DEVELOPMENT OF A BISMUTH TELLURIDE THERMOELECTRIC GENERATOR FOR A VEHICLE WITH 3.5 L FORD ECOBOOST INTERNAL COMBUSTION ENGINE

By

Vasily Ivanov

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ABSTRACT

DEVELOPMENT OF A BISMUTH TELLURIDE THERMOELECTRIC GENERATOR FOR A VEHICLE WITH 3.5L FORD ECOBOOST INTERNAL COMBUSTION ENGINE

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Thermoelectric generator (TEG) is a good opportunity for improving fuel economy and reducing emissions of a vehicle, taking in mind high fuel cost and need for cleaner vehicles. TEG transforms heat to electricity (the Seebeck effect) and could be applied to waste heat in a vehicle. Electricity generated could be used for operating electric motors, powering sensors, or charging a battery.

There are two major issues in TEG development for a vehicle: *heat transfer considerations* and *TE material selection*.

The present work describes the efforts directed towards *heat transfer considerations* and employs bismuth telluride as thermoelectric (TE) material. Effective heat transfer system was developed for TE modules integration into practical TEG as a part of an exhaust system of a vehicle with 3.5L Ford Ecoboost internal combustion (IC) engine. The goal was to optimize the design of a TEG, including size and weight, and to obtain the maximum performance from this device. Experiments were conducted with the TEG developed that simulate real world conditions.

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KEY TO SYMBOLS OR ABBREVIATIONS

°	Degree
μ	Micro-
Ω	Ohm
A	Amp
atm	Atmosphere
C	Celsius
DC	Direct current
EGR	Exhaust gas recirculation
EMF	Electromotive force
g	Gram
gal	Gallon
h	Hour
IC	Internal combustion
J	Joule
JPL	Jet Propulsion Laboratory
k	Kilo-
l, L	Liter
lb	Pound
m	Meter, Mile, Milli-
min	Minute
M	Mega-
MPPT	Maximum Power Point Tracking

mpg	Miles per gallon
MSU	Michigan State University
MPPT	Maximum Power Point Tracking
OTR	Over the road
rpm	Revolutions per minute
s	Second
TE	Thermoelectric, Thermoelectrics, Thermoelectricity
TED	Thermoelectric Device
TEG	Thermoelectric Generator
V	Volt
w/	With
w/o	Without
W	Watt

Chapter 1. Introduction

Technologies such as direct fuel injection, variable valve timing, exhaust-driven turbochargers, brake energy regeneration, and the Auto Start Stop function have made great improvements in engine efficiency over the past few years. However, modern IC engine converts only about *one third* of the energy derived from fuel into the mechanical energy needed to set a vehicle in motion. Other *two thirds* of the generated energy are waste heat and still lost, creating a significant opportunity to reclaim energy [9]. Half of it carried away by the exhaust gas, with the remaining half absorbed by the engine coolant. One of the major goals for engineers is to find ways of recovering this lost heat energy. Turbosteamer, TEG, engine insulation, and a waste heat exchanger for oil heating are among the most practical solutions [2]. TEG is a good opportunity for improving fuel economy and reducing emissions of a vehicle, taking in mind high fuel cost and need for cleaner vehicles.

1.1. TE Overview

TEG generates electricity from waste heat to improve engine efficiency. Fuel economy can be improved considerably if the electrical energy required by vehicle can be produced using waste heat. Achieving increased performance and reducing fuel consumption may happen at the same time.

TEG converts heat directly into electricity (Seebeck effect) and can be used in the exhaust system as well as in the EGR system [9]. Electrical voltage is generated between two semiconductors if they are connected on one side and placed in temperature gradient [6].

TEGs are most efficient during dynamic driving – during acceleration or driving with a high speed, where other energy saving solutions, like engine insulation or waste heat exchanger for oil heating, are not that efficient. Engineers claim that TEGs will save up to 5% of fuel under everyday driving conditions in a few years [2]. Typical TEG efficiency is around 5 – 8% [4].

Older TE modules used metals for TE elements and were bulky. Modern TE modules use bismuth telluride (Bi_2Te_3), lead telluride (PbTe), calcium manganese oxide, skutterudite compounds, or combinations, depending on temperature [4]. Properties of TE materials determine the possibility of producing TE devices on a large scale. Thermal and electrical properties of modern TE materials demonstrate that their potential for practical waste heat recovery is very large. TE materials for automotive TEG applications must have good efficiency, be available at low cost, easily fabricated, and durable, develop good interfaces with other materials, and be chemically stable in the 100-600°C temperature range.

There are a number of special circumstances where TEG use may be beneficial: the need for autonomous operation solution, the need for silent solution, the need for small size solution.

The use of TEG also has its disadvantages.

TEG heat exchanger provides an additional resistance for the exhaust gas, which creates back pressure and reduces the engine performance.

Engine coolant is usually used to cool down heat exchanger cold side rather than ambient air because it is more efficient and has relatively constant temperature. This increases the radiator and piping size because it adds to the radiator load [5].

TEG system contributes a significant weight to the vehicle. Some existing TEGs designed for cars weigh up to 60 kg, for trucks and SUVs – up to 110 kg. The added weight consumes additional energy, which results in lower gas mileage [5].

The cost of replacing TE modules, caused by thermal cycling and vibration of a vehicle, could exceed the savings in fuel [5].

When many TE modules are connected in series, the system has very high output resistance (>10 ohms) and power is efficiently transferred to load with high resistance only.

Because TE modules use materials which usually have low thermal conductivity, this can significantly decrease the heat transfer through such devices [4].

TEG usually contains parts that may oxidize at higher temperatures by the working fluid. In 3.5L FORD Ecoboost IC engine applications, this working fluid is oxygen-containing exhaust. Methods of insulating the oxygen-sensitive components from the flow has to be developed to protect parts from oxidation.

1.1.1. History

Seebeck in 1821 discovered that a compass needle deflects by a closed loop formed by two wires made of deifferent metals, with a temperature gradient across the loop. A current loop and a magnetic field were created because the metals responded differently to the temperature difference [6].

This technology was used mainly in military and space applications until the 2nd half of the 20th century and was considered useless for automotive applications because its efficiency was rather low [5]. During last few years, new TE materials have significantly improved the performance of TE modules.

The first automotive TEG was built in 1963 by Neild et al. Birkholz et al. built a TEG for Porsche 944 in 1988 which could produce tens of watts. In the early 1990s, Hi-Z Inc. designed a 1 kW TEG for a diesel truck exhaust system. In the late 1990s, Nissan Motors designed a 35.6 W silicon germanium TEG for a 3.0 L gasoline engine. Clarkson University, in collaboration with GM designed a 255 W TEG for a GMC Sierra truck [5]. Two TEGs have been successfully integrated and tested by Gentherm, in collaboration with BMW and Ford, on a BMW X6 and Lincoln MKT with over 600 W of power produced [22].

1.1.2. TEG operation principle

The temperature difference between exhaust gas and coolant is several hundred degrees, which is capable of generating 500-750 W of electricity [5].

Local current density is given by $J = \sigma(-\nabla V + E_{EMF})$, where V – local voltage, σ – local conductivity, $E_{EMF} = -S\nabla T$ - electromotive field, S – the Seebeck coefficient, ∇T – gradient of temperature T. Electric current stops when the load is removed, and the circuit serves as a thermal sensor. If the system reaches a steady state (J = 0), then the voltage gradient is given by $-\nabla V = S\nabla T$ [6].

When there is a temperature difference on the sides of a conductor, the heat moves from the hot side to the cold side. The heat transferring also results in electrical charge carrier movement within the conductor in the same direction, which can be used for electrical current generation (Figure 1.1) [8].

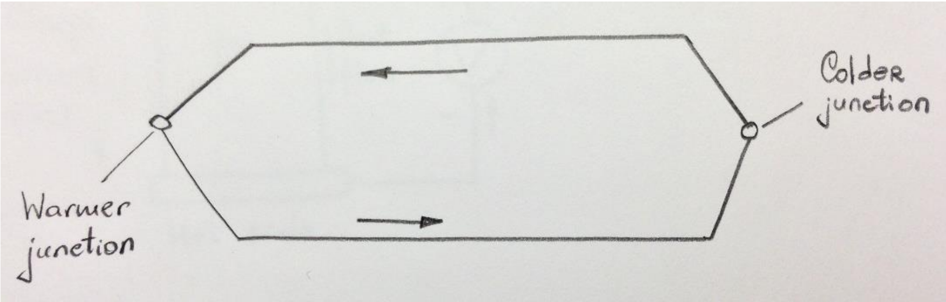


Figure 1.1. Use of two identical conductors

If two conductors are the same, equal charge carrier movement in both conductors will cancel one another. If two different conductors are employed, it creates a circuit with continuous current flow (Figure 1.2). Direction of current flow is determined by the conductor with greater capacity for charge carrier movement.

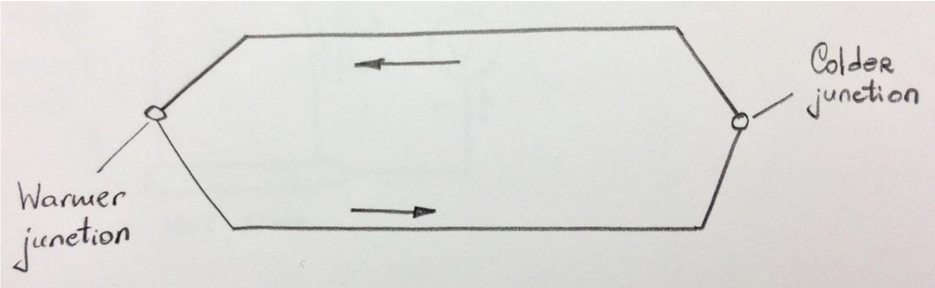


Figure 1.2. Use of two dissimilar conductors

A voltage, which is created through the movement of heat, could be measured by breaking the circuit (Figure 1.3).

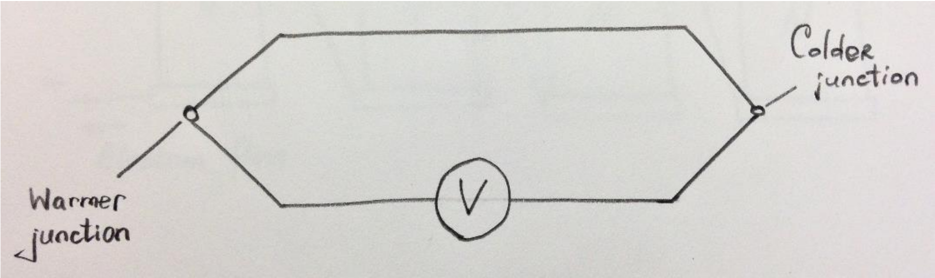


Figure 1.3. Voltage measurement

The voltage generated by a thermocouple is a function of the temperature difference between the two junctions, and the type of the conductors employed.

TEG may be done with a single n-type semiconductor where hot and cold sides are connected with a voltmeter (Figure 1.4). TEGs employ semiconductors for producing the TE effect because they can be easily optimized for heat transfer, and it is easy to change the type of charge carrier. In n-type material electrons are the charge carrier. The second dissimilar material required, is the connection cables to the voltmeter. Current will flow if an electrical load is connected to the device, – if not, the system will generate 'no-load' voltage [7].

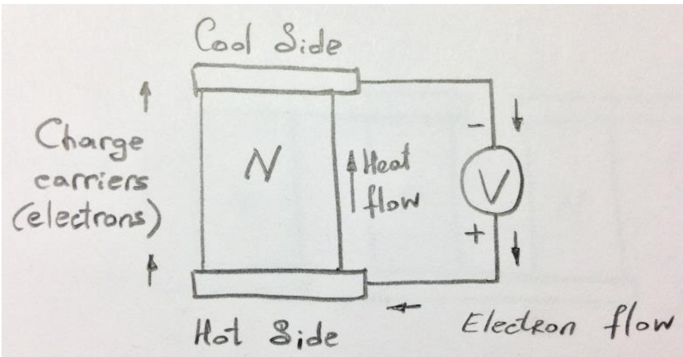


Figure 1.4. N-type TEG

P-type semiconductor may also be used to build a TEG. P-type semiconductors have positive charge carriers - 'holes' – vacant places where electrons can fit. The 'holes' are carried with the heat as the heat moves from the hot to the cold side of the semiconductor. 'Holes' move in a direction opposite to that of electron movement (Figure 1.5).

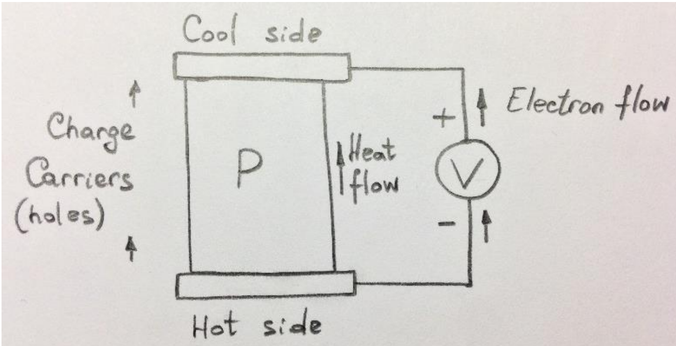


Figure 1.5. P-type TEG

Simple TE device with a single semiconductor cannot produce a lot of electricity. To be able to generate more power, multiple semiconductors are used together. Since TE semiconductor produces a very small voltage (tens of mV) and a substantial current (several amps), they can be connected in series electrically and in parallel thermally (Figure 1.6). Though, this is possible theoretically, that significantly reduces performance.

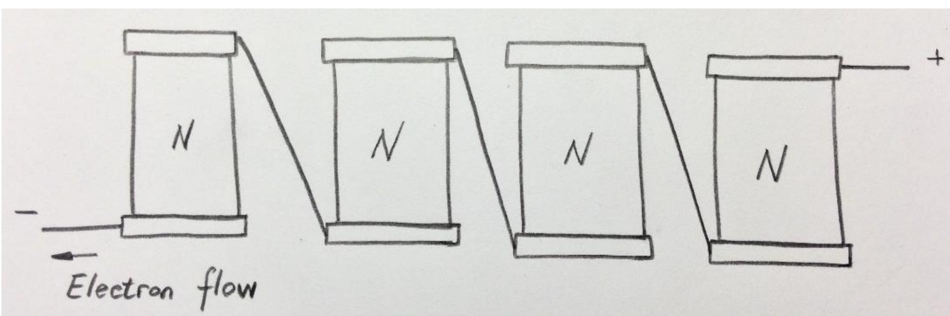


Figure 1.6. Connection of several semiconductors

To eliminate thermal shorting, one need to arrange n- and p-type semiconductors in a couple connecting them with a tab (Figure 1.7).

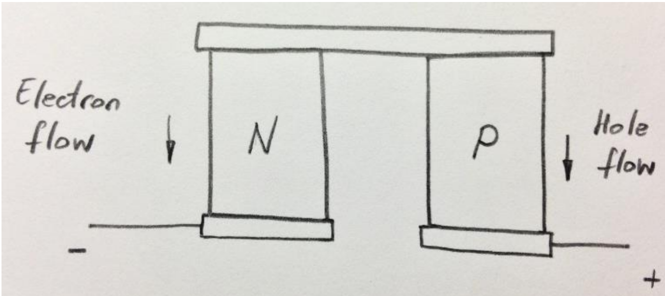


Figure 1.7. Series connection of n- and p-type semiconductors

That is how in a single TEG the TE effect is optimized. The n- and p-type semiconductors are connected thermally in parallel and electrically in series. The charge carriers and heat flow in the same direction. Electrons flow through the 'holes' in the p-type semiconductor in a direction opposite to that of 'hole' flow, so the current generating potentials in the semiconductors do not oppose one another.

