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MECHANICAL ENGINEERING

MAGNETOCALORIC TEST BENCH
25% Report

Francisco Iriarte
Eduardo Garcia
Mikael Liranzo
Advisor: Professor Benjamin Boesl

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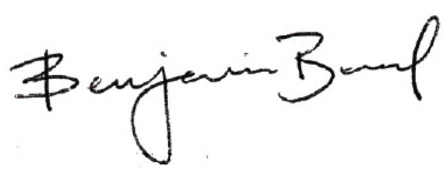
Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Francisco Iriarte, Eduardo Garcia, and Mikael Liranzo and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

Francisco Iriarte	Eduardo Garcia	Mikael Liranzo
Team Leader	Team Member	Team Member



Dr. Benjamin Boesl

Faculty Advisor

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1. Abstract

The magnetocaloric effect, also known as MCE, refers to the thermal behavior of certain materials when exposed to a magnetic field. A sample of said material is maneuvered in and out of a magnetic field and paired with various heat exchangers in order to produce a refrigeration cycle. The device was designed to serve as a test rig which allowed for easy swapping of the magnetocaloric material. Thermo-fluid analysis of the system, as well as the mechanical design of the apparatus, was performed.

The project was divided into various phases. These phases were design, analysis, and manufacturing. The design portion of the project consists of all rough sketches, calculations, and C.A.D. SolidWorks® was the software of choice for all modeling. Simulations were performed in Solidworks® and ANSYS®. Upon finalizing the design, manufacturing and optimization was performed. Testing of several magnetocaloric alloys was performed to ensure that the device functioned properly.

2. Problem Statement

Current refrigeration cycles are based on processes involving the use of compressed gasses throughout the system. These gasses are known to be harmful to the o-zone layer. Some of the more commonly used blends of these gasses are Hydro-Chlorofluorocarbon (HCFC) and Hydro-fluorocarbon (HFC). MCR (Magnetocaloric Refrigeration) rids itself of the negative effects of HFCs and HCFCs, as this is purely a solid material based operation. The solid will replace the gasses used in classical refrigeration systems, eliminating the aforementioned negative effects. The problem with current MCR systems is the use of liquid helium and liquid nitrogen to cool the solid material when it is passed through a magnetic field. The use of liquid helium and nitrogen renders such system of little use for domestic application. This is due to the danger and high cost of these fluids. The goal is to test various materials, and study their MCE. The acquired data could be used to bring MCR to the domestic market as well as to areas of the world with limited access to energy resources.

3. Motivation

The motivation for studying MCR is mainly due to the current growth in this area of research as well as the possibility of developing an alternative method of refrigeration that does not encourage the use of potentially hazardous materials. This alternative refrigeration system will be more efficient in terms of environmental awareness and human safety due to the use of non-hazardous ferrous solids as refrigerants. In addition, as far as the commercial aspect of the project is concerned, MCR shows promise in producing duplicates of the physical apparatus for multipurpose cooling applications. This would result in ease for vast commercial production, namely, house-hold refrigeration appliances or heat generation sources for small common systems such as water-heaters.

Other than the domestic involvement of MCR, another motive for the study of this process is to obtain raw values for the MCE of any solid test specimen. The device will output these numbers. This procedure will result in standardized tabulation of various ferrous materials that may be used as reference for further study or for industrial applications. Ultimately, the values obtained for the materials tested would set standardized results that may be used in the field of materials engineering.

4. Literary Survey

4.1 About MCR

The principle behind MCR is to be able to use the MCE of a desired material in order to produce a change in temperature (ΔT). This change in temperature is then manipulated by using various heat exchangers in order to produce a refrigeration cycle.

Gadolinium (Gd) has been shown to exhibit higher ΔTs when altering its ambient magnetic field in comparison to other materials that may also exhibit the MCE (V. K. Pecharsky and K. A. Gschneidner, 1997). Magnetocaloric materials, such as Gd, are ideal for such application due to the way that they behave when exposed to a changing magnetic field. Upon exposing the solid to a magnetic field, the magnetic moments within it become aligned. During this process, heat is produced as a byproduct of entropy (H. SZYMCZAK*, 2008). This heat is to be extracted from the material while it is still in the magnetic field. Keeping the sample in the field allows for the magnetic moments to remain aligned. Upon removing the sample from the magnetic field and allowing the moments to become disordered once again, the material will naturally become cooler. At this stage in the cycle, the material will be exposed to a second heat exchanger which will become cool as the material sample attempts to achieve thermal equilibrium. This cold heat exchanger is the one which will potentially serve as the cooling component of a refrigerator.

4.2 Previous Work

An understanding of modern, yet typical, refrigeration systems used in today's commercial applications is necessary before any credibility to the MCR method is given.

Once a heat load is established, the most common idea for the removal of this heat is through the basic and widely accepted thermodynamic cycle process composed of a compressor, condenser, expansion valve, and evaporator. In series, each of these components function in unison to accomplish the simple task of removing this heat load (i.e. refrigerator). The most general set-up involving the removal of this heat is illustrated through the following figure:

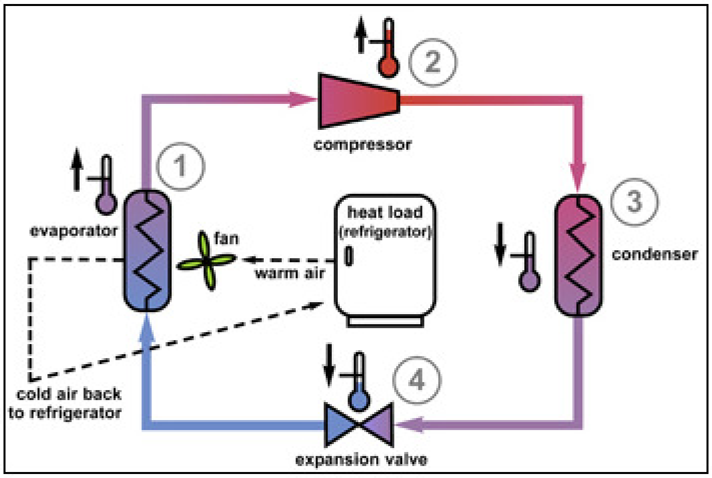


Figure 1: Classical Refrigeration Cycle (D. Liu, 2009)

Within this cycle, there is a working fluid, or refrigerant (usually fluorocarbon based), which allows for the cooling end result. This fluid flows through the compressor causing an increase in temperature due to compression. The condenser removes this heat all while maintaining the current pressure the compressor previously provided. The temperature is then dropped further at the expansion valve due to, as the name implies, expansion. This allows the working fluid to expand and enter the heat load while simultaneously removing the heat stored within through a process of forced convection (fan).

Around the year 1880, a German physicist by the name of Emil Warburg discovered the "cooling by demagnetization" phenomenon. The MCE was, at the time, only found through the use of iron. During 1926 and 1927, adiabatic demagnetization was independently introduced as a thermodynamic process by both Peter Debye and William F. Giauque. The cooling process was experimentally performed by Giauque in 1933 for cryogenic applications, where a temperature drop of .25 Kelvin was achieved. Since then, advancements in this study have been made for industrial sized applications as well as medical purposes.

In 1997, Karl A. Gschneider Jr. at Ames Laboratory developed and first "proof of concept" in-room-temperature MCR process showing a thirty percent improvement in energy efficiency in comparison to previous works in the field. This feat was accomplished through the use of the rare earth metal Gadolinium (Gd) as the refrigerant. The metal, however, was alloyed with other elements such as silicon and germanium in order to produce the maximum amount of MCE possible. This was also mainly due to feasibility in mass production of the Gd alloy commercial grade compound which only required a small amount of the rare earth metal in the alloying process. This accomplishment also made use of a “permanent” magnet, a new feature which promises the continual use of magnets within the system for continual refrigeration system applications.

4.3 Component Breakdown

4.3.1 Magnets

MCE is achieved in a solid material when it is passed through a magnetic field. The magnetic field most commonly used in industrial and laboratory application is a high magnetic field, which heightens the MCE. When the magnetic field is increased the entropy change is raised, which means the MCE has been increased (D. Baldomir a, 2007). Figure 2 shows that the block temperature shifts to lower values as the magnetic field is increased (D. Baldomir a, 2007).

