FABRICATION OF SMA BASED HOT WATER ACTUATED HEAT ENGINE

M.Tech. Thesis

By

AKASH LAHARIA

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

MAY 2017

FABRICATION OF SMA BASED HOT WATER ACTUATED HEAT ENGINE

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

Master of Technology
in
Mechanical Engineering
With specialization in
Production and Industrial Engineering
by
Akash Laharia

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

MAY 2017

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **FABRICTION OF SMA BASED HOT WATER ACTUATED HEAT ENGINE** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from August 2015 to May 2017 under the supervision of Dr. I.A.Palani, Associate Professor, IIT Indore and Dr. Vipul Singh, Associate Professor, IIT Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Akash Laharia

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

Dr. I.A.Palani **Dr. Vipul Singh**

Akash Laharia has successfully given his M.Tech. Oral Examination held on **22th May 2017**.

Signature(s) of Supervisor(s) of M.Tech. thesis
Date:

Convener, DPGC
Date:

Signature of PSPC Member #1
Date:

Signature of PSPC Member #2
Date:

Acknowledgement

I am highly indebted to Dr. I.A. Palani, for believing in me to carry out this work under his supervision. His friendly interactions, encouragement and constructive support have enabled this work to achieve its present form. His innovative perspective towards things and his continuous pursuit for perfection has had a profound effect on me and has transformed me majorly. It feels privileged to be one of his students.

I am grateful to Dr. Vipul Singh, for his recommendations during the time of presentations so as to incorporate them for improvement of design. Discussions with him have been extremely knowledgeable and have significantly shaped this thesis.

I am thankful to IIT Indore for giving me an opportunity to carry out the research work and providing all the facilities. Very special thanks to Prof. Pradeep Mathur, Director, IIT Indore, for supporting and providing us facilities to perform my work smoothly here.

I am extremely thankful to Mr. Tameshwer Nath for guiding me and helping me out from the very first day I joined this project. I would also like to express my thanks to all members of Opto-Mechatronics group for their moral support and the friendly nature we have created in our lab. A heart-felt thanks to my entire M.Tech 2017 Batch for their support. I am thankful to Mr. Ravi Gujrati for his help in experimentation in later part of the project. Lastly I would like to express my gratitude for my parents, for letting me choose my dreams and supporting me endlessly. Your support made this work possible.

Akash Laharia

Dedicated to my Guides –

My parents,

My sister

and my friends.

Abstract

Shape Memory Alloys (SMA's) were invented many years ago, though using of SMA in applications related to engineering is only prominent from last few years. Reason behind using SMA is its ability to change its crystalline structure by applying a temperature gradient. Its simultaneous memory effect and elastic behavior makes it suitable for applications involving actuation and control. In this process of finding application of this interesting material, a device for conversion of waste heat into work could be of utmost importance. In this work SMA is employed for conversion of waste heat energy into mechanical work.

A typical power plant works on Rankin's cycle with condenser temperature of around 70°C thus we need to maintain temperature at condenser by circulating water which gets heated to around 55 to 60 °C. This 60 °C water is waste energy which can be utilized for getting some work output. SMA with its property of hot water actuation is utilized for conversion of heat energy into mechanical work. In later part of work exhaust gases from automobile is used for actuation, and thus serving purpose of waste heat recovery.

SMA (NiTi) springs are used for conversion of heat energy into mechanical work. The design of setup is simple and inexpensive involving very less expenditure. The prototype is tested multiple times and it is serving the purpose of conversion of energy and acting like a **Heat Engine**.

The design consists of Nitinol springs connected radially to a steel rim with a hub (serving purpose of bearing) in middle. When this setup is inserted in hot water of around 60°C the steel rim starts rotating thus serving purpose of converting waste heat into mechanical work.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

1.1 Shape memory alloys

Shape memory alloys (SMAs) are materials possessing ability to regain their original shape when a particular stimulus is applied. Unlike other metallic materials, SMA's undergo large amount of deformation without permanent deformation. This material is a lightweight, solid-state alternative to conventional materials. SMAs have applications in robotics, biomedical and aerospace Industry[1].

As wire, deformation usually involves elongation, where shape recovery is the contraction back to a pre-stretched length. The effect, due to changes in the material's crystal structure, is unrelated to thermal expansion and contraction among the smart materials currently in research. These materials possess property to remember their original shape. This property is due to Crystal structure transformation.SMA material consists of two phases; High temperature phase (Austenite) and low temperature phase (Martensite). This property of transformation from one phase to another is termed as "**Shape memory effect**". Nitinol (NiTi) is widely used SMA material possessing excellent Shape memory behavior.

A reversible, solid phase transformation known as martensitic transformation is the driving force behind shape memory alloys. In case of Nitinol when nickel and titanium atoms are present in the alloy, in a given proportion, the material forms a crystal structure, which is capable of undergoing a change from one form of crystal structure to another. Temperature change or/and loading initiate this transformation.

Thus Shape memory alloy with its special properties can be used in applications involving actuations. Key features of products that possess this shape memory property include: high force during shape change, large movement with small temperature change, a high permanent strength, simple application as no special tools are required; many possible shapes and configurations and easy to use. All these properties make shape memory alloy a material which can be used for solving wide variety of problems.

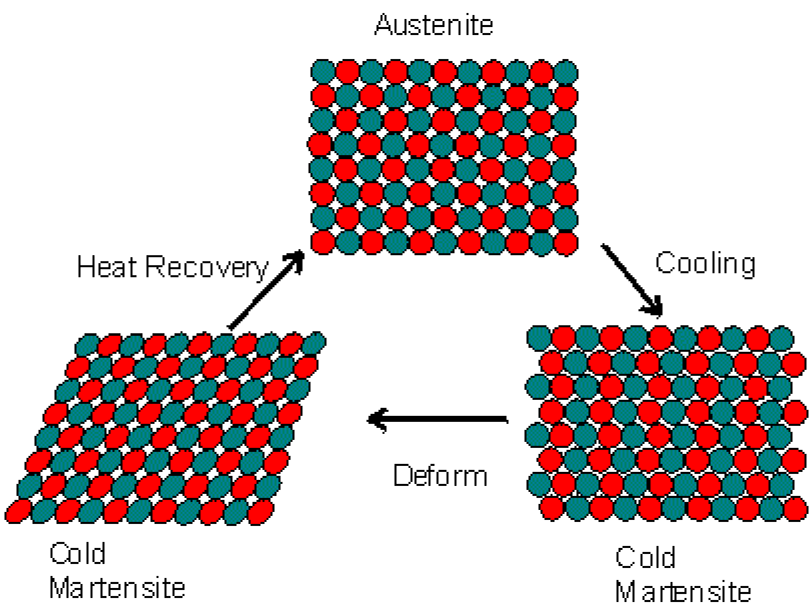


Figure 1 Crystalline arrangement of SMA in different phases (Wikipedia)

The main advantages of NITINOL include high power density, huge displacement, large actuation force, low operation voltage. The use of smart materials such as shape memory alloys is becoming increasingly popular in robotics due to their resemblance to muscles and their biocompatibility. Also its use in actuators has gained popularity, especially in low volume constraint applications, such as medical catheters, stents (thin wires, mesh form) [1] laparoscope surgical tools (patterned tubing, wires) micro- robot actuators (coiled wires) and Industrial applications.

