and other harmful diseases. In conventional systems the work input given is lost to the mechanically moving parts which lead to frictional losses. Hence it is necessary to design the system with less moving parts.

4. METHODOLOGY

The method by which the understanding and the progress of the project was moving is given by:

- Understanding the principle behind the magnetic refrigeration called magnetocaloric effect and to study the various materials exhibiting this property such as transition metals and lanthanide series elements like gadolinium, cerium, and strontium.
- Analysing the thermodynamic relations of gadolinium material when exposed in the magnetic field by formulating mathematical models for entropy generation using MATLAB.
- Investigating and understanding the principle and performance of basic refrigeration system by conducting experiment in the refrigeration tutor available in the lab and to estimate the COP of the system.
- A model of 100mm*50mm*25mm will be developed using STAR CCM design. The flow of the heat transfer fluid over the same model will be analysed for the given boundary conditions using STAR CCM+.
- A model prototype will be build with permanent magnets and the actual readings were obtained.
- A comparison was made between the magnetic refrigeration systems and the compressor based refrigeration systems on COP, work input and refrigeration effect.

5. PRINCIPLE OF MAGNETIC REFRIGERATION

Magnetic refrigeration is based on the magnetocaloric effect (MCE). The MCE is intrinsic to any magnetic material and it peaks in the vicinity of the magnetic ordering (Curie) temperature (i.e., Curie temperature for a ferromagnetic material) [20]. In the case of a ferromagnetic, the MCE is a warming of the material as the magnetic moments of the atoms are aligned upon the application of a magnetic field, and a cooling when the magnetic moments become randomly oriented upon removing the magnetic field [9].

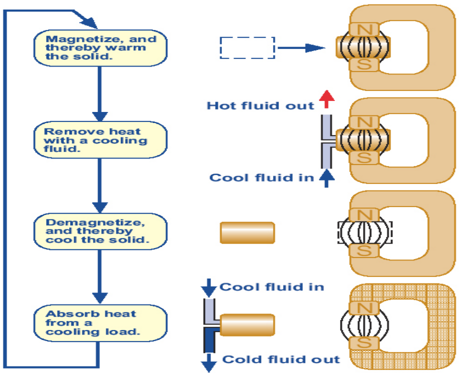

Figure 1. Principal of magnetic refrigeration

When a magnetic field is applied to a magnetocaloric material, the unpaired spins partially comprising the material's magnetic moment are aligned parallel to the magnetic field. This spin ordering lowers the entropy of the system since disorder has decreased. To compensate for the aligned spins, the atoms of the material begin to vibrate, so as to randomize the spins and lower the entropy of the system again [9]. In doing so, the temperature of the material increases. The temperature decreases after the material is taken away from the field owing to increase in randomness again. The warming and cooling process is analogous to a standard refrigerator which implements compressing and expanding gases for variations in heat exchangers and surrounding temperature. In these materials, a significant change in entropy can be effected by the application or removal of a magnetic field, and an adiabatic field change is analogous to an adiabatic pressure change on a gas in a conventional system [7]. By varying the magnetic field, work is performed and the energy of the system changes.

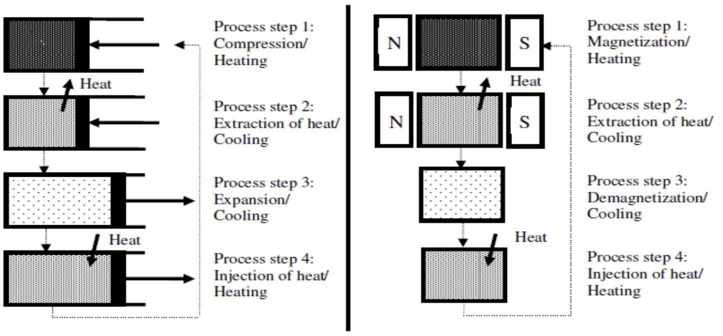

Figure2. Comparison between conventional and magnetic refrigeration

There is a difference between the two processes. The heat rejection and injection in a gaseous refrigerant is a rather fast process, because turbulent motion transports heat very fast and efficient. Unfortunately this is not the case in the solid Magnetocaloric Materials [2]. Here the transport mechanism for heat is the slow molecular diffusion. Therefore, at present filigree porous structures are considered to be the best solution to overcome this problem [17]. The small distances from centre regions of the bulk material to an adjacent fluid domain, where a heat transport fluid captors the heat and transports it away from the material's surface, are ideal to make the magnetic cooling process faster.