To build practical TEG, one need to connect many such semiconductor couples in series (Figure 1.8). These devices can pump considerable amount of heat and are suitable for vehicle DC power network.

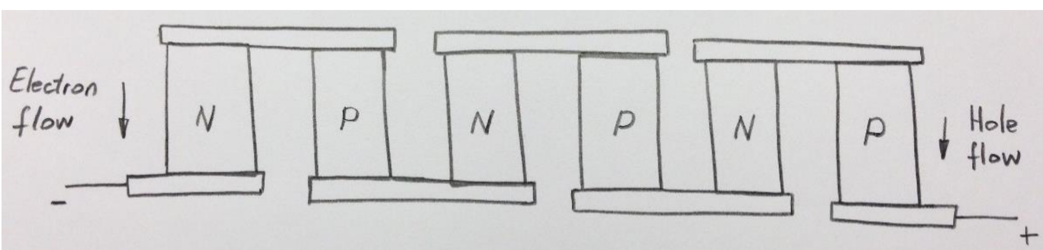


Figure 1.8. Practical TE module scheme

Semiconductors are connected by the conductive tabs which mounted to thin ceramic substrates. Ceramic substrates serve as the thermal interface between TE couples and heat exchangers. Ceramic materials have appropriate strength, electrical resistivity, thermal conductivity, and cost.

There are four basic components in a TEG: heat source, TEG module, heat sink, and electrical load. It is necessary to prevent the hot side temperature of the TE module from exceeding the melting temperature of the solder employed in constructing and rated high temperature for the device. A relatively thick plate between the heat source and the TE module might be employed to prevent uneven heat distribution at the hot side module interface.

The main objective of TEG use is to extract maximum power from TE modules. Maximum power is extracted when the resistance of a TEG equals to the load resistance. Therefore, TE modules must be connected in a certain series/parallel array to generate the desired voltage and have the same load resistance.

1.2. Thesis scope

The present work describes the efforts directed towards TEG heat transfer considerations which employs commercially available bismuth telluride TE modules. Effective heat transfer system was developed for TE modules integration into practical TEG as a part of an exhaust system of a vehicle with 3.5L Ford Ecoboost IC engine. The goal was to optimize the design of a TEG, including size and weight, and to obtain the maximum performance from this device.

Experiments were conducted with the TEG developed that simulate real world conditions. Experiments help to find potential problems that may slow down TE technology implementation.

1.3. Outline of thesis

The first chapter describes the idea of using TE technology to improve fuel economy by converting heat to electricity, history and operation principle of TEG, its advantages and disadvantages, and the scope of this thesis.

The second chapter reviews the literature related to TE research with previous work that has been done. Research questions are brought up.

The third chapter describes the TEG development of two different designs, including heat transfer analysis.

The fourth chapter describes testing procedure, test bench, and instrumentation. Data post-processing is described.

The fifth chapter covers the results and discussion of the development process and testing.

The sixth chapter describes the research achievements and conclusions. Recommendations for future work are given.

Chapter 2. Literature review

Researchers all over the world are working on various TE topics: developing TE materials, optimizing TEG designs, and improving their reliability. Below one can find topics that are especially relevant to the research described in this thesis.

2.1. Previous work

MSU, in collaboration with JPL, has developed TEGs with skutterudite TE modules and power output 50 and 100 W. They estimated that this technology recovers about 4% of the exhaust energy. MSU's most recent TEG (Figure 2.1) has power output 100 W and consists of 200 couples. It is managed by Couple Bypass Technology system which bypasses failed semiconductor couples [1].

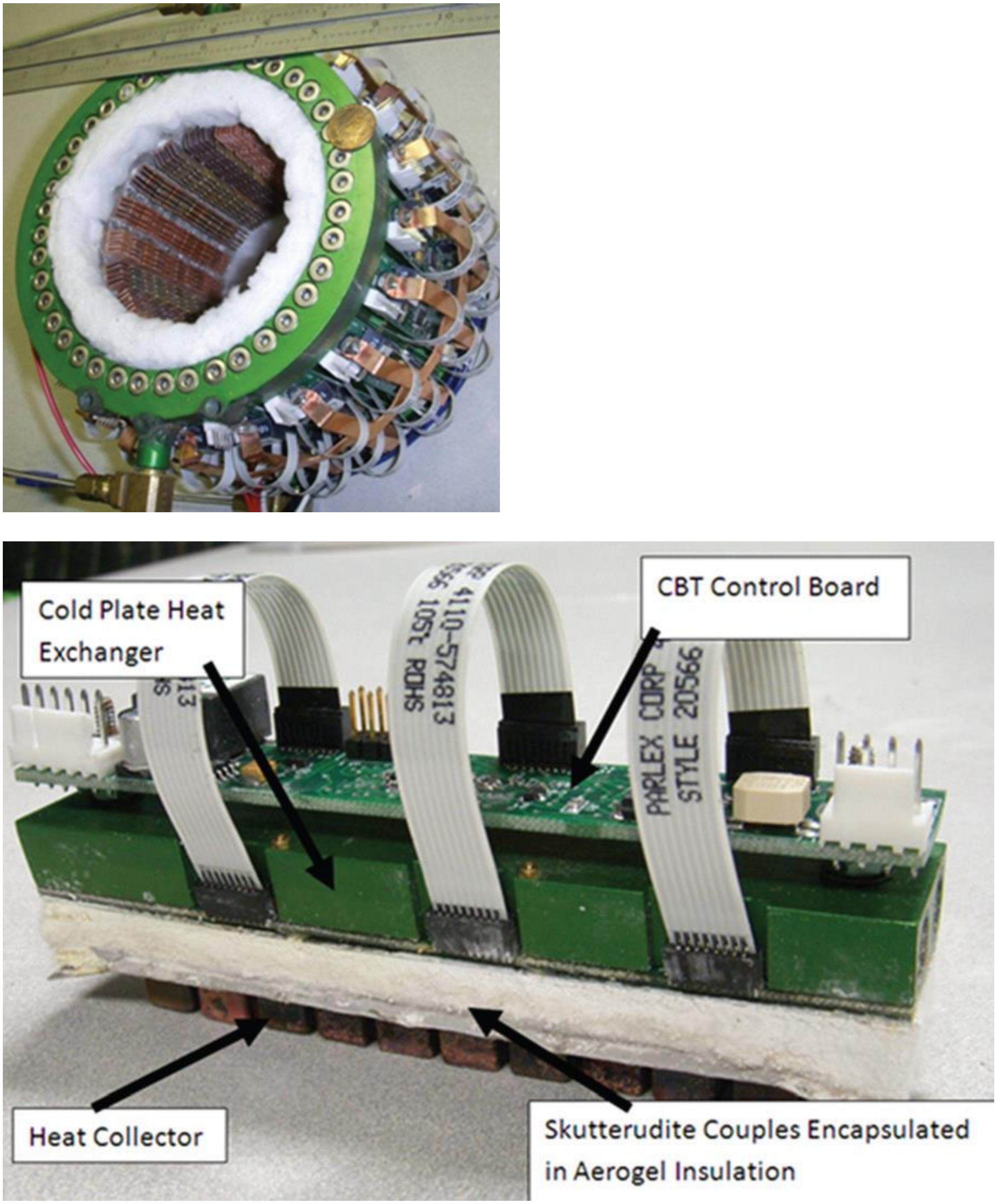


Figure 2.1. Assembled 100 W TEG (left) and subassembly module for the TEG (right) (for interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis)

Research efforts were also made towards 1 kW TEG development, which predicted expected operating conditions, couple failures that occur during operation, and provided an estimate for TEG life time [9].

Much work has been done integrating TEGs into the exhaust system of OTR trucks. By using Ricardo WAVE Engine System Performance Simulation software, a simulation was performed at MSU on Cummins ISX engine to compare the amount of power generated for 3 different TEG configurations: 1, 3, and 6 cylinders per TEG unit [24]. The findings of this study showed that the design with the highest amount of heat energy converted to electrical energy is 1 cylinder per TEG assembly [9].

MSU, in collaboration with Cummins, made an analysis of the potential benefits associated with equipping a 2007 Cummins ISX IC engine on a class 8 truck with TEG [13]. The MSU group calculated that the fuel economy could be improved 3-5% by the TEG system implementation. Operating condition B62 (62% of full power at 1500 rpm – typical road load condition) was assumed. The energy was recovered while the vehicle was in operation and during idling periods. This analysis did not include the gains related with alternator electrical load reduction [1]. Cost analysis at a production rate of 10,000 units per year was made for two skutterudite TEGs: 1 and 5 kW [12]. The cost estimates for each TEG are about $5,000 for 1 kW and $20,000 for 5 kW TEG. The estimated cost of the TEG could be reduced significantly because machine assembly using technology for building circuit boards is now possible. The following assumptions were made during estimation: the cost of diesel fuel is $4/gal, driving fuel economy 5 mpg w/o TEG, 5.02 mpg w/ TEG, idle fuel economy 0.829 gal/h w/o TEG, 0.249 gal/h w/ TEG, vehicle operates 300 days/year, spends 8.3 h on road and 8 h in idle per day, and travels 150,000 m/year. The study found that 1,500 gal of fuel or $6,000 would be saved every year, which translates to savings of $42,000 over the 7 years – expected life of the engine. The 1 kW and the 5 kW TEGs will be compensated within 1 and 3 years respectively. TEG must work longer than the payback period in order to be economically practical [9].

Purdue University, in collaboration with MSU, has made efforts to study fluid flow and heat transfer taking place in TEGs [15-18]. The Hendricks work describes the importance of heat exchanger design to get the maximum power output from a TEG. Crane and Bell described an analysis of a 3-section TE system, where the materials in each section are selected to produce highest performance at the certain temperature gradients [19]. Although multimaterial TEG indeed provide the best performance, they have higher cost and more complicated thermal management.

In 2007, MSU tested 100 W TEG with bismuth telluride TE modules from Tellurex (G1-1.4-219-1.14), new heat exchanger, and controller (Figure 2.2). The hot pipes go through the hot plate to generate an even hot side temperature. 20 TE modules are installed between hot and cold plates. Cold plates are bolted together to keep the heat exchanger as a whole unit.

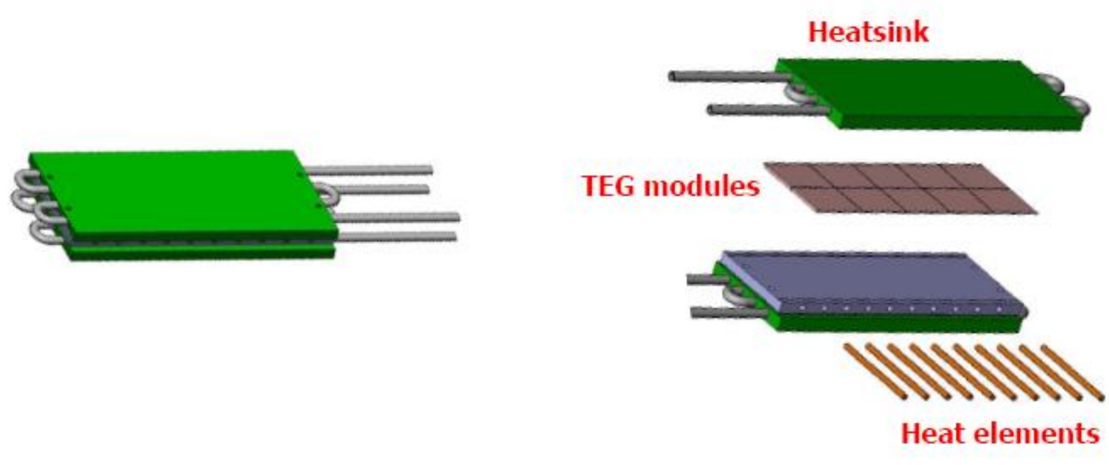


Figure 2.2. Bismuth telluride 100 W TEG (final assembly on the left, decomposed assembly on the right)

Since individual electrical output characteristics of TE modules are different, maximum power extraction methods have to be developed. TE module power output depends on the load connected to it. For a given thermal operating conditions, there is a maximum power output point, at which the load resistance equals to the resistance of the TE module. MSU introduced an analog control algorithm called Maximum Power Point Tracking (MPPT) which allows TE modules to generate maximum electric power at any load conditions, which is impossible if the load is connected directly to TE modules. Another possible MPPT method is to use microcontrollers or digital signal processors and software control algorithm [21].

2.2. Research questions

Taking in mind the results of these studies and experiments, the TEG for an exhaust system of a vehicle with 3.5L Ford Ecoboost IC engine was developed to answer the following questions:

- Which power level is the current bismuth telluride TEG design able to achieve? Which problems need to be solved to achieve higher power level?
- Is the current bismuth telluride TEG design able to meet 20 kg weight limit requirement? (20 kg weight limit requirement is selected on the basic physics analysis which requires 1 kW of mechanical energy for each additional 20 kg of a 2000 kg vehicle to keep the same dynamic characteristics)

2.3. Summary

A number of previous studies helped to develop TEGs and perform experiments detailed in this thesis:

- Variety of skutterudite and bismuth telluride TEG prototypes has been developed

- Fuel efficiency and cost analyses have been made
- MPPT method was designed, which allows a TE module to operate on its maximum power point

Chapter 3. TEG assembly development process

A typical practical TEG consists of four main elements: a hot-side heat exchanger, a cold-side heat exchanger, TE materials, and a compression assembly system. In TEG, TE modules are packed between the hot-side and the cold-side heat exchangers. The heat exchangers are made of metals with high thermal conductivity. The compression assembly system aims to provide a good contact between TE modules and heat exchangers. The cooling system usually uses engine coolant or ambient air as cooling fluid.

There are a number of challenges involving heat transfer in TEG assembly. The *first* is parasitic heat transfer losses. The *second* challenge is getting the highest temperature gradient across the TE module for given fluid temperatures, so that the power output is maximum. This can be done by reducing the thermal boundary layer thickness on the two sides of the TE module. It is especially difficult when the hot fluid is a gas, because gases have much lower thermal conductivities than liquids, and the required heat transfer rate, can be quite high. The *third* is how to extract a significant amount of the available energy in the hot fluid. This can be done by developing designs that involve a system of small diameter channels with large surface area and minimum pressure loss. To increase the heat transfer rate, the heat transfer enhancement techniques must ease the movement of the hotter fluids near the center of the channel to the walls of the plates. The research was focused on all heat transfer challenges by developing heat transfer enhancement techniques through computational fluid dynamics. These efforts were made towards the small diameter channel TEG assembly to achieve optimum heat exchange performance.

3.1. Design 1

TEG shown on Figure 3.1 was proposed at Michigan State University by Energy and Engineering Research Laboratory and consists of hot plates made of copper (400 W/mK) or stainless steel (15.1 W/mK) heated by the exhaust gases at temperature **500°C** and mass flow rate **150 kg/h**, pipes made of aluminum (270 W/mK) embedded in the hot plates, cold plates made of aluminum cooled by 50% solution of ethylene glycol at temperature **80°C** (Table 3.1) (the engine's cooling system can be modified to act as the heat sink) and mass flow rate **20 L/h**, and TEG modules installed in between.