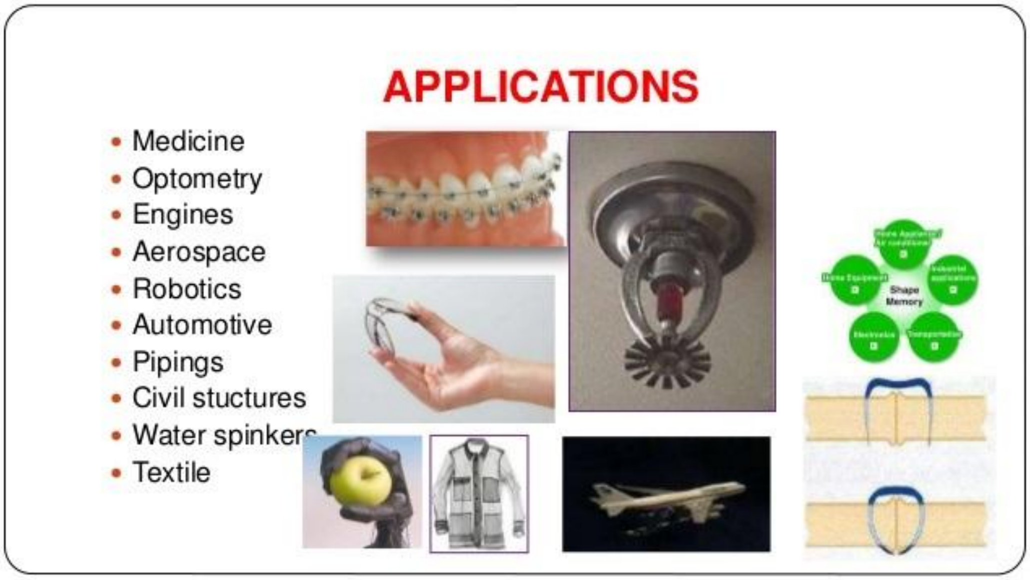


Figure 2 Applications of Shape Memory Alloys (SMA) (Wikipedia)

1.1.1 History

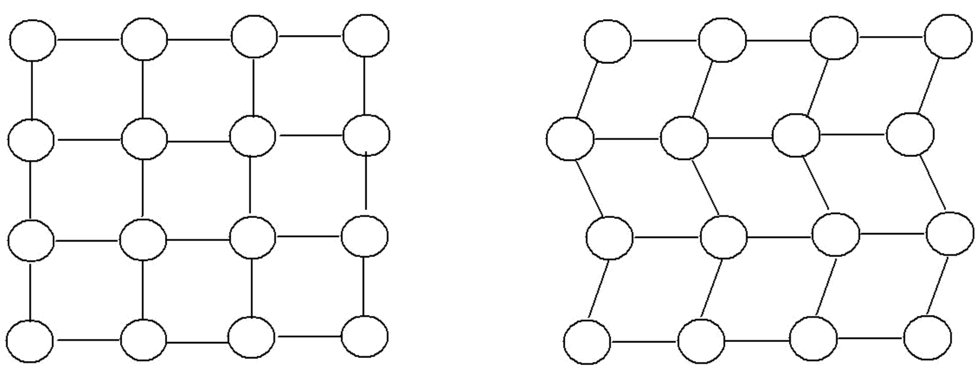
The origin of shape-memory effect in certain alloys dates back to year 1932, when a Swedish researcher named Arne Olader first observed the property in gold-cadmium alloys. The material was deformed when cool, returned to its undeformed state when warmed. Different types of materials since then have been discovered. Some of examples are NiTi,InTi,CuSn,CuAlNi and CuZnAl.

Among all of these stated materials Nickel-titanium alloys (Also known as Nitinol) have been found to be the most useful of all SMAs because of their stable nature, ease in actuation and better thermo-mechanical response. In 1961, Nitinol, which stands for Nickel Titanium Naval Ordnance Laboratory, was discovered to possess the unique property of having shape memory.

William J. Buehler, a researcher at the Naval Ordnance Laboratory in White Oak, Maryland, was the one to discover this shape memory alloy. The actual discovery of the shape memory property of Nitinol came about by accident. At a laboratory management meeting, a strip of Nitinol was presented that was bent out of shape many times. One of the people present, Dr. David S. Muzzey, heated it with his pipe lighter, and surprisingly, the strip stretched back to its original form.

1.1.2 Crystal Structure

Nitinol consists of two phases. These phases, known as martensite and austenite, involve the rearrangement of the position of particles within the crystal structure of the solid. A reversible, solid phase transformation known as martensitic transformation is the driving force behind shape memory alloys. When nickel and titanium atoms are present in the alloy, in a given proportion, the material forms a crystal structure, which is capable of undergoing a change from one form of crystal structure to another. Temperature change initiates this transformation. This change involves transition



(a)High temperature austenite cubic structure **(b) Low temperature martensite(twinned)**

Figure 3 (a) and (b): The Crystalline Structure of Martensite and Austenite Phase (Hodgson, 1988)[2]

from a monoclinic crystal form (martensite) to an ordered cubic crystal form (austenite). The austenite phase is stable at high temperature, and the martensite is stable at lower temperatures.

Martensite phase is low temperature soft phase whereas austenite phase is high temperature hard phase. In the martensite phase, Nitinol can be bent into various shapes. In the martensite phase, atoms orient themselves in rows that are tilted left or right. We refer to this phenomenon as twinning, because the atoms form mirror images of themselves or twins. The martensite twins are able to flip their orientation, in a simple shearing motion, to the opposite tilt, creating a cooperative movement of the individual twins. This results in a large overall deformation.

When martensite phase is heated above transition temperature, the high temperature actuates the atoms to arrange them into the most compact pattern resulting in a rigid cubic arrangement known as the austenite phase. Above the transition temperature, Nitinol reverts from the martensite to the austenite phase which changes it back into its parent shape. This cyclic phase transformation phenomenon is basis of shape memory behavior.

1.1.3 Shape Memory behavior

1.1.3.1 Shape memory effect

Shape memory effect is of two types, one way effect and two way effect. The one way effect is characterized by a deformed specimen changing shape when heated. Cooling has no effect on its shape, since shape change only occurs during heating, the process is called one-way shape memory.

In two-way shape memory effect, sample exhibits one shape when cold, change to a second shape when heated and return to its original shape when cooled again. At temperatures below the transformation temperature, shape memory alloys are in martensite phase. The martensite is soft and can be deformed quite easily by de-twinning. Heating above the transformation temperature recovers the original shape and converts the material to its high strength, austenitic condition.

1.1.3.2 Superelasticity

Superelasticity is an elastic (reversible) response to an applied stress, caused by a phase transformation between the austenitic and martensitic phases of a crystal. It is exhibited in shape-memory alloys. A second characteristic, closely related to shape memory, is super-elasticity. When SMA material is above some critical temperature, it will assume and maintain its high-temperature shape. If sufficiently stressed, the material will soften and deform easily; however, as soon as the load is removed, the material spontaneously returns to its original, high-temperature, shape. Super-elastic wire has a springy feel. It is due to the reversible motion of domain boundaries during the phase transformation, rather than just bond stretching or the introduction of defects in the crystal lattice (thus it is not true super-elasticity but rather pseudo-elasticity). Even if the domain boundaries do become pinned, they may be reversed through heating. Thus, a pseudo-elastic material may return to its previous shape (hence, *shape memory*) after the removal of even relatively high applied strains. These unique alloys also show a Superelastic behavior if deformed at a temperature which is slightly above their transformation temperatures. This effect is caused by the stress-induced formation of some martensite above its normal temperature. Because it has been formed above its normal temperature, the martensite reverts immediately to undeformed austenite as soon as the stress is removed. This process provides a very springy, "rubberlike" elasticity in these alloys.

1.2 Heat Engine

Heat engine is a device which converts heat or thermal energy into mechanical energy, which can then be used to do mechanical work. It achieves this by bringing a working substance from a higher state temperature to a lower state temperature. Thus heat engine is a device which converts one forms of energy into other form so that it can be utilized further.