6. ANALYSIS OF VAPOUR COMPRESSION REFRIGERATION CYCLE

The experiment in the refrigeration tutor was done by keeping the load at 180 Ω and 200Ω. The condenser pressure and evaporator pressure were noted down. The Temperatures at condenser outlet, evaporator outlet, condenser inlet and evaporator inlet were noted. The compressor energy meter and heater energy meter for ten revolutions was noted. The characteristic curve was drawn between work input and actual COP.

Table1. Experimental data for the refrigeration tutor

Sl.no	Details	180 ohms	220 ohms
1	Condenser pressure (kg/cm^2)	12.5	12.5
2	Condenser outlet temperature(°C)	38	38
3	Condenser inlet temperature (°C)	79	80
4	Evaporator pressure (kg/cm^2)	3.64	3.24
5	Evaporator inlet temperature (°C)	8	9
6	Evaporator outlet Temperature(°C)	19	17

From the data from the Table 1 various calculations were performed to obtain the various values such as theoretical COP, actual COP with the work input so as to make comparisons between the existing system and the newly developed magnetic refrigeration systems.

From the Figure 3 it can be inferred that the performance of the system might also be depend on the flow rate of the refrigerant flowing through the coils. The overall capacity of the system is found to be around 0.25 tonnes and with an actual COP of 1.1 to 1.3. The COP of the system might have been affected due to the variation in the condenser and the evaporator pressure. The type of refrigerant used in the system and its physical and chemical properties has greater impact over the heat transfer modes in the process.

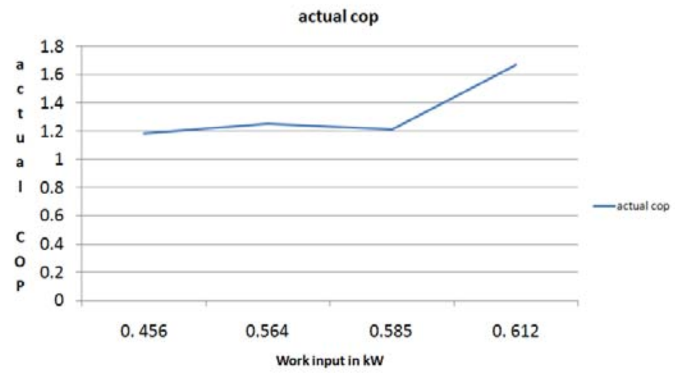

Figure 3. The cop variation with the input power supplied to compressor

7. THERMODYNAMICS OF MAGNETIC REFRIGEERATION

The thermodynamics of gadolinium and the magnetic refrigeration process were analysed. For a paramagnetic material, according to the classic Langevin theory, the mean magnetic moment, M, can be expressed by formula, the magnetocaloric effect is the application of both the first and second law of the thermodynamics to a magnetic system [1].The numerical modelling is done based on magnetic theory [7]. The theory is used to determine the entropy as a function of magnetic field and temperature. The thermodynamic analysis of the magnetic system is as follows:

Consider the magnetic material of mass m undergoing a differential work process and a differential reversible heat process [7]. If control volume is drawn around the system and the energy balance is performed and the result is

$$dU + dW = dQ \tag{1}$$

where dU the differential change in the internal energy of the system is, dW is the work performed by the material and dQ is the heat transferred into the material at temperature T

$$m.ds=\frac{dQ}{T} \tag{2}$$

where m is the differential change in the entropy of the material at temperature T.

For magnetic system, the specific differential magnetic work performed by a magnetic material is given by

$$dU = TdS + \mu VHdM \tag{3}$$

where, μ is the permeability of free space, V is the specific volume of material, H represents the applied magnetic field and dM is the differential change in the magnetisation [25].

This is the combined form of the first and second law for the magnetic systems. This equation is similar to the corresponding equation in the p-v system

$$dU = TdS - pdV \tag{4}$$

where, pdV is analogous to μVHdM. The fundamental difference between the equations is the way in which the work enters and leaves the system [1]. It is the efficiency and simplicity of the magnetic cooling process at low temperature that makes it attractive.