Table 3.1. Properties of 50% solution of ethylene glycol at temperature 80°C / 176°F (provided by Old World Industries)

Density, [kg/m^3] / [lb/ft^3]	1038 / 64.8
Heat capacity, [J/kg K] / [Btu/lb°F]	3525 / 0.842
Thermal conductivity, [W/m K] / [Btu ft/h ft^2°C]	0.412 / 0.238
Dynamic viscosity, [N s/m^2] or [kg/m s] / [centipoise]	$9.4*10^{-4}$ / 0.94
Prandtl number	20

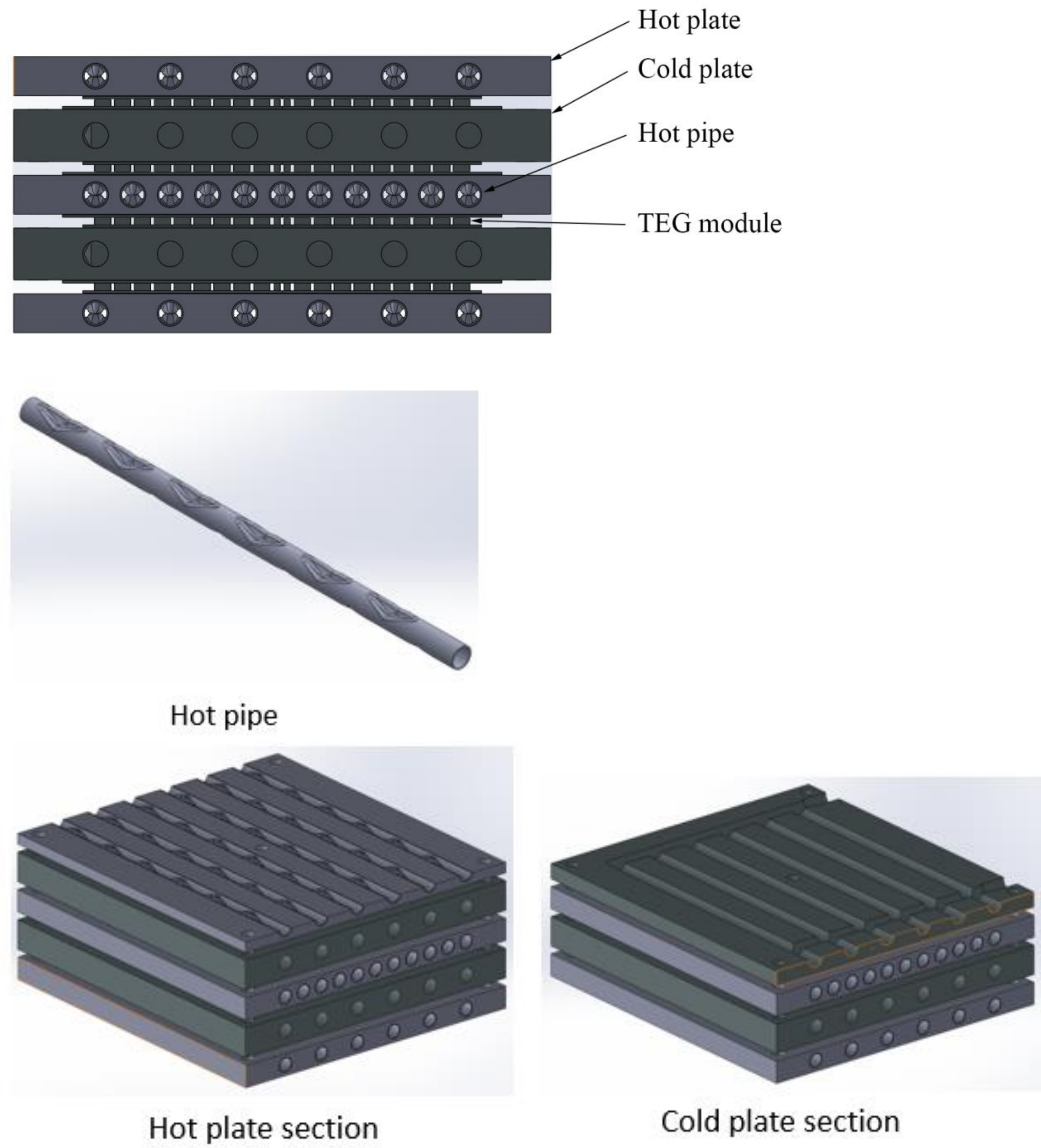


Figure 3.1. TEG (Design 1)

There are two different types of TEG modules presented in this analysis: G1-1.4-219-1.14 and G2-56-0375 by Tellurex. Each TEG module (Figure 3.2) generates **5.7** or **14.1 W** on the condition that hot/cold face temperatures of bismuth telluride TE elements are **150°C (175°C**

max)/50°C for G1 and **300°C (320°C max)/80°C** for G2 modules (Table 3.1) and consists of 5 layers: graphite foil (5 W/mK), alumina Al_2O_3 white 96% (25 W/mK), TE elements (1.2 W/mK), alumina Al_2O_3 white 96%, graphite foil. Each TEG assembly contains 16 TEG modules with a maximum total electric power **91 W** for G1 and **226 W** for G2 modules.

Table 3.2. TE material hot face temperature limits, °C

G1 TE module	G2 TE module
175	320

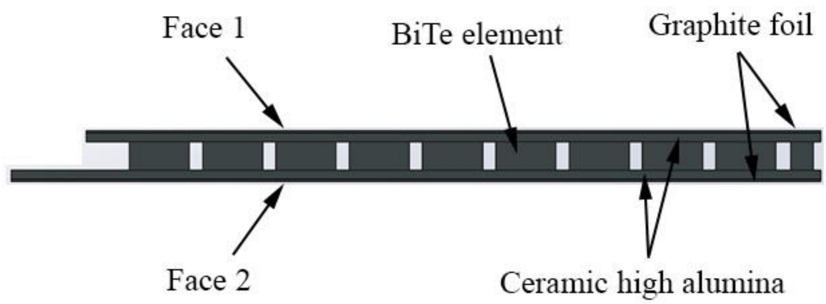


Figure 3.2. TE module for Design 1

Boundary conditions for TEG include *internal heat absorption* by TE modules, caused by thermal to electric energy transformation in TE modules, and *convection* inside the hot and cold plates, caused by hot and cold flows going through them and creating temperature difference. To be able to obtain the maximum performance from TEG, it is required to keep the hot faces at maximum possible temperature and cold faces at near the coolant temperature. That is why it is reasonable to put highest possible mass flow rates through the TEG to have low change in hot and cold faces temperature difference all through the TEG assembly what leads to maximum possible performance and efficiency. Though, one should take in mind that increase in mass flow rates leads to higher back pressure which is limited in real application. Therefore, in the present analysis optimal *convection coefficients* were determined by the *mass flow rates* which in turn are determined by *back pressure limits*. *Temperature limits* are also bound *convection coefficients*. Back pressure limits were selected being reasonable for standard vehicle coolant and exhaust systems **30 kPa** for coolant flow (based on standard 1.3 bar pressure in cooling system of a vehicle) and **10 kPa** for exhaust gas flow which is 10% of atmospheric pressure (Table 3.3).

Table 3.3. Back pressure limits, kPa

Coolant flow	Exhaust gas flow
30	10

Internal heat absorption in the TE elements is determined by the electric power output of each module (Table 3.4). Internal heat absorption per m^3 was evaluated by dividing internal heat absorption of a module to combined volume of all TE elements in a module.

Table 3.4. Internal heat absorption in the bismuth telluride elements

	G1	G2
Internal heat absorption, [W/m^3]/[W/module]	$-2.4*10^6$/-5.7	$-5.9*10^6$/-14.1

3.2. Design 2

TEG of cylindrical design (Figure 3.3) was proposed at Michigan State University by Energy and Engineering Research Laboratory and consists of gas pipe made of copper (400 W/mK) heated by the exhaust gases at temperature **500°C** and mass flow rate **150 kg/h**, heat sink made of aluminum cooled by 50% solution of ethylene glycol at temperature **80°C**, and cylindrical TEG modules installed in between. This is another interesting design which is worth considering as a practical application.

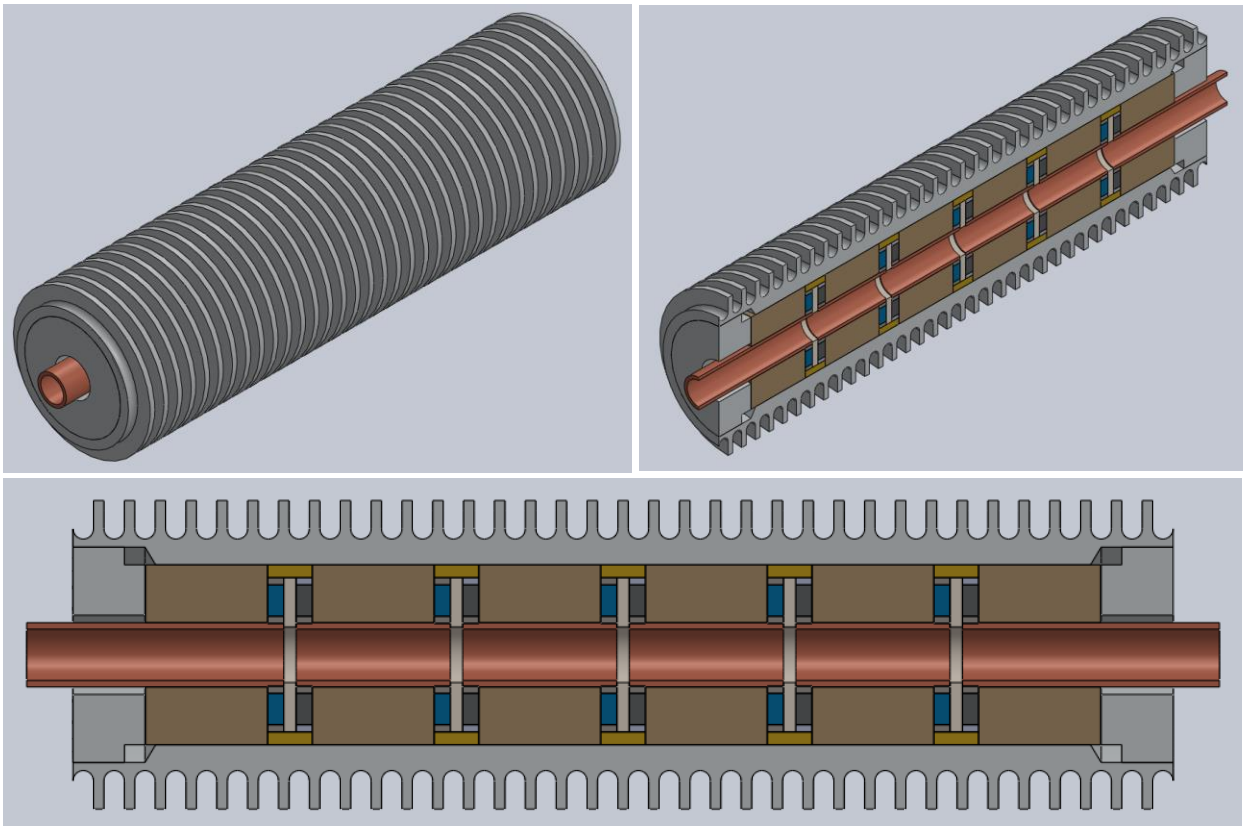


Figure 3.3. TEG (Design 2)

TE module (Figure 3.4) consists of two semiconductor skutterudite washers, n- and p-type (4 W/mK), separated by aluminum oxide washer (30 W/mK). Skutterudite washers are limited by titanium rings (21 W/mK) on the inside and the outside. Each TE module limited by the brass ring (111 W/mK) in the outside and might be separated by the insulating material in a sideway direction from other modules. Each TEG assembly contains several TEG. TE modules are connected thermally in parallel, electrically – in series. Copper pipe consists of sections which are also separated by the washer preventing TE modules from being short.

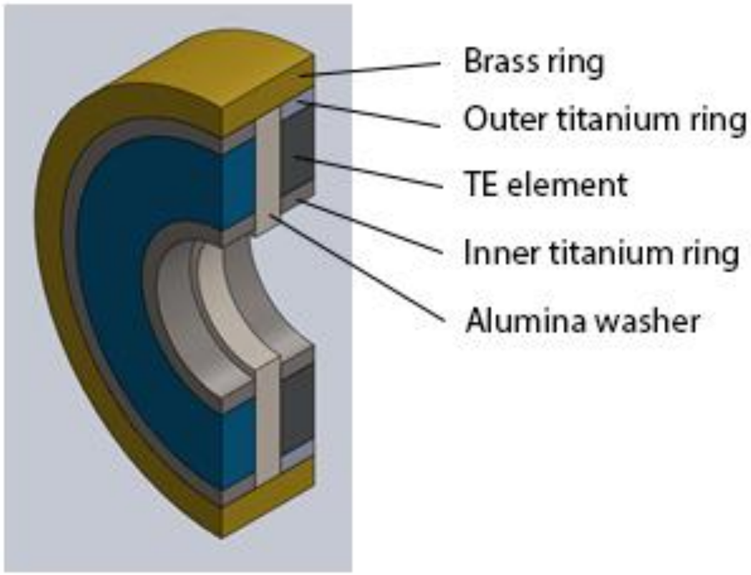


Figure 3.4. TE module for Design 2

Boundary conditions for TEG include *internal heat absorption* needed for electric energy generation, and *convection* in the gas pipe and on the heat sink due to hot and cold flows are going through them. To be able to obtain the maximum performance from TEG, it is necessary to keep the temperature difference between hot and cold faces of the TE module as high as possible. That is why it is reasonable to send highest possible flow rates through the TEG to have low change in temperatures in different regions of flows what leads to maximum possible performance. But one should take in mind that increase in flow rates leads to higher back pressure. Therefore, in the present analysis convection coefficient inside the gas pipe was determined by the gas flow rate which in turn is determined by back pressure limit **10 kPa**.

3.3. Summary

Two different TEG designs were considered for practical application for 3.5L FORD Ecoboost IC engine. Both designs accommodate TE modules for temperature difference generation but only first one is proved to be applied practically because of its relatively high possible temperature difference and electrical energy outcome.

Following factors may significantly improve TEG energy efficiency: improvements in TE materials, exhaust system insulation, and overall system design, including electronics.

Chapter 4. Testing

The main goal of the testing is to validate through experiments TEG assemblies developed. Experiments usually help to reveal operation features that are not predicted by theoretical analysis and can often lead to better understanding of the processes involved.

4.1. Generator design

4.1.1. TEG assembly housing

The TEG assembly is made of 5 metal plates and 16 TE modules (Figure 4.1). 4 modules in between each plate are connected in series and form a pack. There are 4 packs in the TEG assembly which are connected in parallel. 2 side hot plates contain 6 channels for hot gas each, while middle hot plate contains 10 channels. 2 cold plates contain 1 channel for coolant each with inlet and outlet ports. The TEG plates bolted together and TEG assembly flanges bolted to the air heater and the exhauster flanges. The flanges of the air heater and the exhauster connect all 22 hot plate gas channels.

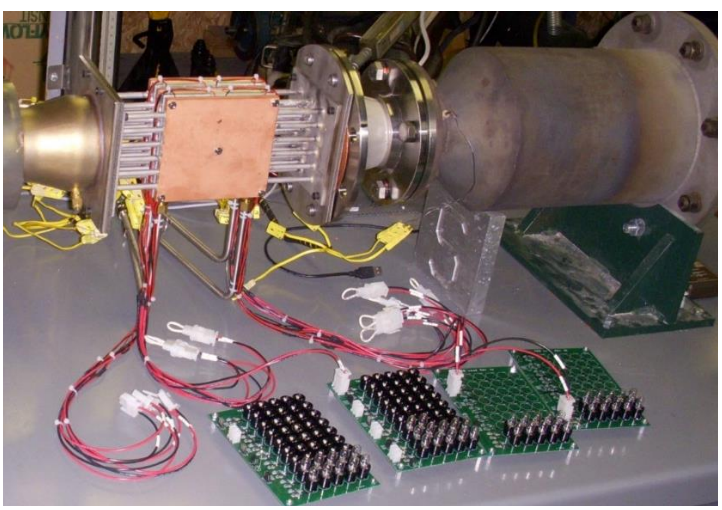


Figure 4.1. Test setup (assembled by Timm, E. and Ruckle, T. at Energy and Automotive Research Laboratory, MSU)

4.1.2. Heat Source

Required conditions were simulated with a 12 kW MHI Airtorch (MTA925-12) and controller. The TEG is bolted to the Airtorch on one side and to the exhauster on the other. The Airtorch and the TEG were insulated with Durablanket to minimize heat loss to environment.

