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Heat Exchanger Design And Development For Automotive Exhaust Waste Heat Recovery Using Thermoelectric Devices

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HEAT EXCHANGER DESIGN AND DEVELOPMENT FOR AUTOMOTIVE EXHAUST WASTE HEAT RECOVERY USING THERMOELECTRIC DEVICES

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Dedication

Dedicated to my parents for whom I am able to see this beautiful world.

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by

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Abstract

In this study several heat exchanger designs were constructed, tested, and the effect of the design on the overall efficiency and power generated by thermoelectric generators was measured. The thermoelectric elements were attached to the heat exchanger and hot gas passed through the system simulating automotive exhaust. An aluminum duct heat exchanger, a copper heat exchanger, and a heat exchanger with a twisted tape insertion were tested. The heat exchangers were all rectangular with similar dimensions and minimum thicknesses near the wall. The flow of exhaust gas was created by heated air flow ranging from 100-150 LPM. The cool side heat exchanger was setup to simulate a coolant pump using ethylene glycol water mixture (automobile coolant). For measurements, all the thermocouples and thermoelectric generators were connected through the data acquisition program LabView. For the heat exchanger designs the availability, cost effectiveness, implementation probability, and overall performance based on literature was considered. It was observed that due to the insertion of the tape, heat enhancement occurred. It was determined that the tape inside the heat exchanger reduced the diameter of the heat exchanger which increased the velocity inside of the heat exchanger thus increasing the overall heat transfer coefficient. This is confirmed by the overall increase in heat exchanger efficiency of nearly 48% and output power generation of 31% when compared to the aluminum duct heat exchanger.

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CHAPTER 1: Introduction and Background

1.1 Introduction

Presently increasing energy consumption and its demand has caused some concern in terms of maintaining security and sustainability for the US. There are many avenues to explore in order to reduce energy consumption one of which is improving the efficiencies of currently operating equipment such as automobiles. In an automobile, energy is wasted after fuel burning in the internal combustion engine. Only 25% of the energy can be used in a typical automobile leaving 75% energy as being wasted through the tailpipe as exhaust and other losses. Out of this 75% energy, 40% energy is being wasted through the exhaust gas manifold of the automobile, friction and other losses. Thermal energy can be recovered using thermoelectric generators (TEG) from which much research work has been done. There are few advantages of TEGs such as no moving parts, lightweight, small size, direct conversion of heat to usable electricity, reliable, environmental friendly, and easy to use. Thermoelectrics can play a role both in primary power generation and energy conservation. One way to improve fuel efficiency and reduce emissions in automobiles, TEGs can be used to harvest the unused exhaust energy. Thermoelectric power generation via waste heat recovery from automobiles shows promise to discard bulkier alternator systems and provide additional charging to a vehicle battery pack. Presently the conversion efficiency of exhaust TEG (ETEG) has increased more than three times but disputes exist as to the thermal design of ETEG systems. Different approaches to increase the efficiency include heat exchangers (hot box and cold plate) design, maintaining a sufficient temperature difference across the thermoelectric modules during different operating conditions and reducing thermal losses through the system as a whole. This work focuses on a review of the main aspects of

thermal design of ETEG systems. The present study was performed in different stages: (i) Selection of different typical ETEGs, (ii) Heat balance and efficiency calculations, and (iii) Comparison to ETEG research activities over the last few years performed at UTEP.

The thermal resistance of the heat exchangers can play a strong role to the electric power generation by an ETEG. There is a need of optimization of a heat exchanger to increase the overall efficiency for ETEGs. In fact an effort by JP Joule looked to enhance the heat transfer coefficients in condensing steam. Enhancement techniques essentially reduce the thermal resistance in a conventional heat exchanger by promoting higher convective heat transfer coefficient with or without surface area increase (represented by fins or extended surfaces). As a result the size of a heat exchanger can be reduced or the heat duty can be increased or the exchangers operating temperature difference can be decreased. Therefore, to increase the overall efficiency of a system, it is a combined effort between the thermoelectric generator performance and heat exchanger behavior or efficiency of the primary heat exchanger (1, 2).

1.2 Thermoelectric Background

This section provide a review of recent literature with an emphasis given to understand the basic architecture of the thermoelectric generator, operating principles, past and present day work including the future work directives limiting the study on waste heat recovery from automobile, heat exchanger design, and enhancement techniques for waste heat recovery from an automobile.

1.2.1 Thermoelectric Effect

The thermoelectric effect is the direct conversion of temperature into electricity and vice versa. There are two types of effects: Peltier and Seebeck effect. The Peltier effect is where electricity is being converted to heat through thermoelectric effect. The Seebeck effect is the conversion of temperature directly into electricity. The voltage created is of the order of temperature difference, typically several microvolts per kelvin difference. If the Seebeck coefficient is constant then the voltage (V) will be:

$$V = (S_B - S_A)(T_2 - T_1) \tag{1.1}$$

Here is the Seebeck coefficient is expressed in terms of two metals a and b, and T_1 and T_2 are the temperature of two junctions.

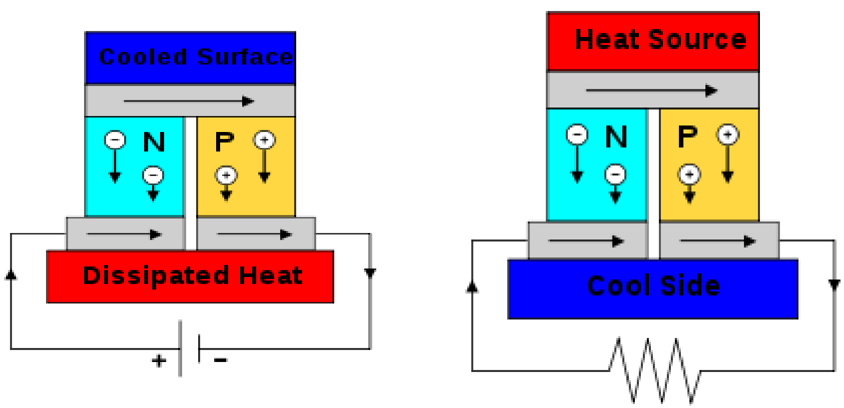

Figure 1: Example schematic of a thermoelectric generator

A charge carrier diffusion and phonon drag cause is the driving principle behind the Seebeck effect. Because of this effect when a conductor is heated one side and another side is 'cooler' the temperature difference charge carrier starts diffusing within the material. If thermodynamic

equilibrium achieved then there is no flow of heat or electricity in this system. If there is no thermodynamic equilibrium then hot carriers move from hot side to cold side due to less density, the movement of heat from one end to the other is heat current but when charge carrier moves then electricity starts flowing. What happened when a material is being heated if we consider about the charge carrier diffusion. Now if we maintained a constant temperature difference on both side there is a constant diffusion of charge carrier ,but if they are in opposite direction and equal there will be no flow of electricity if not then there will be a flow. Although due to impurities some of the charge is scattered and if the diffusion start due to heat the density in hot and cold side diffusion varies and create electrostatic voltage (3).

The thermo power inside a material depends on lot many factor such as its impurities, lattice structure which varies with temperature and electrostatic voltage.in earlier days thermocouples were metallic but now it is being made with the help of p and n type semiconductor along with junction of metallic plate. When a thermocouple is heated, electrons from the n-type conductor start flowing towards the p-type material acting as a power generator – this is the principle behind the Seebeck effect (3).

1.2.2 Figure of Merit

The thermoelectric figure of merit is a value that can help to quickly gauge the effectiveness of a material to convert heat into usable electricity. The figure of merit is shown in Eq. (1.2):

$$Z = \frac{\sigma S^2}{\kappa}, \tag{1.2}$$

Where S is the Seebeck coefficient, κ is the thermal conductivity *and* σ is the electrical conductivity. The ZT value which is another measure of performance is Z multiplied by the average temperature seen in Eq. (1.3):

$$\bar{T} = \frac{(T_2 + T_1)}{2}. \tag{1.3}$$

It is always desirable to have a high ZT value (which range somewhere between 0 and 1). There are several ways to improve the efficiency of the material, including modification of its internal structure so S can be increased can be decreased or σ can be increased (3). Currently, studies aim at increasing material ZT values to 3 with a long term future target set at up to 8.

1.2.3 Device efficiency

The efficiency of a thermoelectric device for electricity generation is given by η, shown in Eq. (1.4):

$$\eta = \frac{\text{energy provided to the load}}{\text{heat energy absorbed at hot junction}}. \tag{1.4}$$

The same term can be expressed in terms of Carnot efficiency in Eq. (1.5):

$$\eta_{max} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + \frac{T_C}{T_H}}, \tag{1.5}$$

Where T_C is the temperature at the surface being cooled and T_H is the temperature at the hot junction. $Z\bar{T}$ is figure of merit, which takes into consideration the thermoelectric capacity of

both thermoelectric materials being used in the device, this term was described in the previous section (3,4).

1.2.4 Architecture of the Thermoelectric Generator

The thermoelectric generator is constructed of p and n type semiconductors arranged thermally in parallel and electrically in series. Heating one side of the generator and keeping the other side cool induces the flow of electricity by partly using heat energy. As mentioned previously, the key issue in the thermoelectric is to invent or develop materials with a significantly increased value of the figure of merit ZT. Thermoelectric performance directly involves a temperature difference or gradient and the intrinsic material property. In order to improve the thermoelectric efficiency a combined effort of material science, physics and chemistry associated with producing high ZT values is needed. New recently available bismuth telluride material whose ZT value is 0.73 is now commercially available and is used in this experiment.

Any TEG attached to an automobile exhaust typically consists of four components: a hot box, thermoelectric modules, and cold plate and assembly elements. The hot box is the component where exhaust heat is to be extracted; the cold plate is responsible for dissipating heat after it passes through the thermoelectric modules and the assembly elements are responsible for applying sufficient compression force to these thermoelectric modules as well as assembling all module contains a large number of n-type and p-type semiconductors, arranged couples, which can convert heat directly into electric power .Throughout this paper the abbreviation 'TEMs' is used to represent thermoelectric modules. Thermal insulation is another important component of any TEG in the exhaust (ETEG) and to decrease the thermal losses across the hot box; also, thermal interface material (i.e. thermal grease). Thermal insulation is another important

component of any ETEG, and is used to decrease the thermal losses across the hot box (5). The below Figures show a thermoelectric element and performance curves provided by the manufacturer.