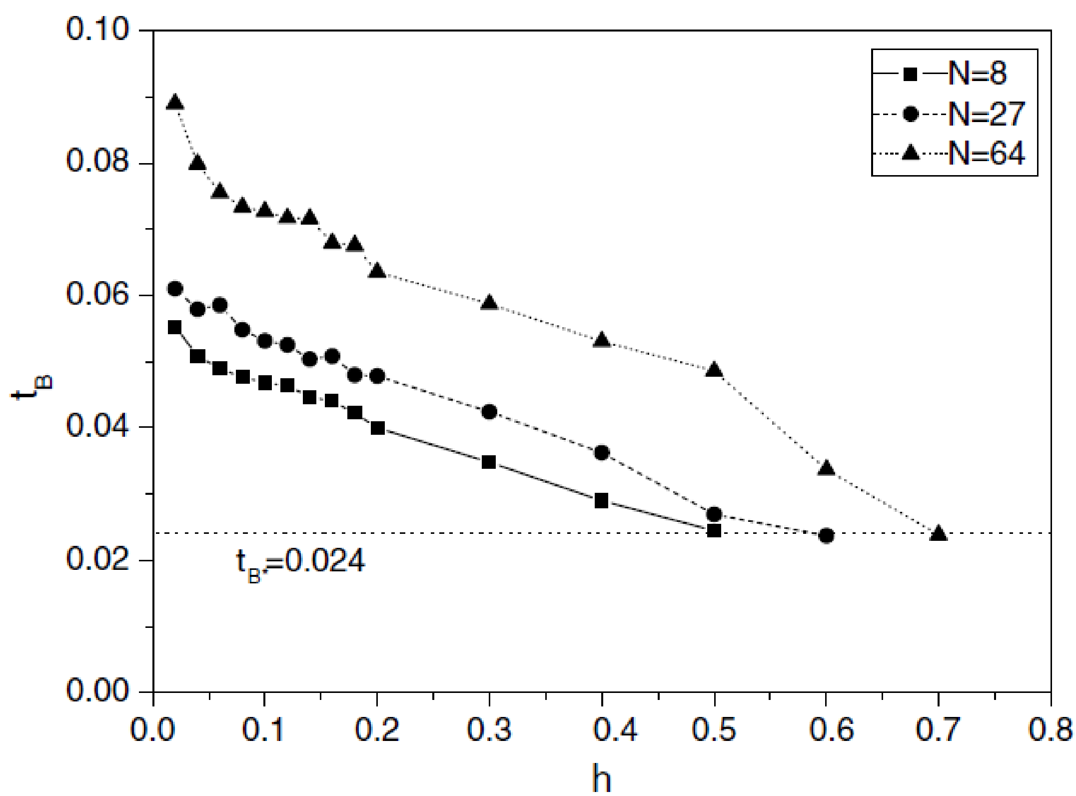


Figure 2: Temperature vs. H (D. Baldomir a, 2007)

Although a higher MCE is achieved, the heat rejection of the solid must be taken into account. The magnet themselves previously used for MCR is a permanent magnet set up or an electromagnet (Bjørk, 2010). An ideal magnet for MCR should have a high magnetic field distributed over the largest volume, while maintaining the minimum amount of magnetic material. The power difference of permanent magnet could be seen in Table 1 according to their composition (LLC, 2007).

Table 1: Properties of Magnets

	Maximum Energy Product *Bhmax(MGOe)*	Residual Flux Density *Br(G)*	Coercive Force *Hc(Koe)*	Working Temperature *ºC*
Ceramic 5	3.4	3950	2400	400
Sintered Alnico 5	3.9	10900	620	540
Cast Alnico 8	5.3	8200	1650	540
Samarium Cobalt 20 (1,5)	20	9000	8000	260
Samarium Cobalt 28 (2,17)	28	10500	9500	350
Neodymium N45	45	13500	10800	80
Neodymium 33UH	33	11500	10700	180

Permanent magnets are compact in comparison to electromagnets and do not consume any energy to produce the magnetic field. Electromagnets on the other hands, although a much higher magnetic field can be produced, the consumption of power and its mere size would counter acts its benefits in domestic use. This does not render them useless for MCR, but it would be focused more for the commercial use were component packaging is less of a problem. Permanent magnet would be the magnet of choice for this test rig to reap the benefits of their size and a decent magnetic field.

4.3.2 Heat Exchangers

There are various types of heat exchangers varying in shapes and sizes. The three most common types of heat exchangers are the coil exchanger, plate exchanger and the shell and tube exchanger. The heat exchanger is a critical component of the system as the refrigeration process would not be possible without them.

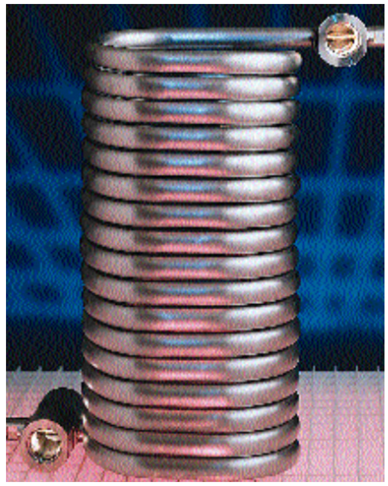


Figure 3: Coil Heat Exchanger (Bartlett, 1996)

The Coil heat exchanger (See Figure 3) has a very simple design, consisting of a coil made from a small diameter tube that it is concentrically wound around a large tube. The small tube holds the cooling fluid and the large tube holds the working fluid. A coil exchanger is a very inexpensive heat exchanger that is robust and capable of handling very high pressures and temperatures. Although inexpensive, these types of exchanger suffer from poor thermal performance due to the small surface area for heat transfer (Bartlett, 1996).

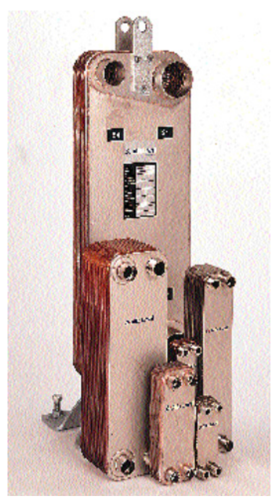


Figure 4: Plate Heat Exchanger (Bartlett, 1996)

Plate heat exchangers are types of heat exchanger that consist of plates with tubes running perpendicular to the plates (See Figure 4). The fluid is pumped through tubes and the plates being very thin and tightly stacked provide a high heat transfer rate due to the high surface area. This exchanger can only experience low pressure applications in comparison to the coil exchanger. They can withstand about 400°F and 300 psig which is considered a low pressure application (Kevin D. Rafferty, 1992).

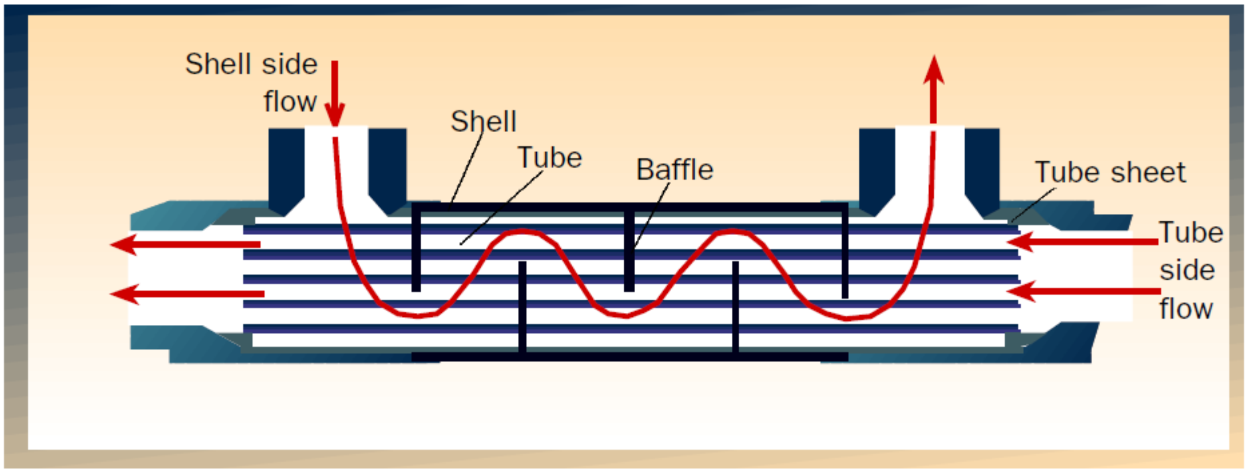


Figure 5: Shell and Tube Heat Exchanger (Bartlett, 1996)

Shell and tube exchanger (See Figure 5) are rather more complex than both the coil and the plate exchanger. Shell and tube exchanger are similar to a plate exchanger, but the stacked fins are enclosed and fluid is pumped through the containing vessel. Such exchangers are the middle ground between the coil and the plate exchangers as they provide higher pressure than the plate exchanger, but not as much as the coil exchanger. The thermal performance is lower values than the plate exchanger, but higher than coil exchangers locating it in the middle ground of the three.