7.1. Entropy variation in Magnetocaloric material

The entropy of the material is being dependant on the applied field and the temperature of the material. Therefore by taking exact differentials,

$$dS = \left(\frac{\partial S}{\partial T}\right)_H dT + \left(\frac{\partial S}{\partial H}\right)_T dH \tag{5}$$

Specific heat at constant field is defined as follows

$$C_H = T\left(\frac{\partial S}{\partial T}\right)_H \tag{6}$$

By using Maxwell relation [11, 16]

$$dS = \frac{C_H(T)}{T} dT + \mu V\left(\frac{\partial M}{\partial T}\right)_H dH \tag{7}$$

For the Curie –Weiss law the $(\partial M/\partial T)_H$ is obtained differentiating the equation and substituting in the above equation

$$dS = \frac{C_H(T)}{T} dT - \frac{CH\mu V}{(T+\theta)^2} \tag{8}$$

Given the specific heat as the function of temperature at zero field and can be integrated along the zero field and then along any constant temperature path to obtain entropy at any value of T and H. The value of the entropy is given by

$$s(T,H) = So + \int_{to}^{t} \frac{C_{H=0}}{t} dT - \frac{\mu o V C h^2}{2(t+\theta)^2} \tag{9}$$

So=reference entropy at T=To &H=0

$$s(T,H) = \int_{to}^{t} \frac{C_{H=0}}{t} dT + \frac{\mu H}{2} \sum_{K=1}^{K=\infty} W_K V \left(\frac{\partial M(T_K,H)}{\partial T}\right)_H \tag{10}$$

7.2. Simulated results

The entropy variations for various fields are calculated using the magnetic field and entropy as variables and graphs were plotted for various fields.The entropy variations at different temperature levels are determined analytically using the equations derived from the basic thermodynamics.

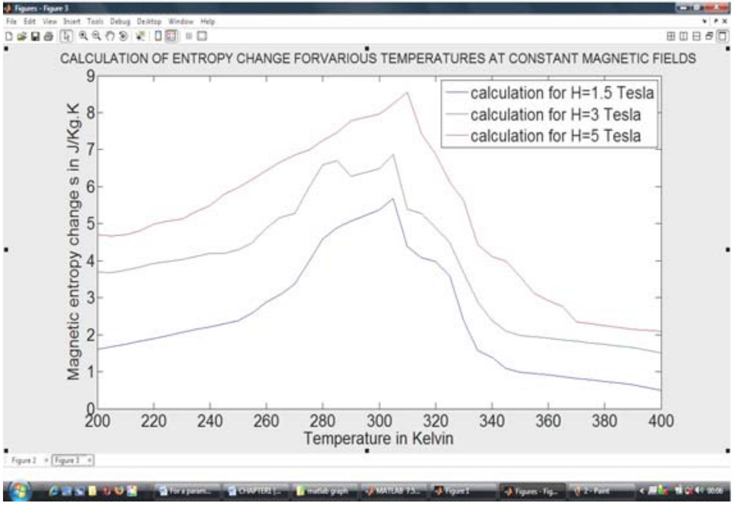

Figure4. The magnetic entropy variation with the input field at different temperature

The graph in Figure 4 is plotted using the above mentioned relation in MATLAB. From the graph depicted in the Figure 4, it is understood that the maximum entropy occurs at Curie temperature. For gadolinium material which is used as magnetocaloric material the Curie temperature comes around 293 K-295K [2, 17]. It matches with the room temperature. Till the Curie temperature the entropy increases with increase in temperature. After Curie temperature the entropy starts decreasing.

Since the permanent magnets giving higher magnetic fields have huge sizes than the normal ones. In order to obtain change in entropy 1.5 T magnetic fields can be used [21]. From the figure 5 it can be inferred that upon the application of 1.5 T field over the gadolinium can bring about a change of 4 J/KgK in the material at Curie temperature. So, for the purpose of room temperature magnetic refrigeration systems a 1.5 T field is applied over the magnetic material which has a decent increase in the entropy during magnetization and demagnetization process [27].

