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Review on Advance Augmentation and Future Opportunity of Magnetic Refrigeration Systems

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Abstract— Since 1748 from the development of first refrigeration system based on vapor compression refrigeration cycle by William Cullen, vapor compression refrigeration system requires advance modification to improve its low coefficient of performance and minimize its environmental impact. In spite of all these modifications over these years world is still dealing with same issues with vapor compression refrigeration system, but these issues can be overcome by using magnetocaloric effect for refrigeration purpose. First room temperature magnetic refrigeration based on magnetocaloric effect was demonstrated by Brown in 1976. Magnetic refrigeration system has not been developed up to that extent since 1976, but from 1990 it draws the attention of researchers due to its advantages over vapour compression refrigeration systems like low noise, no environmental impact, low energy efficiency etc. This review paper is dealing with survey and analysis of resent development in magnetic refrigeration systems and at the end of this paper the possible future magnetocaloric systems are describe to explore the future achievable advancement in magnetic refrigeration systems.

Index Terms— Magnetocaloric Effect, Magnetic Refrigeration System Prototype, Active Magnetic Regenerator, Future Magnetic Refrigeration, Hybrid Cooling Systems, Magnetic Refrigeration Cycle, Magnetocaloric Material.

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1 Introduction

The world energy demand for refrigeration and air conditioning represent nearly 20% of the energy consumption [1]. As well as current vapour compression refrigeration systems (VCRS) having negative impacts on environment and low energy efficiency. In 1881 E. Warburg German physicist reported on the discovery of the magnetocaloric effect (MCE) and in the 1920 Debye and Giaugue suggested it for achieving low temperatures for laboratory use [2]. The active magnetic regenerator (AMR) technology is the first mile stone of magnetic refrigeration system (MRS) after this technology researchers start to think about possibility of commercialization of MRS in current market. AMR system was developed by Barclay in 1982 see in [3]. MRS have 30% to 40% of efficiency than Carnot cycle while VCRS have only 5% to 10% of efficiency than Carnot cycle [4]. That's why scientists looking towards MRS as a future alternative for VCRS.

Magnetic refrigeration systems works on principle of magnetocaloric effect. The working cycles used for MCE refrigeration are magnetic Carnot cycle, magnetic Starling cycle, magnetic Ericsson cycle and magnetic Brayton cycle. Out of these cycles magnetic Brayton cycle is more practical and it is used in most of the MRS. In 1997 active magnetic regenerator refrigeration (AMRR) system with super magnet is continually operated for 18 months and its experimentation revels that more than 6 coefficient of performance is achieve with 500 W of cooling power see in C. B. Zimm et al. [5]. In 2003, P. Colt et al. developed prototype to study magnetic refrigeration with Gadolinium (Gd) material as a refrigerant and cylindrical Halbach magnet for providing magnetic field. Experimental results revels that prototype achieve temperature difference of 4 °C to 7 °C with COP 2 [6]. Recently in 2016 at University of Florida, M. A. Benedict et al. designed and built double Halbach array 1 (HA1) with Gadolinium and experimentally it reveals that for no load conditions maximum cooling power observed is 26 W with temperature span of 21 °C.

The advantages of MRS over VCRS are compactness, low noise level, reduced energy consumption, nontoxic refrigerants and zero ozone depletion potential [7]. But main problem of MRS is the key component, magneto caloric materials (MCM). It is expensive rare earth metal. Many researchers are working on development of new MCM which will provide more MCE and easy to manufacture [4], [7], [8]. Some of the researchers are also working on development of new MRS prototypes to achieve more COP and temperature below 0 °C, by utilizing maximum MCE [9]. This review is dealing with the study and analyses of latest development of new MRS prototypes for demonstration or experimentation purpose and suggest possible future ideas to work. Most of the engineering work in caloric refrigeration has been performed in magnetocaloric refrigeration and heat pumping, which led to today's 65 magnetic refrigeration prototypes [1]. From 1881 only 65 prototypes with 30 magnetic refrigerants where developed and most of them where developed after 1990 [8]. So it is the need of hour to develop more energy efficient and environment friendly MRS.

2 Magnetic Refrigeration Bryton Cycle

MCE phenomenon is nothing but the change in temperature of material due to magnetization of material. When magnetic field is applied to material then there is change in magnetic degree of freedom of molecules and because of this change there is change in magnetic entropy affiliated to magnetic degree of freedom. If this MCE is carryout at constant entropy then instead of change in entropy affiliated to magnetic degree of freedom there is change in entropy affiliated to

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lattice. The change in lattice entropy leads to change in temperature of material [10].

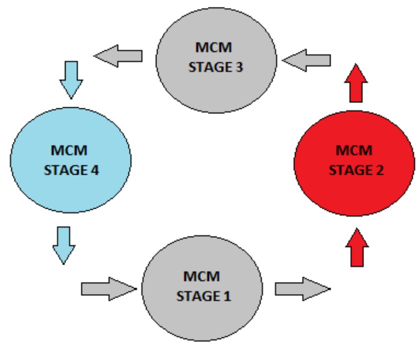

Fig 1. Block Diagram of Brayton Cycle.

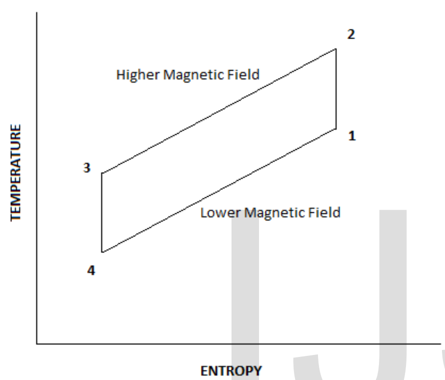

Fig 2 Thermodynamic Brayton Cycle

The operation of Bryton cycle is explained with Fig. 1 and 2. Initially magneto caloric material at room temperature in stage 1. Magnetic field is applied at stage 1 and MCM temperature increases, because molecules of MCM get organized and in this process heat is remove. Now at constant magnetic field temperature of MCM is decreases by using simple fluid to achieve low temp i.e. stage 3. When magnetic field removed at stage 3 then organized molecule of MCM starts go back to random position and MCM starts absorbing heat at stage 4. At the end there is increase in temperature from stage 4 to 1 because MCM absorbs heat from surrounding. Consider example of Gadolinium as MCM with its initial stage 1 at temperature 294 K i.e. Curie temperature. When 2 T magnetic field is applied to stage one then due to MCE there is increase of temperature to 300 K in stage 2. At constant magnetic field we try to decrease temperature of stage 2 to below or equal to 294 K i.e. Curie temperature by using some fluid. When 294 K temperature is achieve at stage 3 then 2 T magnetic field is remove and because of MCE there is decrease in temperature from 294 K to 288 K in stage 4. Magnetic caloric material at 288 K starts absorbing heat from its respective surrounding and it riche s to stage 1 i.e. 294 K and cycle is repeated.