4.3.3 Pumps

Centrifugal pumps operate by creating a pressure head due to an acceleration of the fluid by the impellers. The pressure is increased from the inlet to the outlet though the impellers applying kinetic energy to the fluid and in turn increasing its head. Looked at closer the inner workings of a centrifugal pump and we can see that it is a very simple concept (See Figure 6), but highly effective and inexpensive (Jacobsen, 2002).

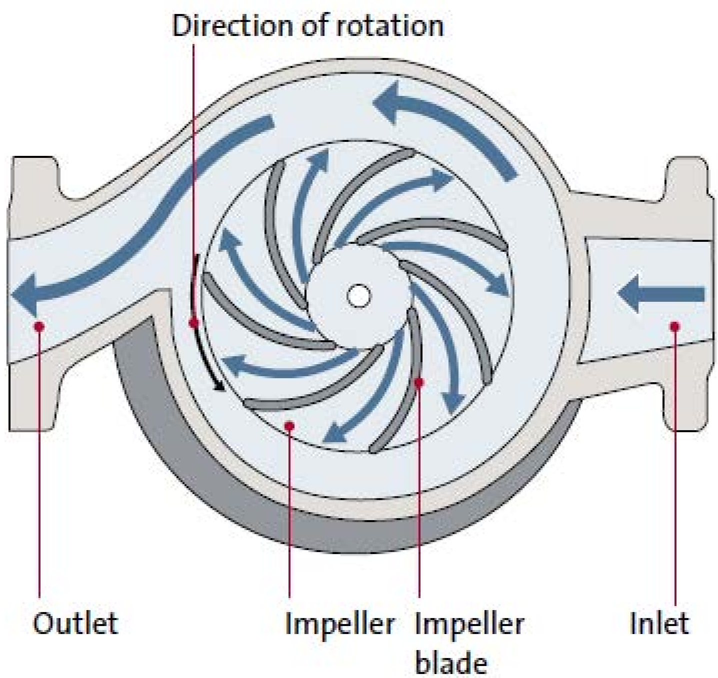


Figure 6: Centrifugal Pump (Jacobsen, 2002)

Centrifugal pumps vary in style such as inline,end suction, double pump and submersible pump. All of these types have the same working principle with slight changes in impeller design, inlet and outlet design, ect. Centrifugal pumps can be addapated to wide range of applications due to this they are very versatile, most likely making it useful for our purpose.

The main difference between a Positive Displacement pump and a centrifugal pump is the operating principle. A Positive Displacement pump creates a flow from inlet to outlet; on the contrary centrifugal pumps create a pressure. A PD pump moves a given volume at suction to discharge it and due to the working principle it maintains a constant volumetric flow in the network at various working pressures (Parker, 1994).

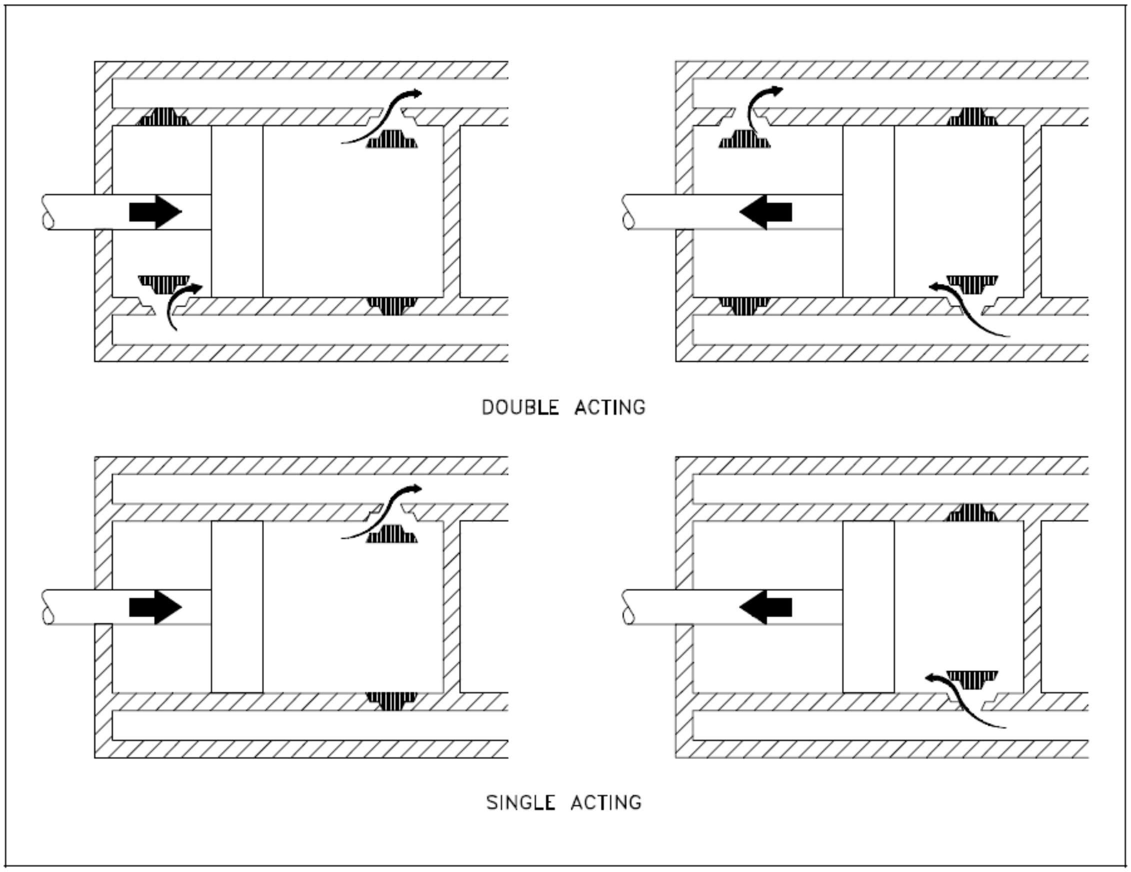


Figure 7: Positive Displacement Pump (Elie Tawil, 1993)

A PD pump has various types. Figure 7 shows two types which are the single action and double action. It could be seen that a check valve lets a set volume in and it displaced out the other valve. The double action has double check valves which allow it to have a constant discharge without pulsation of the fluid.

4.3.4 Microcontroller

A microcontroller consists of components working in unison to receive a command and through programming it will perform an action. Figure 8 shows the general layout of a microcontroller.