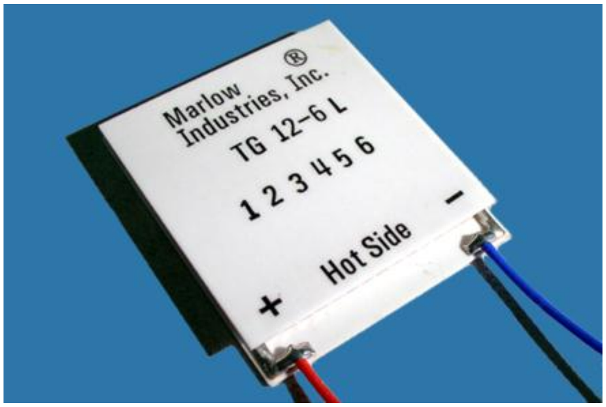

Figure 2: Thermoelectric generator

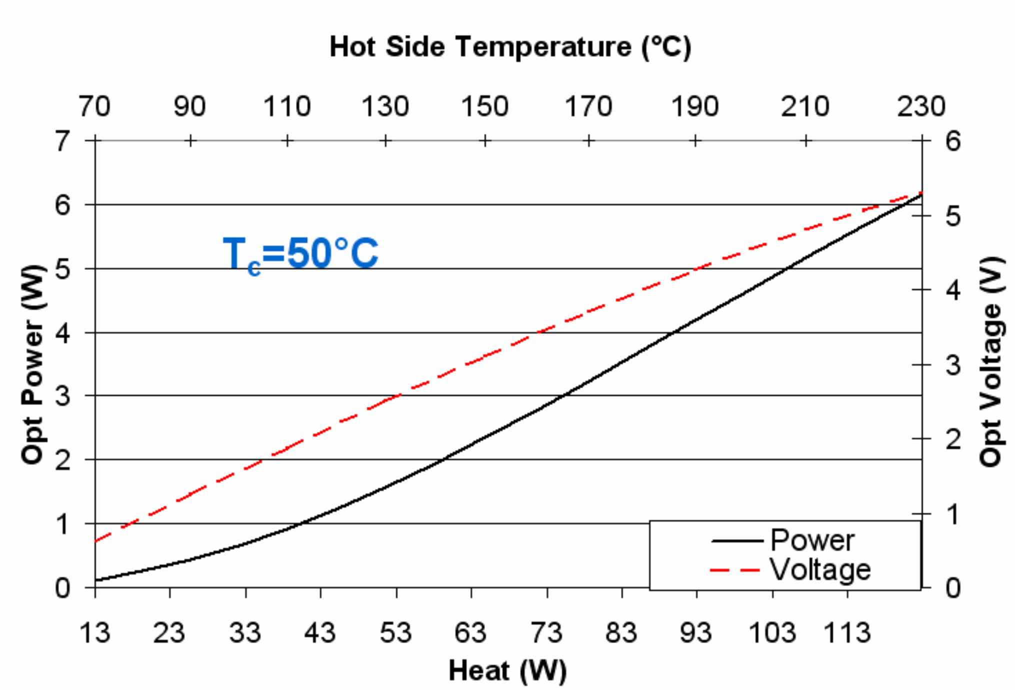

Figure 3: Thermoelectric manufacturers power curve at 50°C

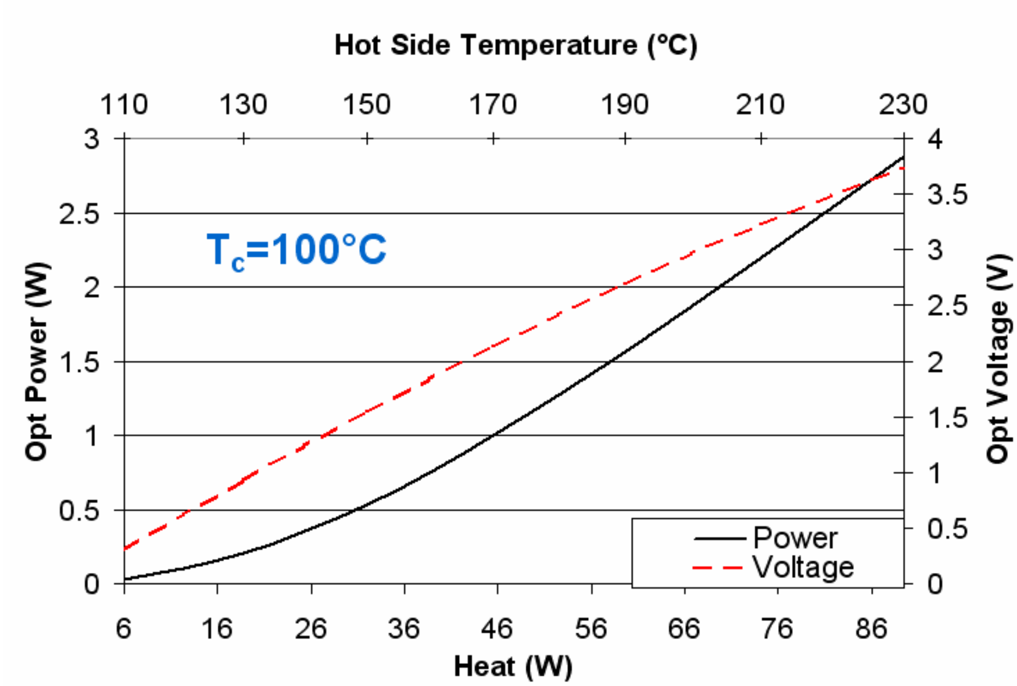

Figure 4: Thermoelectric manufacturers power curve at 100°C

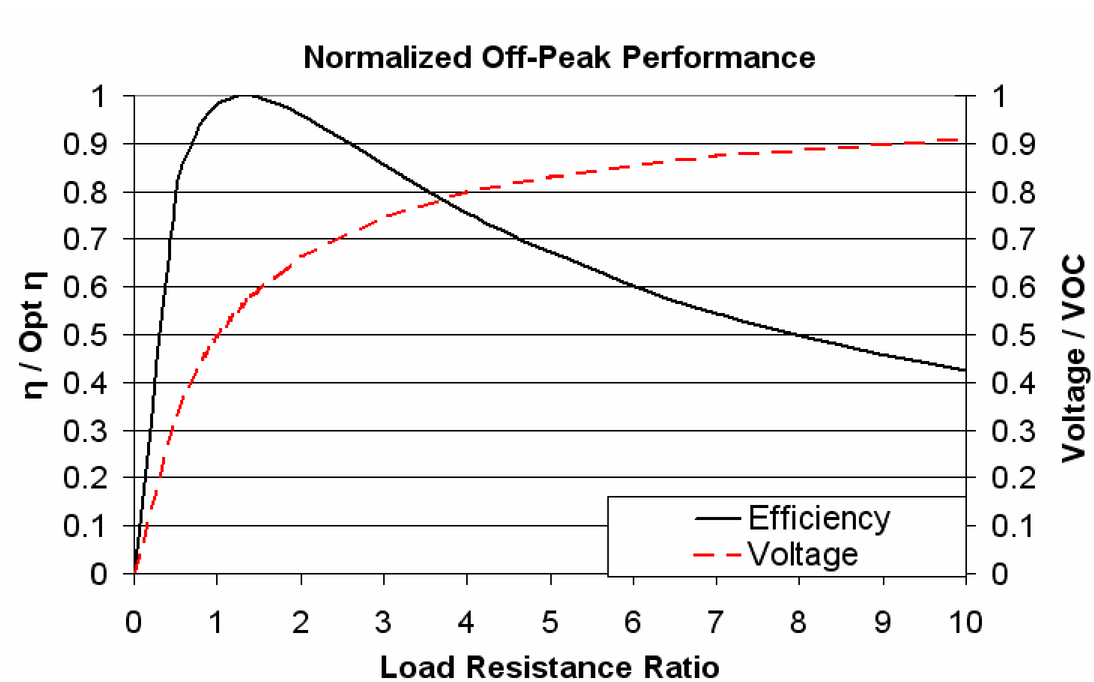

Figure 5: Power and efficiency curve from manufacturer

1.3 Heat Exchanger Background

A heat exchanger is a heat transfer device that is used for transfer of internal thermal energy between two or more fluids available at different temperatures, in most cases the fluids are separated by a heat transfer surface (6).

1.3.1 Classification of Heat Exchangers

Heat exchangers have been classified according to both major and detailed classifications shown in Table 1 (6).

Table 1: Major and detailed description of different types of heat exchangers

Major Categories	Detailed Categories/ Considerations
Construction	Materials
Type of Transfer Process	Operating temperatures and pressures
Degrees of Surface Compactness	Flow rates
Flow Arrangements	Flow arrangements
Pass Arrangements	Thermal Effectiveness
Phase of the Process Fluids	Pressure Drop
Heat Transfer Mechanisms	Fouling tendencies
	Phase of fluids
	Repair possibilities and maintenance
	Economy
	Fabrication
	Intended application

When selecting a heat exchanger it must satisfy the process specifications. The heat exchanger must withstand the service conditions of the environment that it will operate in, it must be maintainable; this usually implies choosing a configuration that permits cleaning and replacement especially vulnerable to corrosion, erosion or vibration. This requirement will dictate the positioning of the exchanger and the space requirement (6).

There may be limitation on the exchanger diameter, length weight and configuration due to the requirement. The most common problem in heat exchanger design are rating and sizing. The rating problem is concerned with the determination of the heat transfer rate. Since the fluid outlet temperature for a prescribed fluid flow rate, inlet temperatures and allowable pressure drop for an existing heat exchanger. The sizing problem on the other hand is concerned with the determination of the dimensions of the heat exchanger, that is, selecting an appropriate heat exchanger type and determining the size to meet the specified hot and cold fluid inlet and outlet temperatures, flow rate and pressure drop requirements (6).

1.3.2 Arrangement of Flow Path in Heat Exchangers

Heat exchangers can be arranged in a variety of ways. The three primary type that are used are Parallel flow, Counter flow, and Cross flow configurations. For the present experiment the counter flow configuration is used with two fluids flowing parallel to one another but in opposite directions. This will help to enhance the heat transfer rate between the fluids and potentially help to increase the efficiency of the system (6).

1.3.3 Basic Heat Exchanger Equations and Design

From the first law of thermodynamics for an open system, under steady state, steady flow conditions with negligible potential and kinetic energy changes, the change of enthalpy of one of the fluid streams is expressed in Eq. (1.6):

$$\delta q = m \; di \tag{1.6}$$

Where m is the rate of mass flow rate, i is the specific enthalpy, and Δq is the heat transfer rate to the fluid. Integrating this equation yields Eq (1.7):

$$Q = m\,(i_2 - i_1) \tag{1.7}$$

The variables i_2 and i_1 represent the inlet and outlet enthalpies of the fluid system. For hot and cold fluids the equation becomes:

$$Q = m_h (i_{h1} - i_{h2}) \quad (1.8)$$

And for cold fluids:

$$Q = m_i (i_{C2} - i_{C1}) \quad (1.9)$$

If the fluid does not have any phase change and constant specific heat, di is equal to c_p dt:

$$Q = (m^{\cdot} c_p) (T_{n1} - T_{n2}) \quad (1.10)$$

$$Q = (m c_p) (T_{c2} - T_{c1}) \quad (1.11)$$

Since the temperature difference between hot and cold fluids ($\Delta T = T_H - T_C$) varies with position in the heat exchanger it is convenient to establish an appropriate mean value of the temperature difference between hot and cold side

$$Q = UA \, \Delta T_M \quad (1.12)$$

Where Q is the rate of heat transfer, A is the total area, and U is the average overall heat transfer coefficient. Here in this study a counter flow heat exchanger is used and our goal is to determine first the total heat transfer rate Q through the heat exchanger. This parameter can be determined by an energy balance to a differential element area (dA) in the hot and cold fluids. For adiabatic steady state steady flow the energy balance yields:

$$\delta Q = - C_h \, dT_h = \pm C_c \, dT_c \quad (1.13)$$

Here C_h and C_c are the hot and cold fluid heat capacity. If we consider counter flow in from Eq. (1.13) then the equation becomes:

$$dT_h - dT_c = \delta Q \, (1/C_c - 1/C_h) \quad (1.14)$$

Now the rate of heat transfer from the hot to cold fluid across the heat transfer area dA may be expressed as:

$$\Delta Q = U(T_h - T_c)\, dA \tag{1.15}$$

Considering both Eqs. (1.14) and (1.15):

$$d(T_h - T_c)/T_h - T_c = u\,(1/C_c - 1/C_h)\, dA \tag{1.16}$$

Now integrating Eq. (1.16) considering U, C_c, and C_h constant:

$$\ln[(T_{h2} - T_{c1})/(T_{h1} - T_{c2})] = U\,A\,(1/C_c - 1/C_h) \tag{1.17}$$

Which can also be expressed as:

$$Q = U\,A\,\Delta T_1 - \Delta T_2/\ln(\Delta T_1/\Delta T_2) \tag{1.18}$$

Where ΔT_1 is the temp difference of fluid on one end and ΔT_2 is the temperature difference of fluid on the other end, so the appropriate temperature difference between the hot and cold fluids over the entire length of the heat exchanger is given by Eq. (1.19):

$$\Delta T_m = \Delta T_1 - \Delta T_2/\ln(\Delta T_1/\Delta T_2) \tag{1.19}$$

This ΔT_m is called log mean temperature difference, LMTD (6).