3 MRS Augmentation

First magnetic refrigeration system was developed by Brown at Lewis Research Center of American National Aeronautics and Space Administration in 1976 [11] and development of MRS began, which is still going on. MRS technology is not developed up to that level which it should be in 120 year. However, after understanding the future significance of MRS many researchers starts focusing on development of MRS. Some recently developed MRS are discussed in this chapter.

3.1 Clot Active Magnetic Regenerative Refrigeration System

The active magnetic regenerative refrigeration (AMRR) experimental device is developed by Clot in 2003, this device is designed for Brayton cycle [6]. Device consist of active magnetic regenerator (AMR) which is nothing but the cylinder with 1 mm thick Gadolinium sheet. Gadolinium sheets of Weight 223 g are placed 0.15 mm apart from each other to form mesh structure. AMRR is placed inside Halbach magnet cylinder to provide magnetic field of 0.8 T. Magnetization and demagnetization of Gadolinium material is carried out by moving cylindrical Halbach magnet with respect to AMRR. Water is used as working fluid to remove heat during magnetization and supply heat during demagnetization and its flow is maintain by two pistons arrangement. One external pump is used to operate two pistons as shown in Fig. 3. Experimental results revels that even for a small flow 0.5 ml/s, temperature difference of 7 °C is possible. At normal condition it is observed that Clots system is providing 8.8 W of cooling power with 4 °C of temperature difference and COP of 2.2.

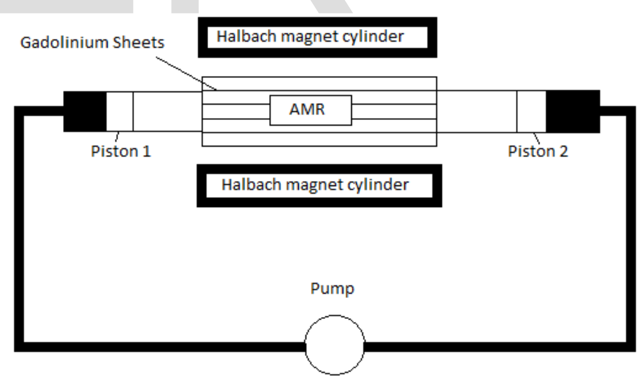

Fig 3 Clot AMRR System.

3.2 Bahl Magnetic Refrigeration Prototype

Bahl et al. built versatile magnetic refrigeration test device in 2008 to study the variation of different parameters in MRS, such as magnetic field strength, working fluids and refrigeration cycle timing [12]. The systematic block diagram is shown in Fig. 4. This device consist of rectangular AMR of 25 mm length and 22 mm width which is placed inside cylinder casing of 40 mm diameter. 13 flat sheets of Gadolinium are arranged in AMR with 0.8 mm spacing between each sheet. To-

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tal weight of Gadolinium material is 92 kg. Working fluid is supplied for heat recovery and rejection with the help of two fixed pistons at each end. Plastic guide of 20 mm are used in both side of AMR, for proper flow of fluid between Gadolinium sheets. The complete AMR system is oscillating inside electromagnet which provides maximum magnetic field of 1.4 T. The power require for movement of AMR is supply by stepper motor.

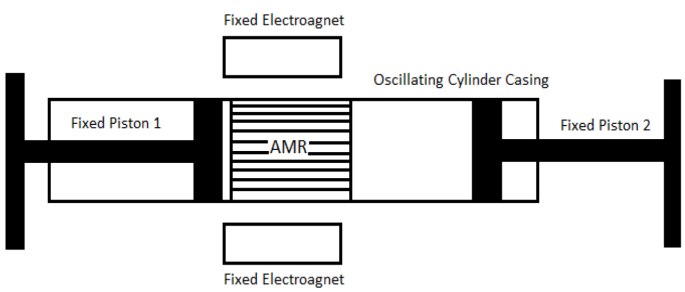

Fig 4 Bahl Magnetic Refrigeration Prototype

This system is works on magnetic Brayton cycle which is having four stages and each stages required some time to carryout process. In this system each stage is of 3 s and total cycle time 12 s. Four different working fluid is tested to find suitable fluid for system. It is observed that demineralized water have low surface tension, Ethylene glycol and propylene glycol is having high density and viscosity. However fourth fluid is virgin olive oil, which shows all suitable property's for device. Hence it is selected for given system.

Bahl et al. carried out experimentation on device in three parts i.e. stroke variation, cycle timing variation and magnetic field variation. First experimental part is stroke variation in which stroke varies from 0.5 mm to 10 mm. The experimental data obtained shows that virgin olive oil gives maximum ΔT of 6 °C for 48% of increase in stroke length. It reveals that as stroke length increase then ΔT also increases up to maximum value and further increase of stroke length causes decrease in ΔT. In stroke variation experimentation, device is operated for cycle period of 12 s and 18 s. It reveals that 12 s cycle period shows maximum ΔT of 7.9 °C while 18 s cycle period shows maximum ΔT of 7.1 °C. In third experimentation part, the magnetic field varies from 0.3 T to 1.30 T and observed that with increase in magnetic field there is drastic increase in ΔT from 0.4 °C to 8 °C. This system is very flexible which helps to study MRS with different aspects.

3.3 Zhang Magnetic Refrigerator

This system is Designed and constructed by H. Zhang et al. in 2010 [13]. This device uses two active magnetic regenerators which oscillates linearly along two permanent magnets as shown in Fig. 5. The regenerator is cylinder casing which contend Gadolinium partials. Each regenerator is having 320 g of Gadolinium. Gadolinium particle used is of 0.8 mm to 1.4 mm diameter and porosity of 0.64. The regenerators are operated for 0.45 Hz and 0.6 Hz of frequency. Required magnetic field is provided by two permanent magnets, 1.5 T each. This device is quite different from privies devices, hear two hot heat exchangers and one cold heat exchanger is used for heat exchange. Experimentation is carried out for both Nitrogen and Helium gas, as a working fluid to recover and reject heat from Gadolinium. The working fluid is circulate in system by using gas displacer which has arrangement of adjusting stroke. While experimentation different strokes of gas displacer are 120 mm, 180 mm and 210 mm.