4.1.3. Cooling System

To make cooling fluid is able to circulate through the cold plate channels, the coolant supply and return lines have to be attached to the coolant ports of the TEG assembly. Tapped water was used to create an open loop cooling cycle in this testing.

4.1.4. Instrumentation and data acquisition system

Data acquisition system, which consists of Omega OMB-DAQ-56 data acquisition modules and the accompanying Personal Daqview software system, was implemented to enable heat transfer analysis of the TEG assembly. Measurements were recorded every 5 seconds during the test. The following properties were measured:

- Air flow rate, measured using a Meriam 50MH10 laminar flow element
- Inlet air temperature (K-type thermocouple)
- Hot plate temperature (K-type thermocouple)
- Cold plate temperature (K-type thermocouple)
- Voltages of TE module packs (voltmeter)
- Outlet air temperature (K-type thermocouple)
- Coolant flow rate, measured using Omega FLR 1000 flow sensor

- Inlet coolant temperature (T-type thermocouple)
- Outlet coolant temperature (T-type thermocouple)

Power output produced by the TEG was loaded by a light bulb (14V, 4.9 W) banks connected in parallel (Figure 4.2).

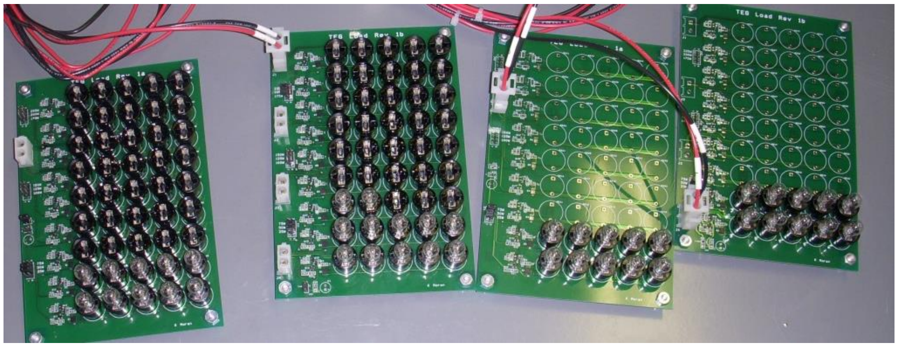


Figure 4.2. Light bulb bank

4.2. Testing process

The process used during the test:

1. Turn on the air pump.
2. Turn on the coolant flow.
3. Set air flow rate to the desired value.
4. Set coolant flow rate to the desired value.
5. Begin recording measurement from data acquisition system.
6. Ramp Airtorch temperature up to the desired value.
7. Load generator with light bulb bank
8. Measure current and voltage of each TE module pack.
9. Ramp Airtorch temperature down.

10. Turn off the air pump.

11. Turn off the coolant flow.

4.3. Data post-processing

Post-processing of the data collected from the testings is required to obtain TEG power output and heat transferred through TEG. TEG power output is one of the most important calculations because it is the main function of the TEG. Heat transferred through TEG calculation is necessary to estimate its efficiency.

4.4. Summary

TEG testing process consists of assembling the modules and plates into a TEG assembly, heating the hot plates with hot air, cooling the cold plates with tapped water, and measuring maximum power output, flow rates, and temperature values. Modern instrumentation used to measure and record these values. Data post-processing described provides TEG power output and efficiency.

Chapter 5. Results and Discussion

As described in chapter 3, two TEG assembly designs were developed, tested, and possible combinations for 3.5L FORD Ecoboost IC engine were evaluated for practical application.

5.1. Design 1

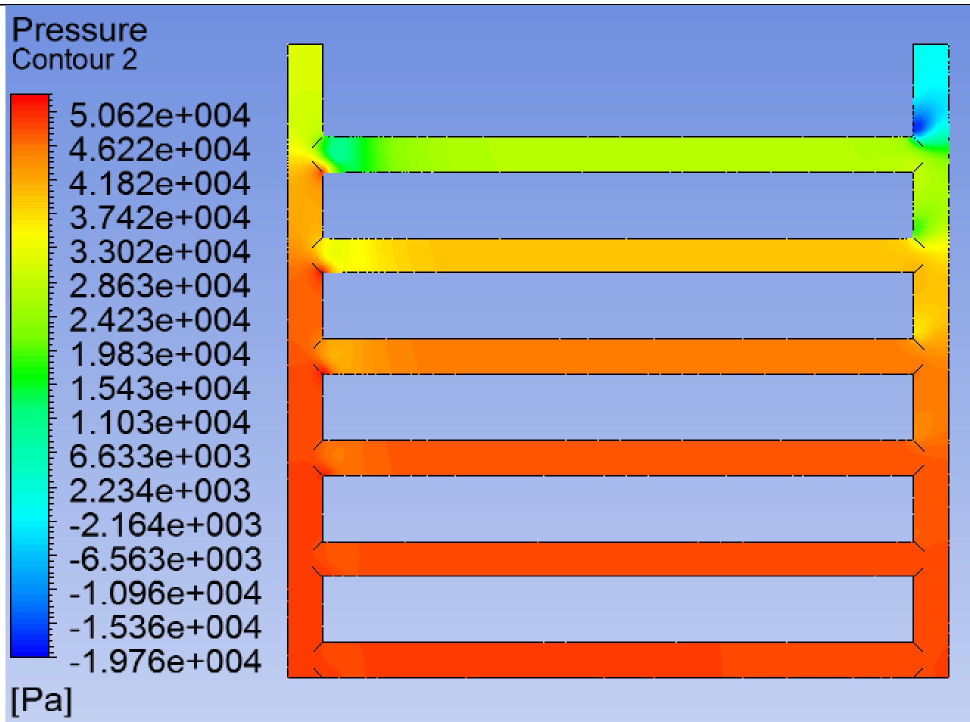
Several parameters were considered and varied when making analysis. Most important are:

- Pipe shape: straight and curved
- TE module type: G1 and G2
- Coolant temperature

Taking into consideration parameters of table 3.2, solid models of the cold plate and hot pipe channels were uploaded into ANSYS software package and exhaust gas flows were sent through them virtually with their *velocity manually adjusted* until back pressure at the channels' inlets reached specified limits (Figure 5.1). Velocity distribution in channels and mass flow rates at the channels' outlets under specified back pressure were also easily derived in ANSYS software package (Figure 5.2, Table 5.1).

Software systems like ANSYS or NX solve numerically conduction, convection, continuity, and Navier-Stokes differential equations.

Cold plate channel



Hot pipe channel

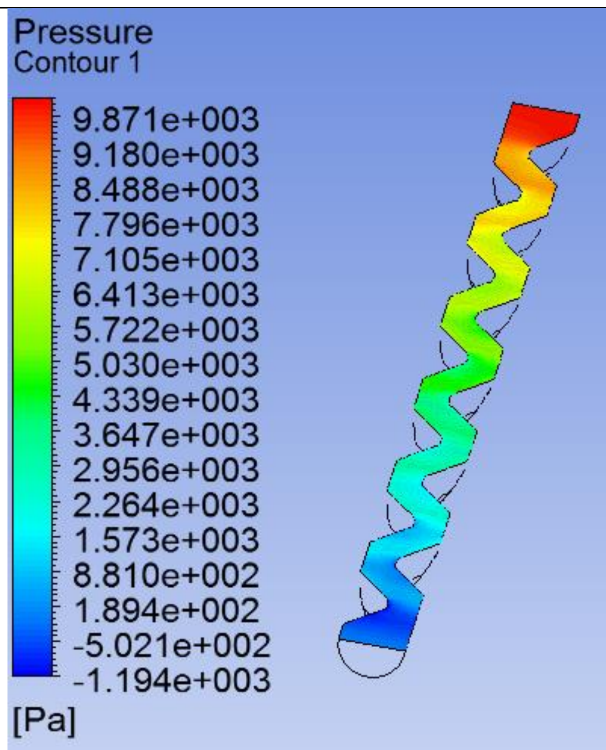
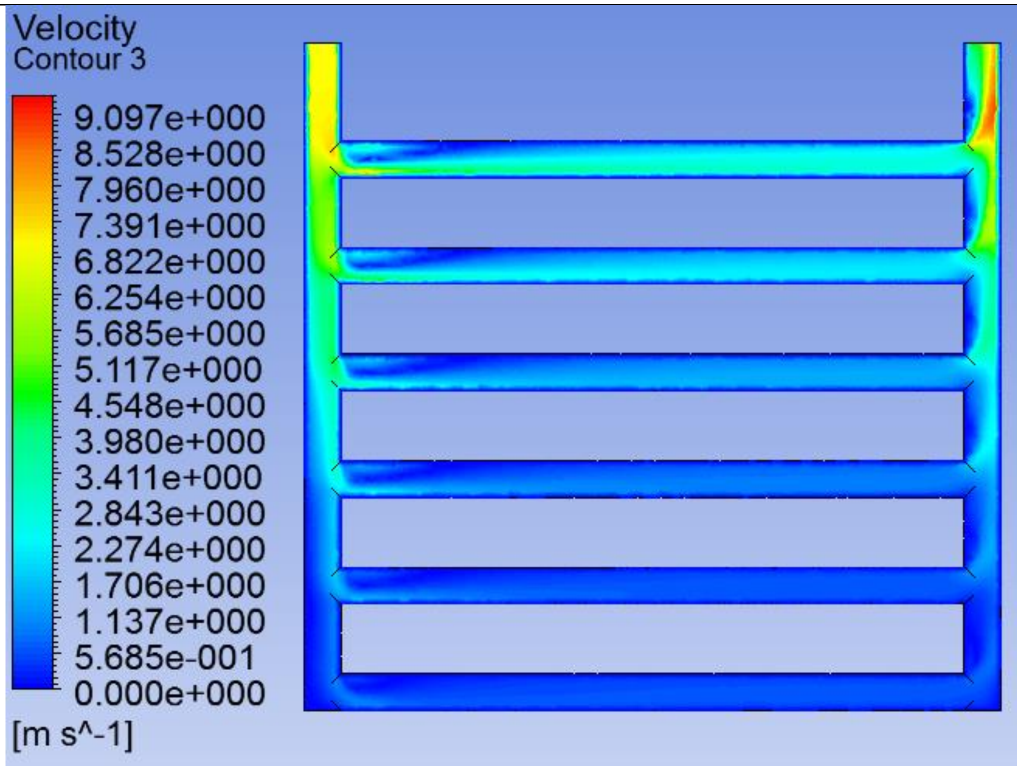


Figure 5.1. Pressure distribution in the cold plate and hot pipe channels (inlet back pressure is 30 and 10 kPa respectively; cold plate channel has inlet on the left)

Cold plate channel



Hot pipe channel

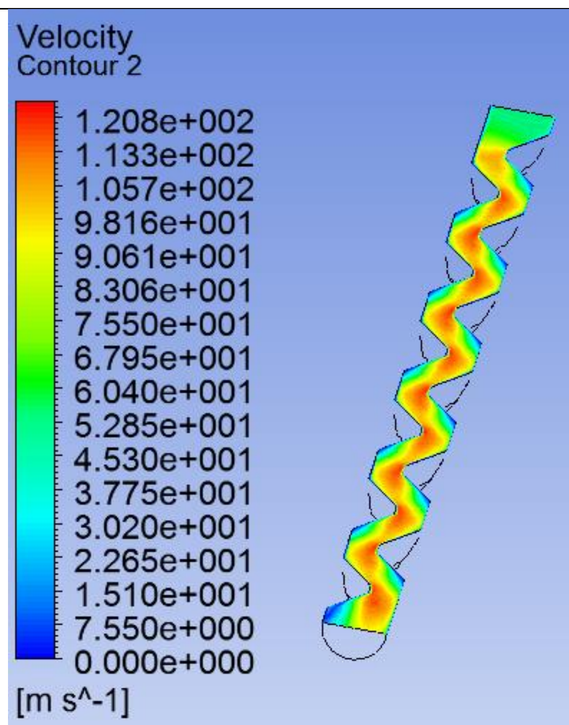


Figure 5.2. Velocity distribution in the cold and hot pipes under specified back pressure

Coolant and exhaust gas mass flow rates were calculated for individual channels and for the TEG assembly which contains 2 coolant channels and 22 hot pipe channels. Single channel mass flow rates were simply multiplied by the number of channels in the TEG assembly to get the total mass flow rates for TEG assembly.

Table 5.1. Average velocities (m/s) and mass flow rates at the outlets under specified back pressure limits

Coolant velocity (average / inlet)	1.1 / 7.0
Exhaust gas velocity (average / inlet)	53 / 53
Coolant mass flow rate (channel / TEG assembly), l/min	13.2 / 26.4
Exhaust gas mass flow rate (channel / TEG assembly), kg/h	2.3 / 50.6

Convection coefficients calculation was initiated for both channels using flow velocities found.

Reynolds number calculation for cold plate channel:

$$\mathrm{Re}_c = \frac{u_c \cdot \rho_c \cdot D_c}{\mu_c} = \frac{1.1 \cdot 1038 \cdot 6.35 \cdot 10^{-3}}{9.4 \cdot 10^{-4}} = 7713,$$

where u_c - average coolant velocity, ρ_c – coolant density, D_c - cold pipe diameter, μ_c - coolant viscosity.

Nusselt number calculation:

$$Nu_c = 0.023 \cdot \mathrm{Re}_c^{\frac{4}{5}} \cdot \mathrm{Pr}_c^{0.4} = 0.023 \cdot 7713^{\frac{4}{5}} \cdot 20^{0.4} = 98.2,$$

where Pr_c – coolant Prandtl number.

Convection coefficient calculation:

$$h_c = \frac{k_c \cdot Nu_c}{D_c} = \frac{412 \cdot 10^{-3} \cdot 98.2}{6.35 \cdot 10^{-3}} = 6370,$$

where k_c - coolant thermal conductivity.

Reynolds number calculation for hot pipe channel:

$$\mathrm{Re}_h = \frac{u_h \cdot \rho_h \cdot D_h}{\mu_h} = \frac{53 \cdot 0.4354 \cdot 5.56 \cdot 10^{-3}}{369.8 \cdot 10^{-7}} = 3470,$$

where u_h - average exhaust gas velocity, ρ_h – exhaust gas density, D_h - hot pipe channel diameter, μ_h - exhaust gas viscosity.

Nusselt number calculation:

$$Nu_h = 0.023 \cdot \mathrm{Re}_h^{\frac{4}{5}} \cdot \mathrm{Pr}_h^{0.3} = 0.023 \cdot 3470^{\frac{4}{5}} \cdot 0.709^{0.3} = 14.1,$$

where Pr_h – exhaust gas Prandtl number.

Convection coefficient calculation:

$$h_h = \frac{k_h \cdot Nu_h}{D_h} = \frac{57.3 \cdot 10^{-3} \cdot 14.1}{5.56 \cdot 10^{-3}} = 145,$$

where k_h - exhaust gas thermal conductivity.

Table 5.2. Estimated convection coefficients, W/m^2 °C

Cold plate channel	6370
Hot pipe channel	145

After convection coefficients were estimated, ANSYS software analysis was launched to determine *temperature distribution* in the TEG assembly under specified *flow temperatures* and *convection coefficients* found. Two different materials of hot plates were addressed in the analysis: copper and stainless steel. Meshed TEG geometry can be found on Figure 5.3. Temperature distribution plots can be found on Figure 5.4.