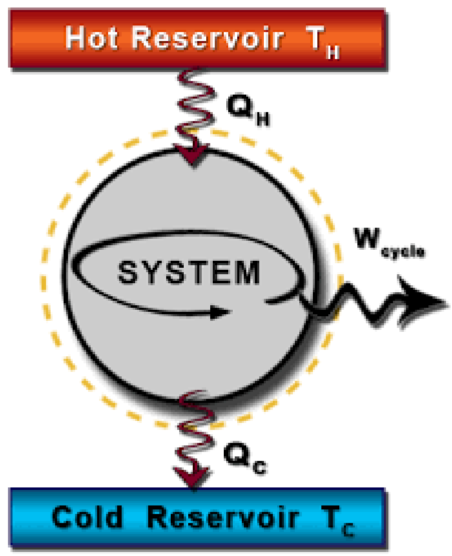


Figure 4 Heat Engine working principle

It is a device which transforms energy from one form to other. The Kelvin–Planck statement (or the heat engine statement) of the second law of thermodynamics states that it is impossible to devise a cyclically operating device, the sole effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work. Thus a heat engine cannot convert heat completely into work, a part of heat goes to sink.

1.3 SMA Heat Engine

Shape memory alloy heat engine is a device which uses shape memory effect for conversion of waste heat into mechanical work. A shape memory alloy (SMA) specimen is deformed to a new configuration by a small external force at low temperatures and recovers its original shape with substantially greater force at high temperatures. Using this shape memory effect (SME) a heat engine can be developed.

In this work we have used Nitinol springs for development of Heat engine. Thus Shape memory alloy with its special properties can be used in applications involving actuations. One important application of SMA can be in actuation of waster heat into useful work. The device is termed as heat engine. The device could be of utmost importance in energy conversion and utilization of waste energy. The actuation of SMA is reliable with sufficient force thus can be used for heat engine application.

1.4 Motivation

Part of energy always goes to waste in any system in our universe. Some waste source of energy include industrial waste heat, geothermal heat, oceanic thermal gradients, and solar radiation. It is a novel thought to present a method to convert such low-grade energy into mechanical work. The major drawback to the exploitation of these sorts of energy sources is the relatively small temperature gradients. Past efforts to generate useful forms of energy from small temperature difference heat sources were unsuccessful because standard recovery techniques generally have not approached competitive efficiency.

Smart materials have received increased demand in recent years due to their immense potential in revolutionizing engineering applications.Among the smart materials currently in research, Shape memory alloys predominant for the reason that large recoverable strains occur within it due to crystallographic transformation.

It is the intention of this thesis to present a heat engine that uses an SMA Springs attached to steel rim via bearings. The engine will continuously convert heat energy directly to useful mechanical power. The proposed design promises to have improved efficiency compared to previous Nitinol heat engine

1.5 Research Objectives

1.5.1 Overall Objective

The overall objective of this thesis is “Fabrication of Shape memory alloy actuated Heat Engine”, which is capable of conversion of waste heat into mechanical work.

1.5.2 Intermediate Objective

I. To search for methods using shape memory alloy for conversion of waste heat into mechanical work.

II. To develop 3-d drawing of setup to be fabricated.

III. To fabricate experimental setup for study of actuation.

IV. To optimize size of developed setup for obtaining better actuation.

V. To optimize operating parameters for obtaining best possible power.

VI. To select best design of heat engine for further analysis.

VII. Device Application :

- Identifying other possible applications of device(Eg: Power plant, Waste heat recovery in automobile)
- Fabricating the prototype.
- Performing experiments with the fabricated part.

VIII. To develop small 3-d printed model to study actuation from exhaust gases for automobile applications.

IX. To perform experiments on 3-d printed model to predict behavior under practical condition.

Chapter 2 Literature Review

This Chapter gives detailed information of the research carried out in the past on Shape memory alloy Heat Engine. One of the first applications of SMAs, in the 1970s, was in heat engines. A heat engine is a mechanism that is capable of converting heat energy to mechanical or electrical energy. The discovery of SMAs made it easy to do the energy conversion, which is a desirable feature when we think of its application in extracting work from waste energy. The actuation media is divided into three major categories.

2.1. Heat Engine by Ridgway Banks [1973]

Ridgway M. Banks invented the first continuously operating heat engine that uses SMAs, at the Lawrence Berkely Laboratory of the University of California, in 1973. He filled half of a small circular cylinder, about the size of a cookie tin, with hot water. He then constructed a flywheel, holding 20 nitinol-wire loops suspended from the spokes of the wheel, and set it into the cylinder. Figure 5 shows a top view of the flywheel. The wheel-hub is on an offset axis. The eccentric position of the hub causes the SMAs to stretch more on one side of the wheel than on the other." Because the nitinol loops contracted powerfully and straightened out as they went through the hot water, with a force of somewhere around 67,000 pounds per square inch, they were able to turn the flywheel, and then because they quickly assumed their original shape in the cold water bath they were able to exert their force again when they hit the hot-water side.

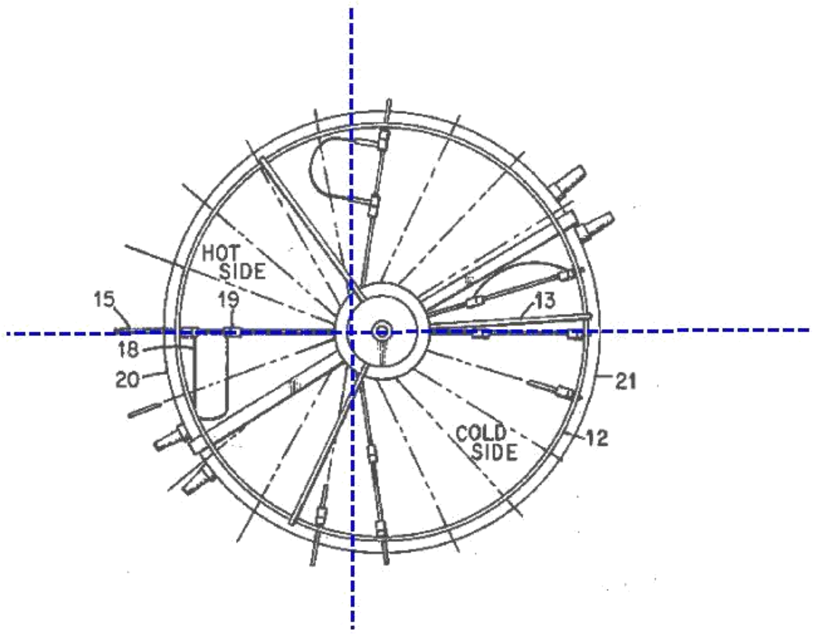


Figure 5 A plan view of Banks' heat engine[3]

The engine's thermodynamic inefficiency comes from the fact that the engine's cold Nitinol elements are heated by immersion in a hot fluid and then the elements get cooled in a heat sink at a much lower temperature. Such extreme temperature differences are a source of irreversibility, because of the large amount of entropy generated. Therefore, the engines cannot approach the efficiency of an ideal engine, or Carnot efficiency.

2.2 Heat Engine by Alfred Davis Johnson (1977)

He built two kinds of engines shown in Figure 6. In Figure 6a, Johnson's engine includes a SMA coil made into a non-slip engagement (grooved pulley) about a pair of small and large diameter pulleys, mounted in a heat source and heat sink. The pulleys rotate in one direction, at the same angular velocity by gears, which synchronize them. The conjoint rotation makes the cold wire portion to stretch, and thereafter, the heated portion of the wire contracts to its memory-shape during its movement past the heat source.The difference in tension between the two portions of the coils result in a net torque on the larger diameter pulley, which produces power output. In Figure 6b, we see that the setup of the coil is in such a way that the inner and outer sets of pulleys mount on a common shaft that run to a heat sink and a heat source, respectively. The pulley in the heat sink is of a larger diameter than the pulley in the heat source. The pulleys are constrained for rotation in a clockwise direction. The efficiency of these helical-band engines is certain to be low, because water is readily transported by the helix so that the hot and cold reservoirs are rapidly mixed. The design of this engine requires the coils to slip or jump teeth relative to the pulleys, which reduces efficiency.