System required minimum 3600 s to rich steady state. Comparative experimental study of Nitrogen and Helium as working fluid is performed for 0.45 Hz and 0.6 Hz frequency. It reveals that Helium gas with 1.2 MPa pressure shows cooling power of 20.5 W at temperature span of 4.5 K, if frequency is maintain at 0.6 Hz. Prototype is also studied for stroke length, out of which 120 mm is observed to be most suitable for system. At 120 mm stroke prototype shows 23.9 K of maximum temperature span at 1 MPa of Helium, 0.45 Hz frequency and 90 phase angle. So prototype with 1.2 MPa helium pressure and 120 mm stroke length operates at optimum conditions.

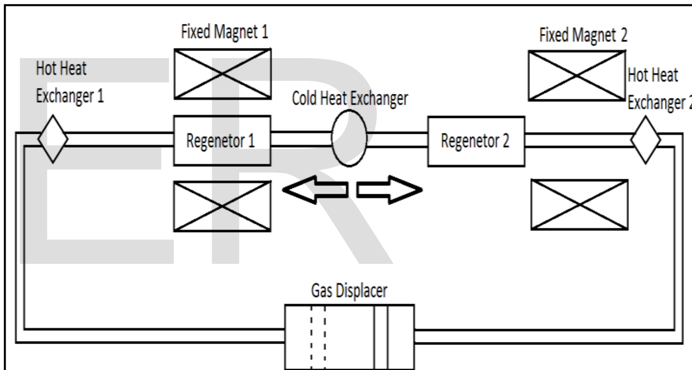

Fig 5 Zhang Magnetic Refrigerator

3.4 Kuhn MagCool MRS

Theil Kuhn et al. in 2011, work on MagCool project in which designing, construction and experimentation of rotary type MRS is carried out successfully [2]. MagCool follows three main steps first step is material selection, in second step prototype AMR and magnetic field designing and third step is successful demonstrating efficient MRS. In first step suitable material for prototype is select by literature survey and lanthanum manganite's like $LaFe_{13-x-y}Co_xSi_y$ (LCSM) is select. The LCSM have cure temperature of 354 K, it also work for broad temperature range from 255 K to 315 K and most important LCSM shaping for AMR can be done by simply using laser. In next stage proper prototype is designed. It is observed that with rotary systems, use of maximum magnetic field with continues momentum can achieve. That's why in given system rotary cylindrical AMR is used which is rotating in between two permanent cylindrical magnet. The AMR system is designed with mesh of LCSM, with cross section 0.8 × 0.8 mm^2 with thickness of 0.4 mm. The both permanent magnets used are having 250 mm length. Inner cylindrical magnetic has 20 mm inner diameter and 140 mm outer diameter and outer cylindrical magnetic has 200 mm inner diameter and 270 mm outer diameter. The required magnetic field for MCE is provided by using 4 alternating regions of high 1.24 T and low 0.01 T magnetic field. The cross section block diagram of prototype is explained in Fig. 6, where AMR is fixed between two rotating permanent magnets. With Gadolinium as a MCM the prototype shows 40 K of temperature difference with 100 W of cooling power. The prototype is currently under work, for studying with LCSM as a working MCM.

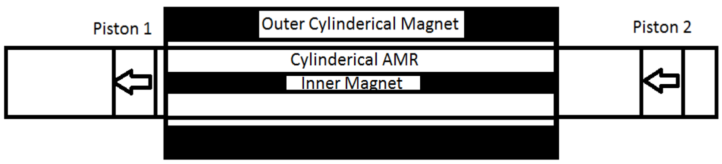

Fig 6. Kuhn MagCool MRS

3.5 Permanent Magnet Device II

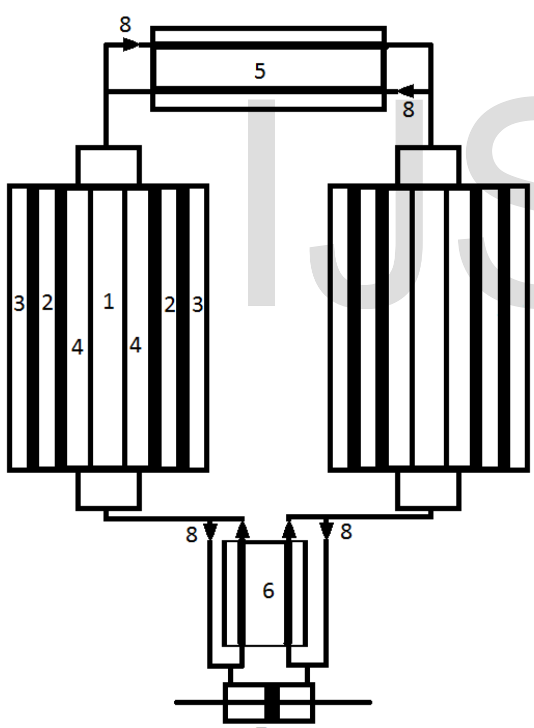

Fig 7. Arnold Permanent Magnet Device II

Tura and Rowe in 2011 built and test a permanent magnet device I (PM I) and achieve temperature span of 29 °C [14]. Arnold et al. in 2014 did modifications in PM I and improve its refrigeration effect and performance[15], [16]. The schematic diagram of permanent magnet device II (PM II) is shown in Fig. 7. The magnetic field in PM I was provided by two Halbach cylindrical magnets with 8 segment, one cylinder was rotating and other was fixed inside it with same centers. Experimental results revels that in PM I during demagnetization stage there is still magnetic field available which reduce its performance. To overcome this drawback Arnold made [1] two adjustments in PM I. First adjustment is to install three arrays of Halbach cylindrical magnets with 12 segments. Out of three arrays two are rotating in opposite direction and one is fixed inside with same center. With this adjustment it is observed that low field intensity reduce from 0.57 T to 0.29 T. In second adjustment check valves are used to flow fluid continue in one direction instead of oscillating flow. The water-glycol mixture (80:20) working fluid is supply to system by piston cylinder arrangement. The AMR used is cylindrical with 22 mm diameter and 150 mm length, it is fixed between Halbach cylindrical magnets. In PM II 650 g of Gadolinium is used in AMR. From experimental results it is observed that 33 K temperature span can be achieve at no load condition with high field intensity of 1.25 T and 0.8 Hz frequency. Still experimentation on these systems with different materials, fluid, fluid supply devices etc. is going on. We will see modified and improved version of this system in coming future.