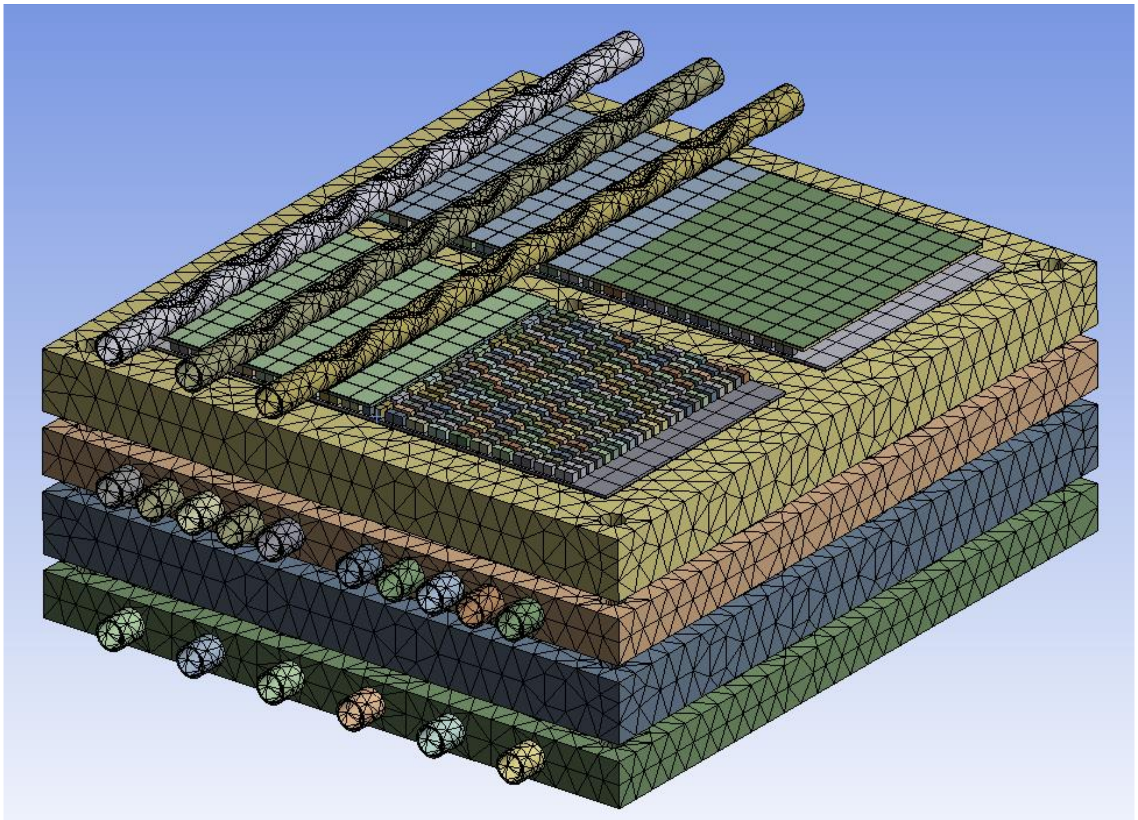
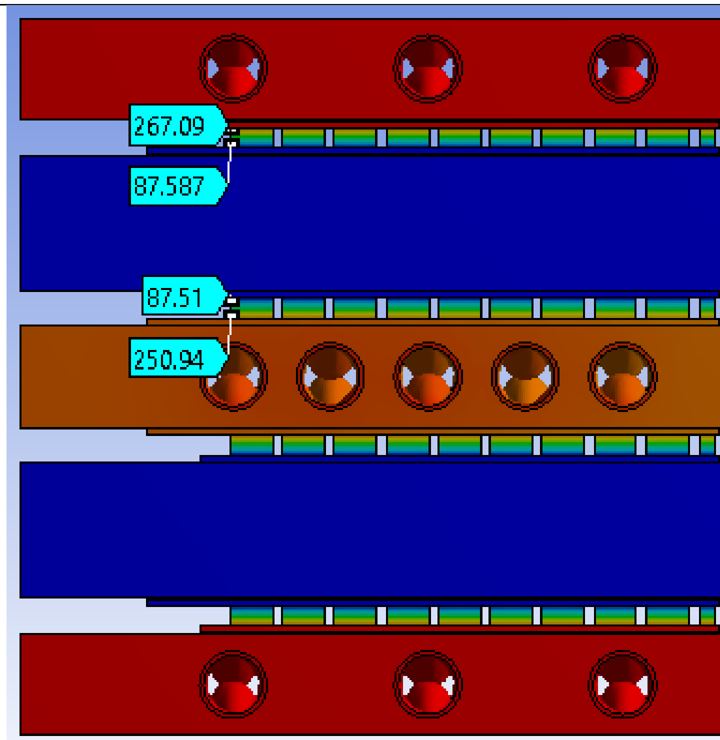


Figure 5.3. Meshed TEG geometry in ANSYS software package (upper hot plate and several other elements are not shown)

Copper hot plates



Stainless steel hot plates

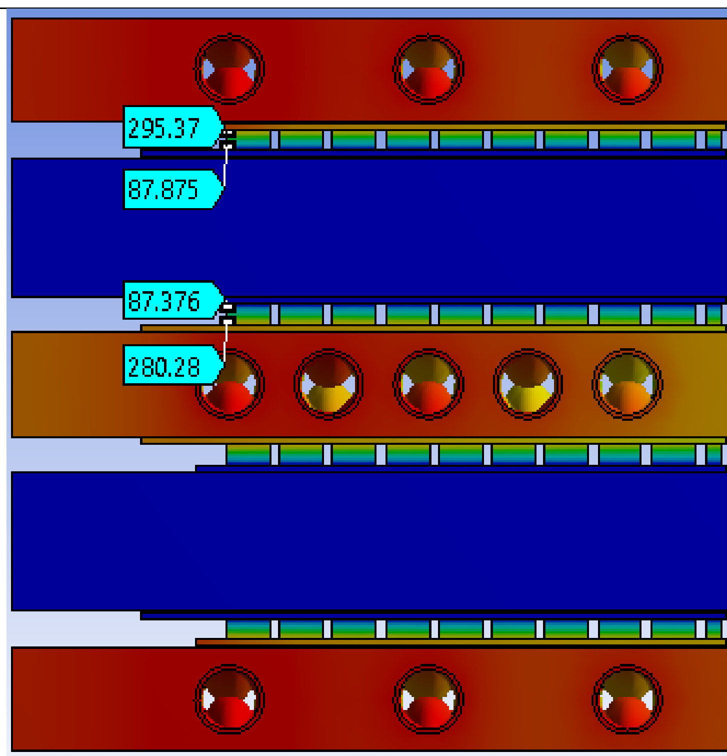


Figure 5.4. Temperature distribution in TEG assembly under convection coefficients 6370 and 145 for copper and stainless steel hot plates, [°C]

From Figure 3.6 one can notice that copper hot plates have much lower temperature than stainless steel. Copper hot plates provide much better heat release and temperature performance which allows higher flow rates in the TEG assembly. Therefore, the design with copper hot plates was selected for precise analysis below.

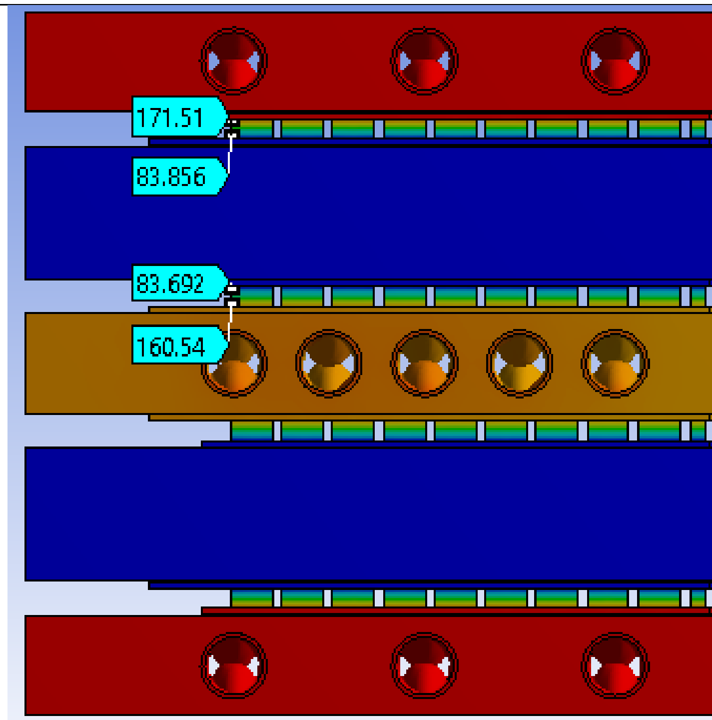
Taking into consideration temperature limits, new convection coefficients were assigned separately for TEG with G1 and G2 modules, and adjusted manually for TEG with G1 modules to meet temperature requirements (Table 5.3).

Table 5.3. Adjusted convection coefficients, W/m^2 °C

	G1	G2
Cold plate channel	6370	6370
Hot pipe channel	**50**	145

ANSYS software analysis was launched to determine temperature distribution in the TEG assembly under specified stream temperatures and adjusted convection coefficients (Figure 5.5).

TEG with G1 modules



TEG with G2 modules

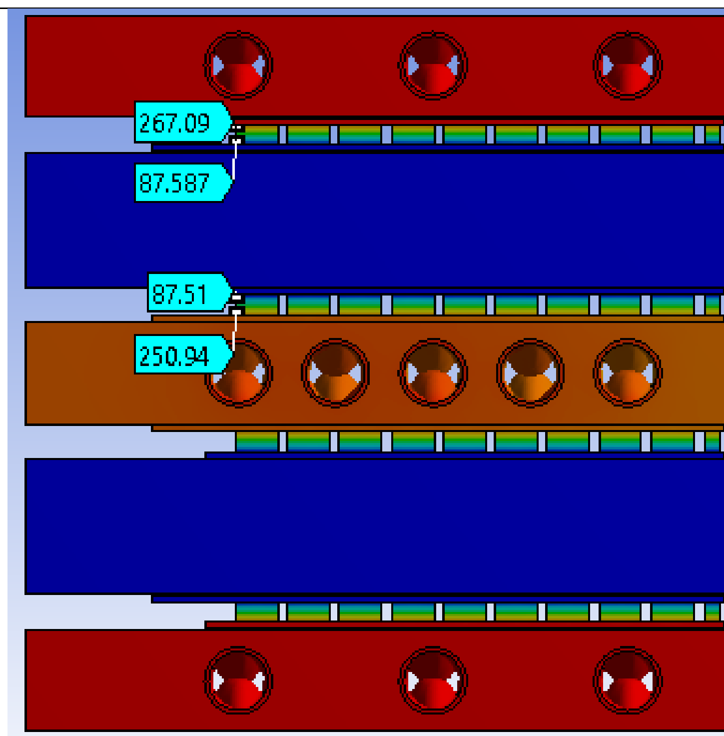


Figure 5.5. Temperature distribution in TEG assembly with G1 and G2 TE modules under specified stream temperatures and adjusted convection coefficients, [°C]

Since convection coefficient for TEG with G1 modules was adjusted manually to meet temperature requirements, flow velocity in the hot pipe channel for TEG with G1 modules needs to be recalculated below.

Nusselt number calculation:

$$Nu_h = \frac{h_h D_h}{k_h} = \frac{50 \cdot 5.56 \cdot 10^{-3}}{57.3 \cdot 10^{-3}} = 4.85.$$

where h_h - hot pipe channel convection coefficient, D_h - hot pipe channel diameter, k_h - exhaust gas thermal conductivity.

Reynolds number calculation:

$$\mathrm{Re}_h = \left(\frac{Nu_h}{0.023 \cdot \mathrm{Pr}_h^{0.3}} \right)^{5/4} = \left(\frac{4.85}{0.023 \cdot 0.709^{0.3}} \right)^{5/4} = 915,$$

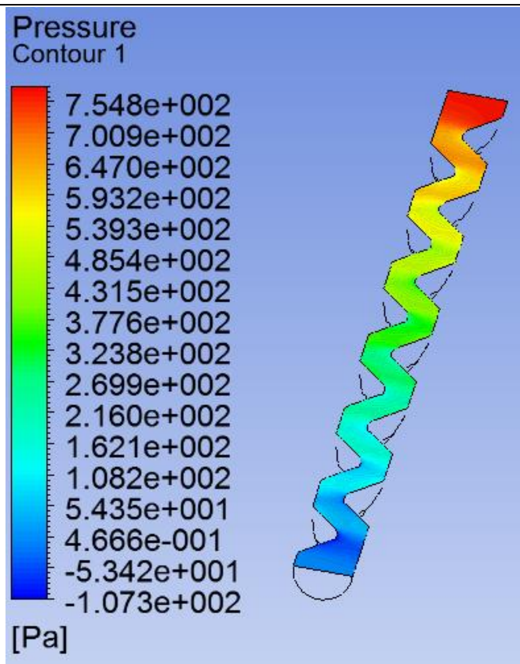
where Pr_h – exhaust gas Prandtl number.

Velocity of the exhaust gas:

$$u_h = \frac{\mathrm{Re}_h \cdot \mu_h}{\rho_h \cdot D_h} = \frac{915 \cdot 369.8 \cdot 10^{-7}}{0.4354 \cdot 5.56 \cdot 10^{-3}} = 14.0\, m/s,$$

where μ_h - exhaust gas viscosity, ρ_h – exhaust gas density.

Pressure



Velocity

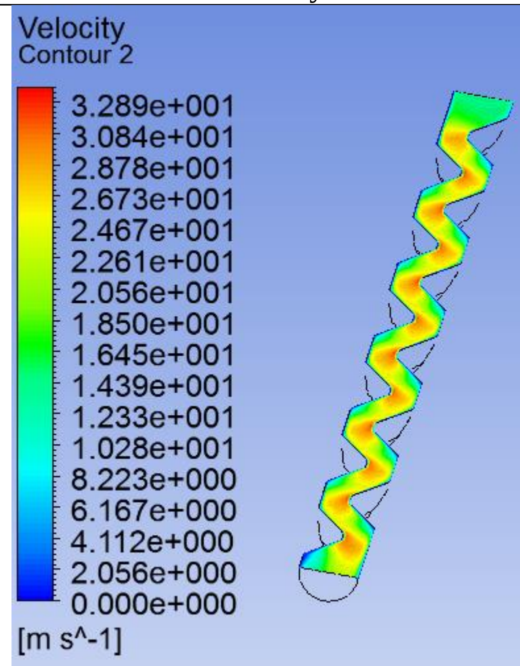


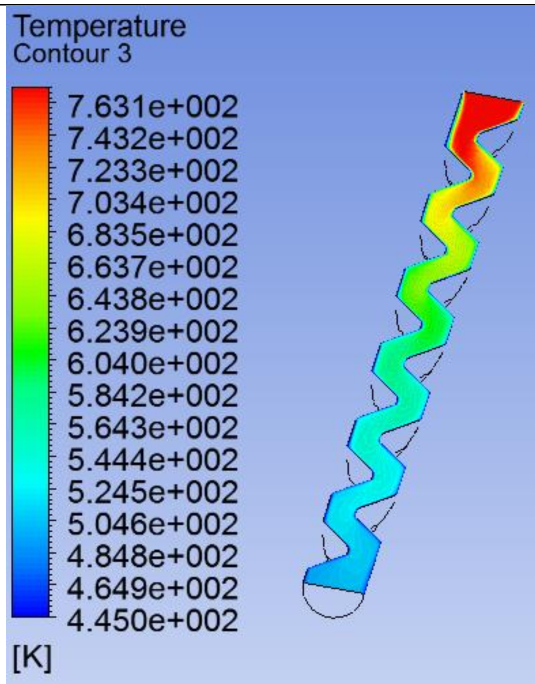
Figure 5.6. Pressure and velocity distribution in the hot pipe channels of TEG with G1 modules under specified velocity (back pressure is 0.75 kPa)

Table 5.4. Final velocities and flow rates

	G1	G2
Coolant velocity (average / inlet), m/s	1.1 / 7.0	1.1 / 7.0
Exhaust gas velocity (average / inlet), m/s	14 / 14	53 / 53
Coolant flow rate per pipe/TEG, l/min	13.2 / 26.4	13.2 / 26.4
Gas flow rate per pipe/TEG, kg/h	0.6 / 13.2	2.3 / 50.6

ANSYS calculations were made to determine temperature distribution in the hot pipes (Figure 5.7).