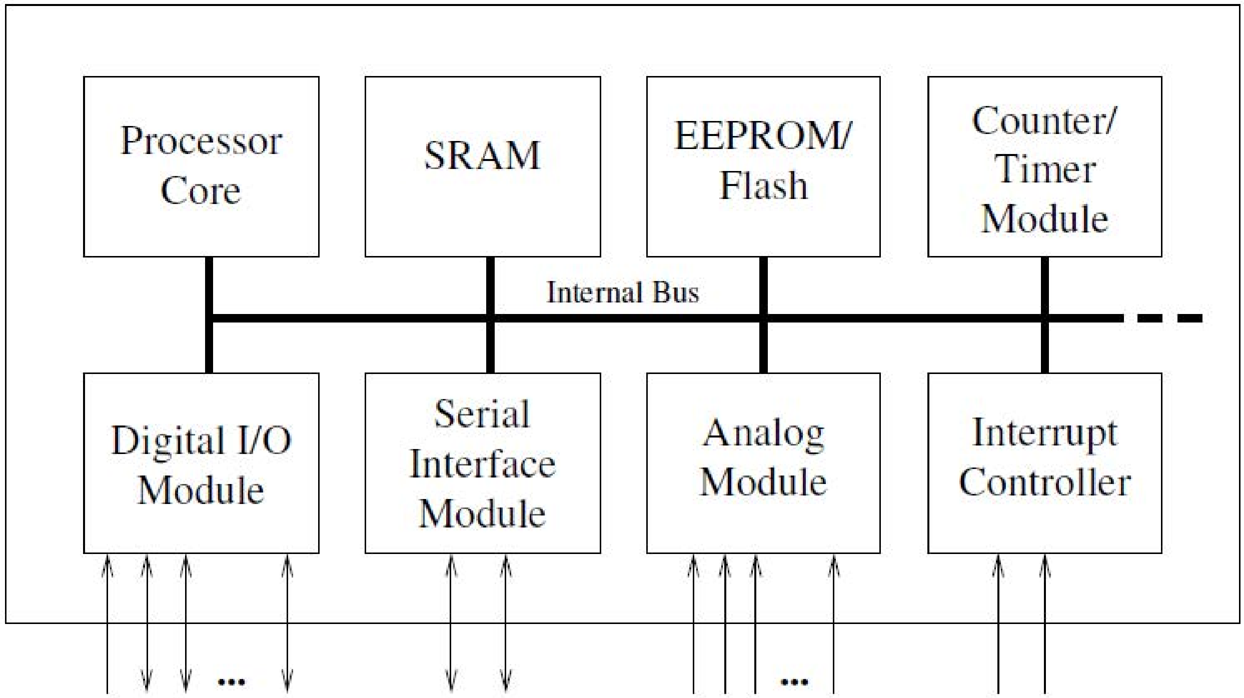


Figure 8: Basic Layout of a Microcontroller (Gunther Gridling, 2007)

The microcontroller will allow for the measurement of values which would be the input and according to the programming it will perform an operation. Microcontrollers can controller electric motors, they have the ability to control various external components without the need of a hard wire circuit. The versatility provided by microcontrollers is exceptional as any change can be performed through the programming intead of solder and wires. Also, their compactness allows their use in a wide variety of application in the field such as household appliance, automotive, aerospace and mostly any electronic that could be thought off will be using a microcontroller (Gunther Gridling, 2007).

4.3.5 Motors

The electric motor has been around for ages, one of the oldest types of electrical motor is the Barlow Wheel made by Peter Barlow in 1822 (See Figure 9).

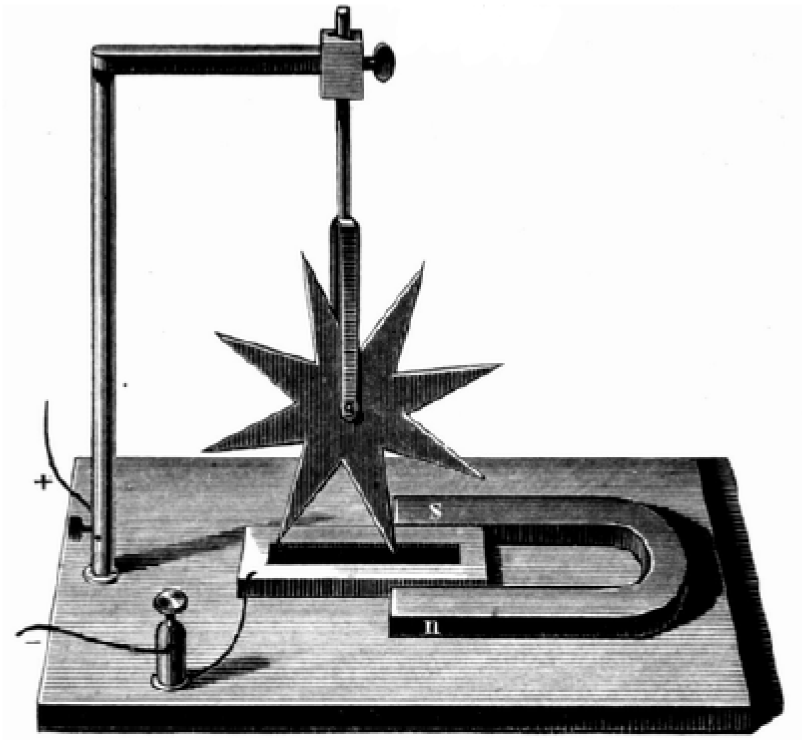


Figure 9: Barlow Wheel (Ucke, 2004)

The Barlow wheel is considered a novelty toy since it has low power and no practical application, but it shows the principle of an electric motor as it shows a continuously flowing current and continuous motion. The electric motor performs the energy conversion of electrical energy to mechanical energy. The electric motor has many different types of motor such as DC and AC current which according to each current the motors are further broken down to their types, such as a shunt motor, stepper motor, brushless motor, etc. The selection of a motor will be due to our design intent and the parameters required according to the performed calculations.

4.3.6 Thermo-couple

A thermocouple is a very simple method to attain a temperature reading using a microcontroller as the data logger. The principle of a thermocouple is rather simple, two conductors are connected in a close loop to a material, no since the material is different an electric potential is created in the closed loop. This referred to as the thermal electromotive force (Zhang, 2010). Figure 11 shows the thermal effect principle as the change in temperature could be observed. By attaining the voltage difference of the thermocouple with the microcontroller the temperature could easily be found by converting the equivalent voltage to temperature.

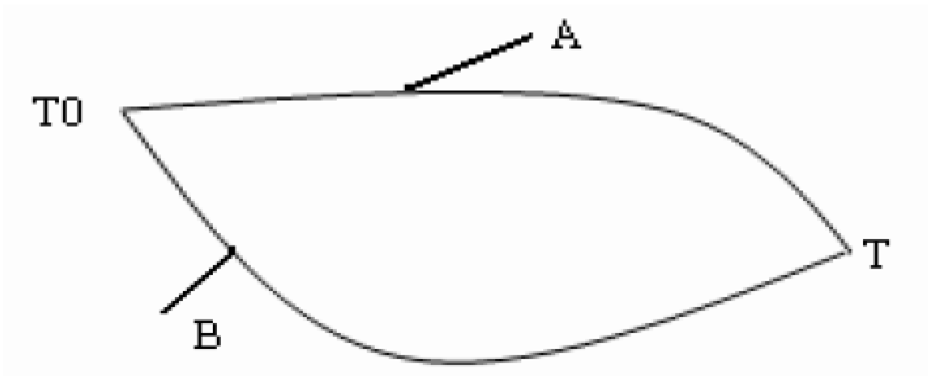


Figure 10: Thermoelectric Effect Principle (Zhang, 2010)

5. Project Objectives

The main objective of this project was to design, manufacture, and test a reliable test bench. This test bench task was to measure the MCE of materials. The device was designed in a manner which allows the operator to easily, and safely, replace the material specimen to be tested. A simple, yet efficient, design allows for the device to run cyclically with little need for maintenance. User, Repair, and maintenance manuals for the device will be provided. A display allows for the user to easily set boundary conditions for the system as desired, and doubles as a place to look for all dynamic signals coming from the various sensors within the system.

Overall, a test bench which is easy to use and reliable is what has been designed. A quick run-through of the User manual will allow anyone with slight knowledge of machinery to successfully use the device and acquire the data necessary. The option to export data to an excel spreadsheet has also been implemented in order to provide the user with a complete end user experience.

6. Designs

This project was a new experience for the team E-Mech. Various design alternatives were necessary as more research was performed, and constraints and budgets were changed. The first three designs were individually done by the team members in order to allow for each multiple design options without any bias opinions. This allowed for a wide spectrum of designs to choose from.

6.1 Design #1

The first design (See Figure 11) is a linear design where the material will reciprocate from one heat exchanger to the other. The design is composed of thermal electric plates on one extremity and a copper heat exchanger in the other with water as coolant. Figure 12 shows the location of the magnets and the thermo electric plates below for the heat rejection stage of the material.