3.6 Chiba Cleaning Cooling System

Recently in 2014 Chiba et al. developed Clean Cooling Systems at University of Applied Sciences of western Switzerland [17]. For demonstration purpose experimentation is performed on this system with Gadolinium material as MCM. Clean Cooling Systems is cascade type system with two regenerator as shown in Fig. 8. This regenerator is fixed inside 1.5 T magnetic field provided by linearly moving permanent magnets. The working fluid i.e. water is supply to system after magnetization and demagnetization only, to recover or reject heat isentropically. Pump is used to supply water to cold heat exchanger where heat get absorbed and water temperature increase, which is further supply through AMR with magnetic field which increase temperature of water. Simultaneously water is supply to hot heat exchanger where heat is reject to surrounding and water temperature reduce, which is further supply through AMR without magnetic field to provide low water temperature. This hot and cold water get mixed and achieves intermediate temperature. In reverse cycle this half of intermediate water is supply through AMR without magnetic field which reduce water temperature lower for cooling effect in cold heat exchanger and on other side at the same time other half of intermediate water is supply through AMR with magnetic field which increase water temperature and cool in hot heat exchanger atmospheric air. This system gives lower side temperature of 281 K and higher side temperature 308 K and this steady state temperature gradient is achieve in 650 s at 0.33 Hz. From experimentation it is come to know that at 1.5 T magnetic field maximum COP of 2.8 can be achieve with mass flow rate of 0.025 kg/s. This observations are only for demonstrating the system. In future there is scope for development and modification of system with good MCM, working fluid, fluid displacer, Magnetic field etc.

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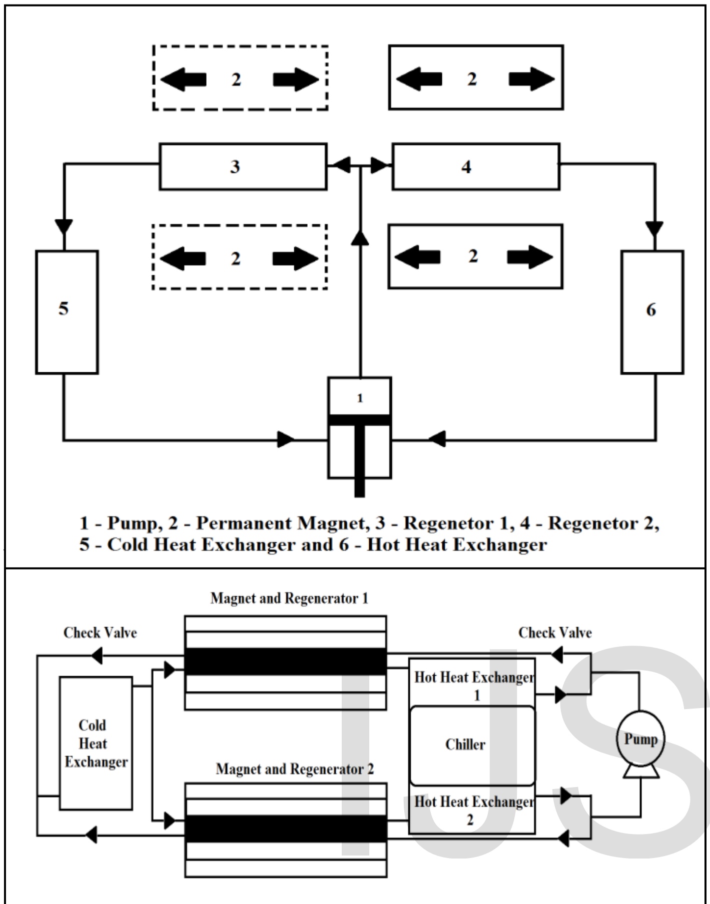

Fig. 9. Benedict Dubbed Halbach Array Prototype One (HA1)

In 2014 Arnold developed one system permanent magnet device [16], similar kind of MRS is developed by Michael A. Benedict et. al. at University of Florida in 2016 [18]. Three numerical model for given first order magnetic material with strength and weakness was given by Benedict in 2016 [19] and for validation HA 1 system is developed and experimentally studded. Dubbed Halbach Array Prototype One (HA 1) consists of two regenerators which are mounted inside individual Halbach magnets. The magnet used in Halbach array is Neodymium Iron Boron with 12 segments and 200 mm long. There is possibility to achieve more uniform field in AMR with 12 divided segments. The inner magnetic array is of 19.8 mm and 41.1 mm inner and outer diameter. The outer magnetic array is of 47 mm and 96.5 mm inner and outer diameter. Double Halbach system provide maximum high field of 1.5 T and low field of 0.1 T. The MCM used is 1 mm to 4 mm particles of Gadolinium. Regenerator used are tubular with internal diameter and outer diameter 16 mm and 160 mm. Working fluid water and ethylene glycol mixture is flowing continually through system by using pump displacer and check valve. The device is flexible which helps to study as many parameter as possible with changing some arrangements. The optimum mass flow rate required for HA 1 system is decided by studying system with different mass flow rate and it reveals that 10.05 cm^3/s and 17.6 cm^3/s are suitable for system good performance at different respective conditions. The experimental results shows that for stroke of 16.8 mm, frequency 0.62 Hz and rejection temperature 308.7 K suitable mass flow rate is 10.05 cm^3/s. HA1 system is experimentally studied for different dwell times such as 0.32 s, 0.64 s and 0.16 s to find suitable frequencies for respective dwell time. For no load condition maximum temperature span is observed to be 21 K and maximum cooling power for constant temperature 0 °C is observed to be 26 W. The lowest temperature shown by HA1 system is 277 K.