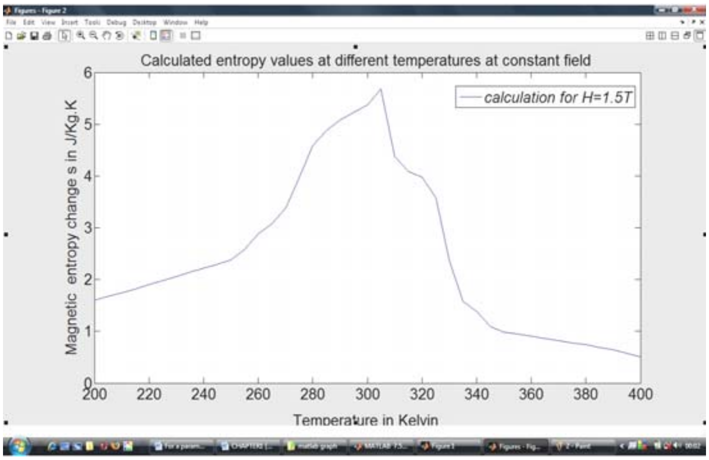

Figure5. The magnetic entropy variation with the input field of 1.5t at different temperature

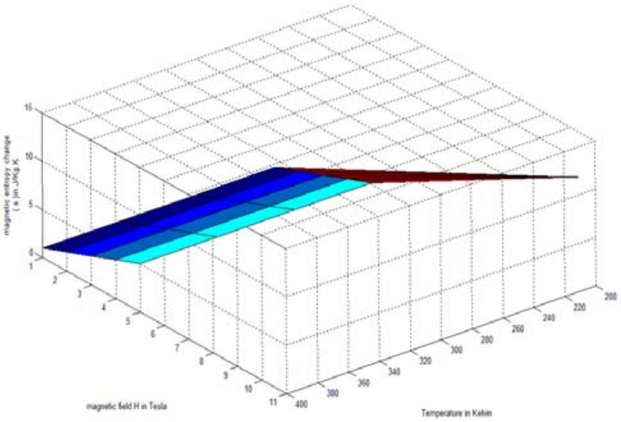

Figure6. The magnetic entropy variation with the input field at different temperature in three dimensions

From the Figure 6 it is observed that the entropy is a function of both temperature and magnetic field which will be varying as these two variables change [22, 11]. From the graph the entropy generation is maximum at the point of the Curie temperature of the material which is nearly about 293K for the pure gadolinium metal used in this experiment.

From these simulation it can identified that suitable magnetic field can be used for particular range of entropy generation by varying the magnetic field. It is used to optimize the magnetic field for which better cooling effect can be obtained with minimum material and minimum field over the entire region of the material.

8. FLOW ANALYSIS IN STAR CCM+

The particles of gadolinium are approximated as a sphere and model is created [5]. The inlet and outlet boundaries are selected. Except for the inlet and outlet all other boundaries are chosen as wall. The inlet velocity is given as 0.1m/s and pressure as 1 bar. A 50mm*15mm model block with an array of gadolinium material is used. The model is developed in star CD Design. It is then imported to star CCM to analyse the flow pattern.