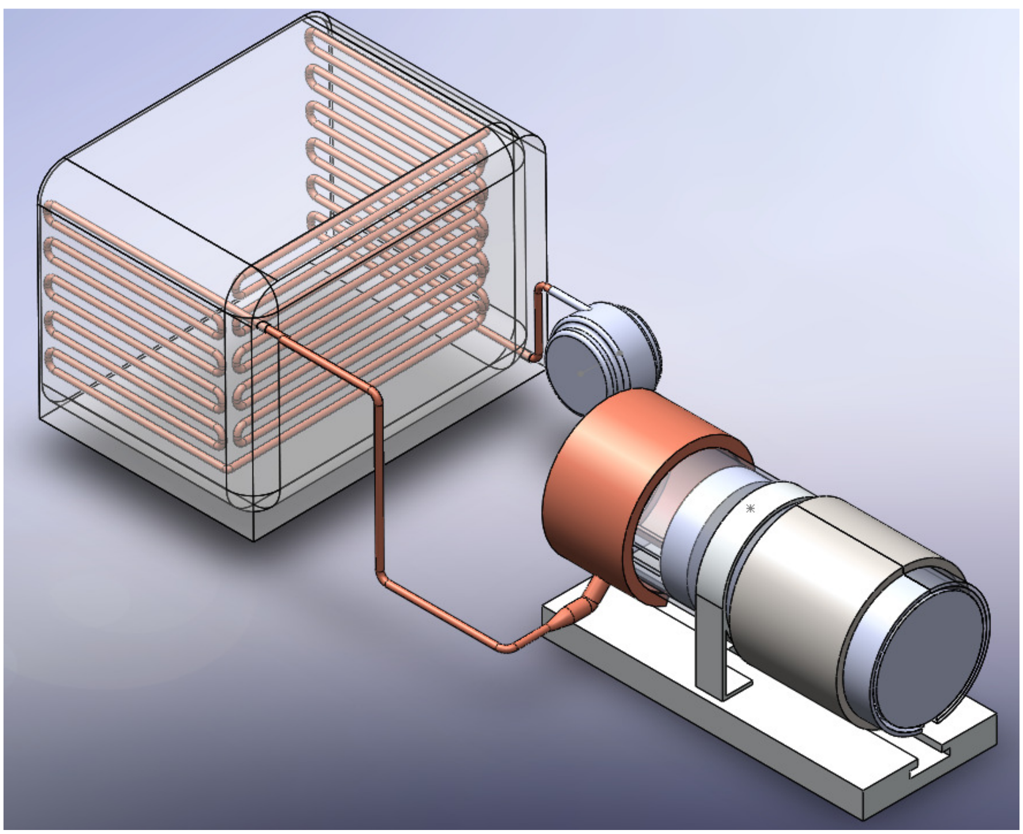


Figure 11: Design #1 (Linear-Reciprocating)

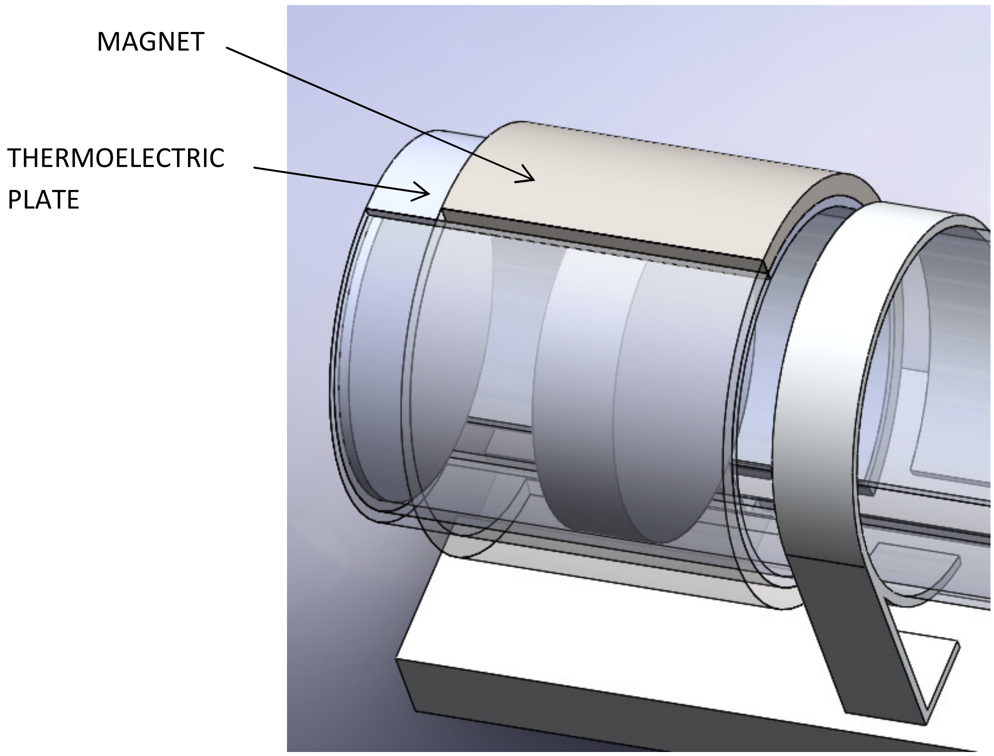


Figure 12: Magnets and Thermoelectric Plates

The advantage of this design is that the linear motion would allow the material to stay longer periods of time in contact with each heat exchanger. A higher heat removal is beneficial as it would provide a higher ΔT to use in the heat absorption stage. However, this design does not come without its disadvantages, the main one being the puck has a small contact surface area, so although contact time is increased the smaller surface area counter acts the benefits. Also, the reciprocating motion would have the material move from one heat exchanger to the other, which means that at any given time one of the heat exchangers would be consuming power without any heat transfer happening due to the material current position.

6.2 Design #2

Design #2 (Figure 13) uses circular motion where the material is spun through various chambers. The benefit of this design is that a circular motion allows for a larger surface area of contact with the heat exchanger in comparison to design 1. Also, the motion mechanism would decrease cost as all that it is required is an electric motor attached to an arm.

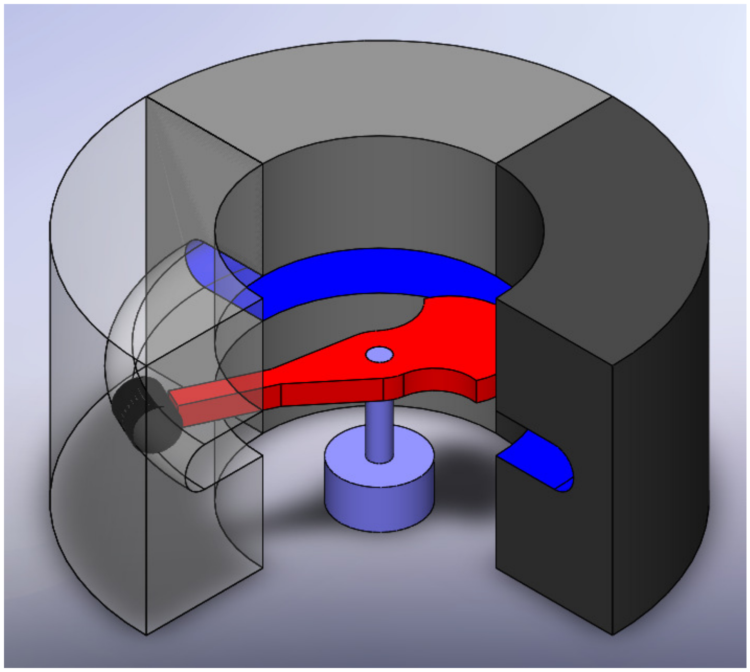


Figure 13: Design #2 (Rotary)

The enclosing chambers (Figure 14) insulate the system making a semi hermetically sealed system giving more accurate results towards the ΔT of the material. Consequently, this design suffers from the same issue as design one were at any given time one of the heat exchangers is not doing any heat transfer. This design would be very labor intensive due to the curved chamber and it would have a high cost as well because of a mold needed to form the chambers.