3.8 8 Mag Refrigerator

Aprea et al. [20] developed a rotary magnetic refrigeration device which is also known as 8 Mag at university of Salerno. The top view of 8 Mag system is explained in Fig. 10 This system consists of rotating Halbach permanent magnet which provide maximum 1.25 T and minimum 0.01 T magnetic field. The free gap between Halbach magnets are 43 mm and in that space magnetocaloric regenerator is located. This regenerator is combination of 8 small regenerator of size 20 mm × 45 mm × 35 mm with 1.5 aspect ratio. Each regenerators are filled with spherical grains of Gadolinium. Total 1.2 Kg of MCM is used and regenerating fluid used in system is demineralized water. Performance of 8 Mag is tested at three flow rate 5 L/min, 6 L/min, and 7 L/min with keeping hot side temperature at 296 K. Experimentation revels that 8 Mag achieve maximum 10.9 K temperature span at 0.77 Hz frequency and 5 L/min flow rate. System shows 200 W of cooling capacity at zero temperature span and 50 W of cooling capacity at 6.7 K temperature span. During experimentation 8 mag shows maximum COP of 2.5 for 200 W cooling capacity and 0 K temperature span. Analysis of 8 Mag revels that there is reduction in thermal losses as compare to other present prototypes and it also shows advantages like compactness, continue cooling and frequency operation.

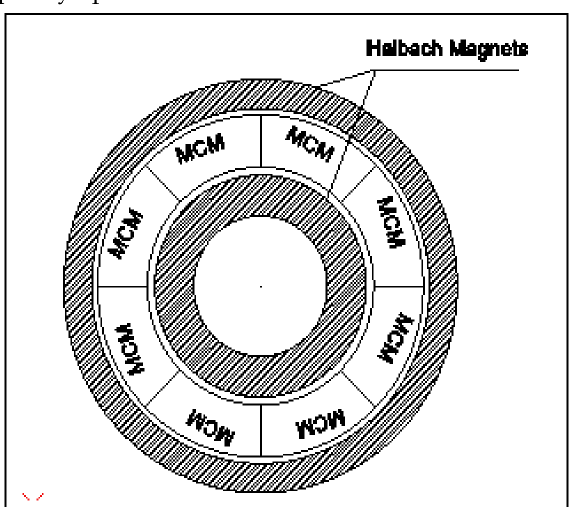

Fig. 10. 8 Mag Refrigerator

3.9 Eriksen Rotary ARR

Erikesen et al. design, built and test rotary active magnetic refrigerator prototype see [21]. The regenerator material used is steel with cylindrical shape and it divided into 11 equal parts as shown in Fig.11, each divided block is separated by glass fiber reinforced epoxy (GFRE) plates of 0.5 mm thick. Each 11 compartments is filled with spherical particles Gd alloy layer by layer as shown in Fig. 11. The MCM used is in spherical shape with diameter of 500 µm to 600 µm for Gd and 300 µm and 500 µm for Gd alloys. The AMR is surrounded by 12 rotating permanent NdFeB magnets. Total volume of magnet 1.5 L and it provide maximum magnetic flux of 1.13 T. The inner part of cylinder filled with laminated plate of Iron and GFRE to reduce eddy current losses. The different experimentation is performed at 18 °C constant hot heat exchanger temperature with AMR frequency 0.75 Hz and fluid flow rate of 3 L/min. the working fluid used is 5% ethylene glycol based automotive antifreeze solution. Experimental results revels that 3.1 COP can be achieve with 10.2 K temperature span at 102.8 W of cooling capacity. This COP is 11.3 % of the Carnot efficiency. It is possible to improve magnetic flux density from 1.13 T to 1.4 T by minimizing insulation provided at inner core of regenerator.

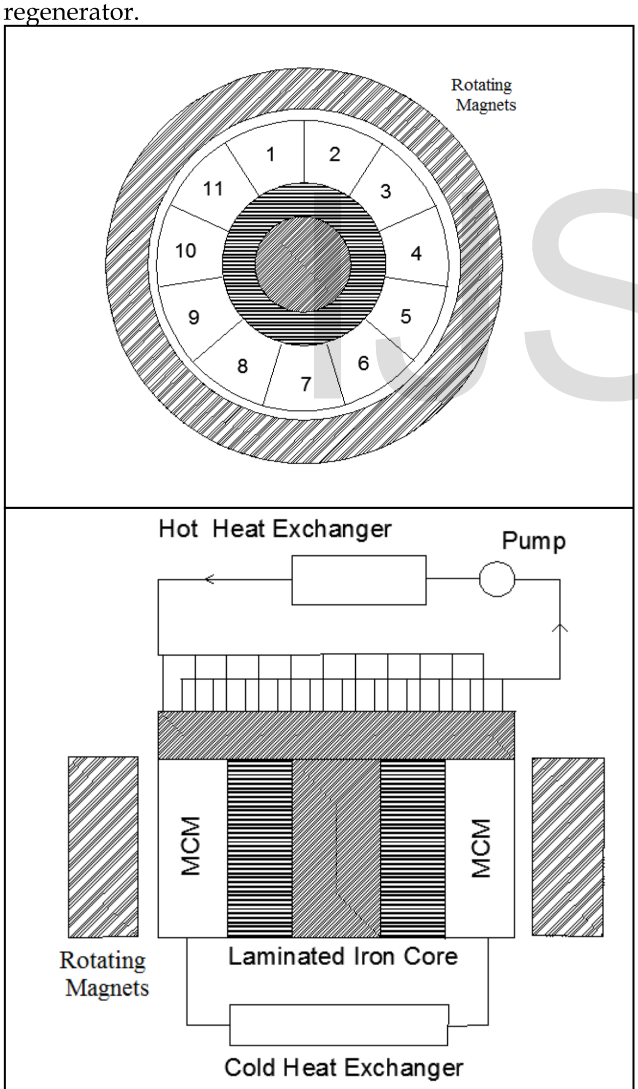

Fig 11 Erikesen Rotary ARR

3.10 Multi Layer Gd-Alloys MRS

Recently Akiko T. Saito et al. developed environment friendly magnetic refrigerator by using spherical grains of ferromagnetic Gadolinium alloys [22]. Device consist of cylindrical container which is filled with 63% of Gd alloys spherical grains and remaining space is filled with heat transfer fluid i.e. water or 20% of ethylene glycol solution. The experimental investigations was performed for different parameters, such as 0 °C to 30 °C ambient temperature, 5 mm to 10 mm piston displacement and 0.1 to 0.4 Hz cycle frequency. With single and multi-layers of Gd alloys (Gd_{100}, $Gd_{98.5}Y_{1.5}$, $Gd_{90}Ho_{10}$, $Gd_{95}Y_5$). In $Gd_{100-x}R_x$ alloys as x increases then Curie temperature decrease linearly (in range x<=15), this is the basic principle used to operate MRS to achieve maximum temperature span of 40 °C with lowest temperature of -11 °C. The particles of Gd alloys are selected with optimum size of 500 µm diameter, so that maximum heat transfer can achieve with minimum pressure losses. Device is installed with air conditioning system to adjust required surrounding temperature to study setup at different surrounding temperature. Experimentation revels that multi-layer and single layer both systems shows same AMR temperature variation results at 20 °C and 15 °C ambient temperature. To achieve lowest temperature i.e. -11 °C it is required to operate system at 10 °C and 15 °C ambient temperature. The block diagram of multi-layer Gd alloy MRS is shown in Fig. 12.