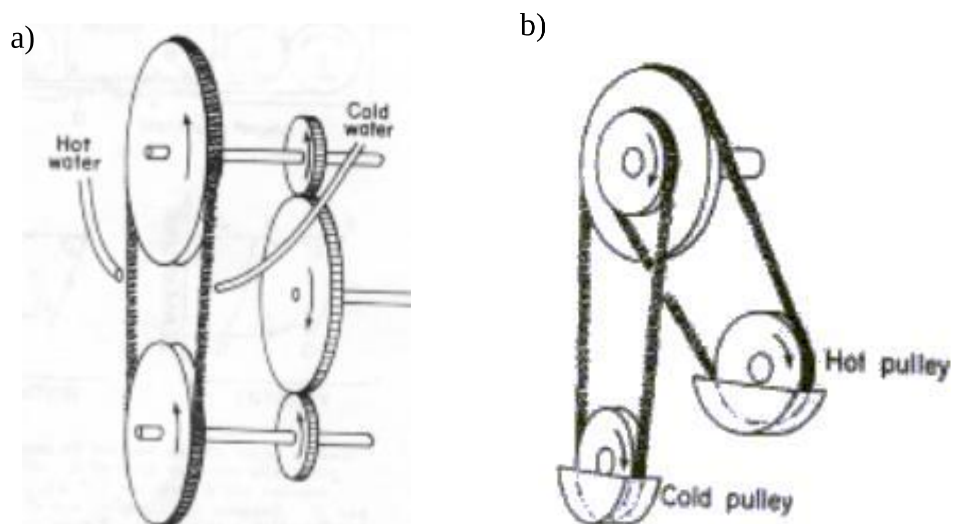


Figure 6 Johnson's engine (a)NiTi in form of continuous helix and (b)Two pulley fixed on same shaft [4]

2.3 Heat Engine by John J. Pachter [1975]

Pachter's work, like Johnson's engine, is similar to the engine presented in this paper. He uses continuous SMA belt, lengthened and shortened at different portions by thermal means. The belt is wrapped around a pair of pulleys of different diameters, one pulley being of slightly smaller diameter than the other is. The pulley shaft of each pulley then connects to the shaft of another pulley.

The engine uses multiple pulleys used simultaneously for obtaining more power. Having two sets of pulleys whose belts are heated at alternate locations is responsible for generating a continuous rotation. The connection prevents reverse rotation of the pulleys with respect to each other. Like Johnson's device, this engine also requires slip between the belt and the pulleys in order to function. This slip reduces efficiency and probably results in erratic operation.

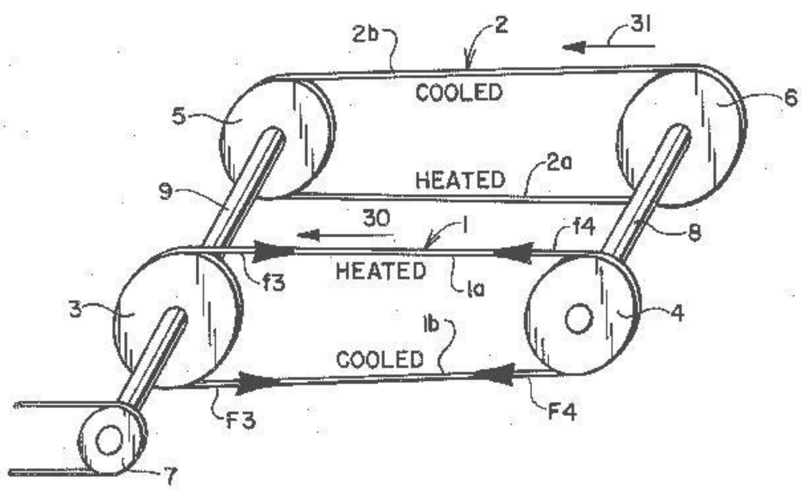


Figure 7 A simplified representation of Pachter's engine [5]

2.4 Heat Engine by Alan L. Browne[2011]

Sprocket with idler pulley design was presented by Alan L Browne in Smart Materials, Structures & NDT in Aerospace Conference held in Canada 2011. In this model two chain sprockets work simultaneously on two parallel shafts to support the setup, while actuation is achieved by SMA coil whirled around three pulleys (two main pulleys and one idler pulley).

Although the model showed better results but due to complexity involved in design and friction due to chain sprocket interaction and

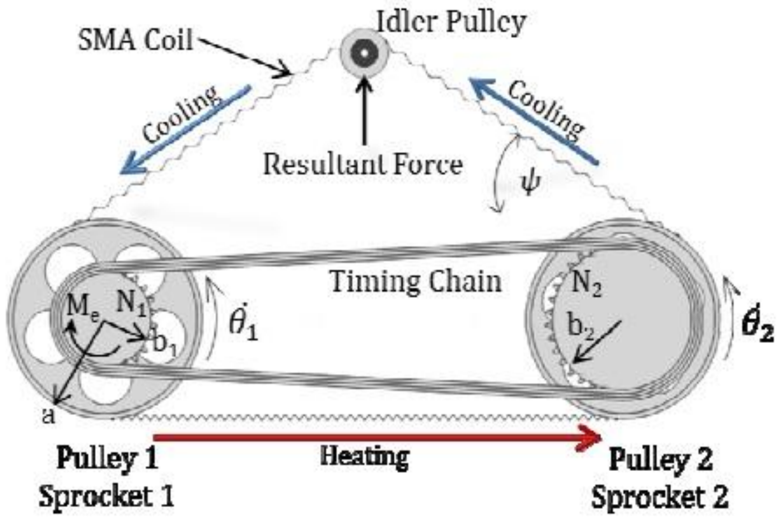


Figure 8 Browne's heat engine[6]

impartibility in implementation did to achieved to serve its objective.

2.5 Heat Engine by Hisaaki Tobushi [1990]

Hisaaki Tobushi presented his research work in JSME International journal. His work is focused on basic research on SMA Heat Engine, which includes suggesting different methods of actuation and comparing basic output characteristics for achieving best design.

One of the designs of heat engine given by Hisaaki Tobushi is shown in above figure. The simple design consists of SMA wire whirled around two pulleys, when SMA wire comes in contact with hot water it gets contracted and try to pull other part of wire (which is open to atmosphere). In this process wire gets displaced from its position, this process repeats and wire starts revolving onto two pulley.

Researchers investigated different designs of engine and suggested some results. The results are summarized as follows:

1. The output power of engines increases with the hot water temperature.
2. The range of rotational speed where the output power is maximized is wide.
3. The maximum output power increases with the number of wire loops of the shape memory alloy.