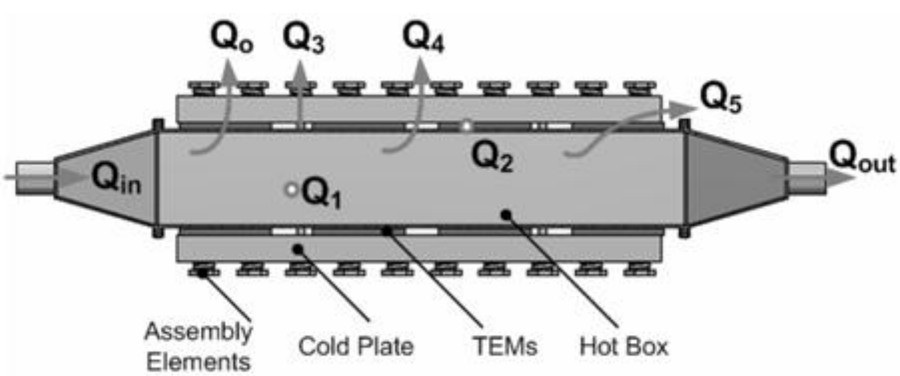

Figure 6: Example automotive heat exchanger unit showing heat flow paths

1.4 Heat Balance and Efficiency

In internal combustion engines about 75 % of energy in the form of heat is lost through the exhaust pipe. Approximately 40% is lost through engine coolant, 5% through radiation and friction, and 25% is reserved for vehicle mobility and accessories. Thermoelectric placed in the exhaust of an automobile tends to recover heat from the first 40% of the heat loss; however, due to many factors, current TEGS can only have about 5-6% efficiency. The heat flows through an example system is shown in Figure 6. Q_{in} and Q_{out} are the exhaust gas energies at the inlet and exit of the hot box, respectively, and Q_o is the effective heat transferred through the TEMs. The heat losses in the system are expressed as losses and Q_1 is the heat lost from the nonuse sides of the hot box by radiation and convection (i.e. heat transferred normal to the drawing plane). Q_2 is the heat lost from the leg-sides of the TEMs by convection and radiation, and Q_3 is the heat lost by conduction through the assembly structure. The heat lost through gaps between the TEMs is Q_4 and Q_5 is the heat lost by conduction in the TEMs due to thermal contact resistance. The heat balance for a system with these expressions can be seen in the following equations:

$$Q_{in}-Q_{out}= Q_0+ Q_{Losses} \tag{1.20}$$

$$Q_{Losses}=Q_1+Q_2+Q_3+Q_4+Q_5 \tag{1.21}$$

and the overall efficiency of the ETEG can be expressed as:

$$\eta_{ov} =\eta_m \, \eta_{ex} \, P_O \tag{1.22}$$

Where η_m represents the generated power and heat absorbed by the TEMs, Po is the electric output power from the ETEG. The efficiency of the heat exchanger can be expressed as:

$$\eta_{Hx} = Q_0+Q_4/Q_{IN} - Q_{OUT} \tag{1.23}$$

The percentage of each component of the heat loss, as well as that of the useful amount of heat passing through TEMs to the available heat entering the ETEG, are primarily based on the design

of the ETEG. However, a recent case study suggested that Q_{out} represents 45% of the total exhaust heat, while another 45% is represented in Q_2, Q_5, and Q_o together (5).

1.5 Temperature Distribution In the Exhaust of an Automobile

This section shows areas in the vehicle that were considered for the placement of the heat exchanger. Before designing the heat exchanger for the exhaust of automobile the heat distribution chart in the exhaust system needed to be analyzed. Figures 7 and 8 show the heat distribution chart observed in an experiment by BMW where it was found the lowest temperature of the two exhaust systems were 240°C and 430°C, with this parameter in mind the lowest temperature of the experiment was selected as 240°C (6).

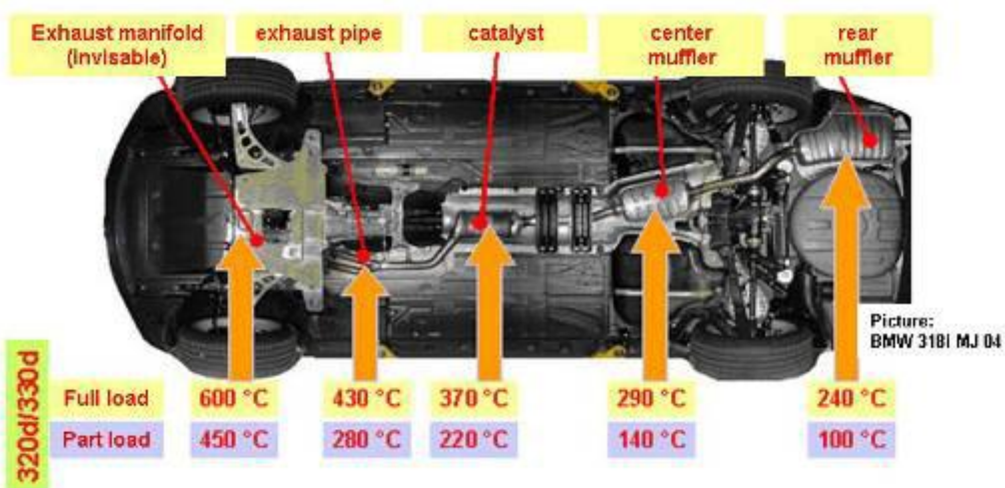

Figure 7: Temperature distribution of exhaust manifold of 320d BMW

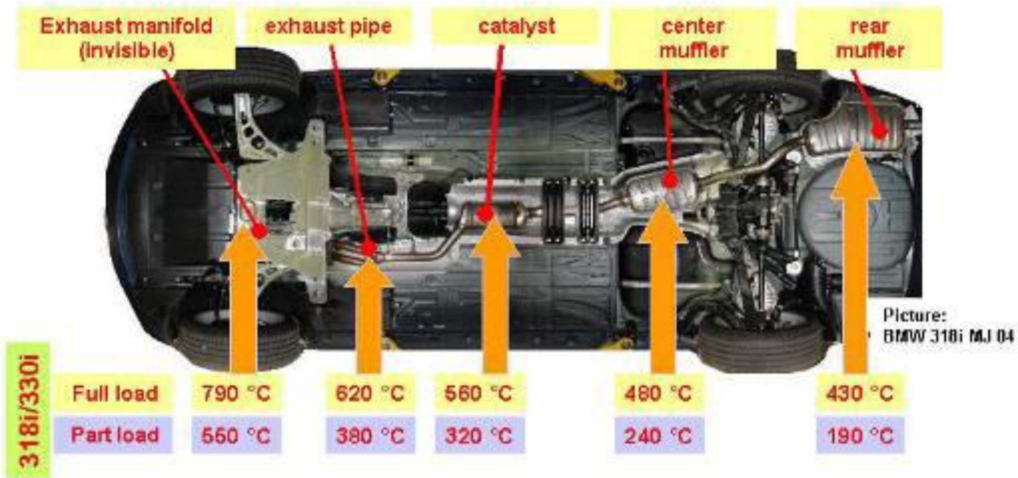

Figure 8: Temperature distribution of exhaust manifold of 330i BMW

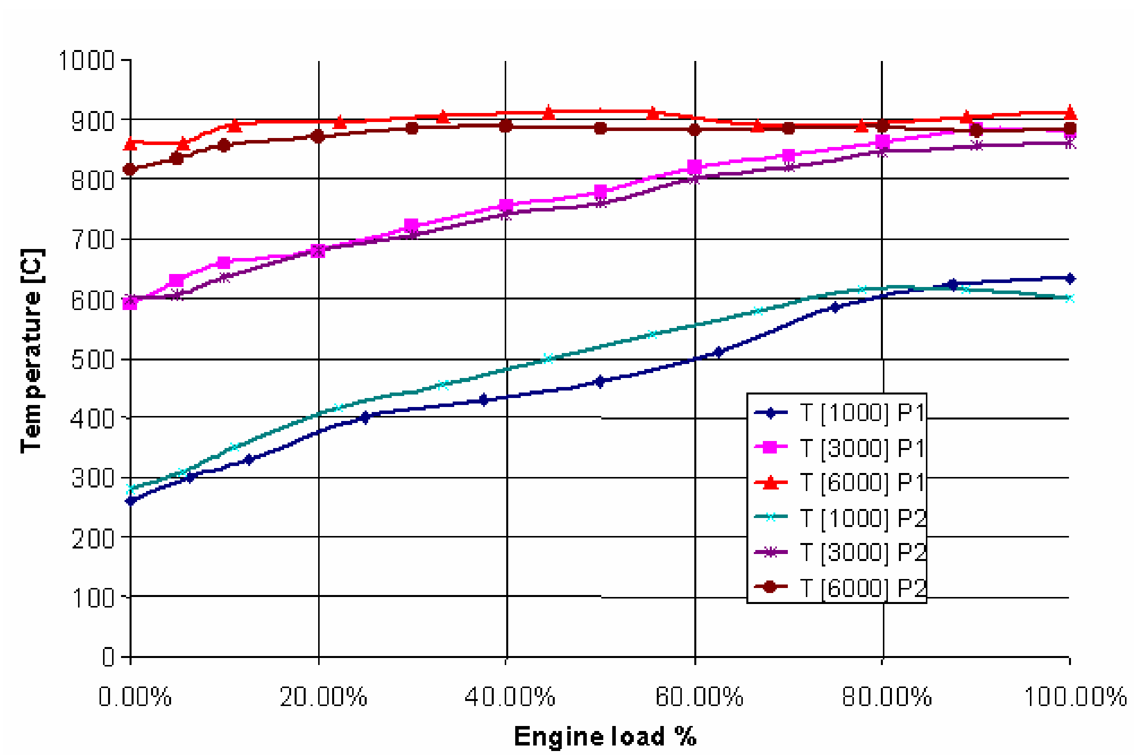

Figure 9: Exhaust gas temperatures of cars shown in previous figure at different engine speeds (6)

1.6 Challenges for Thermoelectrics

Increasing the overall efficiency is the main objective in any ETEG design; this increase can be achieved by numerous techniques. The thermal efficiency can be increased by reducing the heat dissipated due to the thermal contact resistance (Q_5), which can be implemented by applying a uniform compression to the TEMs and using highly conductive thermal interface material between the hot/cold sides and the modules. Because the hot and cold parts of the heat exchanger are normally electrically conductive, electrical insulation should always be applied to the TEMs; ceramic wafers are ideal for fulfilling the thermal interface and electric insulation requirements. A temperature drop of about 10~15^{o}C can therefore be achieved across these wafers. Other solutions, such as silicon- and metal-based grease, might not be suitable for ETEG applications because of the high operating temperature of the modules (> 200^{o}C) as well as the cost considerations. The efficiency of the heat exchanger can be controlled by many methods. When the hot box has a relatively large cross-sectional area, the exhaust gas velocity is damped when entering the hot box channel. This sudden drop in gas velocity forms a thick thermal boundary layer that causes the overall heat transfer coefficient to be sharply decreased. Internal fins, tabulators, and corrugated surfaces are most favorable solutions for eliminating the effect of this boundary layer. However, an important factor that should always be considered is the free cross-sectional area for the flow, because it may cause the engine efficiency to decrease. To minimize conduction losses through the assembly, the number of assembly elements contacting the hot box directly should be minimized as much as possible and free surfaces should be strictly insulated. This can be easily achieved by using thermal insulation to prevent convection from the hot box surface. Also, spray insulation with conductivity as low as 0.03 W/m-K is available and also sustainable for high temperature applications. The ability of the cold plate to provide sufficient

cooling for TEMs at all operating conditions is another important thermal requirement in ETEG. Generally, the cold side can be classified to two types according to heat dissipation from the system: Radiator-based cold plate, Heat sink-based cold plate. In the first type, the cold plate dissipates exhaust heat to the engine radiator through the engine coolant (i.e., water), while in the second type the cold plate dissipates heat to the ambient air through a heat sink.