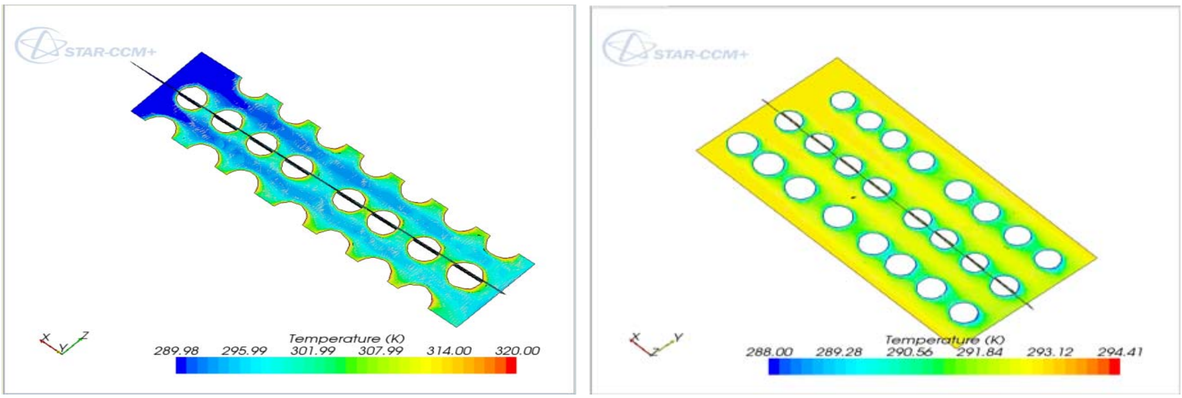

Figure 7. The velocity variation at the given boundary conditions

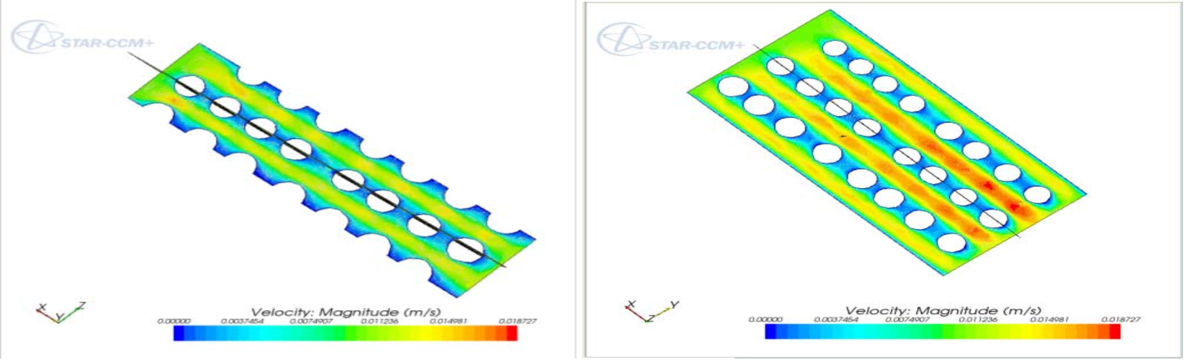

Figure8. The temperature variation at the given flow velocity

Figure 7 represents a typical temperature field in a plane normal to the x axis at an inner section of the crystalline domain. The field is well rendered even in the smallest inter-particle channels. Since for a given velocity the inlet temperature of water which was about 290K on the application of the field the outlet water temperature was increased to a nominal value of 295K on application of 1.5T field.

The flow field shown in Figure 8 exhibits inertial cores like the ones observed in the flow regimes classification work realized by Dybbs and Edwards [5]. In these cores, typical of the inertial flow regime, inertia is the dominant force whereas in the boundary layers, both inertia and viscous forces are important. The velocity field over the entire region of the crystalline gadolinium was varying from 0.05m/s in the inlet to the 0.01m/s at the outlet. For the mass flow under consideration, the boundary layers are very close to the particles surface. Both figures give a good sight into the detailed level of the simulations [12].

9. MATERIALS EXHIBITING MCE

The lanthanides Gd, Tb, Dy, Ho, Er and Tm have very high magnetic entropies (roughly 2 - 3 times as large as iron) [6]. When these materials are considered along with their proper transition temperatures (Gd is the only element with a Curie temperature near room temperature) as well as cost/material (Ho is prohibitively expensive for a refrigerator), one finds that Gd and its alloys are good fits for magnetic refrigerators. Gadolinium is a silvery grey metal with atomic number 64.It is gust placed below the periodic table in the lanthanides group. As all the transition elements and lanthanides exhibit magnetocaloric effect.

The two most important features to materials used in magnetic refrigerators are the Curie temperature (or the magnetic transition that yields the largest MCE) and the magnetic entropy [23]. The Curie temperatures of various lanthanide elements and their alloys have yielded MCEs across a broad range of temperatures between 0 - 300 K [26].

For this project 350 grams of gadolinium was purchased with 99% purity and was used for the application. The main purpose of gadolinium is its curie temperature of 293 K which is in the range of room temperature which makes it ideal for use at the normal refrigeration applications [14]. Chemical Composition of Gadolinium is pure Gadolinium 99% and other impurities include La, Ce, Pr, etc.

Figure 9 above depicts the 350 grams of gadolinium used for producing the cooling effect in the refrigerator. They were composed of 99% pure gadolinium with some rare earth impurities present in it. The lump pieces are broken down into small pieces to produce more refrigeration effect in the proposed prototype.