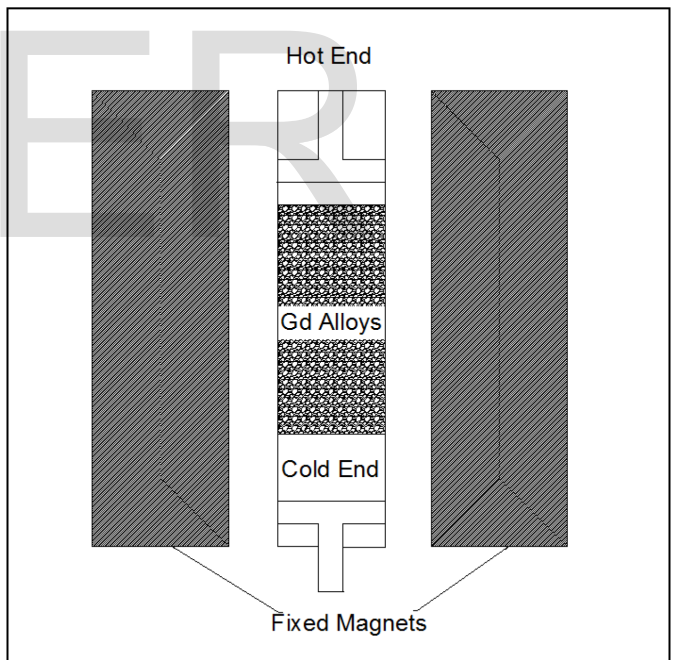

Fig 12 Multi-Layer Gd-Alloys MRS

3.11 Hybrid Stirling with Magnetic Refrigerator

In 2013 He et al. developed hybrid refrigeration system (HR-I), which is combination of Stirling gas refrigeration effect and magnetocaloric effect [23]. At 1.5 Hz frequency HR-I archives 3.5 K of temperature span for no cooling load condition and for cooling load of 10 W it shows 7.9 K temperature span. Gao et al. modified HR-I and improve and enhance its performance with modified version HR-II which is built and tested see [24]. In HR-II piston stroke is increase from 40 mm to 50 mm and piston diameter is decrease from 54 mm and 50 mm. Requirement of magnetic field is reduce from 1.5 T to 1.4 T with improved operating frequency from 1.5 Hz to 2.5 Hz. With this modification and with same Helium as working fluid for HR-II, experimental study revel that 10 W of cooling capacity can be achieve at 1 MPa operating pressure and 56 W cooling capacity at 5.5 MPa operating pressure. The systematic block diagram shown in Fig. 13. This setup is divided in two parts first is Stirling refrigerator with compressor and expander and second is magnetocaloric refrigerator with Helbach magnet and AMR. Four bunch of 0.6 mm thick Gd sheet of 10 mm width are fitted inside AMR as shown in Fig.13. To reduce dead volume impact on refrigeration performance poly tetra fluro ethylene (PTFE) tube with 7 mm inner diameter is attached to AMR system. Hot heat exchanger is placed just after compressor and cold heat exchanger is arranged with thermal buffer tube.

Experimental analysis revels that HR-II achieves maximum temperature span with 60° phase angle. Therefore system operating condition are maintain at phase angle 60° with 5.5 MPa operating Helium gas pressure and 2.5 Hz system frequency. With this operating condition the cooling power achieve at 283 K and 292 K is 40.3 W and 56.4 W which is higher than single Stirling refrigeration system.

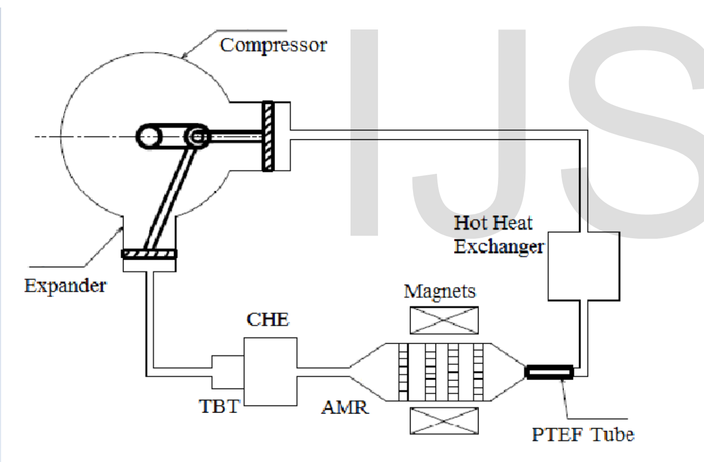

Fig 13 Hybrid Refrigeration System

3.12 Astronautic Magnetic Refrigerator

Astronautic Corporation of America and BASF design, built and test world's first commercial magnetic refrigerator (MR), which provide cooling capacity of 2 kW at 12 K temperature span see S. Jacobs et al. work [25]. Astronautic MR occupied with 12 MCM beads which are arrange in circumference with 30° separation angle between each other. The Halbach array magnets are rotating about these 12 MCM beads, such that at a single time 4 MCM beads are magnetize, remaining 4 MCM beads are demagnetize and remaining 4 MCM beads are in transit from magnetization stage to demagnetization stage. Four ports are provided to each bead i.e. hot inlet, hot outlet, cold inlet and cold outlet. Each bead is having length of 3.8 cm and cross section area of 7.9 cm^2. Each bead is filled with six layer of $La(FeSi)_{13}H$ spherical particles with 177 µm and 264 µm diameter. Total 1.52 kg of MCM is used in system. According to design consideration system performed better at 4 Hz of cycle frequency for that purpose cycle frequency of system is maintain at 4 Hz and performance of system is test at different flow rate 12.5 L/min, 15.5 L/min, 19.4 L/min and 21.2 L/min. Experimental data revels that system achieves cooling capacity of 3.042 kW at zero temperature span and at 12 K temperature span it achieves 2.09 kW cooling capacity. The MR system attended COP of 1.9 for 11 K temperature span and maximum COP of 3.3 is attended at zero temperature span with 15.5 L/min flow rate. Block diagram is explained in Fig. 14. On the bases of MR technology Astronautic Corporation of America and BASF launch magnetocaloric wine cooler of first kind at International Consumer Electronics Show at Las-vegas in 2015.