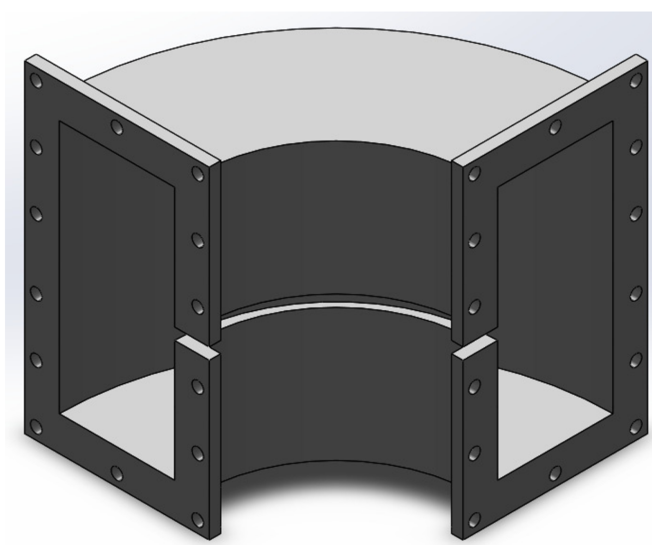


Figure 14: Enclosing Chamber

6.3 Design #3

A rotational approach was taken with this design as well, but using a shift of chamber shape was done. Design 3 (Figure 15) uses the circular chamber approach which gives the benefit of easy manufacturability due to readily available tubes. It being a rotational motion, it will allow for a simple mounting mechanism as well as high surface area for convective heat transfer.

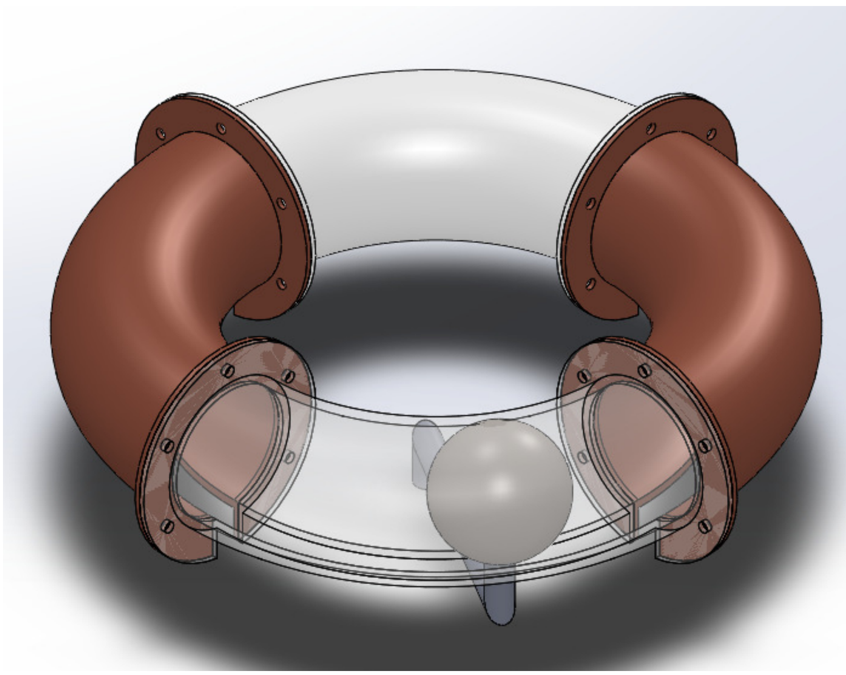


Figure 15: Design #3 (Rotary)

The disadvantages of this design are the complexity of molding the material specimen into a sphere, surface stress created when magnetized due to the spherical shape, and small surface areas closely in contact with the heat exchangers.

6.4 Final Design

The final design (Figure 16) was not any of the previous mentioned designs, but rather a design where the advantages of all three initial designs were implemented and the disadvantages minimized.

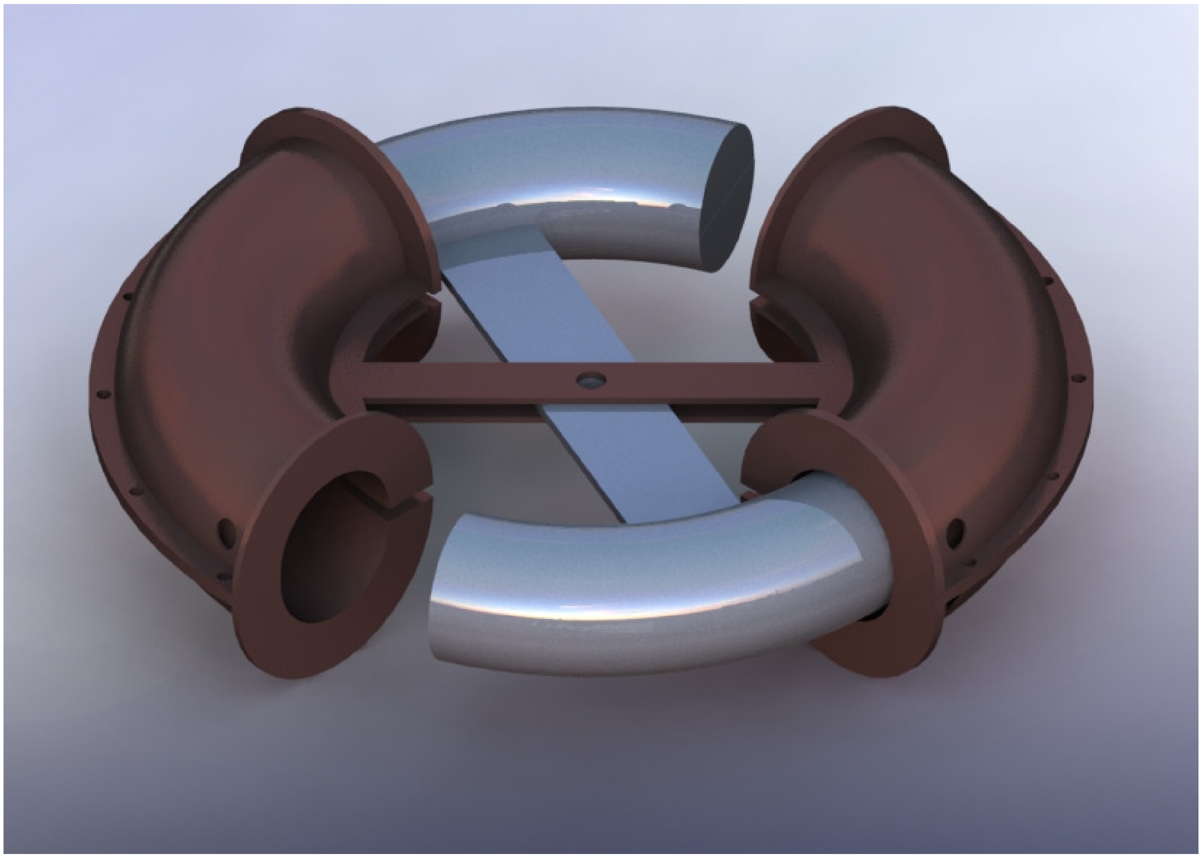


Figure 16: Final Design (Rotary)

The advantages the final design gave were substantially greater than all other previous designs beginning with the movement mechanism. As seen in figure 16, a circular approach was taken due to the simplicity of the mechanism to put the material in motion. Furthermore, using a tubular design allowed for ease of manufacturability since copper pipes are readily available commercially. Material shape wise, disadvantages spread through three designs were manufacturability issues, low surface area and surface stress due to the curved shape. Figure 18 shows the improved material shape as this would be easy to cast, high surface area for heat transfer and the double material opposing each other would make both heat exchanger transfer heat at any given time.

Figure 17: Material Specimen

The design uses Neodymium magnets (figure 19) of .125 in diameter and .063 in thick. The inside of the chambers will be lined with the magnets for the magnetization stage. These magnets produce a flux density in range of 1.25 to 1.28 Tesla which is a decent flux density for our purpose (Magcraft, 2013).