G1



G2

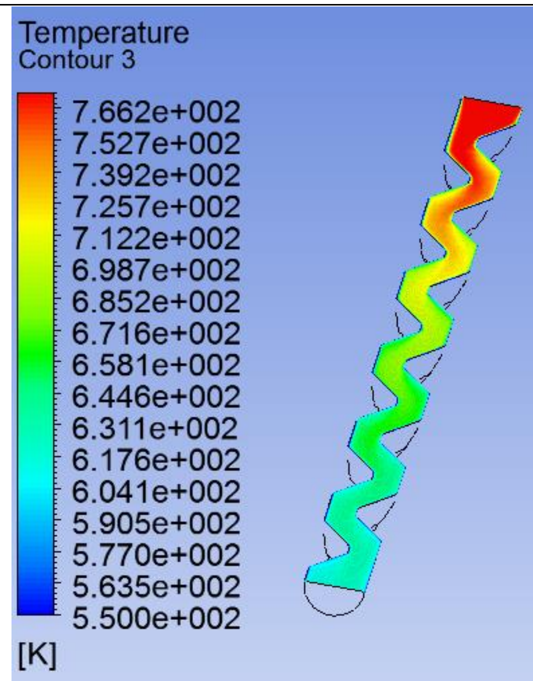
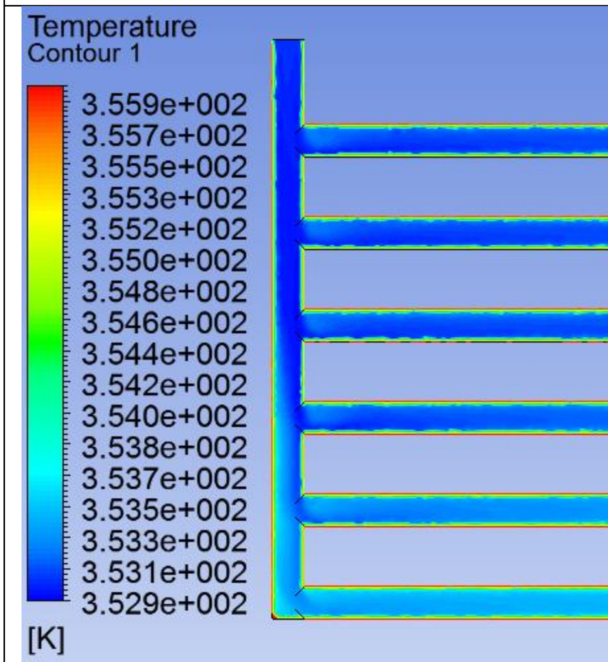


Figure 5.7. Temperature distribution in the hot pipe channels

ANSYS calculations were made to determine temperature distribution in the cold pipes (Figure 5.8).

G1



G2

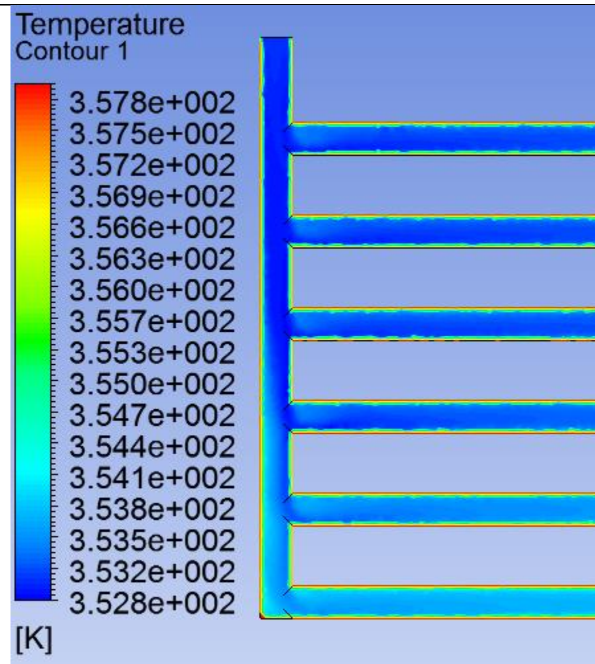


Figure 5.8. Temperature distribution in the cold pipes

Engine with 150 kg/h exhaust gas mass flow rate requires 12 TEG with G1 modules and 3 TEG with G2 modules. Total electric power produced (on the assumption that gas temperature does not change):

$91W \cdot 81\% \cdot 60\% \cdot 12 = 531W$ – for TEG with G1 modules,

$226W \cdot 78\% \cdot 70\% \cdot 3 = 370W$ - for TEG with G2 modules.

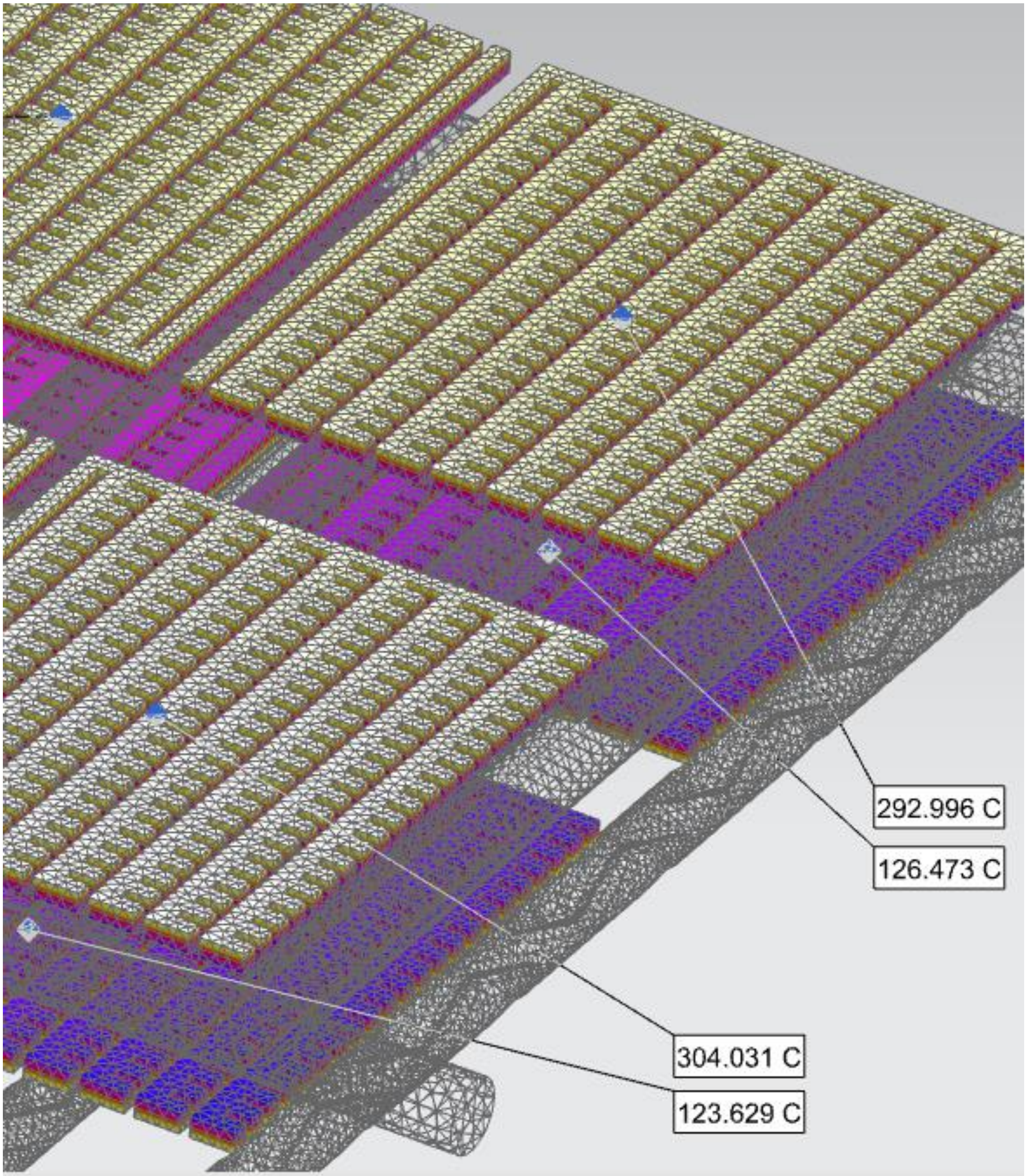


Figure 5.9. Temperature distribution in TE elements (curved hot pipes, G2 modules, NX analysis)

Table 5.5. Results for TEG Design 1 with G1 and G2 modules and curved hot pipes

	G1 (ANSYS)	G2 (ANSYS)	G2 (NX)
ΔT/ΔT desired, °C	81/100	171/220	180 / 220
Fraction of optimum performance based on ΔT near the hot pipe inlet, %	81	78	82
Fraction of optimum performance based on ΔT fall through the hot pipe, %	60	70	89
Number of TEG assemblies required	12	3	3
Back pressure in the cold pipe inlet, kPa	30	30	1.6
Back pressure in the hot pipe inlet, kPa	0.75	9	7.5
Total coolant flow rate per TEG / system, l/min	26.4 / 316.8	26.4 / 79.2	5.6 / 16.8
Total gas flow rate per TEG / system, kg/h	13.2 / 150	50 / 150	50 / 150
Weight per TEG / system, kg	5.5 / 66	5.5 / 16.5	5.5 / 16.5
Gas inlet temperature, °C	500	500	500
Coolant inlet temperature, °C	80	80	80
Total electric power produced per TEG / system, W	**44 / 531**	**123 / 370**	**165 / 495**

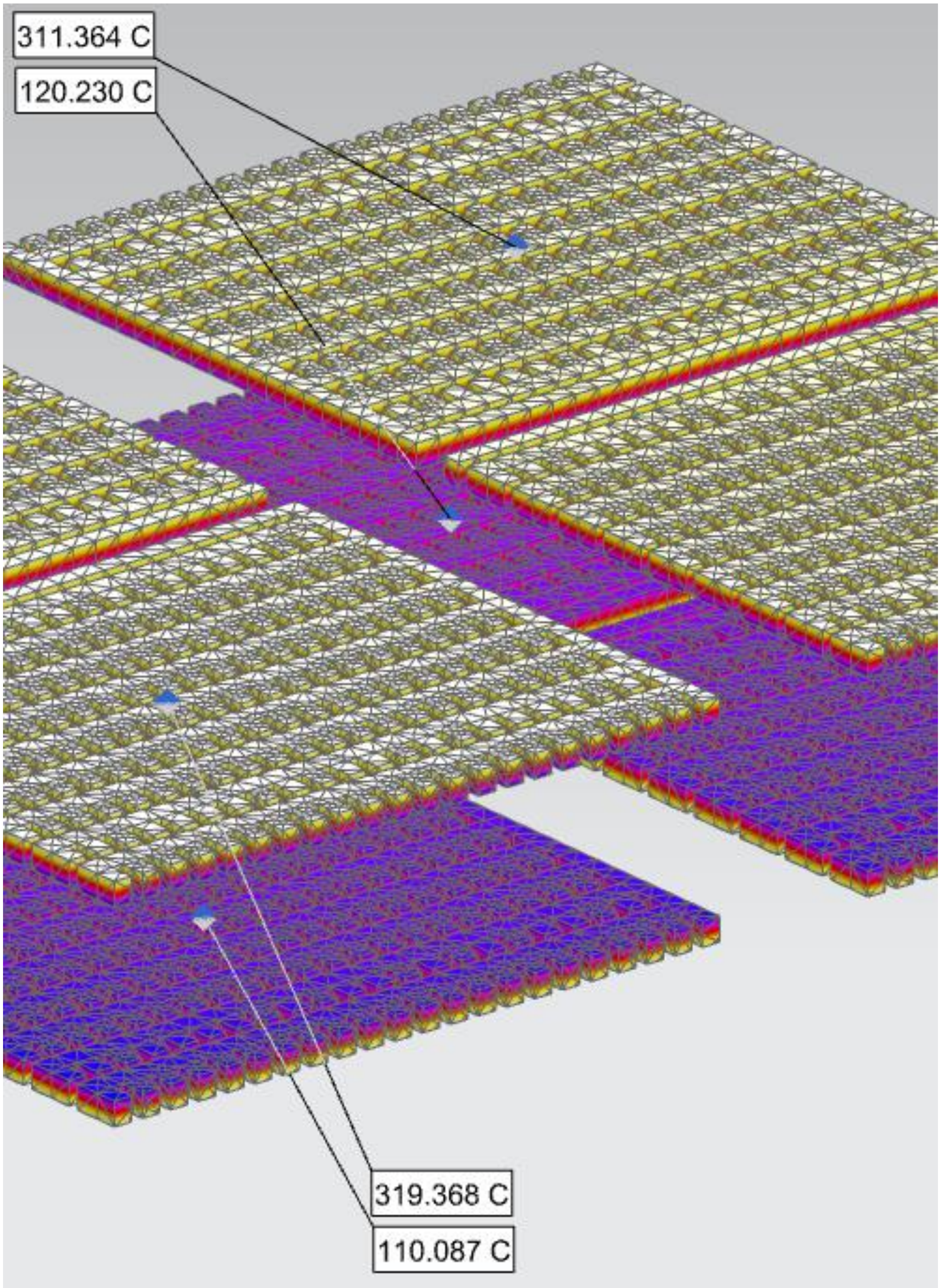


Figure 5.10. Temperature distribution in TE elements (straight hot pipes, G2 modules, NX analysis)

Table 5.6. Results for TEG Design 1 with G2 modules and straight hot pipes

ΔT/ΔT desired, °C	220 / 220
Fraction of optimum performance based on ΔT near the hot pipe inlet, %	100
Fraction of optimum performance based on ΔT fall through the hot pipe, %	95
Number of TEG assemblies required	1
Coolant inlet velocity, m/s	3
Gas inlet velocity, m/s	120
Back pressure in the cold pipe inlet, kPa	27
Back pressure in the hot pipe inlet, kPa	8
Total coolant flow rate per TEG / system, l/min	22.8 / 22.8
Total gas flow rate per TEG / system, kg/h	150 / 150
Weight per TEG / system, kg	5.5 / 16.5
Gas inlet / outlet temperature, °C	500 / 415
Coolant inlet / outlet temperature, °C	80 / 82.5
Total electric power produced per TEG / system, W	**213 / 213**