To increase the thermal performance of heat exchangers heat transfer augmentation techniques are used. Heat transfer augmentation techniques refer to different methods used to increase rate of heat transfer without affecting much the overall performance of the system. These techniques broadly divided in two groups: passive and active. Active techniques involve some external power input for the enhancement of heat transfer; some examples of active techniques include induced pulsation by cams and reciprocating plungers, the use of a magnetic field to disturb the seeded light particles in a flowing stream, etc. Passive techniques generally use surface or geometrical modifications to the flow channel by incorporating inserts or additional devices, for example, use of inserts, use of rough surfaces etc. In the present work passive technique of augmentation is used. The concentric tube heat exchanger is fitted with inner twisted tape and flow side protrusions to outer tube as additional inserts (6).

1.7 Objectives

The main objective of the thesis was to increase the heat exchanger performance as well as the thermoelectric generator performance. To accomplish that task the heat exchanger efficiency was increased. Considering the constraints of availability, cost effectiveness, experimental setup and material properties the heat exchanger was designed. An aluminum rectangular heat exchanger

was chosen along with tape insertion (passive heat augmentation technique). The tape was made of the same material (Al) selected since it was thought to improve the efficiency of the heat exchanger. Due to this twisted tape insertion, the overall area inside the heat exchanger will be reduced and it will create a tangential component of the flow (swirl flow) which increases the velocity of flow in the inner wall of heat exchanger and overall heat transfer coefficient. In order to achieve higher heat exchanger efficiency, thermoelectric efficiency, system efficiency and the effectiveness compare to two previous experiments with only copper and aluminum heat exchanger the aim was set up and experiment completed accordingly.

1.8 Passive Heat Exchanger Augmentation Methods

Passive heat transfer augmentation methods, as stated earlier, does not need any external power input when considering one of the most dominant mechanisms of heat transfer, convective heat transfer. This can significantly enhance performance by increasing the effective surface area and residence time of the heat transfer fluids. The passive methods are based on this principle. Use of this technique causes the swirl in the bulk of the fluids and disturbs the actual boundary layer so as to increase effective surface area, residence time and consequently heat transfer coefficient in existing system (7).

Following methods are generally used:

Table 2: Typical methods of heat exchanger augmentation

Inserts	Extended surface
Surface modifications	Use of additives

1.8. 1. Inserts

Inserts refer to the additional arrangements made as an obstacle to fluid flow so as to augment heat transfer. Different types of inserts are listed in Table 3. In the present study twisted tapes and fin inserts are analyzed.

Table 3: Types of inserts used with a heat exchanger

Twisted tape and wire coils	Ribs, Baffles, plates

1.8.2 Twisted Tape

Twisted tapes are the metallic strips twisted with some suitable techniques with desired shape and dimension, inserted in the flow. The following section lists the main categories of twisted tape which is incorporated into this study:

- *Full length twisted tape:* These tapes have length equal to length of test section.
- *Varying length twisted tape:* These are distinguished from first category with regards that they are not having the length equal to length of test section, but less than the length of the section.
- *Regularly spaced twisted tapes:* These are short length tapes of different pitches spaced by connecting together.
- *Tape with attached baffles:* Baffles are attached to the twisted tape at some intervals so as to achieve more augmentation.
- *Slotted tapes and tapes with holes:* Slots and holes of suitable dimension made in the twisted tape so as to create more turbulence.

- *Tapes with different surface modification*: Some insulating material is provided to tapes so that fin effect can be avoided. In some cases dimpled surfaced material used for tape fabrication (7).

1.9 Heat Exchanger Design Requirements

The design of heat exchanger should fulfill the process requirements. The design specifications contain different detailed information which is necessary. This information includes flow rate, operating pressure, pressure drop limitation for fluids, size, length, temperatures, cost, type of material, heat exchanger type, and other arrangements. The heat exchanger design provides missing information based on experience, requirement, and judgment. Table 4 lists considerations for the design of a heat exchanger.

Table 4: Design considerations for a heat exchanger

Construction type	Surface or core geometry	Operating pressure and temperature
Flow arrangements	Materials	Reliability
Safety	Availability	Maintenance requirements
Manufacturability	Cost	

While considering the thermal designs there are two main things to consider: sizing and rating. For the sizing problem, the surface area and dimension of heat exchanger need to be determined, input rating of flow, temperature (inlet and outlet) surface geometry, pressure limitations, thermochemical properties of fluid and material of the heat exchanger need to be determined. In cases of rating determination, keeping in mind the limitation of process requirement, other factors are considered like the surface geometry, inlet and outlet (flow rate, temperature and

pressure) parameters are determined. There may be several designs to fulfill the requirement but there always needs to be a more advantageous benefit on one side than the other. Computational processes can be done by hand or computer programmed to see the overall advantage of selected rating. The selection criteria are always that which heat exchanger is withstanding the process requirement. So after thermal design mechanical design will be conducted (6).

1.9.1 Previous Heat Exchanger Designs

An experiment carried out shown in ref. (8) flowed servotherm oil in an acrylic circular tube fitted with stainless steel insulated twisted tape inside. The authors determined the effect of varying pitch and length of twisted tape with different twist ratio on friction factor and heat transfer rate. Their findings showed that short length twisted tape reduces pumping losses as well as heat transfer rate but uniform pitch twisted tape gave the maximum heat transfer rate used different twist ratio, it was found that the friction increased ¾ times but getting higher heat transfer was achieved with small twist ratio rather than greater twist ratio (9). To investigate the efficiency enhancement of heat transfer and how to reduce friction factor in case of heat transfer (10) made an experimental set up with a concentric double tube plexi glass material heat exchanger. In the experiment air (hot) was as used inner fluid and water (cold) was used as annulus. After that tape with different twist ratio was inserted in the inner tube made of stainless steel. Due to twist and blockage of the tape flow velocity increases, as a result the efficiency, Nusset number, and friction factor all increases improving convection heat transfer. Another experiment by (11) used a double tube heat exchanger fitted with aluminum twisted tape inside. In that experiment it was observed the effect of relevant parameters on heat transfer and pressure. After the insertion of twisted tape, heat transfer rates were enhanced but the friction factor also increased. The author observed a correlation between heat transfer coefficient and friction factor.

Another study performed experiments with double pipe copper tube along with helical screw made of stainless steel (12). In the experiment it has been observed for both cases by using core rod inside and also using hot and chilled water. This was observed to have a significant effect on heat transfer rate and friction factor. Without core rod friction is less and higher heat transfer rate obtained rather than core rod inside. Without core rod 34% increase was seen but with core rod it was 50-60% higher but only with helical screw friction is 50% less. In another study by (13) it was shown that regularly spaced full length twisted tape performs better compared to short length tape. They did this in square and rectangular acrylics ducts. Regarding augmentation test by (14) the following results come as per Table 5 (15).

Table 5: Summary of different findings using different heat exchanger modifications

Details of tape used	Remark
1. Full length twisted tape	1. Heat transfer rate increases but increase in friction factor also observed
2. Short length twisted tape	2. Low friction factor and low nusset number observed. As the length of the tape reduces friction factor reduces and heat transfer coefficient also reduces.
3. Twisted Tape with uniform pitch	3. Performs better than gradually decreasing length tape.
4. Twisted tape with gradually decreasing length pitch	4. Poor performance as compared to uniform pitch tape.
5. Baffled twisted tape with holes.	5. Better heat transfer rate is observed but as turbulence increases, increase in friction factor is also observed.
6. Tight fit and loose fit tapes	6. Tapes having tight fitting give more frictional loss , whereas reduced width and centrally located loose fit tape gives better result.

CHAPTER 2: Experimental Setup and Methodology

2.1 Heat Exchanger Design Methodology

It is important that the heat exchanger withstands the process in which it will be used. Performing thermal, mechanical, and functional design calculations includes considerations of plate size, shell and header thickness, its length diameter and flow arrangement. The selection of material takes into consideration the environment and corrosion factor. Sizes of inlet and outlet nozzles, connections, pressures and temperature measurement, thermal stress calculations under steady state and transient condition, were all taken into account with the present design. After the mechanical design was completed, cost analysis should also be considered; however, was not performed for the current project. There are many other interdependent factors considered for optimizing a heat exchanger. The problem of heat exchanger design is intricate, with some parts of it quantitative and others qualitative (6)

2.2 Experimental Setup

The flow arrangement used for the present experiments is a counter flow heat exchanger. As per the schematic diagram shown in Fig. 7, it is clearly seen that the hot side and cold side heat exchanger along with thermoelectric generator in between. There are mainly three basic part of the apparatus (i) hot side heat exchanger, (ii)thermoelectric element, and (iii) cold side heat exchanger. There are also the exhaust system, inlet and outlet of coolant stream, pump and air inlet, and heating element used as axillary part of the system.

Figure 10: Mass flow meter used in the experiment

For this experiment FMA 1700/1800 series electronic mass flow meters were used. These flow meters provide monitoring the flow for a wide variety of gases from up to 1000 LPM. Utilizing heat transfer through a heated tube to measure molecular gas flow rate, the thermal mass flow meter provides measurements of direct gas mass flow rate.

Figure 11: Temperature controller

The is a digital on/off thermocouple temperature controller used for the experiments. The size of this controller is 203mm x 121 mm x 9 mm. The meter measures temperature in both degrees Fahrenheit and Centigrade. The thermocouple connected to monitor temperature fluctuations is K-type. To pump the liquid coolant through the system the circulation coolant pump shown in Fig.12 was used. It has a model number of SM 1212 ST 26 and has a ¾ inch inlet and outlet 140 watt motor with 1.3A input, the flow capacity is 12 gallon per minute.

Figure 12: Coolant circulation pump

In order to provide the correct amount of voltage and current to the heated section of the exhaust recovery system, a step up down transformer used here to provide power to the temperature controller. The unit is a Simron AC 5000w transformer and is shown in Fig. 13.

Figure 13: Step up transformer

All the measurement work in the experiment was done with the help of LabView software. A data acquisition board was used to communicate between the thermocouple sensor and the lab view software and the computer, a transducer is used to convert the analog signal into digital signal. While developing lab view connection diagram the total signal was added into two parts, in one part sixteen connections were used through thermocouple to measure the temperature in different hot and cold positions of both the heat exchanger and in another part five connections was used to measure the generated voltage and current keeping the load resistance fixed. The signal was recorded at a rate of 5 Hz. The detailed connection diagram is shown in Fig. 14. In the whole experiment there are two circuits working simultaneously, one is cold circulation circuit and another one is hot gas flow circuit.

