Refrigeration Using Nano-Magnetic Ferro Fluid

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Abstract*-The current AMRR (Active Magnetic Regenerative Refrigeration) system uses water as a heat exchanger fluid. The adiabatic temperature change in hot heat exchanger in current technology is limited. This can be enhanced by increasing the thermal conductivity of the heat exchanger fluid. Nano-magnetic fluid (Ferro-fluid) is one such fluid whose thermal conductivity is higher than water and it can also be varied with change in magnetic field making it a better candidate as a heat exchanging fluid. It also has the property of variation in magnetization power with variation in temperature due to which it has a potential to work as automatic pumped fluid decreasing the pump load. The main barrier to use Ferro-fluid is to design a system which can make best use of its properties. This paper compares the results of Ferro-fluid as heat exchanging fluid with water and proposes the design that can comprehend all the properties of Ferro-fluid.*

Keywords-AMRR, Ferro-fluid, Magnetization power, Temperature, Thermal conductivity, Water

I. INTRODUCTION

Magnetic refrigeration is a cooling technology based on the magneto-caloric effect. The Magneto caloric effect (MCE) is an intrinsic property of magnetic materials; it consists of absorbing or emitting heat by the action of an external magnetic field. This results in warming or cooling (both reversible) of the material. [1,3,7]There are varieties of fluids used as secondary heat exchanger fluid in magnetic refrigerator with water as most preferred choice due to easy handling, low cost and availability. But the refrigeration effect obtained is limited and is unable to compete with latest VCR technology due to design restrictions of available technology[5]. To make it a more viable option, use of Nano-magnetic fluid (Ferro fluid) as a heat exchanging fluid is presented with the design to comprehend the same in this paper.[2,4,6].

II. COMPARISON OF WATER AND FERRO FLUID

For a significant cooling effect to take place the fluid used for heat exchanging process needs to have high thermal conductivity property. Till date in all the magnetic refrigeration systems made, water is used as heat exchanging process. The thermal conductivity vs temperature graph (fig. 1.1) of water shows that the conductivity goes on increasing but generally limits itself to 0.67W/mK. also the change in thermal conductivity doesn't vary much with magnetic field.

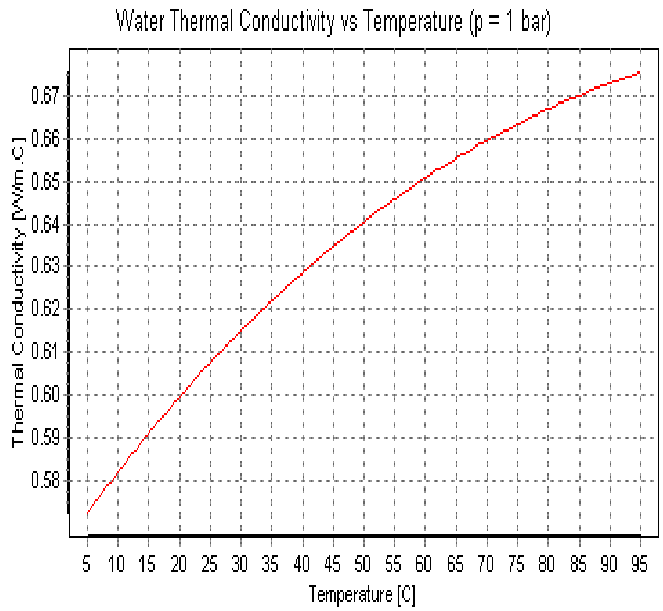

Fig. 1.1 Thermal Conductivity vs Temperature for water

Ferromagnetic fluid (Ferro fluid) used is a colloidal suspension of submicron-sized iron oxide particles in a carrier fluid such as kerosene or water, with a dispersing agent added to prevent aggregation and sedimentation. When a magnetic field is applied to a Ferro fluid, a body force is developed within the fluid which can change its response to a magnetic field while retaining the essential fluid characteristics.

There are basically two different types of Ferro fluids which can be used i.e. Kerosene based Ferro fluid and Water based Ferro fluid. Use of Water based Ferro-fluid is preferred over Kerosene based because of its better thermal properties required for the application. The various properties are:

- Density =1400 kg/m3
- Maximum Heat capacity = 3000 J/kg K
- Viscosity = 6.64×10^{-3} kg/ms
- Thermal Conductivity = 2.7 W/mK [8]

The plot in fig.1.2 shows the variation of thermal conductivity of Ferro-fluid vs Time under the magnetic field intensity of 1000G (0.1 T) at 25^0 C [2]

The plot shows that the thermal conductivity of the Ferro-fluid starts increasing with the presence of magnetic field and reaches values beyond that of water. The rate of increase of thermal conductivity with respect to time is higher for higher value of magnetic field intensity which can be seen from the plot in fig. 1.3