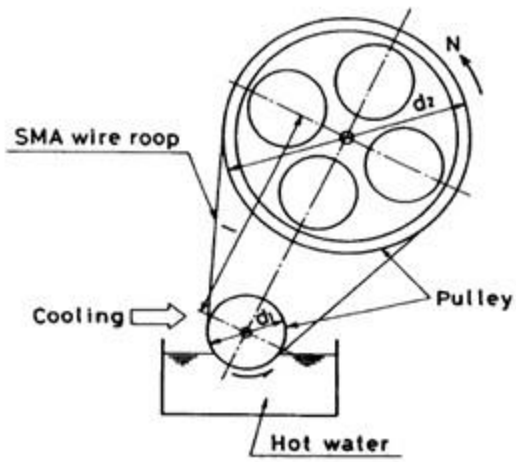


Figure 9 Tobushi's engine [7]

Chapter 3 SMA Heat Engine

3.1 Introduction

Shape memory alloy heat engine is a device which converts waste heat into useful work. In our work we have tried to develop a simple device for achieving waste heat recovery from different systems for improving their efficiency. A prototype is constructed for experimentation so as to optimize its design for obtaining an improved design with better actuation capabilities.

3.2 Principle of Actuation

The principle of actuation of SMA Heat engine is that when a force is acted at a distance from hinge point, a moment is generated. If in

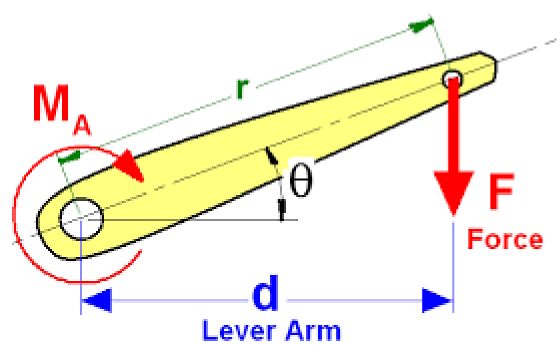


Figure 10 Moment generated by force

place of hinge a bearing is used an act of rotation is generated.

In the present work, above stated principle is utilized for achieving purpose of actuation. SMA springs are connected radially to steel rim, other side of spring is connected to hub (containing bearing). Initially when springs are equally stretched, Centre of gravity (CG) is at the geometric centre of rim. When lower springs comes in contact with hot water they get compressed, rim CG shifts from Hinge point (It can either shift to left or right). Due to this shifting of CG about hinge point moment or torque is produced which causes rotation.This phenomenon is explained in the figure given below by using a

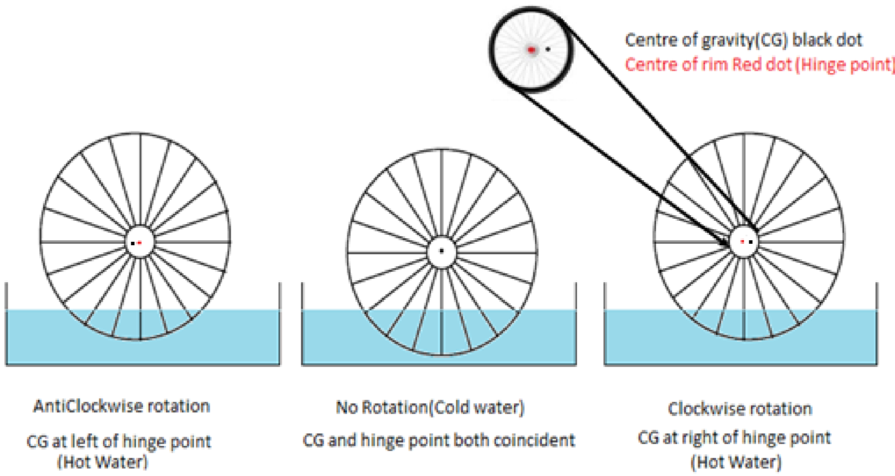


Figure 11 Principle of Actuation

diagram. In diagram springs are shown in form of straight lines.

The rotation of wheel can occur in any direction depending on direction of movement of CG from its position. Consider the case, in which CG shifts in right direction from its centre position, a clockwise moment is generated in this case causing rotation of wheel in clockwise direction (and vice versa in other case).

3.3 Components of SMA Heat Engine

Following are some of main components of Heat engine prototype:

1. **Steel Rim**: A stainless steel rim is used for connecting SMA springs radially for providing stiffness to model. Diameter of rim used is 280 mm.

2. **Hub containing ball bearing**: A stainless steel hub of 25 mm diameter is used.
3. **Mild steel stand**: Mild steel stand is fabricated to hold the hub and to provide height for mounting the wheel.

4. **SMA springs:** Nitinol springs are used for actuation of Heat engine model. Following are specifications of springs used:

   Wire diameter- 0.77 mm

   Coil Diameter- 5.69 mm

   No of Turns- 18

   Length of spring- n*d = 18*0.77 = 13.86 mm

   Modulus of Rigidity G = 26 GPa

   Stiffness constant = W/δ = G*d^4 / 8 D^3*n = 0.344 N/mm
5. **Electric heater**: A heater is used to maintain temperature of hot water.
6. **Colour coated sheet container**: A container is used for heating water. Although, SMA Heat engine is developed with a view point of waste heat recovery from different systems. Input energy is consumed for heating water because of non-availability of waste heat source.

Figure 12 SMA Heat Engine model

3.4 Drawbacks in present Heat Engine design

As stated above prototype of SMA heat Engine was fabricated for experimentation to reach an optimum model. While performing experiments in the prototype following were the observations:

1. In the present form of work, springs are connected in inclined manner with wheel hub. The reason for using inclined springs is the fact that CG shifts more when springs are inclined to axis.
2. During experimentation of present prototype Wobbling of Steel rim was observed about transverse axis.
3. In present form of work steel hub is used, and actuation of ball bearing occurs due to SMA Springs around hub, the high moment of inertia of hub was opposing motion of rim.
4. Due to Higher weight of hub and bearing, high initial torque is required for motion of rim.

All these problems were rectified in modified prototype of Heat engine which is explained in next section.

3.5 Modifications done in model

Following modifications were incorporated in previous model for its improvement:

1. **Hub containing bearing replaced by shaft containing mild steel bearing holder:** In the prototype developed, wobbling of steel rim was a major problem. To rectify the problem hub is replaced by bearing holder. When initially hub was used, springs were inclined to the axis. Due to inclined nature of springs wobbling of wheel was prominent. Thus springs are connected in radial manner in new design.

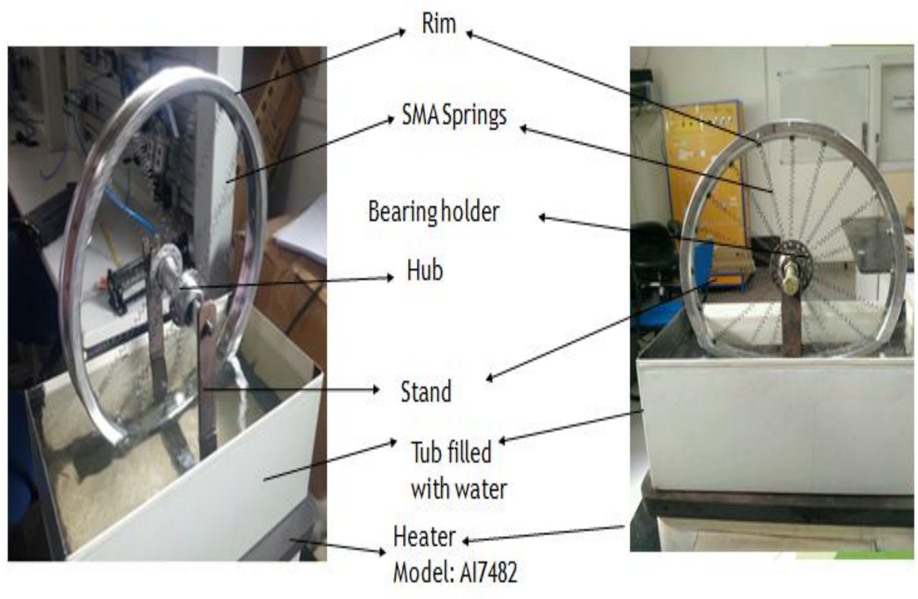


Figure 13 Hub replaced by mild steel bearing holder

In the figure 13 mild steel bearing holder is shown, the bearing is attached at centre of bearing holder.