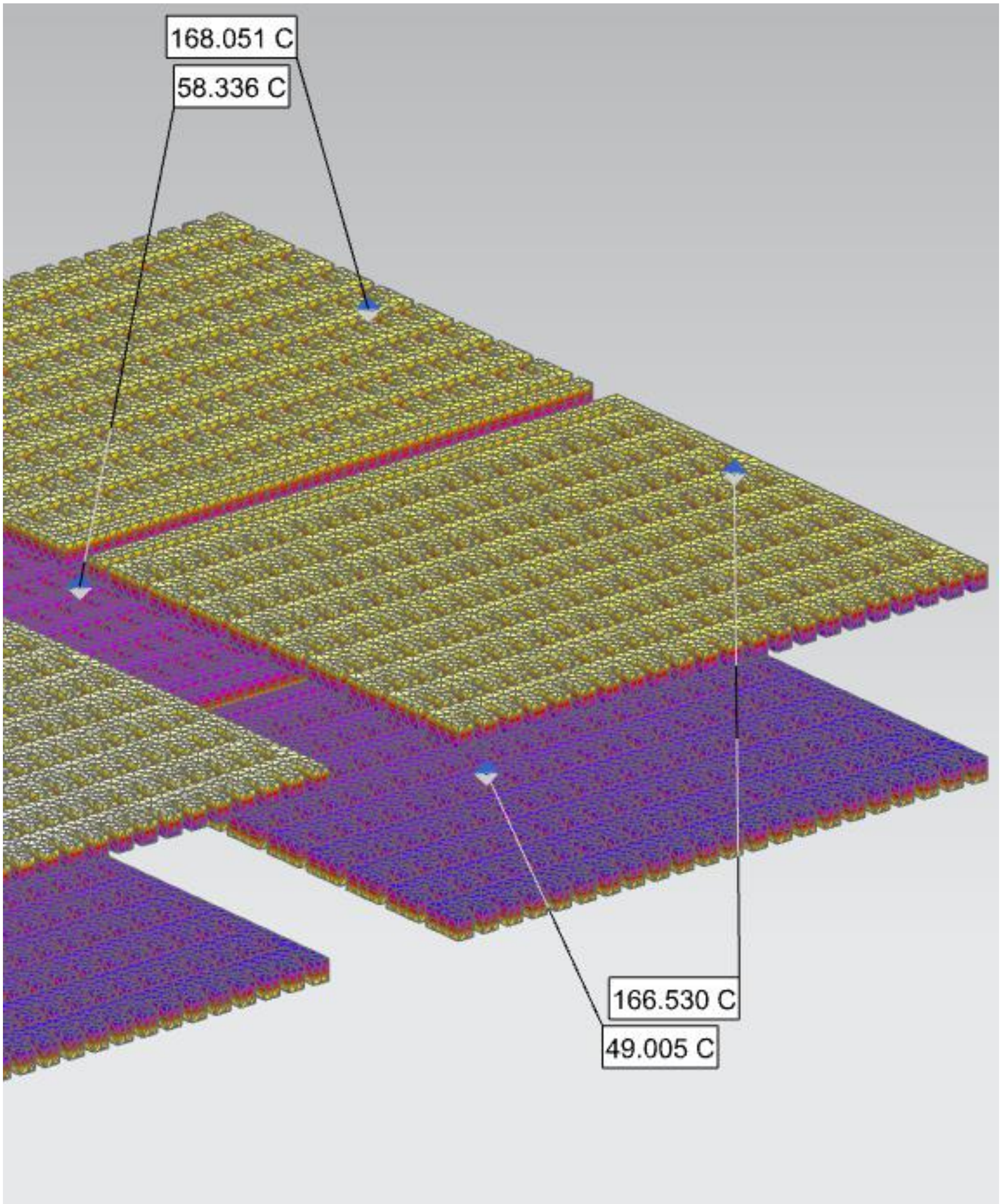


Figure 5.11. Temperature distribution in TE elements (curved hot pipes, G2 modules, NX analysis, Test 1 conditions)

Table 5.7. Results comparison for TEG Design 1 with G2 modules and curved hot pipes (Test 1)

	NX analysis	Test (made by Timm, E. and Ruckle, T. at MSU)
ΔT/ΔT desired, °C	150 / 220	173 / 220
Fraction of optimum performance based on ΔT near the hot pipe inlet, %	68	79
Fraction of optimum performance based on ΔT fall through the hot pipe, %	87	n/a
Number of TEG assemblies required	7	7
Coolant inlet velocity, m/s	1.32	1.32
Gas inlet velocity, m/s	22.4	22.4
Back pressure in the cold pipe inlet, kPa	1.2	n/a
Back pressure in the hot pipe inlet, kPa	1.8	n/a
Total coolant flow rate per TEG / system, l/min	5 / 35	5 / 35
Total gas flow rate per TEG / system, kg/h	21.4 / 150	21.4 / 150
Total gas flow rate per TEG / system, scfm	10.7 / 74.8	10.7 / 74.8
Weight per TEG / system, kg	5.5 / 38.5	5.5 / 38.5
Gas inlet / outlet temperature, °C	500 / 199	500 / 190
Coolant inlet / outlet temperature, °C	20.2 / 26.5	20.2 / 27.6
Total electric power produced per TEG / system, W	**110 / 770**	**17 / 119**

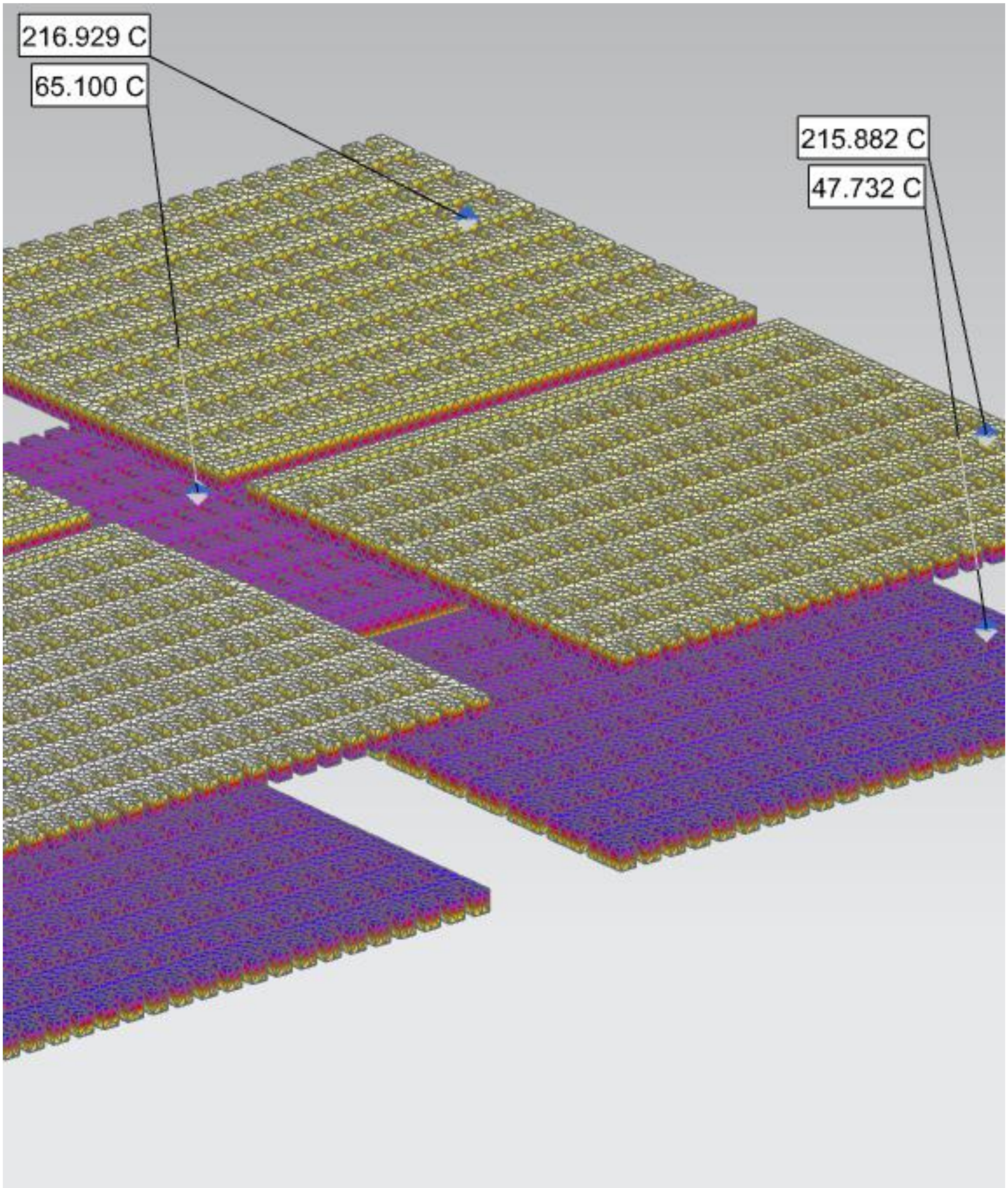


Figure 5.12. Temperature distribution in TE elements (curved hot pipes, G2 modules, NX analysis, Test 2 conditions)

Table 5.8. Results comparison for TEG Design 1 with G2 modules and curved hot pipes (Test 2)

	NX analysis	Test (made by Timm, E. and Ruckle, T. at MSU)
ΔT/ΔT desired, °C	190 / 220	185 / 220
Fraction of optimum performance based on ΔT near the hot pipe inlet, %	86	84
Fraction of optimum performance based on ΔT fall through the hot pipe, %	89	n/a
Number of TEG assemblies required	3	3
Coolant inlet velocity, m/s	1.76	1.76
Gas inlet velocity, m/s	52.3	52.3
Back pressure in the cold pipe inlet, kPa	2	n/a
Back pressure in the hot pipe inlet, kPa	7.5	n/a
Total coolant flow rate per TEG / system, l/min	6.7 / 20	6.7 / 20
Total gas flow rate per TEG / system, kg/h	50 / 150	50 / 150
Total gas flow rate per TEG / system, scfm	24.3 / 72.9	24.3 / 72.9
Weight per TEG / system, kg	5.5 / 16.5	5.5 / 16.5
Gas inlet / outlet temperature, °C	440 / 283	427 / 310
Coolant inlet / outlet temperature, °C	20.2 / 26.3	17.3 / 23.7
Total electric power produced per TEG / system, W	**173 / 520**	**75 / 225**

As follows from Table 5.5, it is possible to reach 531 W and 370 (495) W as a power output for TEG with G1 and G2 modules correspondingly. TEG with G2 modules seems much practical to implement because of its reasonable weight. ANSYS and NX analysis results are very close, which means they could be considered as trustable.

Table 5.6 reflects findings for TEG assembly with straight pipes which could be an alternative option for TEG with curved pipes. Though its estimated power output is smaller (213 W) than for TEG with curved pipes (770 W) its weight and size are considerably less (5.5 kg) which may be the option when developing smaller vehicles with limited space for systems.

Tables 5.7 and 5.8 provide a summary on idealized 3D model analysis and real TEG testing comparison. All initial conditions in idealized analysis were considered the same as in real testing.

Possible reasons for the difference in power outputs:

- Contact heat resistance presence in the real TEG
- Heat losses into environment
- Assumption was made that heat transfer from hot to cold plate only takes place through TE modules.

Transient heat conduction analysis of TEG was performed in ANSYS to estimate how much time it takes for TEG to reach steady-state condition. To make the analysis representative, exhaust gas mass flow rates for TEG with steel hot plates were decreased to provide the same hot plate steady state temperature as in copper hot plates.

It follows, that it takes about 10 min for TEG to reach steady-state operation and about 5 min to reach 80% of steady-state temperature difference. It happens a little bit faster for TEG with G2 modules and copper hot plates, which operates at much higher exhaust gas flow rate.

5.2. Design 2

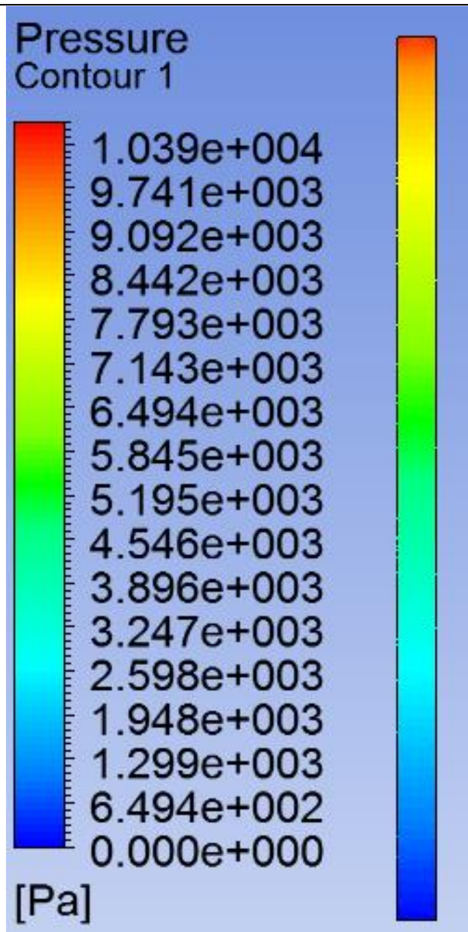
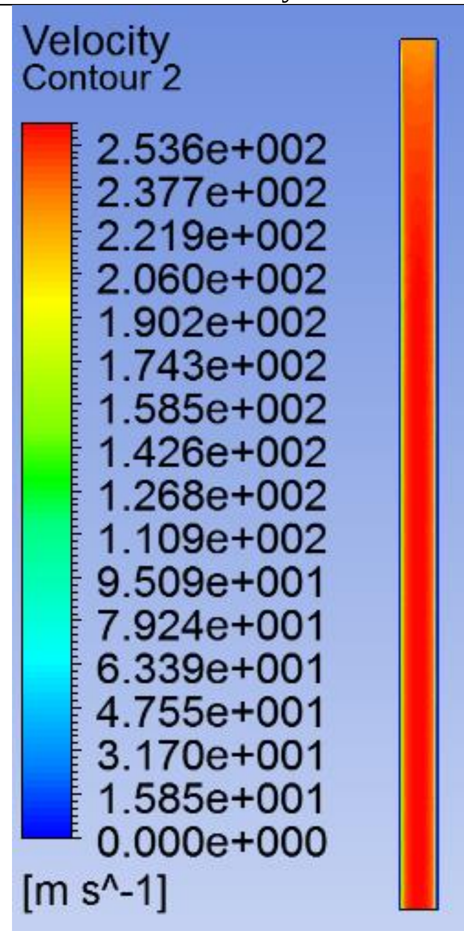
Pressure	Velocity
	

Figure 5.13. Pressure and velocity distribution in the gas pipe (back pressure is 10 kPa)

Table 5.9. Gas velocity and flow rate under specified back pressure limits

Gas velocity, m/s	230
Gas flow rate per pipe, kg/h	5.76

Convection coefficient calculation was initiated for gas pipe using flow velocity found.

Reynolds number calculation:

$$\mathrm{Re}_c = \frac{u_h \cdot \rho_h \cdot D_h}{\mu_h} = \frac{230 \cdot 0.4354 \cdot 6.324 \cdot 10^{-3}}{369.8 \cdot 10^{-7}} = 17{,}125 \, ,$$

where u_h - inlet gas velocity, ρ_h – gas density, D_h - gas pipe diameter, μ_h - gas viscosity.

Nusselt number calculation:

$$Nu_h = 0.023 \cdot \mathrm{Re}_h^{\frac{4}{5}} \cdot \mathrm{Pr}_h^{0.3} = 0.023 \cdot 17{,}125^{\frac{4}{5}} \cdot 0.709^{0.3} = 50.6,$$

where Pr_h – gas Prandtl number.

Convection coefficient calculation:

$$h_h = \frac{k_h \cdot Nu_h}{D_h} = \frac{57.3 \cdot 10^{-3} \cdot 50.6}{6.324 \cdot 10^{-3}} = 460,$$

where k_h - gas thermal conductivity.

Convection coefficients may be found in Table 5.10.

Table 5.10. Convection coefficients, W/m^2 °C

Cold Pipe	1000
Hot Pipe	460

ANSYS calculations were made to determine temperature distribution in the hot pipe (Figure 5.14).