Figure 9. Pieces of the gadolinium metal used in this project

10. PROTOTYPE OF MAGNETIC REFRIGERATOR

From the Figure 11 it is observed that a cost effective and efficient system was designed to produce the required cooling effect. The base structure containing the prototype is designed by having mild steel plates of thickness 10mm and 200*200mm. These plates are also supported by the four supports to overcome the torque produced by the motor and the field of the magnet.

From the Figure 10 it is inferred that the optimum flow rate of heat transfer fluid can be limited in the range of 0.1 to 0.5 lpm [18]. So that there will be optimum heat transfer and the velocity variations.

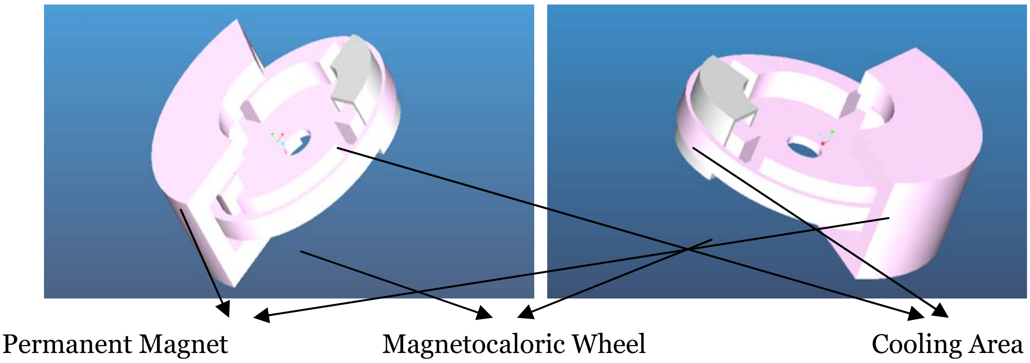

Figure 10. Design of the rotating wheel modelled in Pro-E

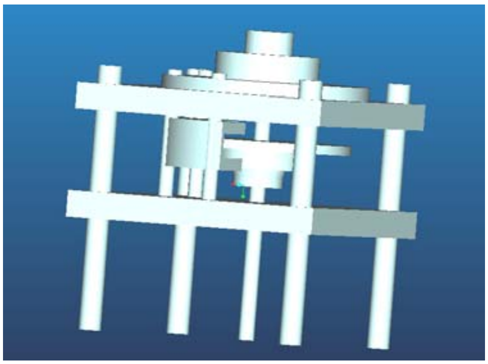

Figure 11. The fully developed prototype of the magnetic refrigerator

The repeated heating and cooling occurs when the Gadolinium material enters and leaves the permanent magnet respectively. The coolant is pumped immediately after the gadolinium leaves the magnet and also before it enters into the magnet [14]. It is evident from the Figure 10 the gadolinium material is placed in the rotating magnetocaloric wheel [16]. The wheel is rotated by a drive motor of 0.25 hp. A provision is made for permanent magnet [19].

11. CONCLUSION

This magnetocaloric effect will be the future major tool in the refrigeration sector. The present study was to acquire fundamental understanding of the magnetocaloric effect and to quantify the performance increase expected in actual Room Temperature Magnetic Refrigerators when optimised magnetocaloric materials and working conditions were employed. As this magnetic refrigeration system produces cheap and cost effective solution to the current existing problems faced by the refrigeration industries around the world. Even though the temperature drop provided by these systems was small, they operate quietly over large range of frequencies efficiently.

Since the working fluids are usually air and water, magnetic cooling will be considered as an environmental-friendly technology. There are lots of research are going on this field currently to develop refrigeration system which suits best for room temperature. Magnetic cooling technology can be applied to household refrigerators, air-conditioning systems, food freezing applications, process engineering, and heat pumps. So, developing a prototype to test and validate the results would be useful in the development of efficient magnetic refrigeration systems which can be commercially used in many households and industries in future.