2. **To reduce weight mild steel bearing holder is further replaced by Poly Lactic Acid (PLA) material:** When mild steel bearing holder is used weight of high density material offers resistance in motion of steel rim, to reduce weight 3-d printed bearing holder is used of poly lactic acid material. The polylactic acid bearing holder is manufactured using 3-d printing technique and is modeled in CATIA Software. It has advantages over Mild steel bearing holder that it is easy to manufacture product with low weight.

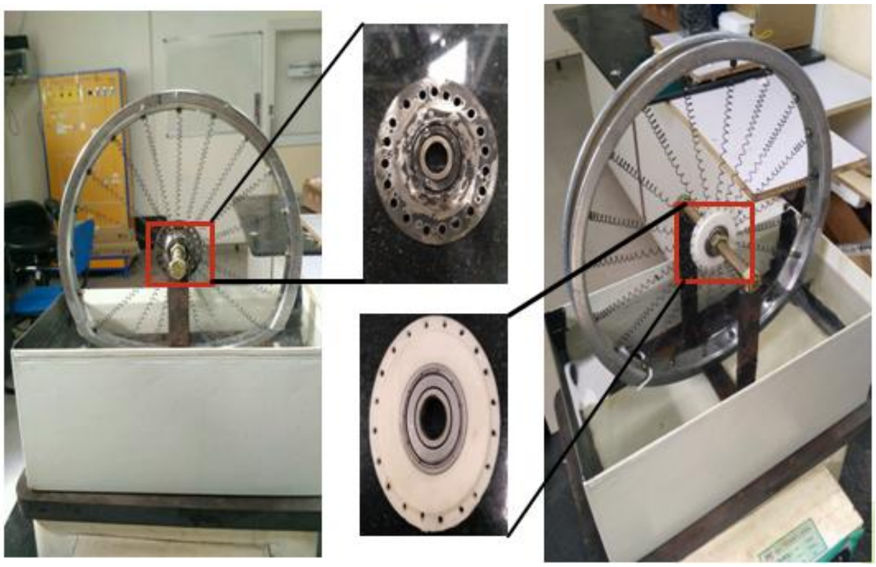


Figure 14 MS bearing holder replaced by PLA material

The Poly Lactic Acid (PLA) bearing holder used offers relatively lesser resistance in motion of rim as compared to mild steel, which is further analyzed by comparing rpm values in later part of this work.

3.6 Characteristic curves comparison in two models

After performing modifications as stated in previous section. A comparative study was performed to analyze improvement in design of Heat Engine. Rotations per minute calculations with temperature analysis showed improvement in actuation behavior of the proposed Heat engine. Figure below shows graph of RPM vs Temperature in two cases.

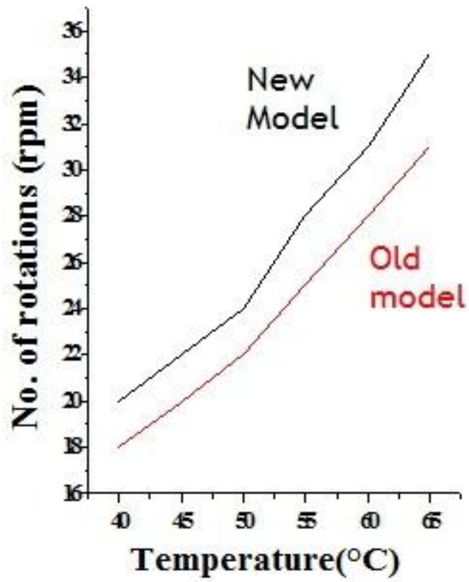


Figure 15 MS bearing holder replaced by PLA material

3.7 Optimum height of Axis of bearing from bottom

Figure below shows optimized design of SMA Heat engine prototype

Figure 16 Optimized design of Heat Engine

after incorporation of different modifications for better actuation.

In all previous experiments height of axis of bearing from bottom surface of container was 22 cm. The height determines the number of springs coming in contact with hot water thus experiment were performed at different heights so as to achieve optimum height of axis.

Experiments were performed at different height, above and below the mean height.

Figure 17 Experimental Setup to study optimum height

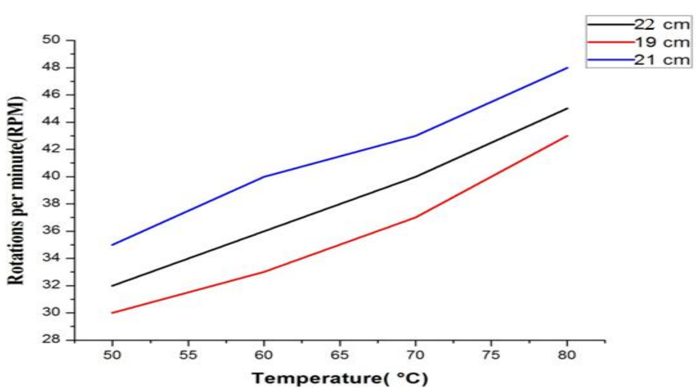


Figure 18 RPM vs Temperature graph

Graph is plotted at three different height showing optimum height of axis.

S.No.	Temperature of hot water (°C)	Rotations per minute (RPM) With variation in center height.		
		H1=22 cm	H2=21 cm	H3=19 cm
1	80	45	48	43
2	70	40	43	37
3	60	36	40	33
4	50	32	35	30

Table 2 RPM values at different centre heights

Observations from above experiment:

- Initially all experiments were performed with centre height of 22 cm.
- As height is decreased , power is increased up to a particular optimum height.
- Best results were obtained at height of 21 cm.
- When height is reduced below 21cm, RPM of wheel is reduced.
- Increased resistance due to viscosity of water is the reason for reduced RPM.

Besides hot water actuation the developed Heat engine also possesses potential for actuation by hot exhaust gases from automobile. Although actuation from hot gases is been tested at its preliminary stage but results are positive and we can look forward in implementation of engine in this area also for utilization of energy produced.

The actuation of heat engine is due to Shape memory behavior of NiTi material, the material possesses this behavior due to temperature gradient provided to by hot water (or any source as the case be). Thus it is essential to study heat transfer in NiTi and to check for cyclicity of actuation for long better performance of heat engine

Different equations of heat transfer can be applied to NiTi for developing a model for heat transfer.Further results can be verified from simulations. In the next chapter we will discuss the heat transfer aspects of Heat engine and try to analyze cyclic behavior of SMA springs.

Chapter 4 Thermal Analysis and modeling of heat engine

4.1 Introduction

Heat is transferred from hot water to Shape memory alloy (SMA) springs, by virtue of which actuation of spring occurs and hence rotation of Heat engine takes place. SMA exhibit special properties that make them a preferred choice for industrial applications in many branches of engineering. When heat flux is provided, as the temperature reaches 60 °C - 90 °C, spring gets fully compressed for the Ni-Ti Shape memory alloy. The temperature imparted to the spring with this thermal energy when reaches the transformation limit in turn actuates the spring. Heat transfer from hot water to SMA spring takes place by convection and radiation modes of heat transfer. Scaling of heat engine to analyze change in number of springs with increase in rim size, is also of utmost importance to study, the analysis of which is presented in this chapter.

4.2 Heat transfer analysis from hot water to SMA spring

Heat transfer analysis in hot water actuation is performed to understand how heat is being transferred so as to improve the actuation for obtaining better performance. Since the spring is fully immersed in hot water and heat transfer is taking place from Hot water to spring.