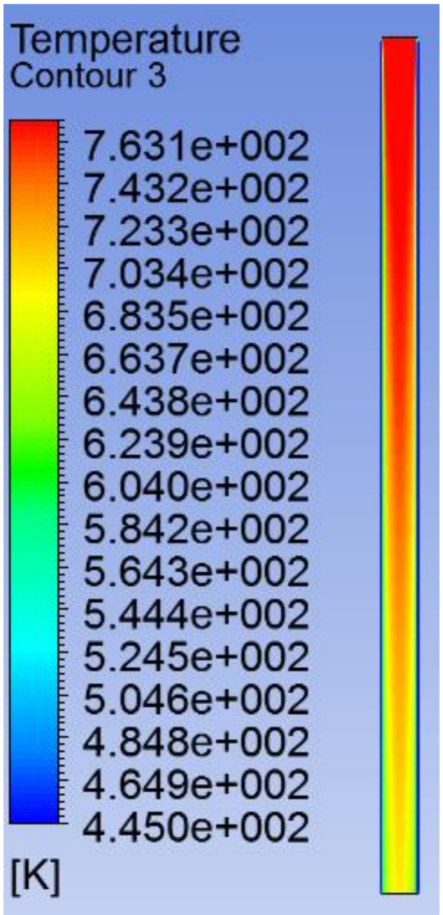


Figure 5.14. Temperature distribution in the hot pipe

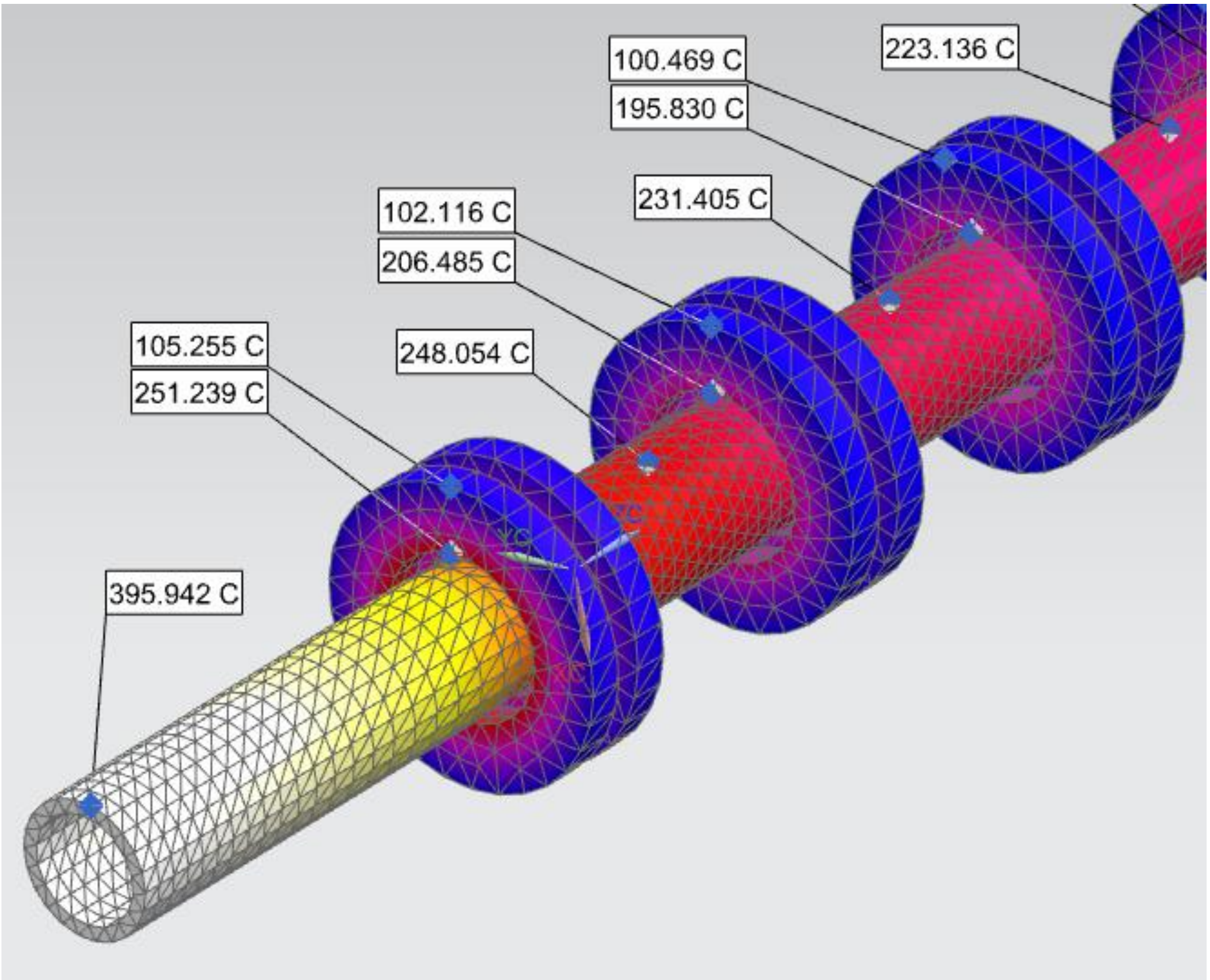


Figure 5.15. Temperature distribution in TE elements (NX analysis)

Table 5.11. Results for TEG Design 2

ΔT/ΔT desired, °C	100 / 500
Fraction of optimum performance based on ΔT near the hot pipe inlet, %	20
Back pressure in the hot pipe inlet, kPa	10
Gas flow rate, kg/h	13.1
Gas inlet temperature, °C	500
Gas outlet temperature, °C	408
Coolant inlet temperature, °C	80
Coolant convection coefficient, °C	1000

5.3. TEG efficiency estimation

One of the most important operations is the TEG efficiency estimation. It allows to compare a normalized performance of different designs and materials.

The efficiency of TEG is governed by the conversion efficiency of TE material and the thermal efficiency of the two heat exchangers. Efficiency of a TEG can be expressed as:

$$\varsigma_{OV} = \varsigma_{CONV} \cdot \varsigma_{HE} \cdot \rho ,$$

where ς_{OV} - overall efficiency of TEG, ς_{CONV} - conversion efficiency of TE material, ς_{HE} - efficiency of the heat exchanger, ρ - ratio between heat passed through TE material to that passed from hot side to cold side [5].

In the present estimate, assume $\rho = 1$ for simplicity, which means that all heat from hot side to cold side goes through TE modules and leads to:

$$\varsigma_{OV} = \varsigma_{CONV} \cdot \varsigma_{HE} .$$

Assume also that a negligible amount of heat transfer occurs across the insulation.

Figure 5.16 illustrates ς_{OV} formation.

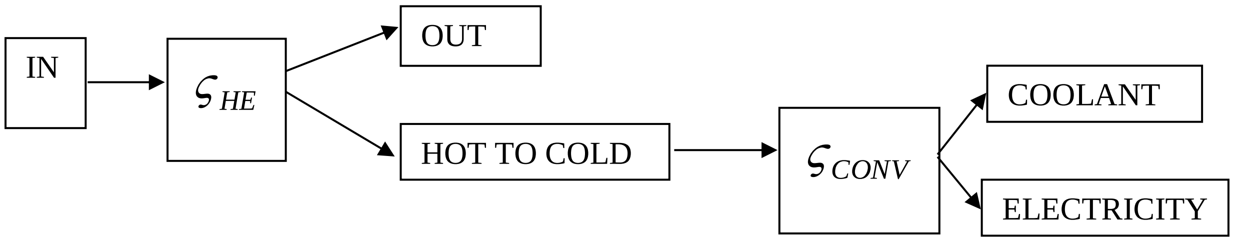


Figure 5.17. ς_{OV} formation: IN – represents hot gas thermal power at the inlet, OUT – represents hot gas thermal power at the outlet, HOT TO COLD – represents heat transfer from hot to cold plate, ELECTRICITY – represents electrical power generated, COOLANT – represents thermal power sent to coolant

Efficiency is defined as the useful energy output of a device divided by the energy input:

$$\varsigma_{HE} = \frac{HOT\,TO\,COLD}{IN}, \; \varsigma_{CONV} = \frac{ELECTRICITY}{HOT\,TO\,COLD}.$$

To calculate the efficiency of a TEG ς_{OV}, one need the mass flow rates and the inlet and outlet temperatures of the exhaust gas and cooling water. Efficiency of heat exchanger ς_{HE} is found analyzing how much heat enters and leaves TEG and assumption that all heat lost by exhaust gas goes to cold plates. Dividing the *electrical energy output* of the TEG by the heat transfer from hot to cold plate gives the efficiency of the TE material ς_{CONV} [9].

Table 5.12 summarizes TEG efficiency results for different TEG types found virtually and during testings.

Table 5.12. TEG efficiency (numbers based on the data for separate TEG assembly)

	Straight hot pipes, G2 modules, NX analysis	Curved hot pipes, G2 modules, Test Conditions 1, NX analysis	Curved hot pipes, G2 modules, Test Conditions 1, Test 1	Curved hot pipes, G2 modules, Test Conditions 2, NX analysis	Curved hot pipes, G2 modules, Test Conditions 2, Test 2
IN, [kW] / %	21 / 100	3.14 / 100	3.14 / 100	6.27 / 100	6.08 / 100
OUT, [kW] / %	18 / 83	1.10 / 35	1.04 / 33	3.80 / 61	4.40 / 69
HOT TO COLD, [kW] / %	3 / 17	2.04 / 65	2.10 / 67	2.47 / 39	1.89 / 31
ς_{HE} , %	17	65	67	39	31
ELECTRICITY, [kW] / %	0.21 / 7.0	0.110 / 5.4	0.017 / 0.8	0.173 / 7.0	0.075 / 4.0
ς_{CONV} , %	7.0	5.4	0.8	7.0	4.0
ς_{OV} , %	**1.2**	**3.5**	**0.5**	**2.8**	**1.2**

5.4. Summary

TEG with curved pipes and G1 and G2-type TE modules were analyzed. Power output of the TEG with G1-type TE modules is 531 W. For TEG with G2-type TE modules analysis was done in ANSYS as well as in NX to compare the results. Power outputs correspondingly are 370 and 495 W.

TEG with straight pipes was analyzed in NX and could be considered as a substitute for TEG with curved pipes. Its power output is 213 W.

NX analysis and testing were done for TEG with G2-type TE modules under specified testing conditions in the laboratory with the coolant temperature 20°C. 2 testings were made for 2 different air mass flow rates: 21.4 kg/h and 50 kg/h. Power outputs are 116 W and 225 W correspondingly, which is considerably less than during NX simulation.

Design 2 was analyzed and results showed that temperature difference in TE elements is not sufficient with the present design. Further investigation is needed to improve its performance.

Chapter 6. Conclusions

For automotive applications, the best source of waste heat is the exhaust gas flow. Amount of heat available depends on engine size and load conditions. The exhaust gas thermal power output for a V-6 engine can be as much as 40 kW under a heavy load conditions [20]. The exhaust gas temperature can exceed 700°C, and the engine coolant temperature is approximately 80°C, and these can be used as the heat source and sink, respectively, to provide a large temperature difference for TE modules. While TEG development has not reached the desired goal of producing several kilowatts of electric energy, there are other results and discoveries that one can learn.

6.1. Research Achievements

The present research shows a possibility of implementing TEG in a real vehicle which results in decrease of fuel consumption.

- A procedure for practical TEG design, assembly, material selection, flow rates specification and effective heat transfer system has been successfully developed.
- A procedure for obtaining the maximum performance has been established. This allows building TEGs of optimal weight and cost.
- Experiments on TEG performance were conducted and the results were compared with software analysis.

6.2. Conclusions of Research

Based on the results of this thesis and previous research, a number of conclusions can be made about the optimal performance of TEGs.

Weight of a TEG system in a vehicle is one of the most important parameters which could override all the benefits it might bring. Current analysis showed that efficiency of a TEG rises with increase in heat exchange surface area and back pressure it creates for the exhaust gas. Increase in heat exchange surface area can be done without adding any weight to an assembly only up to some point, then it requires to make an increase in heat exchanger length which leads to increase in weight of a TEG assembly. Therefore, compromise between TEG weight and efficiency has to be found when making TEG system development for a real vehicle, taking in mind that in approximation, infinite length of TEG will return its maximum efficiency.

Though, according to previous findings in chapter 2 regarding optimal quantity of TEG per engine cylinder, one can conclude that one TEG assembly per engine cylinder (or more) is the most optimal solution, but it takes at least six TEG assemblies per engine which might not be appropriate in terms of system weight.

Current analysis showed that for best efficiency one need to use materials with high thermal conductivity to be able to provide instantly temperature difference to TE modules. In reality, compromise between material weight, cost, and thermal conductivity has to be found. In current analysis two different materials were tested for TEG assembly hot plates: copper and stainless steel. Apparently, since stainless steel has much lower thermal conductivity, it reached higher temperature at the same exhaust gas flow rate which means that stainless steel hot plate will not release heat as good as copper hot plate and that less thermal energy goes through TE modules and less thermal energy is taken away by cold plate. Notice, that exhaust gas mass flow rate for TEG assembly with stainless steel hot plates in the analysis was decreased to provide the same hot plate steady state temperature.

Transient analysis was performed on TEG assemblies with G1 and G2 modules. Analysis showed that within 5 min TEG starts to operate at near steady state performance which may be too slow for short trips (1-2 miles) but practical enough for longer trips (over 1-2 miles) which are more common. Transient performance is high when high thermal conductivity materials applied and improves with decrease in weight and size of TEG assembly because it provides shorter way for heat transfer.

Two different materials were tested during transient analysis for TEG assembly hot plates: copper and stainless steel. Plots show that it takes longer time for steel hot plates to reach the same steady state temperature than for copper hot plates.

6.3. Recommendations for Future Work

The TEGs developed in this thesis has shown great potential to meet the power outcome requirements necessary to improve fuel economy without great increase in weight and cost. While some work has been done, much work remains in TEG research to further develop this useful technology. Additional improvements and experiments should be done that focus on its practical applicability.

While design 1 already has showed good electrical energy outcome results, design 2 still provides very low temperature difference for TE materials, and this could be improved by sending the coolant through the internal pipe and exhaust gases to the outside radiator what may be done by designing a box which would enclose the TEG and provide a channel for the exhaust gases.

Improvements could be also made by varying the dimensions and spacing of different elements in TEG assembly. Additional tests should be conducted to evaluate the optimal size of the elements in TEG assembly.

6.4. Summary

The research questions described in chapter 2:

- Which power level is the current bismuth telluride TEG design able to achieve? Which problems need to be solved to achieve higher power level?
    - While the best TEG design with G2 TE modules analyzed here is fully capable of achieving 770 W, attaining this power level is only possible when the exhaust system of a vehicle's engine produces an exhaust gas mass flow rate 150 kg/h which corresponds to the exhaust gas mass flow rate of 3.5L FORD Ecoboost IC engine operating at approximately 3000 rpm which is the most probable. Low efficiency of the heat exchangers and contact resistance are the major problems to producing higher power in TEGs.
- Is the current bismuth telluride TEG design able to meet 20 kg weight limit requirement? (20 kg weight limit requirement is selected on the basic physics analysis which requires 1 kW of mechanical energy for each additional 20 kg of a 2000 kg vehicle to keep the same dynamic characteristics)
    - As follows from the TEG development results, design that capable to provide 770 W weighs 38.5 kg which is almost two times more than desired but designs with

smaller power output satisfy weight requirements. Even though this will affect dynamic characteristics of a vehicle, TEG will still bring a lot of benefits during a steady-state regime of a vehicle operation, which is mostly happens when driving on highway. Moreover, there is a great potential to decrease the weight considerably using lighter materials for TEG assembly components (for example, aluminum instead of copper).

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