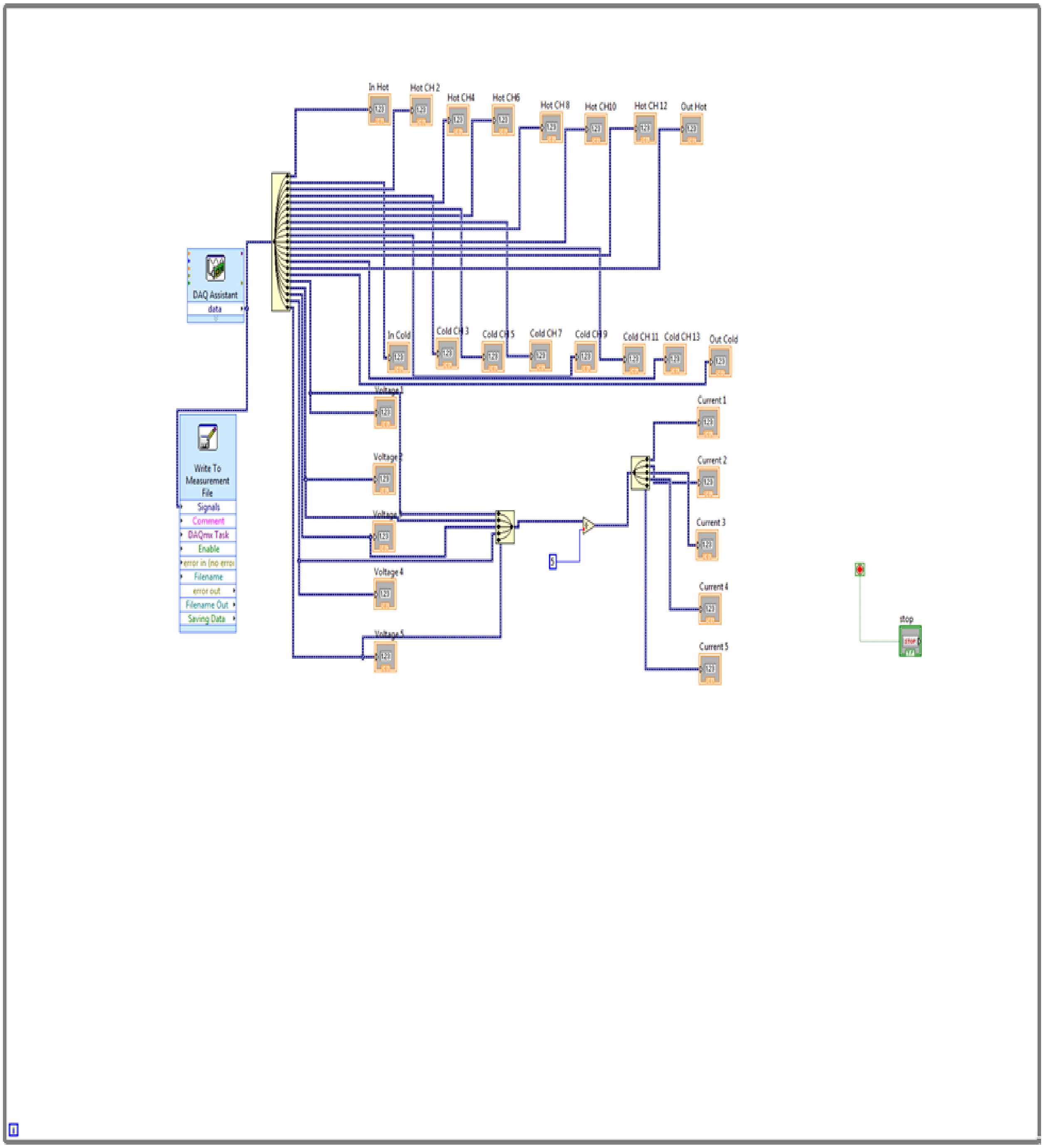

Figure 14: LabView connection diagram for hot and cold side heat exchangers

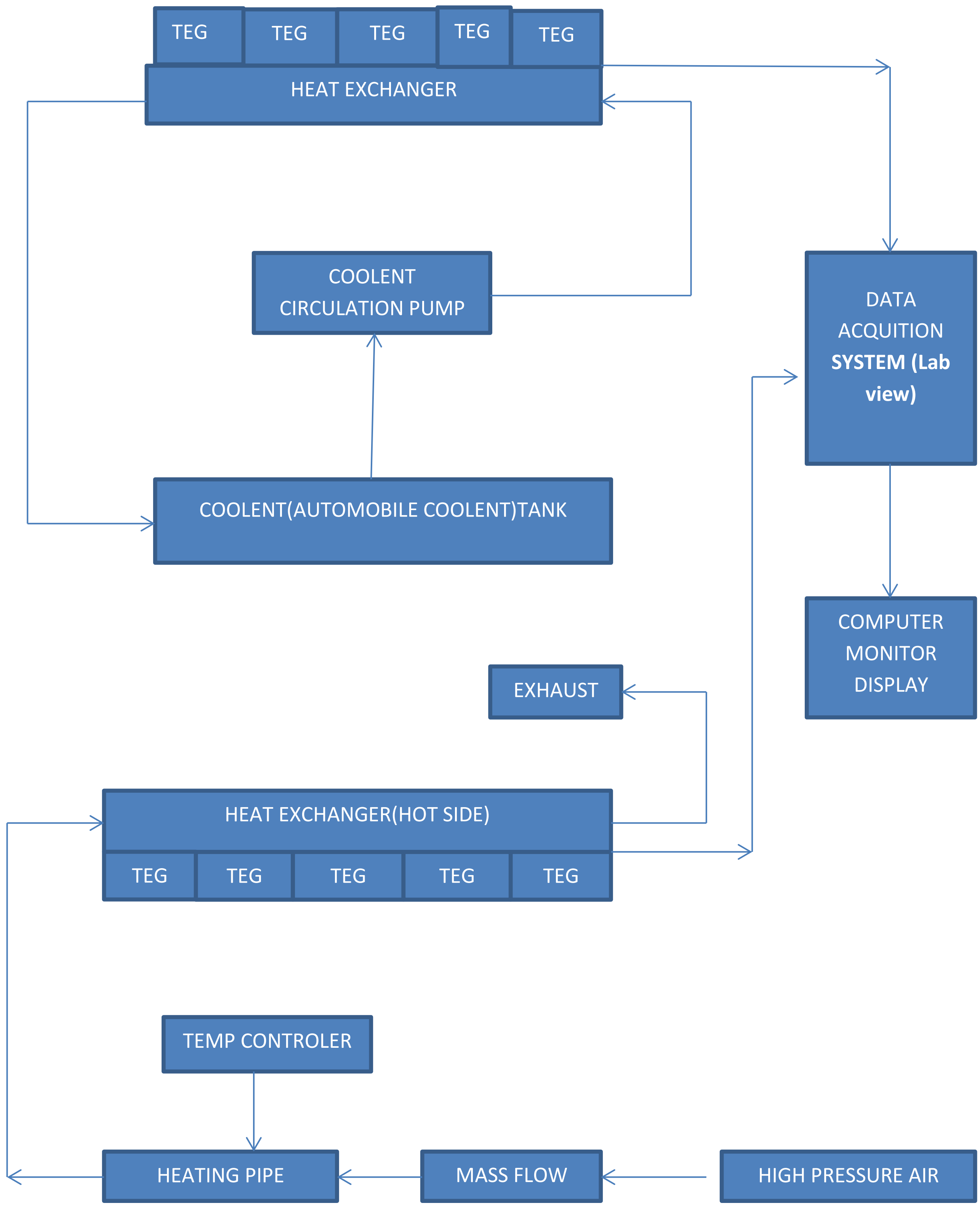

Figure 15: Block diagram of experimental setup

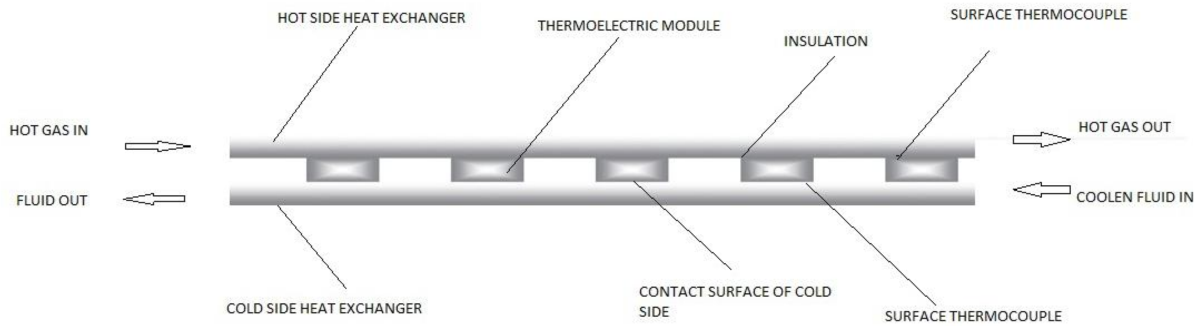

Figure 16: Schematic diagram of counter flow heat exchanger used for experiments

Table 6: Dimensions of the heat exchanger and tape used in the schematic shown above

HOT SIDE HEAT EXCHANGER			COLD SIDE HEAT EXCHANGER		
Length	Cross Section	Wall Thickness	Length	Cross Section	Wall Thickness
406 mm	51mm x 25 mm	3 mm	457 mm	51 mm x 25 mm	3 mm
TAPE			ORIFICE PORT		
Length	Thickness	Pitch Ratio		Diameter	
304.8 mm	3 mm	0.125mm		3 mm	

The hot side heat exchanger was made of aluminum duct and the twisted tape inserted. The cold side heat exchanger was made of aluminum duct. Engine coolant for vehicle was used in a 50-50 blend mix with water for the cold side. An electric coolant pump was also used with a flow rate of 12GPM to pump the coolant in a closed loop. This coolant was delivered from a tank using a pump of quarter horse power. Here the heat exchanger was designed keeping in mind the exhaust manifold of vehicle and its boundary conditions in respect to size, length, and attachment. There are five columns and three rows of orifice ports to have set up the k-type thermocouples which monitored the temperature of the cold fluid and hot air inside the chamber along with thermocouple on the surface of hot and cold side of the thermoelectric generator. It is being

done from 50.8 mm to 355.6 mm downstream of the duct inside the aluminum heat exchanger and cooler. For maintaining a constant air flow rate, a mass flow controller was set up before the air inlet to hot chamber to make it hot, it is 75 mm upstream of the experimental set up. The heated hot air is connected to heat exchanger which is placed at the top and cold side fluid flow is placed at the bottom, both are attached with a bucket mounted and is not touching each other, in between the hot and cold duct thermoelectric generator was installed so that it can have direct contact with the hot and cold surface with insulation rapping around both the part. The hot air is going to the atmosphere through air outlet at the end of the heat exchanger. The detailed dimension of each side of the heat exchanger is shown in Table 6. Here the insulation used is laboratory refractory insulation and unused part other than thermoelectric generator insulation was used. To reduce the contact thermal resistance of the heat exchanger and thermoelectric generator the surfaces were machined, smooth, cleaned and thermal grease with high conductivity was used. Each resistance of 5 Ω is connected with each thermoelectric generator as a load for to get the flow of electricity. The whole experimental set up can be seen in Fig. 16. A data acquisition board was also connected to convert this analog data to digital and transferred this data to computer and measured with the help of Lab View. The air inlet pressure was 7 psi and heating element was capable to heat up to 500 degree centigrade (16).

The thin twisted helical tape that was inserted into the heat exchanger shown in Fig. 16 is shown in Fig. 17. The tape was made of 3mm thick aluminum, with 305 mm length and 6.35 mm width with a twist ratio 0.125. A clearance was kept between the heat exchanger and tape so that it can be inserted. The resistance caused by the thickness of the tape increases the velocity of the flow which got a positive impact on the heat flow inside the heat exchanger. Here heat transfer enhancement occurred mainly because it reduces the hydraulic diameter of the inner aluminum

tube and it causes a tangential velocity component, both of this particularly increase the velocity at the near wall (17).