Assume SMA wire is considered as a cylinder. Parameters related to SMA spring are:

d = wire diameter (mm)

h = convection coefficient, W/m^2 /°K

T = starting temperature, °K

T_∞ = Hot water temperature, °K

σ = Stefan-Boltzmann constant, W/m^2 /°K^4

$$m * c * \frac{dT}{dt} = -\pi dl * \square\ (T - T_\infty) - \pi dl\ e\ \sigma\ (T^4 - T_\infty^4)$$

$$\frac{dT}{dt} * \rho\ c * l\ \frac{\pi d^2}{4} = -\pi dl * \square\ (T - T_\infty) - \pi dl\ e\ \sigma\ (T^4 - T_\infty^4)$$

$$\frac{dT}{dt} * \rho\ c\ \frac{\pi d^2}{4} = -\pi d \square\ (T - T_\infty) - \pi\ d\ e\ \sigma\ (T^4 - T_\infty^4)$$

$$\frac{dT}{dt} = \frac{-\pi d \square\ (T - T_\infty) - \pi\ d\ e\ \sigma\ (T^4 - T_\infty^4)}{\rho\ c\ \frac{\pi d^2}{4}}$$ ....Eq 1

Following are predictions based on heat transfer analysis:

- Thin spring is expected to give better actuation as compared to thick wired spring.(As diameter of wire is coming in denominator of equation)
- Length of spring wire is not present in equation derived, thus length of wire is not having any effect on actuation.
- The second result is very important in sense that it gives us idea that this small prototype of heat engine can give same performance even with long wire spring when we make large model for more power generation.

4.3 Scaling of heat engine

Heat engine discussed in present work can be enlarged for obtaining better actuation. Number of springs can be increased for reduced depending on the requirement of actuation. More the number of springs attached to rim, more are the springs which are in contact with hot water, hence better is actuation obtained.

Number of springs connected to rim is related to size of rim and wire diameter of spring. An equation stating the relation is derived in present section.

Consider following parameters in Heat engine model with springs arranged perfectly radial manner

D = Diameter of steel rim

C = Diameter of bearing holder

cl = Clearance given between each holes in bearing holder

l = Length of a spring

d = Wire diameter of spring

n = number of coils in spring

N_s= Number of springs attached in wheel

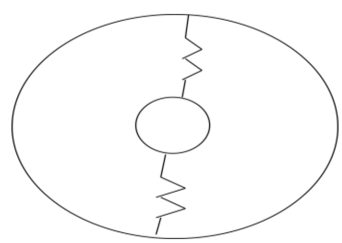


Figure 19 Line diagram of rim with springs

$D = C + 2l$

Where $l = \pi * d * n$

$D = C + 2 * (\pi * d * n))$ .... Eq 2

Consider small bearing holder attached in centre, springs are attached from Bearing holder to rim radially,

Lets clearance(Distance provided to avoid overlapping) is cl

$$\pi * C = N_s (d + cl)$$

$$C = \frac{N_s (d + cl)}{\pi}$$

Putting value of C in eq 2

$$D = \frac{N_s(d+cl)}{\pi} + 2(\pi * dn) \quad \text{.........Eq 3}$$

No. of springs attached in Wheel of diameter D,

$$N_s = \frac{\pi*(D-2*(\pi*dn))}{(d+cl)} \quad \text{.........Eq 4}$$

The relation derived above is very important for heat engine design. More the number of springs attached to rim, more will be Springs which are coming in contact with hot water thus better will be actuation obtained.

4.4 Efficiency of developed SMA Heat Engine:

Although application of SMA Heat engine is in waste heat recovery, and whatever which can be extracted from waste energy is always beneficial for improving net output of the system. The derivation of efficiency expression for SMA heat engine is presented in this section.

Let m= mass of water in container

c= Specific heat of water

ΔT=Temperature difference produced due to heating.

t= Time required for heating

Output = n*current(I)*Voltage(V)

Where,

I=current flowing in circuit.

V=voltage across DC motor

n= number of LEDs connected in series

Output = n*I*V=100*10 mA*5V =0.5 W

Input =Average rate of heat Input=$\frac{m*c*\Delta T}{t}$=$\frac{1*4200*30}{7200}$=11.4 W

$Efficiency\ in\ percentage = \frac{Output}{Input} x100$ %

$Efficiency\ in\ percentage = \frac{0.5}{11.4} x100$ %= 4.38%

4.5 Simulation results of SMA spring

Shape memory alloy spring is the prime component of heat engine. The characteristic study of SMA spring of dimensions and properties in chapter 3 is performed using Ansys software.

The results of which are explained in this section. Spring is fixed by providing two supports at ends(i.e. boundary condition:fixed at both ends) The streched length of spring is taken as 11.5 cm (same as in case of heat engine prototype). The analysis of the spring were done by Ansys 14.0 software and the required analysis such as directional deformation, equivalent stress, shear stress, shear strain, total deformation and total heat flux were found.

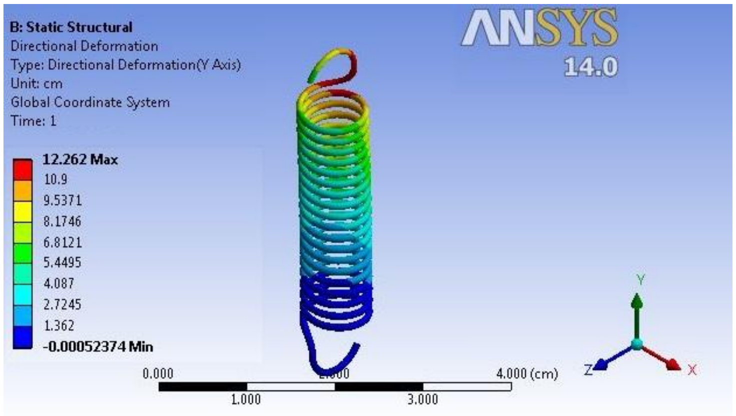


Figure 20 Directional deformation in Y-axis direction

Results of directional deformation of SMA spring is shown in above figure showing maximum deformation spring can sustain with different color codes. Some other results of Ansys simulations are shown in below figures

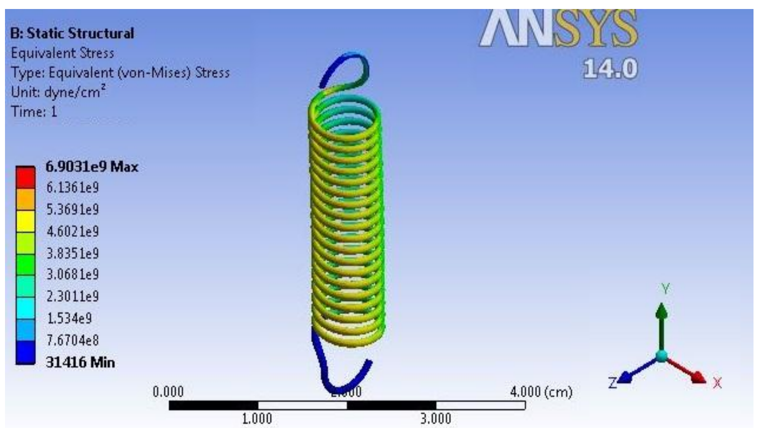


Figure 21 Equivalent Stress (Von mises distribution)