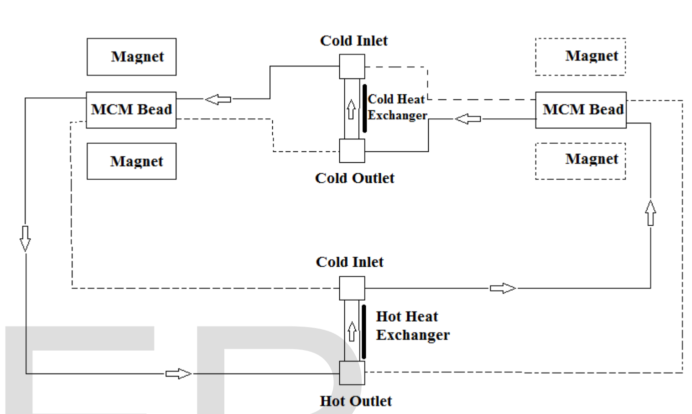

Fig 14 Astronautic Magnetic refrigerator

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4 Future Opportunities

4.1 MRS with Bar Shape Rotating Magnets

Bouchekara et al. suggested new way of providing magnetic field in MRS [26]. This proposed system consist of odd number of bar shape magnets (N ≥ 3), with more number of magnets it is possible to achieve more uniform magnetic field. The odd numbers of magnets are kept fixed and even number of magnets are rotate to achieve magnetization and demagnetization. In 5 bar magnet type MRS, magnet 1, 3 and 5 are made fixed and magnet 2 and 4 are rotated by 90° and 270° to provide magnetization at upper part and demagnetization at lower part. To achieve revers magnetization effect Magnets 2 and 4 are rotated by 270° and 90°. Two AMR are fixed at top and bottom of bar shape magnets as shown in Fig. 15. Working fluid is flowing back and forth in both AMR to provide required cooling effect.

Designing and modeling of proposed system is carried out by Bouchekara et al. with finite element method [26]. Five magnets with 20 mm radius and 1.4 T magnetic induction are kept 10 mm apart from each other. The length and thickness of AMR is 180 mm and 20 mm. With these arrangements maximum magnetic field achieve is 1.02 T and minimum magnetic field is 0.04 T. The maximum torque required to rotate bar is found to be 18 Nm and active bead required 1322 N force to flow liquid over it. Compare to other existing MRS it is observed that rotating bar magnet MRS shows good advantages like more compact system, small size, less vibration and less noise. This concept is proposed in 2011 and still development is going on, so there is good scope for research.

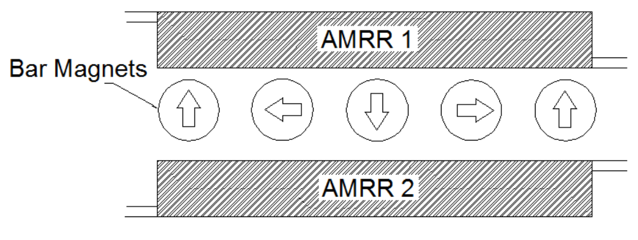

Fig 15 Bar Shape Magnet MRS

4.2 MRS with Thermal Diode Mechanism

Andrej Kitanovski present future magnetocaloric refrigeration technique in 2015 see [1]. According to this technology thermal diode is used to transfer heat from MCM to working fluid. The systematic block diagram is shown in Fig. 16. MCM is sandwich between thermal diode A and B. This thermal diode is operated by using electrical signals. When magnetic field applied to MCM then heat is transfer from MCM to working fluid by micro channels through thermal diode A, at the same time diode B is off hence heat is transfer only through diode A. During demagnetization stage diode A gets off and diode B stars operating. Hence heat from working fluid get absorb by MCM. Use of thermal diode mechanism in magnetic refrigeration system will help to design more compact and silent operating system.

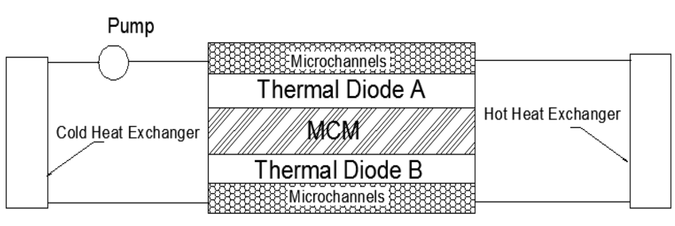

Fig 16 Thermal Diode MRS

4.3 Magnetocaloric Fluid Device

In 2010 Kitonvoski [27] explained the MRS with magnetocaloric fluid (MCF) technology. Device consist of four rings arrange in series as shown in Fig. 17 R_1, R_2, R_3 and R4 respectively. Through each ring magnetocaloric fluid with different Curie temperature is circulating in clockwise direction. Selection of Curie temperature of MCF for different rings is done by studying temperature distribution along axis. To transfer heat from MCF to cold and hot heat exchanger cross flow arrangement of tubes are provided. As shown in cross sectional area Fig. 17, whole cylinder is divided into even number of tubes. Each alternate tubes with corresponding portion of rings are magnetize and demagnetize simultaneously, so that tubes with corresponding portion of rings which are magnetized is used to transfer hot fluid toward hot heat exchanger and tubes with corresponding portion of rings which are demagnetized are used to transfer cold fluid toward cold heat exchanger. Moving parts used in this device are negligible, system is compact and leak less and most important eddy current loss are negligible. System shows good advantages but it is very complicate and costlier to build, hence there is opportunity to work on this system to improvise it in terms of cost as well as performance.