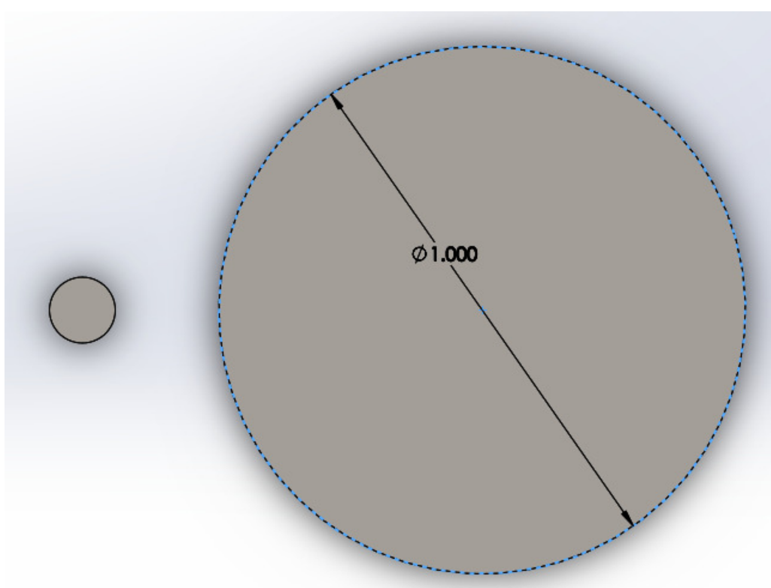


Figure 18: Size comparison of Magnet to 1" Circle

The heat exchanger for this design will be plate heat exchangers as mentioned previously they have a very high thermal performance. Our system is a low pressure, high flow application which would dictate the why a plate heat exchanger (Figure 19) was chosen.

Figure 19: Plate Heat Exchanger (Bartlett, 1996)

7. Analytic Analysis

7.1 Material Selection

The material selection for this project is critical as the heat rejection and heat absorption are the two most critical stages of the process. The material must have a high thermal conductivity to allow the most heat transfer as possible. Table 2 shows various materials and their thermal properties and it could be seen that the thermal conductivity of copper is substantially greater than the other materials in the table. Although this table does not provide all the possible materials it does show the materials currently used for microprocessor, which they have the same goal as us, transferring as much heat as possible. We must also consider an insulator material due to the fact that when the material is not in the heat exchanger, the heat transfer needs to be minimized. The thermal conductivity K is the most critical property of the material. Also, the material must not degrade and have a long use life before replacement as the cost for maintenance should be the lowest possible or nearly nonexistent.

Table 2: Thermal Properties of Materials

Item	Material	Characteristic Dimensions (mm)	Characteristic Thickness (mm)	Thermal Conductivity (W/m-K)
MOSFET (IXFD21N50)	Silicon	8.84 x 7.19	0.425	118
DBC Ceramic Substrate	Alumina (Al_2O_3)	28.45 x 27.32	0.635	26
DBC Base	Copper	28.45 x 27.32	0.3	395
DBC Traces	Copper	N/A	0.3	395
Hybrid Gate Driver	Alumina (Al_2O_3)	21.08 x 8.51	0.635	26
Ceramic Frame	Alumina (Al_2O_3)	27.32 x 25.4	0.625	26
Dielectric Layer	Polyimide	N/A	0.125	0.3
Epoxy Interface	Epoxy	N/A	0.3	1.4
Gap Filler	Silicone Gel	N/A	0.254	0.2
Chip Attached	Solder	N/A	0.127-0.475	51

7.2 Heat Exchanger

The heat exchanger as mentioned in the previous section makes it into the critical component list as the thermal performance of the heat exchanger is critical. Choosing a heat exchanger must first be analyzed by what application it will be used in. Our application requires a high thermal performance and low pressure heat exchanger which would make a plate heat exchange ideal. The fluid fundamentals for heat transfer are largely due to the fluids characteristics such as the density, specific heat, thermal conductivity and viscosity. One of the major dependencies is fluid flow as inside a heat exchanger the flow could be laminar or turbulent. A laminar flow uses solely the thermal conductivity of the fluid in comparison to turbulent flow which produces a higher heat transfer (Bartlett, 1996). The governing equation for fluid flow is Reynolds number:

$$Re = \frac{\rho * v * D}{\mu}$$

Where the v is the fluid velocity, D is the tube diameter and u is the dynamic viscosity of the fluid. A Reynolds number higher than 4000 is considered turbulent flow, but although turbulent flow provides higher heat transfer it will affect the pressure drop through the heat exchanger requiring more pumping power. The heat exchanger is governed by the balance equation:

$$\dot{Q} = \dot{m} * C_p(T_{out} - T_{in})$$

The balance equation must be balance meaning that the heat transfer from the hotter fluid to the colder fluid must be equal to each other. The mass flow rate m dot is what would allow for a higher heat transfer as a larger mass flow rate through the exchanger would result in a higher heat transfer (Bartlett, 1996). It must be known that more mass flow equals more expensive pumps, higher turbulence in the flow and higher pressure drop through the heat exchanger meaning that a compromise must be reached before any specific heat exchanger is selected.

The effectiveness of the heat exchanger or better known as the efficiency for the heat exchanger is given by:

$$\varepsilon = \frac{(\dot{m} * C_p)_{hot} * (T_{in} - T_{out})_{hot}}{\left(\dot{m} * C_p\right)_{min} * (T_{in\,hot} - T_{in\,cold})}$$

The denominator of the equation is the maximum heat transfer rate of the heat exchanger (Bartlett, 1996). Figure 20 shows how the temperature changes according to the length of the exchanger and the effectiveness.

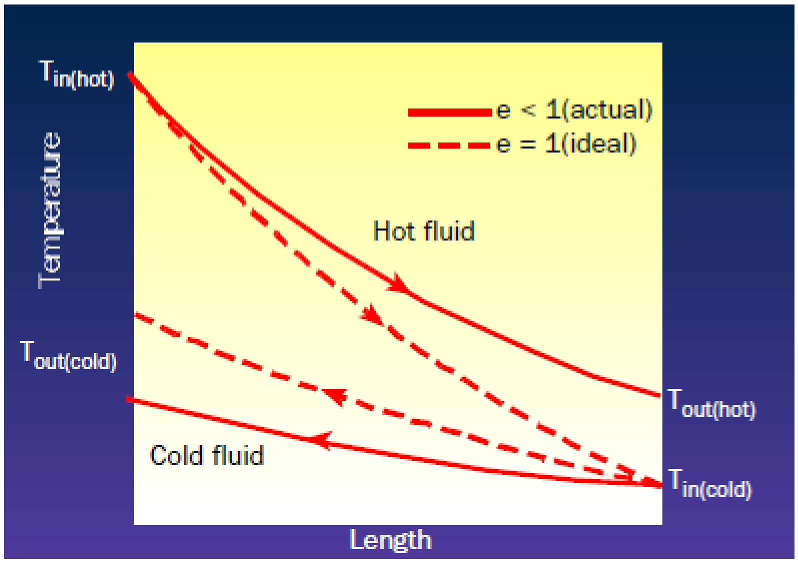


Figure 20: Stream Temperature through a Heat Exchanger (Bartlett, 1996)

The thermal performance of the heat exchanger is calculated by:

$$\dot{Q} = U * A * \frac{(T_{in\ hot} - T_{out\ cold}) + (T_{out\ hot} - T_{in\ cold})}{2}$$

where U is the heat transfer coefficient and the heat exchanger area (Bartlett, 1996). The heat exchange from the material to the exchanger will happen through convection and radiation as the material spins inside the tube. The convection equation is:

$$\dot{Q} = h(T_{hot} - T_{cold})$$

And to figure out the total transfer to the fluid a thermal resistance equations are used to find out the heat transfer.

7.3 Pump

In order to pick and choose a specific pump that is compatible with the MCE tester, a couple of preliminary calculations need to be assumed before the actual acquisition of it. The method in choosing a pump calls for preliminary assumptions as follows such as knowledge of the volumetric flow rate, working fluid, and the ambient pressure the MCR system will be working under. Given these parameters, selection of the pump in terms of horsepower is governed by equation:

$$HP_{min} = \frac{\frac{\text{GPM} * \text{PSI}}{1710}}{\eta}$$

This equation provides the engineer with horsepower from which a particular pump may be chosen from any catalog with respect to English units. GPM is given as gallons per meter and PSI is a value of pressure given as pounds per square inch.

8. Major Components

The design and build of the MCE testing machine features high influencing components crucial to the functionality of the refrigeration cycle. In other words, without the full contribution of certain elements in the design, the system will not function as expected. The components that are termed as “major” are:

- Heat Exchangers
- Magnets
- Electronics
- Pump

8.1 Heat Exchangers

This device is used as a storage unit to transfer heat by convection using water as a medium. The determining factors for choosing the correct heat exchanger is the total head produced by the system as well as the volume flow rate desired for the fluid. The most efficient type of heat exchanger for this MCE application would involve the use of plated heat exchangers (See Figure 4) since the system would not essentially produce large differences in pressure but will involve varying volumetric flow rates. Considering the small size of the apparatus, high end heat exchangers are not necessary.