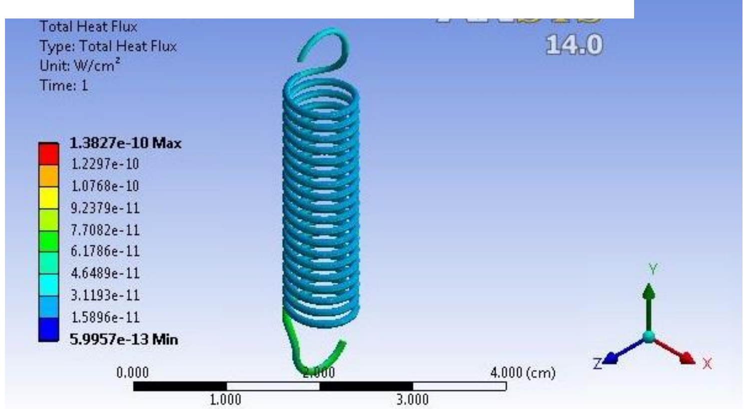


Figure 22 Heat flux distribution

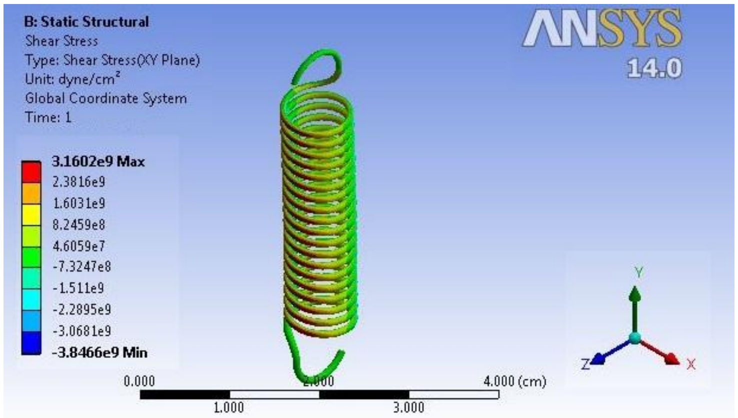


Figure 23 Shear Stress distribution

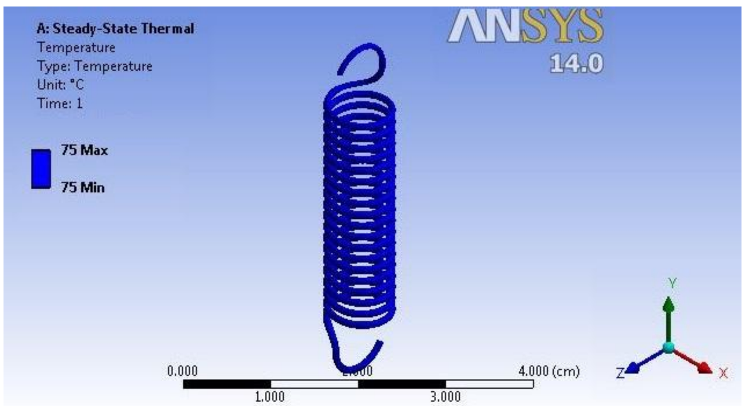


Figure 24 Steady state temperature distribution

Chapter 5 Conclusion and future scope

5.1 Conclusion

The purpose of this thesis work was to present the design and analysis of an improved heat engine made using shape memory alloy. In light of the past work that has been attempted in this area, it seems unlikely that the earlier inventions could be scaled up to the point where they have practical utility. This thesis presents a new design that has the potential to be the basis for large SMA engines.

The first part of the work presented a review of some of the theoretical background on SMA’s. We saw that SMA’s are materials that "memorize" their shape at specific temperatures. At low temperatures, they are easy to deform, but at increased temperatures they exert large forces as they try to recover their original shape. This reversible property is attributed to their unique solid phase transformation known as martensitic transformation.

A novel design has been proposed for creating a heat engine from shape memory alloy springs. Following a review of alloy behavior and the prior art of SMA engines, it was suggested that this design advances that art. Subsequent analysis and creation of a working prototype helped to substantiate the claim, though additional experimentation will be needed to make a conclusive determination.

5.2 Pros of proposed design

Proposed design has following advantages over previous SMA and conventional heat engines:

- **Simplicity:** Design is simple with spring arrangements radial. Moreover parts involved are ready to manufacture.

- **Low maintenance:** Since less number of parts involved which are simple maintenance required is less.
- **Scalable:** Increasing the size of rim with more number of springs will involve more springs to come in contact with water at a time, which will enhance the actuation properties, thus scaling of device is possible or obtaining enhanced actuation.
- **Control over actuation:** The actuation involved can be easily controlled by regulating the temperature.
- **Stable design:** The actuation is stable with motion involving less wobbling after incorporation of all the modifications.
- **Reliable:** Life cycle analysis of SMA spring has already been performed by researchers stating its life of multiple cycles without loss of its SMA behavior. The proposed design has SMA springs with its primary component thus the design is reliable.

5.3 Opportunities for improvement

The proposed work has following areas where analysis needs to be done for further improvement:

- **Weight reduction:** Steel rim involved may be replaced by different light weight material rim and tested for its performance.
- **Scaling:** Scaling of model with simulations need to be performed for understanding its actuation behavior.
- **Multiple steel rim installations:** The same shaft can be mounted with multiple rims each consisting of SMA Springs for obtaining better actuation.
- **Power transmission system development:** A transmission system need to be developed which can be used for different

applications for utilizing power produced.

5.4 Potential application areas

Following are potential application areas where the device can be incorporated:

- **Power plant waste water energy recovery:** Cooling tower hot water of power plant can be used for actuation of heat engine and waste heat can be utilized.
- **Automobile waste heat recovery:** Exhaust of automobile can be made to pass through heat engine, the power thus obtained will lead to enhancement of automobile efficiency.
- **System involving waste energy with temperature gradient:** Any system which has temperature gradient in form of waste energy can use this device for waste energy recovery for improving the output.

Chapter 6 Bibliography

[1] Tung, Alexander T., et al. ""Design and fabrication of tubular shapememory alloy actuators for active catheters." ." *The First* IEEE/RAS-EMBS International Conference on. IEEE. Biomedical Robotics and Biomechatronics. , 2006.

[2] Hogdson, et al. “A comparison of muscle with artificial actuators” In Technical Digest of the IEEE Solid-State Sensor and Actuator Workshop, Hilton Head, South Carolina, 1988, 178–185.

[3] Banks,Olive M., PatentUS03913326, Energy Conversion Systems, 1975

[4] Johnson,et al. “Shape Memory Alloy Utilization in Actuation” International journal for Advanced Material and structures Series II,Vol. 14, No. 8,1977

[5] Patchter., PatentUS03913326, Energy Conversion Systems, 1975 Browne Alan, William J and Goldstein, David. M, US3403238, Conversion of heat energy to mechanical energy, 1975

[6] Browne Alan N, Hao, and Qingping Sun. ""Temperature variation in NiTi shape memory alloy during cyclic phase transition." ." *Journal of materials engineering and performance 21.12* , (2012): 2505-2508.

[7] Tobushi Hisaaki,et al.“Basic Research on Shape Memory Alloy Heat Engine” JSME International journal Series I, Vol. 33, No. 2, 1990

[8] Tameshwar Nath, Priya Chouhan, Reena Disawal and I.A. Palani "Comparative Study of Electrically and Hot Water Actuated Shape Memory Alloy using Developed Thermo-mechanical Cycletest Bench" Defence Science Journal, Vol. 67, No. 1, January 2017.

[9] Wu, Ming H., and L. M. Schetky. "Industrial applications for shape memory alloys." Proceedings of the international conference on shape memory and superelastic technologies. . 2000

[10] Ginell, W. S., McNichols, J, L, Jr, and Cory, J. S., Nitinol Heat Engines for Low-Grade Thermal Energy Conversion, Mechanical Engineering, Vol, 101, No. 5 (1979)

[11] Churchil Christopher B. and John Shaw "Thermo-mechanical modeling of shape memory alloy heat engine "ASME 2011 Conference on Smart Materials,Scotland USA