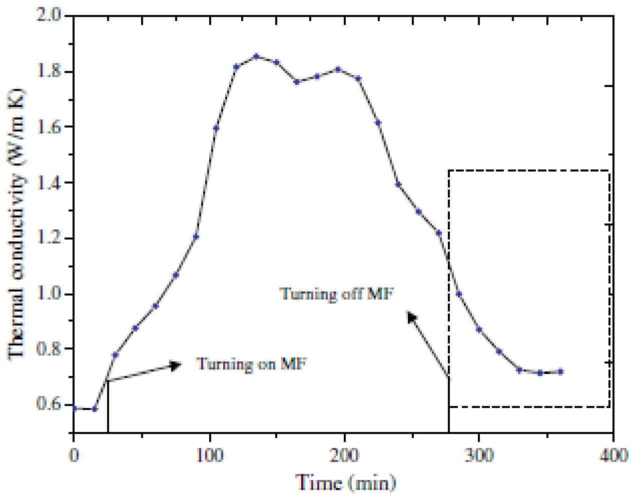

Fig. 1.2 The variation of the thermal conductivity of the Ferro fluid under magnetic field intensity of 1000 G at 25 _C. [2]

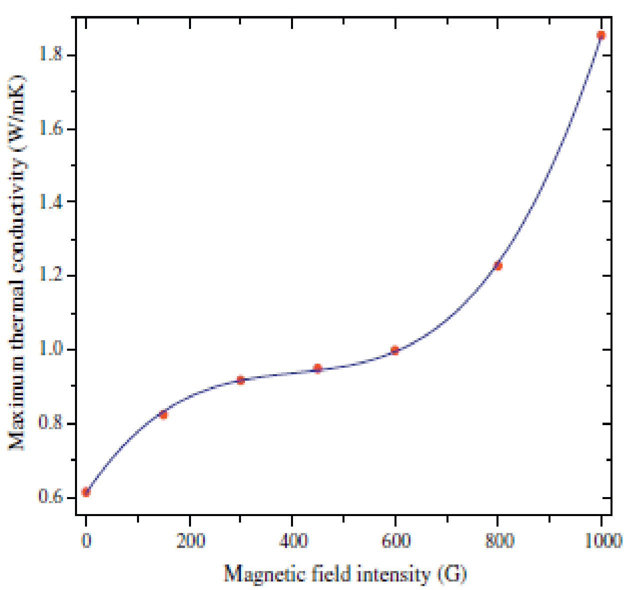

Fig. 1.3 Maximum value of the thermal conductivity of the Ferro fluid versus the magnetic field intensities at 25^oC. [2]

The above plots shows how Ferro-fluid has better thermal conductivity which can be varied with intensity of magnetic field, making it a better option over water as heat exchanging fluid.

III. DESIGN AND FABRICATION

Table.1 Part details of prototype

Part Name	Material	Dimensions
1. Magnet	Neodymium (N52)	20mm x 12.5mm x 50mm
2. Regenerator (Hollow)	Acrylic	O.D. = 20mm I.D. = 15mm
3. Outer Casing (Rectangular)	Aluminium	144mm x 124mm x 150mm
4. Shaft	Aluminium	Φ15mm
5. Core	Aluminium	Φ40mm
6. Base Plate	Mild Steel	250mm x 300mm

1. Neodymium (N52) magnet is preferred due to its high coercivity (H_{ci} =0.875 to 1.99) which prevents it from losing its magnetic property over time, also the ratio of magnetic field intensity to size of magnet (Volume occupied) is higher compared to other permanent magnets which helps to make system more compact.

2. Acrylic is selected as regenerator tube material since the permeability of acrylic is nearly same as that of neodymium, this lets all the magnetic fields reach the gadolinium material without much resistance. It is also light weight (ρ=1180 kg/m^3) reducing the power required to rotate the regenerators. More than that, the thermal conductivity of acrylic is low as 50W/mK which prevents heat transfer to and from environment.

3. Aluminium is preferred for casing, shaft and core due to its light weight, easy machining and low thermal conductivity. It also has low magnetic permeability (μ=1.2566 × 10^{-6})