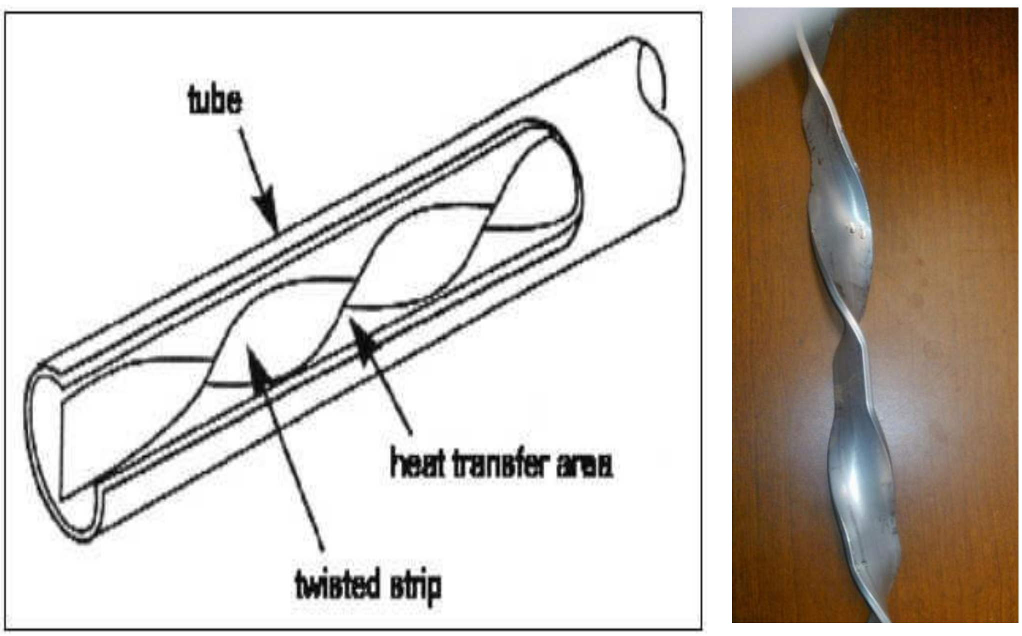

Figure 17: Twisted tape insert for hot side heat exchanger with a 0.125 twist ratio

Figure 18: Top view of the how side heat exchanger

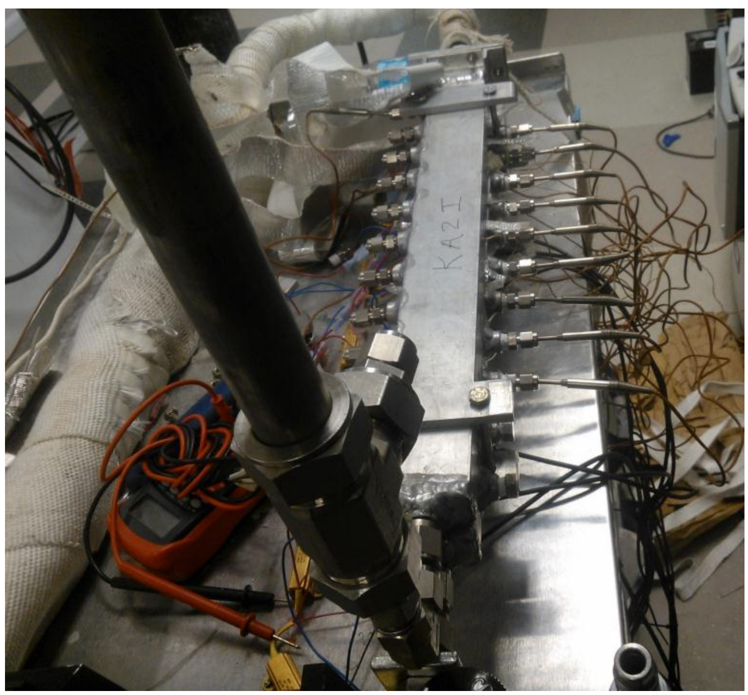

Figure 19: Isometric view of heat exchanger setup

CHAPTER 3: Results and Discussion

3.1 Results

During the experiment an emphasis was given to increase the efficiency of the heat exchanger by inserting metallic twisted tapes inside the heat exchanger and observe the power output of the thermoelectric generator. The overall efficiency and effectiveness of the system were the calculations of interest for the system. The following are the comparative data of both earlier and present experiments. In Table 7 the data was achieved by using cooper heat exchanger and aluminum heat exchanger with inserted tape is shown, it is clearly visible in the table as well as in the graphs in Figs 20-32 that for the same temperature it has increased in relation to power generation, thermoelectric efficiency, system efficiency, and heat exchanger efficiency. There is also an observed relationship between ΔT with effectiveness. In Table 8 the data achieved by using aluminum (Al) and Al with inserted tape heat exchanger is shown. Here also it is observed that there is a definite improvement of thermoelectric power generation, heat exchanger efficiency, and system efficiency, Figs 20-32 demonstrate this. Finally the data obtained by using three different heat exchangers is summarized in Table 9.

Table 7: Comparison of different parameters between two heat exchangers: copper and aluminum with an inserted tape operating at 462K

Heat Exchanger Arrangement	Power Generated (W)	Heat Exchanger Efficiency (%)	Effectiveness	System Efficiency	Temperature Difference Between Hot And Cold
Material Copper	0.092	9.44	0.29	0.32	432
Material Aluminum With Aluminum Tape Inserted	0.457	17.11	0.44	0.43	462

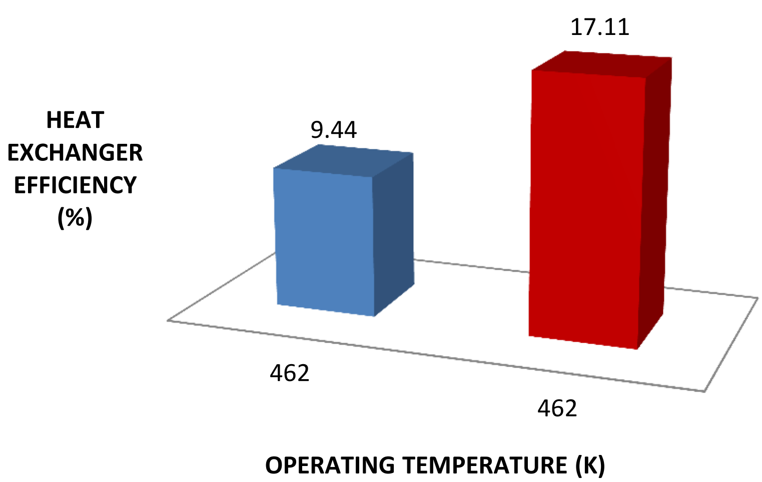

Figure 20: Comparison of heat exchanger efficiencies for copper (blue) and aluminum heat exchanger with aluminum tape inserted (red)

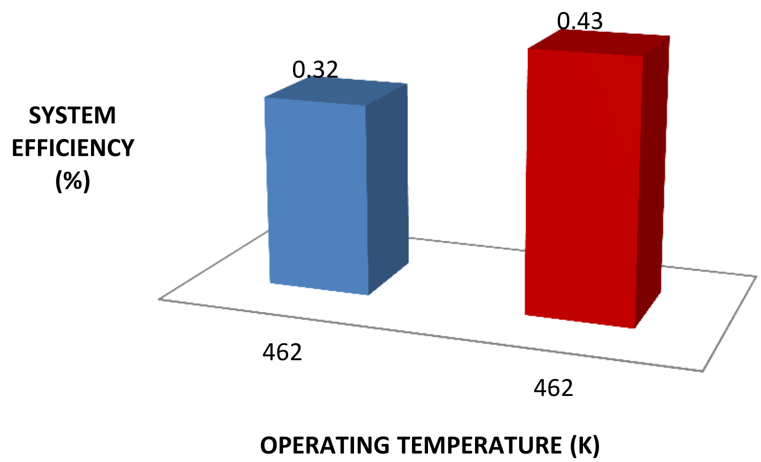

Figure 21: System efficiency comparison between copper (blue) and aluminum with an inserted tape (red)

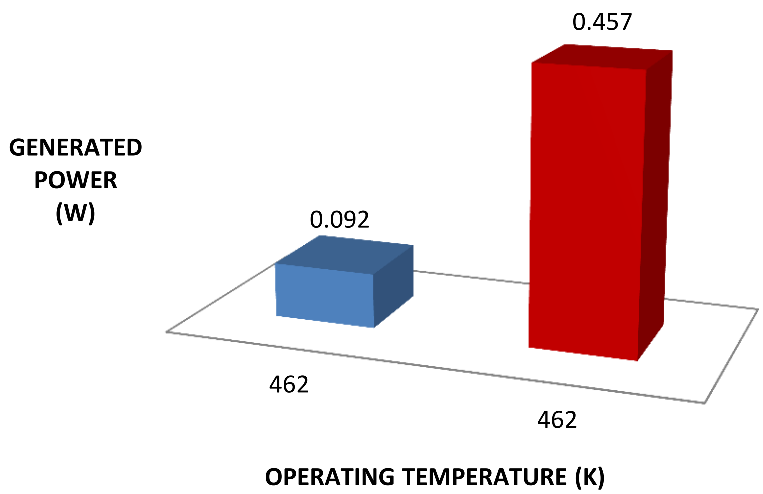

Figure 22: Power generation comparison between copper(blue) and aluminum with an inserted twisted tape(red)

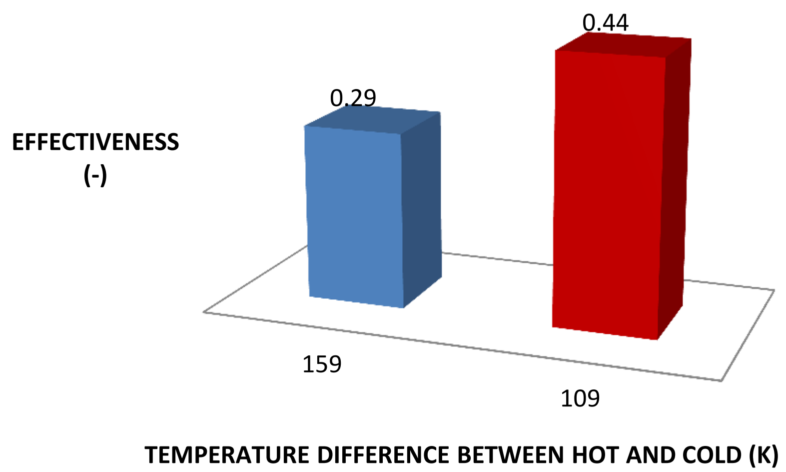

Figure 23: Comparison between copper(blue) and aluminum with an inserted twisted tape(red) for different delta T across the thermoelectric

Table 8: Comparison of different parameters between two heat exchangers: aluminum and aluminum with the twisted tape. Operation temperature was 513 K for these measurements.