8.2 Magnets

The focus of this project centralizes on the use of magnets. Magnets are what define the unique processes within the MCR cycle. Most Magnetocaloric Refrigeration systems contain magnets capable of changing the intensity of their magnetic field. However, for the current task of developing a testing apparatus that will periodically run for lengthy periods of time For this case, the use of permanent magnets will used. Neodymium magnets provide the highest flux density and maintain a constant magnetic field at all operational temperature making it the only candidate in magnetic material.

8.3 Electronics

Arduino packages will be used to display temperature on a screen as well as send signal in order to operate motorized components of the system. For this to work, circuits will have to be constructed after detailed planning of the circuit diagram. This portion of the prototype will be looked over and designed by an Electrical Engineer.

8.4 Pump

In order for any heat transfer to occur, a working fluid such as water needs to flow through a path that will enable it to extract heat from a source. This flow however is produced by a pump. The pump that is used in this design of MCF is a centrifugal pump. The testing apparatus, due to the applications and conditions, the centrifugal pump is preferred due to the system's low viscosity flow for water and the relatively low cost. Choosing the pump is also dictated by the amount of fluid flow needed to be forces into the pipe system for heat transfer.

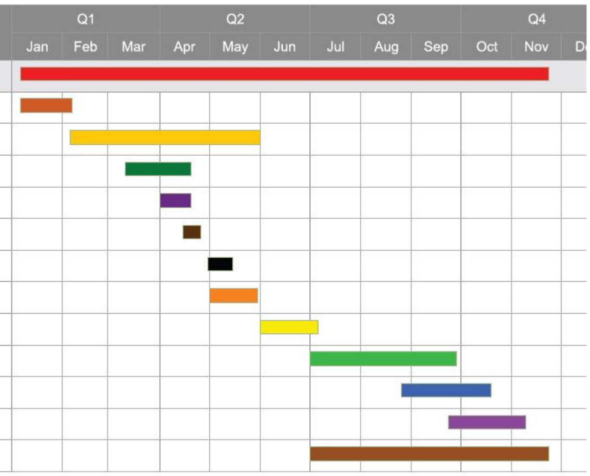
9. Project Management

9.1 Labor and Time Management

Table 3 shows a Gantt chart depicting the major phases of the project as well as the delegation of work divided amongst the team members.

Table 3: Project Timeline & Division of Labor

Task Name	Members	Start Date	End Date
Magnetocaloric Refrigeration		01/07/13	11/22/13
Project Formulation	EG-ML-FI	01/07/13	02/06/13
Research & Development	EG-ML-FI	02/06/13	05/31/13
Conceptual Design	ML-FI	03/11/13	04/19/13
CAD Model	EG	04/01/13	04/19/13
Software Simulation	ML-FI	04/15/13	04/25/13
Proof of Concept	ML	04/30/13	05/14/13
Design Optimization	EG-ML-FI	05/01/13	05/29/13
Component Testing	FI	06/01/13	07/05/13
Prototype Fabrication	EG-ML-FI	07/01/13	09/27/13
Prototype Testing	EG-ML-FI	08/26/13	10/18/13
Prototype Optimization	EG-ML-FI	09/23/13	11/08/13
Final Report	EG-ML-FI	07/01/13	11/22/13



9.2 Cost Analysis

In determining the cost for the development of the magnetocaloric effect testing apparatus, three categories which would best sum up and take into account the amount of work and cost necessary are as follows:

- Travel
- Materials
- Manufacturing

9.2.1 Travel

This category involved investing in round trip to Ames, Iowa for all E-Mech team members. The flight to Iowa was proposed in order to greet and meet the members responsible for a similar MCR cycle stationed at the Ames Laboratory. Generally, this idea was primarily used to motivate and facilitate growth in team spirits in order to build a common interest for the task of developing the MCE tester. Visiting the Ames Laboratory also provided deeper understanding on the subject, servicing as a reference aid in development of the MCR cycle.

9.2.2 Materials

The bulk of total cost belonging to the designing and prototyping E-Mech's MCR system is taken up mostly by this category. Various metals and machines such as motors as well as circuit boards are included in this cost analysis. All materials will, with the exception of the working MC material, are purchased through various distributors across the United States. Some of these distributors include Speedy Metals, McMaster, and Online Metals. The most expensive piece of material taken into consideration above all other accompanying components are the previously mentioned curved copper tubing, seeing as thought the alloyed copper tube has a relatively high market value. The next costly items to consider in terms of importance are the hot and cold heat exchangers for which there is only one of each. In the case where either of the these components is to ultimately fail or become unusable, although relatively low in price, the resultant cost for disassembly and reassembly of the system in reinstalling the heat exchangers would require the purchase of additional copper tubing in addition to purchasing new heat exchangers. Thus, the value of importance that each major component contributes to the cooling system greatly affects and directly links to the total monetary value of the design.

9.3.3 Manufacturing

There are certain accommodations unique to the final design of the MCR cycle that requires customized manufacturing of specific components. For example, the curved copper tubing utilized as a medium for convective heat transfer is has an axially-curved geometry that cannot be, by any other means, purchased or obtained commercially. In this case, the cost in manufacturing this piece increases in addition to the purchased price for the material itself. Examples such as these are found in other components of the cooling system that have small, detailed and or complex geometric features. Although this challenge increases the resultant cost, precise and professional custom manufacturing reduces the work load and relaxes the amount of taken in completing the task of prototyping the MCE tester prototype.

Table 4 is the representation of the approximate cost analysis taken from the trip and materials section which includes only general information of the major components used in the MCE tester design.

Table 4: Projected Estimated Cost of Project

Travel			
Description	Qty.	Price (EA)	Total
Round Trip	3	$648.00	$1,944.00
Material			
Description	Qty.	Price (EA)	Total
Copper Tube **ID**: 3in - **L**: 4ft	1	$489.00	$489.00
Copper Tube **OD**: 3.5in - **L**: 4ft	1	$200.00	$200.00
Copper Tubing	2	$50.00	$100.00
Copper sheet	2	$100.00	$200.00
Steel sheets	1	$80.00	$80.00
Hot Heat Exchanger	1	$200.00	$200.00
Cold Heat Exchanger	1	$200.00	$200.00
Pump	1	$150.00	$150.00
Motors	1	$30.00	$30.00
Arduino	1	$80.00	$80.00
Thermocouples	4	$30.00	$120.00
Total Estimated Cost			$1,849.00

The physical cost of research, design, and prototyping as opposed to the financial aspect of the project is also taken into account. This analysis gathers, in detail, the number of hours dedicated into and up to the development of the Magnetocaloric Effect Tester. Generally, this time study may very well simulate the amount of work hours in an industrial-type setting. Table 5 illustrates, in detail, the collective project hours dedicated to the MCE Tester.

Table 5: Projected Time Spent on Project

Category	Task	Hours	Total Hours
Research	MCE Applications	4	61
	MCE Materials	8	
	MCE Process	18	
	MCR Components	15	
	MCR Designs	8	
	Trip: Ames Labs, Iowa	8	
Design	Individual Concept Design	15	129
	Team Design Meeting	30	
	Design of Mount Station	8	
	Final Design	10	
	Design of Chambers	8	
	Design of Heat Exchangers	8	
	Design of Enclosure	4	
	Design of Test Piece Implementation	8	
	Design of Arduino Implementation	12	
	Design of Temperature Reading	6	
	CAD Modeling	20	
Prototyping	CAD Simulations	15	128
	Construction of MCE Station Mount	6	
	Construction of MCE Chambers	24	
	Modification of Heat Exchangers	8	
	Construct Material Mount	8	
	Build Circuit	20	
	Building The Enclosure	12	
	Installing Thermocouples	3	
	Test Apparatus	20	
	Modifications to Apparatus	12	
Reports & presentation	Senior Report	40	77
	Presentations	20	
	Rehearsals	4	
	Drawings	3	
	Poster	10	
Total Amount of Hours			395

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