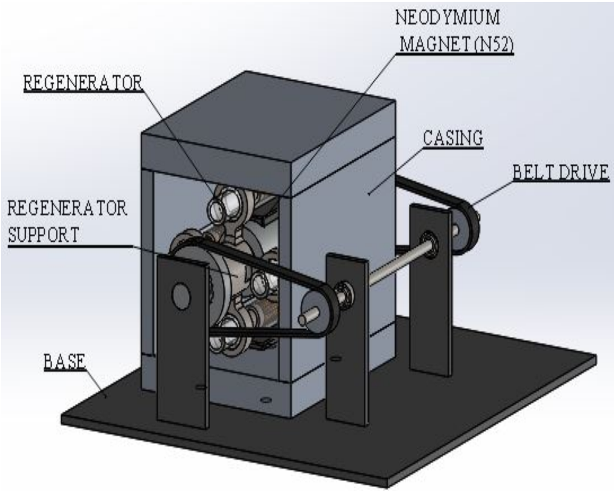

Fig.1.4 Prototype Design

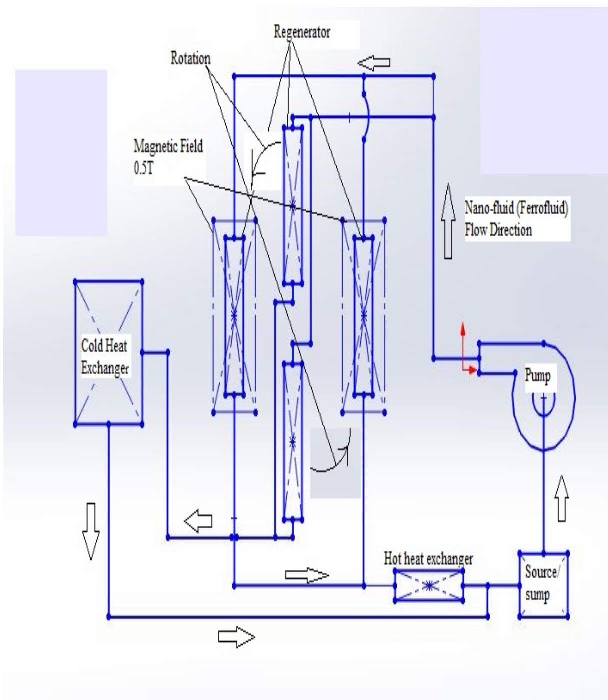

Fig. 1.5 Schematic of flow of Ferro-fluid through regenerator tubes placed in magnetic field in turns with other units like pump, heat exchangers and sump

- **Advantages of Design:**

i. 4 tubes rotating with précised timing increases the volume in which more gadolinium can be stored resulting in more heat exchange with Ferro-fluid in less time.

ii. The system is more compact and less complex making the design a more viable option in consumer market refrigeration.

- **Magneto Caloric Material**

Gadolinium: Gadolinium, a rare earth metal and exhibits one of the largest known magneto-caloric effects. It was used as the refrigerant in many of the early magnetic refrigeration systems. Pure gadolinium may be regarded as being the ideal substance for magnetic refrigeration, just like the ideal gas is for conventional refrigeration. But just as conventional systems are practically cannot be operated with ideal gases, magnetic refrigerators using pure gadolinium is also not possible and it performs better with specially designed alloys [7]. Below is the list of the promising categories of magneto-caloric materials for application in magnetic refrigerators

1. Gadolinium- Silicon- Germanium Compounds
2. Binary and ternary intermetallic compounds
3. Magnetite
4. Lanthanum iron based compounds

IV. CALCULATIONS

- Total Volume of Regenerator = $\frac{\pi}{4} \times 15 \times 15 \times 50$
  = 8835.73 mm^3
- Effective Volume of regenerator = $\frac{\pi}{4} \times 15 \times 15 \times 40$
  = 7068.58 mm^3
- Volume of Gadolinium= $\frac{2}{3} \times$ Effective Volume of regenerator = 4712.38 mm^3
- Total volume of gadolinium effective= No. of regenerators × Volume of Gadolinium
  = 4 × 4712.38
  = 1.8849×10^4 mm3
  = 1.8849×10^{-5} m^3

Therefore, Joules of Energy produced= Total volume of gadolinium * Energy density

$=1.8849 \times 10^{-5} \times 7.5 \times 10^5 = 14.13675$ J

(Since Energy density = 7.5×10^5 J/m^3 for gadolinium [9])

- Total Cycle time= 3sec

Therefore amount of heat produced per sec $=\frac{14.13675}{3}$

= 4.71225 J/s = 4.71225 W

Considering 100% efficiency in heat transfer

Amount of heat transferred to Ferro-fluid = 4.71225 W

A. $\dot{m} * C_p * \Delta T = 4.71225$ W

ṁ = Density * volume of Ferro-fluid

Density = 1.4167×10^3 kg/m^3

Volume of Ferro fluid = 0.5×Volume of Gadolinium = 0.5 $\times 1.8849 \times 10^{-5}$ m^3 $=0.94245 \times 10^{-5}$ m^3

(since the remaining volume in regenerator is half that of which is already occupied by gadolinium)

$\dot{m}$ =1.4167×10^3 kg/m^3 ×0.94245 ×10^{-5} m^3 = 13.35 ×10^{-3} kg/s
Therefore, 13.35×10^{-3} × 3×10^3 * ΔT = 4.71225W
ΔT = 0.1176 ^{0}C

Therefore a temperature change of 0.1176 ^{0}C can be easily obtained in a single pass.

Similarly, with the use of water (C_p = 4187J/Kg.K and Density =1000Kg/m^3, total cycle time =12 sec since the thermal conductivity of water is ¼ th of ferrofluid) temperature difference obtained is ΔT = 0.0210 ^{0}C in single pass

V. CONCLUSION

From above study it can be said that ferro-fluid can be a much preferred option in magnetic refrigeration when compared to water and the design proposed makes the best use of the properties of Ferro-fluid to improve the cooling effect produced by the refrigerator. The design is also compact and less complex making it more consumer friendly option.

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