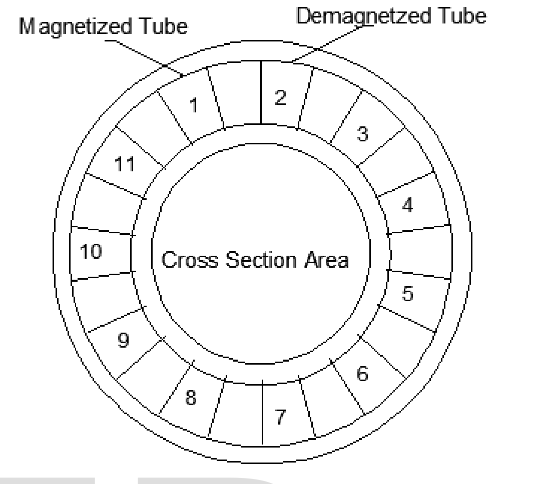

Fig 17 Cross Section of Magnetocaloric Fluid Device

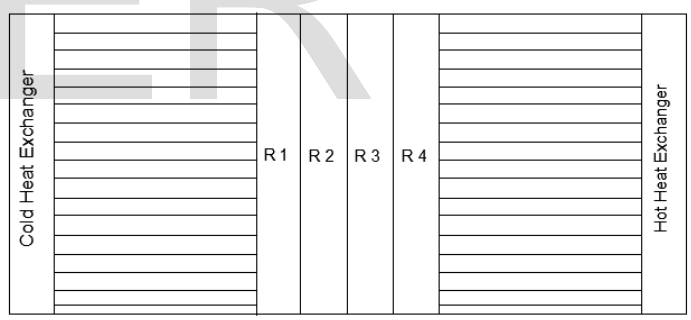

Fig 18 Magnetocaloric Fluid Device

4.4 CPV Magnetocaloric Cooling Technology

Concentrated photovoltaic (CPV) solar cells perform better at low temperature. As temperature of CPV cell increase above 25 °C then output power reduces i.e. for 1 °C rise in temperature output power is reduce by 0.25 %. So to operate CPV cells effectively it need to operate at low temperature [28], but in sunny days most of the area rich 40 °C or above. During operating CPV cells at such high temperature external cooling of cells required and in most of the cases cooling is done by supplying high velocity air or water. Kitanvoski et al. [27] discuss the idea to maintain CPV cells at low temperature by using magnetocaloric technology. In this system magnetocaloric fluid (MCF) is circulated through CPV cells by micro channels and to produce required cooling effect permanent magnet provide required magnetization just before CPV panel. MCM particles used magnetocaloric fluid should be in micron to maintain high volume of solid fraction. Block diagram is explained in Fig. 18, which consist of solar collector with PV cells, magnetic field is applied to MCF just before it enters into micro channels used to transfer heat from CPV cells to MCF. In magnetic field MCF rejects its heat and gets cool down and then it transfer to CPV cells to remove heat from it. Heat taken from panel is rejected in atmosphere with hot heat exchanger and again send back to magnetization and cooling. In some cases it is possible to utilized heat from hot heat exchanger for heating, cooling, energy generation etc. by using different heat recovery systems like magnetohydrolic, thermoelectric, Peltier effect etc.

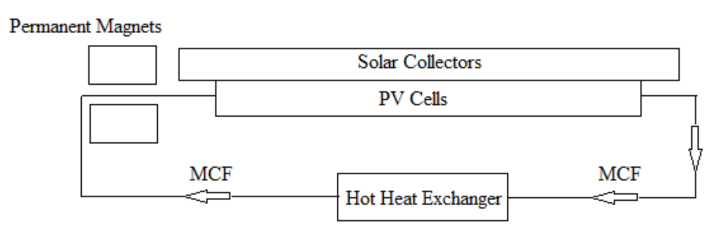

Fig 19 Magnetocaloric Cooling in CPV device

4.5 Hybrid Evaporative Magnetocaloric AC

Air conditioning (AC) purpose evaporating cooling and magnetocaloric cooling are good environment friendly options as compare to VCRS. But because of high costing and small temperature span its use is limited. Kitanvoski in 2010 in review paper [27] discuss the concept of hybrid evaporative-magnetocaloric air conditioning. It is possible to reduce cooling power cost and increase temperature span of both system by merging both technology. The systematic block diagram is shown in Fig. 19. The fresh air is supplied to heat recovery wheel where its temperature lower down by evaporative effect then it pass to MRS where it decrease incoming air temperature to required level and supplied to room. The used air from room is provided to humidifier chamber as shown in Fig. with the help of blower. In humidifier chamber very minute particles of water is spray over incoming air to lower down its temperature and provided to heat recovery wheel. With this hybrid arrangement it is possible to achieve low temperature cooling by consuming very small amount of energy for operation and without any negative effect on environment.

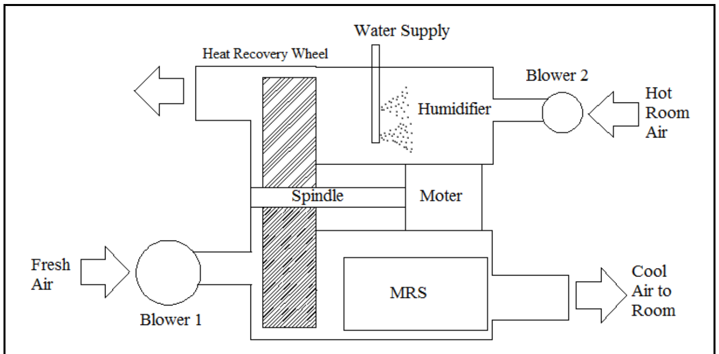

Fig 20 Hybrid Evaporative Magnetocaloric

5 Conclusion

The progress of magnetic refrigeration research is on its way and it is going on worldwide consistently but at very slow rate. Different kinds of work which is presently going on and possible work that can be possible in future are studded and examine. With goal of providing society an environment friendly, energy efficient and low cost refrigerator and air conditioners three conclusions are made. First conclusion is that very few researchers are working on hybrid combination of MRS with other environment friendly refrigeration systems. So it is required to focus more on hybrid systems to achieve high cooling capacity and low temperature cooling without negative environmental impact. The MRS literature survey reveals that it is possible to improve cooling capacity up to 2 kW by using spherical particles of different types of MCM with suitable Curie temperatures. Therefore second conclusion is to work on combinations of different MCM and different shapes for achieving low cooling temperature span and high cooling capacity. Third conclusion is done on the bases of magnetocaloic fluid refrigeration systems, very few researchers are working on this technology and it is required to ameliorate this research area because of its advantages like negligible eddy losses, less noise and no moving parts. Therefore the third conclusion is to focus research on MRS with different MCF systems to take MRS to next level.

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