Heat Exchanger Arrangement	Generated Power (W)	Thermo Electric Efficiency (%)	Heat Exchanger Efficiency (%)	System Efficiency (%)	Efficiency (%)
Material Used Aluminum	3.4	3.43	17.91	0.48	0.29
Material Used Aluminum with Aluminum Tape Inserted	4.96	4.02	26.65	1.01	0.44

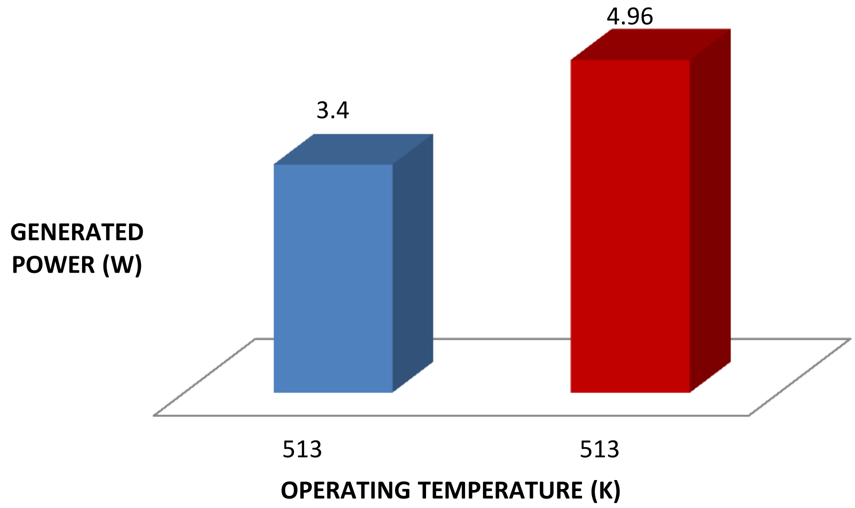

Figure 24: Power generation comparison between aluminum heat exchanger with(red) and without an inserted twisted tape(blue)

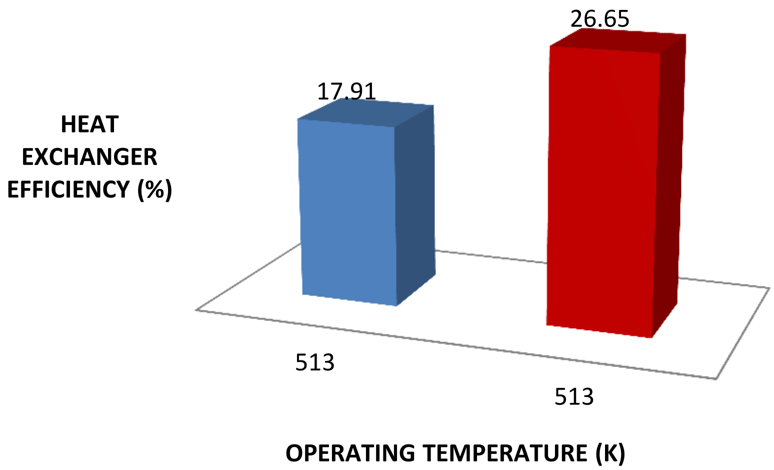

Figure 25: Heat exchanger efficiency comparison between aluminum heat exchanger with (red) and without an inserted twisted tape(blue)

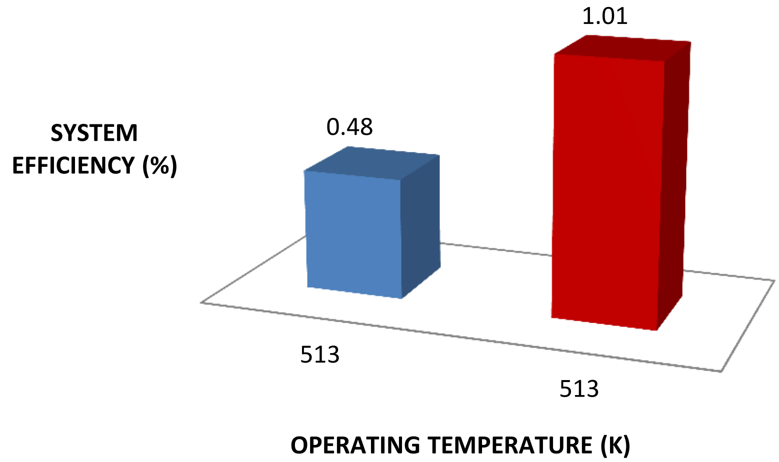

Figure 26: System efficiency comparison between aluminum heat exchanger with(red) and without an inserted twisted tape(blue)

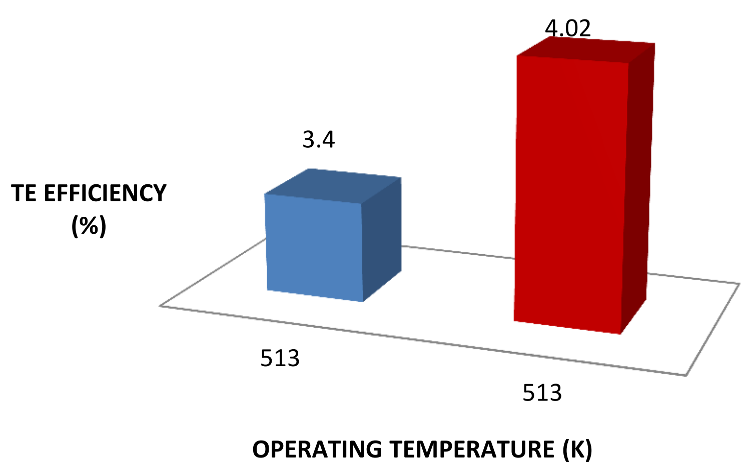

Figure 27: Thermoelectric efficiency comparison between aluminum heat exchanger with (red) and without an inserted twisted tape (blue)

Table 9: Different parameters of three different heat exchangers made of copper, aluminum, and aluminum with a twisted tape inserted

Heat Exchanger Arrangement	Delta T (K)	Power Generated (W)	Thermoelectric Efficiency (%)	Heat Exchanger Efficiency (%)	System Efficiency (%)	Effectiveness
Copper	432 K	0.092	3.43	9.44	0.32	0.29
Aluminum	473 K	3.4	2.68	17.91	0.48	0.63
Aluminum and Aluminum Tape Inserted	462 K 484.5 K	0.457 4.96	2.55 4.02	17.11 26.65	0.43 1.01	0.44 0.44

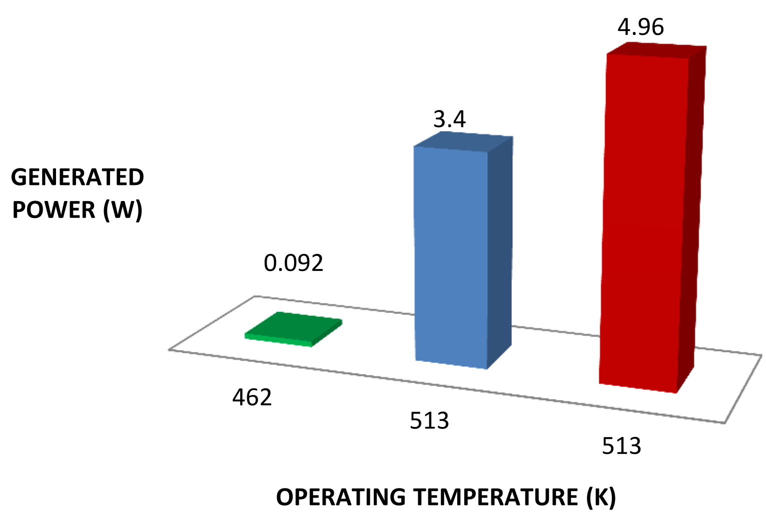

Figure 28: Power generation comparison between copper(green) and aluminum heat exchanger with(red) and without an inserted twisted tape(blue)

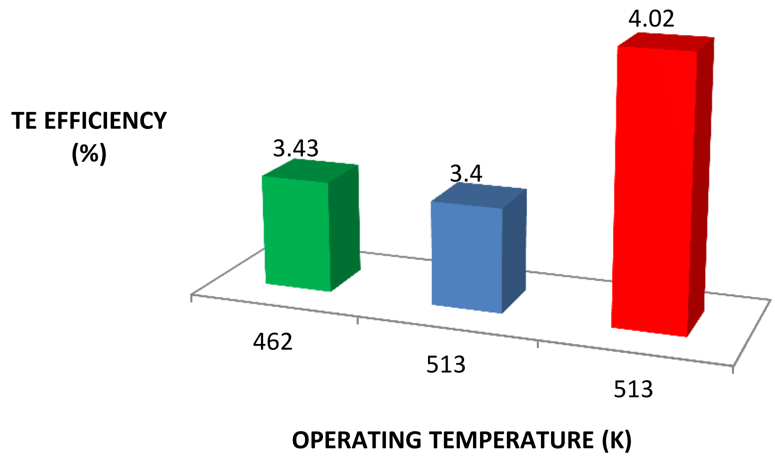

Figure 29: Thermoelectric efficiency comparison between copper(green) and aluminum heat exchanger with(red) and without an inserted twisted tape(blue)

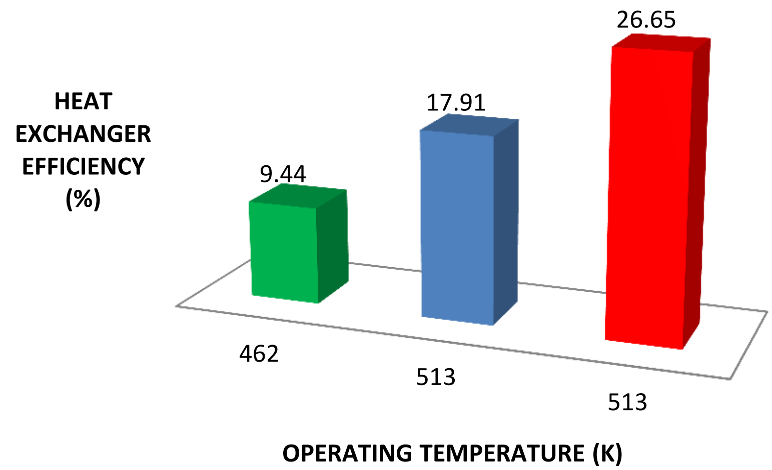

Figure 30: Heat exchanger efficiency comparison between copper (green) and aluminum heat exchanger with(red) and without an inserted twisted tape (blue)

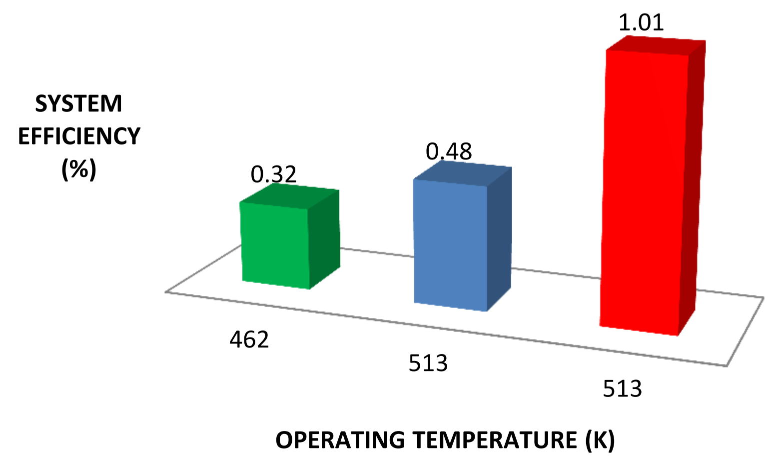

Figure 31: System efficiency comparison between copper(green) and aluminum heat exchanger with(red) and without an inserted twisted tape(blue)

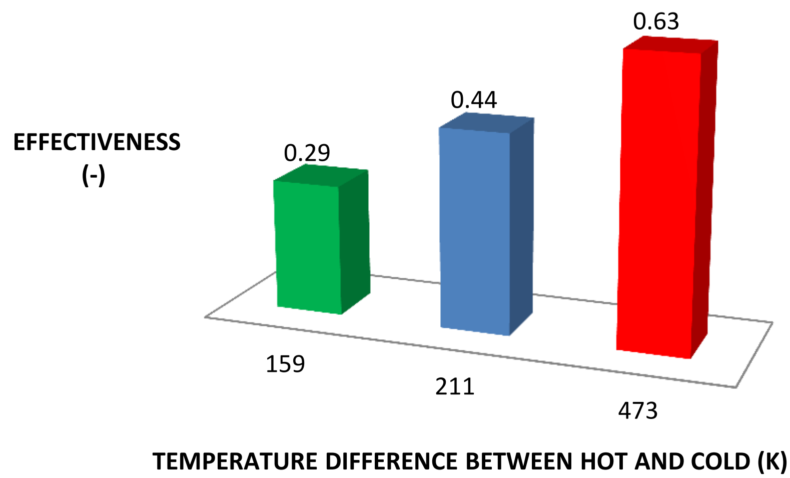

Figure 32: Comparison between copper(green) and aluminum with(red) and without inserted twisted tape(blue) for different delta T across the thermoelectric

3.2 Discussion

After the measurement of generated power from the thermoelectric and their efficiencies with and without the aluminum tape inside the heat exchanger the pattern of generated power was seen to behave as a sinusoidal wave which means due to the increase and decrease of the flow of heat flux on the wall of heat exchanger the power generation was altered. So it is not only the temperature flow and velocity increase of exhaust gas inside the heat exchanger that affects the power generation but also the periodic behavior within the heat exchanger that alters the output.