REFERENCES

[1] Allab F. and Kedous-Lebouc A., Numerical Modelling for Active Magnetic Regenerative Refrigeration, IEEE transactions on magnetics, vol. 41, October 2005.
[2] Bohigas X., Molins E., Roig A., Tejada J. and Zhang X., Room-Temperature Magnetic Refrigerator Using Permanent Magnets, IEEE Transactions on Magnetics, vol. 36, May 2000.
[3] Chunfang Tanga and Qinghai Luob, Comparison of Several Eco-friendly Refrigeration Technologies, Renewable Energy Resources and a Greener Future Vol.8.
[4] Deardoff D. and Johnson D., Magnetic refrigeration development radiofrequency and microwave subsection.
[5] Dybbs A., Edwards. R.V., A new look at porous media fluid mechanics-Darcy to turbulent, Fundamental Transport Phenomena Porous Media, 1984.
[6] Gschneidner K. and Pecharsky, Magnetic Refrigeration Materials, Journal of Applied Physics, Vol.85, April 1888.
[7] Gregory R. and Gallogahor, Analysis of Active magnetic regenerator,BSME University of Rhodes Island.
[8] John T Mcmullan, Refrigeration and environment –issues and strategies for the future, International Journal of Refrigeration, Vol. 25, 2002.
[9] Kitanovski A., Vuarnoz D., Diebold, Gonin C. and Egolf P.W., Application of Magnetic Refrigeration and its Assessment.
[10] Kim S., Ghirlanda S., Adams C. and Bethala B., Design, fabrication and thermal characterization of a magnetocaloric micro cooler, International Journal of Energy Research Int. J. Energy Res, vol.31,2007.
[11] Kamiya K., Takahashi H., Numazawa T., Nozawa H. and Yanagitani T., Hydrogen Liquefaction by Magnetic Refrigeration.
[12] Kitanovski A., Vuarnoz D., Diebold M., Gonin C. and Egolf P., Application of Magnetic Refrigeration and its Assessment.
[13] Kitanovski, Andrej and Sari Osmann ,Magnetic refrigerator and/or heat pump using magneto-caloric fluid and process for magnetic heating and/or cooling with such a refrigerator and/or heat pump, European Patent Application Bulletin 2006/52 05405382.1, 27.12.2006.
[14] Kurt Engelbrecht, A Numerical Model of an Active Magnetic Regenerator Refrigeration System.
[15] Okamura, Tetsuji *et al,* Performance of a room-temperature rotary magnetic refrigerator, International Journal of Refrigeration, Vol. 29, 2006.
[16] Peter W., Egolf Andrej kitanovski and Didier vuarnoz, An Introduction to Magnetic Refrigeration.
[17] Rowe, Andrew and Chahineb R., Near Room Temperature Magnetic Refrigeration, IGEC-1 Proceedings of the International Green Energy Conference, Waterloo, Ontario, and Canada, Paper No. 084, June 2006.
[18] Steyert W., Magnetic Refrigerators For Use At Room Temperature And Below, Colloque C6, supplement au no 8, Tome 38, 1878.

[19] Steven Dr. and Carl Zimm Dr., Modelling Magnetic Refrigeration, Astronautics Corporation of America Madison and Milwaukee WI USA.

[20] Tagliafico L.A *et al.,* Performance analysis of a room temperature rotary magnetic refrigerator for two different gadolinium compounds, International Journal of Refrigeration, Vol. 29, 2006.

[21] Tang, Y. B., Chen, Y. G., Li, H. X. and Tu M. J., Design of a Permanent Magnetic Circuit with Air Gap in a Magnetic Refrigerator, IEEE transactions on magnetics, vol. 40,May 2005.

[22] Utaki T., Nakagawa T., Yamamoto A. and Numazawa T., Research on a Magnetic Refrigeration Cycle for Hydrogen Liquefaction.

[23] Yu B. F., Gao Q., Zhang B., Meng X. Z., Chen Z, Review on research of room temperature magnetic refrigeration, International Journal of Refrigeration ,Vol.26,2006.

[24] Yao G.H. , Gong M. Q., Wu J. F., Experimental study on the performance of a room temperature magnetic refrigerator using permanent magnets, International Journal of Refrigeration, Vol. 29, 2006.

[25] Zheng Z.G. *et al.,* Design and performance study of the active magnetic refrigerator for room-temperature application, International Journal of Refrigeration, Vol. 32 , 2009.

[26] Zimm C *et al.,* Design and performance of a permanent-magnet rotary refrigerator, International Journal of Refrigeration, Vol. 29, 2006.

[27] Zhang, Zheng Guo and Hui Gu Guobiao, The Research of Room Temperature Magnetic Refrigeration Technology, Institute of Electrical Engineering of Chinese Academic Science.