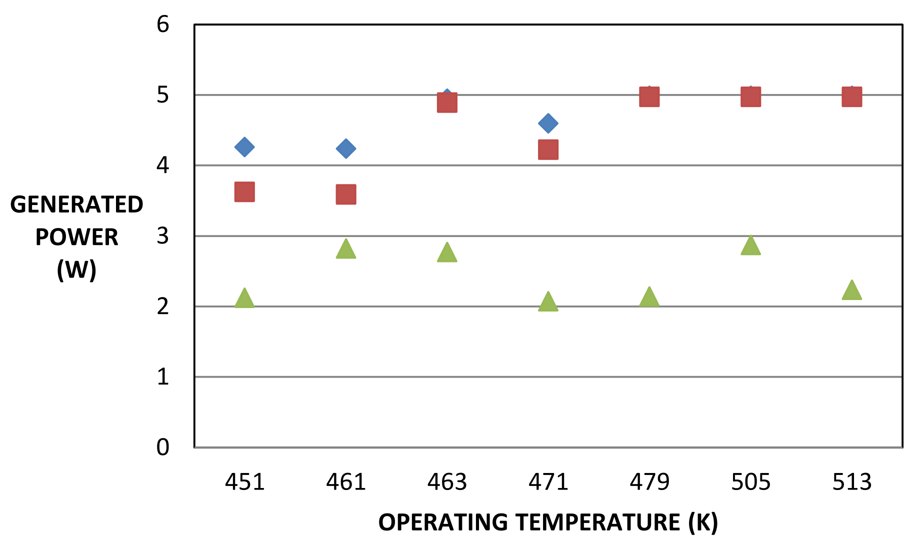

Figure 33: Thermoelectric power generated at various temperatures. Blue diamond represents TE closest to heat exchanger entrance, Red square represents TE in middle of heat exchanger, and Green triangle represents TE furthest from heat exchanger inlet port

Thermoelectric power is related to figure of merit value as well as the temperature of hot and cold side of thermoelectric generator. It was also observed that it varies due to the aluminum tape, see Fig. 34.

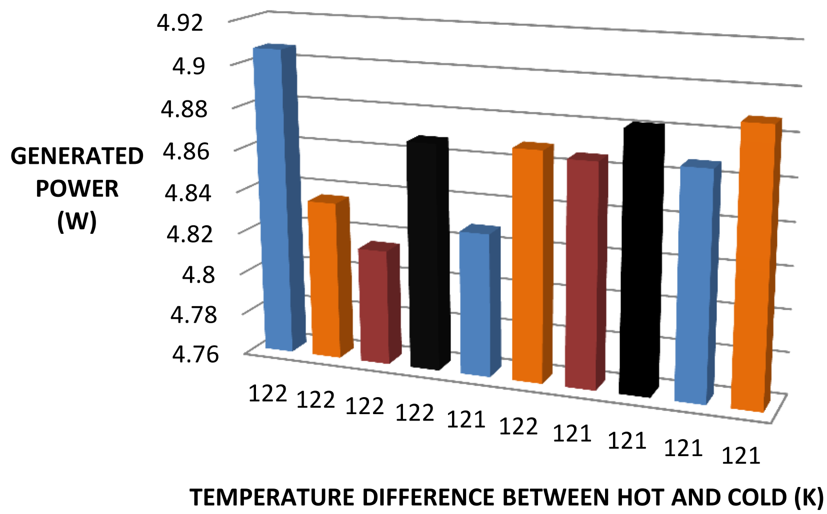

Figure 34: Generated power at different locations on the heat exchanger for the same ΔT. Blue represents TE nearest the heat exchanger entrance, orange represent middle of heat exchanger, purple near the heat exchanger exit, and black the TE furthest from the heat exchanger entrance

Effectiveness was observed to decrease with a temperature increase but increasing for higher ΔT values, Fig. 35.

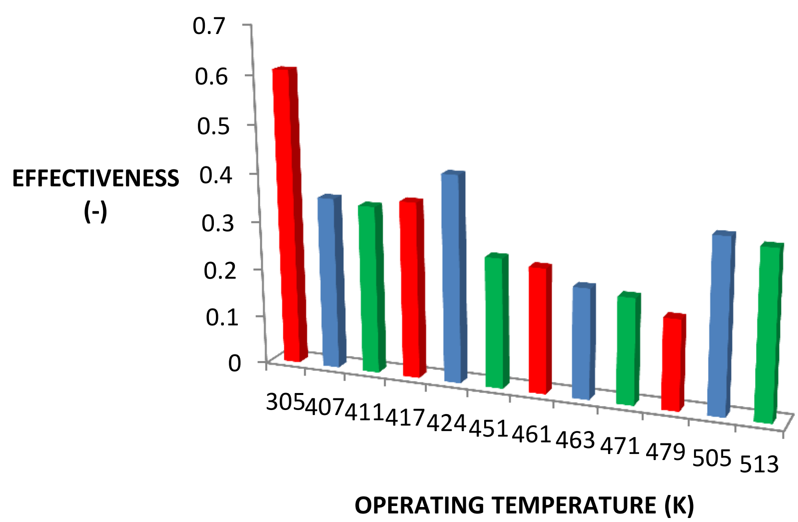

Figure 35: Heat exchanger effectiveness at different operating temperatures. Red represents heat exchanger with twisted tape insert, blue represents aluminum heat exchanger, and green copper heat exchanger

In terms of material used and with the inserted tape inside reveal that the largest benefit is seen with the heat exchanger with the twisted tape inserted. The detailed test results and its related graph have already been shown in the chapter. So the following observations can be drawn from the result of this experiment:

a. At 462K the same cross sectional area of heat exchanger made with aluminum (with and without inserted tape) has provided 0.365 W more power, 0.88 more thermoelectric efficiency, 0.15 more effectiveness, 7.67 more heat exchanger efficiency, and 0.11 more system efficiency.

b. At 513K for the same cross sectional area of heat exchangers made with aluminum (with and without inserted tape) has provided 1.56 watt more power,1.34 more thermoelectric efficiency, 0.21 less effectiveness, 8.74 higher heat exchanger efficiency, and 0.52 more system efficiency has been observed.

c. Due to insertion of tape inside the heat exchanger the flow velocity of the hot gas increases, as a result the heat exchanger efficiency has increased for a combined effect of this tangential component on the inner surface of the wall and increase in overall heat transfer coefficient.

d. The power generation from the thermoelectrics were increased due to heat input on the hot side and better cooling on the cool side. This means the temperature difference between the hot and cold side (ΔT) has got a definite relation with the power generation and keeping ΔT to the optimum value as per the design requirement of the TEG, has got definite role to improve power generation.

e. The effectiveness of the heat exchanger was reducing with the increase of the ΔT. As mentioned previously ΔT must be maintained to have a better efficiency of the system.

f. The twisted tape insert looks promising in providing existing heat exchangers with a inexpensive boost in performance.

g. Coolant side of the heat exchanger has also got equally important role to keep the ∆T at the optimum condition, so the method of cooling, heat exchanger material of cooling side play an equally important role to improve overall efficiency like heat exchanger of hot side.

h. The heat exchanger may not be hotter in a sequential way at the same time due to the absence of the swirl component of hot gas flow inside the wall of the heat exchanger.

i. By increasing the pitch ratio (distance of each twist/total distance of the tape) or the twist ratio (total distance of the tape/number of twist) of the inserted tape the heat exchanger efficiency can be increased provided if the friction factor can be kept low.

CHAPTER 4: Summary and Conclusions

4.1 Summary and Conclusions

The main objective of the study was to design a heat exchanger to increase the overall efficiency, electrical power generation and its effectiveness by using thermoelectric generators to harness the waste heat from automobile exhaust. Here a simple design was taken into consideration by inserting tape inside an aluminum rectangular heat exchanger keeping the flow at 150 LPM. In terms of cost effectiveness it is cheaper to modify the heat exchanger to include a twisted tape than include other costly methods of modification such as the inclusion of fins or complicated flow paths. Increases in heat exchanger efficiency can be primarily attributed to an increase in the flow velocity due to the insertion of tape. The increased velocity also increased the overall heat transfer coefficient at the surface of the thermoelectric generator.

4.2 Cost Benefit Analysis

In the study of cost effectiveness aluminum is available in the market with cheaper price but if I consider the cost of thermoelectric generator and its generated power through this exhaust waste heat recovery in terms of the required power for the automobile, it is not a cost effective solution. Although tape insertions increased the overall efficiency while maintaining a low cost. But the overall cost effectiveness for the heat exchanger is justified other than the cost of the thermoelectric. For example if the cost of a vehicle is $40,000 and cost of installation of the system of thermoelectric generators is $4000 dollar then the overall cost-effectiveness will be reduced in terms of its utility in the overall system requirement in an automobile. So other than the improvement of the thermoelectric generators figure of merit and its cost in the market it needs some timespan to become cost effective.

4.3 Future Recommendations

To further increase heat exchanger performance methods would be needed to further increase the velocity thus increasing the overall heat transfer coefficient. Heat transfer across materials of higher thermal conductivity than aluminum may also improve the heat transfer rate. The chemical relationship between heat exchanger material and the fluid/gas and friction also need to be considered. Here in this case for studying the thermoelectric generator output with automotive exhaust, alloy material with higher conductivity and low cost can be used with heat exchanger enhancement technique.

In this thesis one critical parameter is the heat flux which flows through the thermoelectric generator. Another recommendation is to operate the TEG close to the optimum temperature of its requirement and also attempt to reduce the thermal resistance which includes the thermal resistance from the exhaust gases to the inner wall of heat exchanger and from inner wall to the hot surface of the module. To solve this heat conduction problem after analyzing the thermal properties of steel, stainless steel, aluminum, copper and alloy ,aluminum was chosen because it is lighter and comparatively and has better properties value of different parameters withstand capability as per the temperature requirement. In future work similar experiments can be conducted by increasing number of tapes with different twist ratios, same twist ratios with holes and testing at different pitch ratios and different materials. Superior alternative to metals, glass and other materials to enhance heat exchanger efficiency, reliability, high thermal conductivity, universal corrosion resistance, high hardness and strength is silicon carbide hexoloy tube. This material has twice the thermal conductivity than tantalum, five times that of stainless steel, ten

times that of iron, and fifteen times of glass. It has got higher efficiency and less heat transfer area. Presently it is lighter in weight and available in the market with reasonable cost(18).

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Vita

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