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Waste heat energy harvesting using thermoelectric generation

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Abstract: The demand for passenger vehicles has grown significantly over the past 20 years due to the world's population growth and the vehicle industry's rapid expansion. The energy used to burn fuel in a diesel engine is only 41 % turned into work that is useful for moving a car and its supplementary loads. The remaining heat is lost by radiation and convection from the engine block, as well as waste heat released by the exhaust system of the engine. This leads to a severe energy crisis and has an impact on the environment by increasing fuel usage. As much as 30 to 40% of exhaust gases with thermal energy released from internal combustion engines, reaching temperatures of 200 to 250 degrees Celsius, are released straight into the atmosphere. Utilizing the heat energy produced by an internal combustion engine is the project's objective. By doing so, the amount of fuel heat energy that is used by the internal combustion engine can be decreased, increasing the engine's efficiency. The task is to create a duct that can be altered to improve heat transfer and dissipate as much heat as possible to the TEG module's hot side. Additional fins can be incorporated into the duct's design to further enhance heat transfer.

I. INTRODUCTION

Recent studies indicate that, if this waste heat of IC engines could Recent research studies have highlighted the potential for significantly augmenting the output power of internal combustion (IC) engines without incurring additional fuel consumption by efficiently recapturing the waste heat they generate. This prospect holds the promise of substantial conservation of fossil fuels and a corresponding reduction in the emission of edu.in
harmful exhaust gases into the environment, thereby contributing to the mitigation of global warming. It is essential to note, however, that estimations of energy savings resulting from enhanced energy efficiency are based on fundamental principles of physics and engineering models. In practice, the realized energy savings often fall short of these estimates due to the rebound effect. This effect implies that improvements in energy efficiency can inadvertently stimulate greater energy consumption, offsetting some or all of the anticipated gains.The escalating price of fossil fuels, driven by a severe energy crisis, underscores the growing importance of renewable and clean energy sources. Consequently, improving engine efficiency through waste heat recovery systems represents a viable solution. Such an approach holds substantial promise, both in terms of environmental sustainability and economic benefits.The advent of micro- and nanotechnologies has opened up new opportunities for the efficient recovery of waste heat. The key to identifying suitable applications for thermoelectric generator (TEG) waste heat recovery lies in situations where the thermal exchange between existing process fluids is either unavailable or provides no tangible technical or economic advantages. The quality of waste heat, which includes factors such as temperature, composition, energy content, and accessibility, varies significantly and is contingent on the industrial process from which it emanates. As a result, numerous research initiatives and projects are dedicated to improving engine performance and thermal efficiency with the primary objectives of reducing fuel consumption and mitigating emissions that are detrimental to human health. One particularly intriguing and contemporary avenue for waste heat recovery involves the conversion of exhaust heat into electricity through the utilization of thermoelectric generator modules. These modules have the capability to transform a temperature gradient into electrical energy or, conversely, convert applied electrical energy into a temperature gradient.

II. METHODOLOGY

2.1 Thermoelectric Power Generation: Thermoelectric power generation hinges on the phenomenon known as the Seebeck effect. When heat is applied at the junction of two dissimilar conductors within a circuit, it gives rise to the generation of an electric current. An extensive examination of materials was conducted by Seebeck, encompassing naturally occurring semiconductors like ZnSb and PbS [2]. The Seebeck coefficient, expressed in microvolts per Kelvin, is the metric employed to quantify the open- circuit voltage produced between two points on a conductor when a uniform temperature differential of 1 Kelvin exists across those points.

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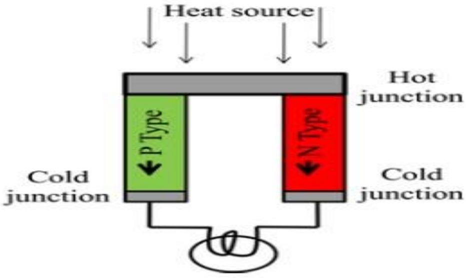

Fig.1 Electric power generation

2.2 Thermoelectric Heating and Cooling: Devices for thermoelectric heating and cooling are rooted in the Peltier effect. By passing an electrical current through a circuit comprising two dissimilar conductors, a temperature alteration at the junction is induced, contingent upon the direction of current flow. In the scenario depicted in Figure 4, when electric input is administered to a thermocouple, electrons migrate from the p-type material to the n-type material, absorb thermal energy at the cold junction. These electrons subsequently release their excess energy at the hot junction as they traverse from the n- type back to the p-type material from the electrical connector. The removal of heat from the hot side leads to a swift reduction in temperature on the cold side.

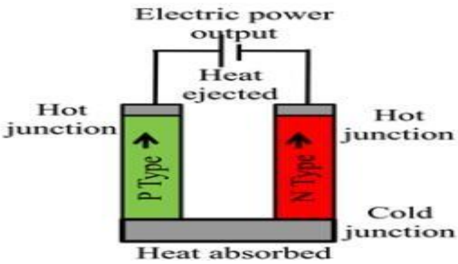

Fig. Thermoelectric cooling

2.3 Material used for TEG

Among the extensive array of materials in existence, only a relatively limited subset qualifies as thermoelectric materials. These materials can be classified in two primary groups: novel and conventional l. presently, thermoelectric materials, such alloys based on Bismuth Telluride (Bi2Te3) and Pb-Te, exhibit a ZT value of approximately unity (at room temperature). However, for thermoelectric power generators become competitive with other power generation systems, it is imperative to attain a ZT value within the 2-3 range. Effective thermoelectric materials should exhibit less thermal conductivity while simultaneously demonstrating high electrical conductivity. A substantial portion of thermoelectric material research has been directed towards augmenting the See beck coefficient and diminishing thermal conductivity, with particular emphasis on the non-structural aspects of these materials. The choice of thermoelectric material depends on the temperature difference between the hot side and cold side of the TEG module. A comprehensive listing of materials suited to the temperature range for which TEG modules are designed is presented in the table below.

Table-1.1: Material used in TEG with range of temperatures

Sno	TEG Material	Temperature Range
1	Alloys based on Bismuth (Bi) in combinations with Antimony(An), Tellurium (Te) or Selenium (Se)	Low temperature up to 450K
2	Materials based on alloys of Lead (Pb)	Intermediate temperature up to 850K
3	Material based on Si-Ge alloys	Higher temperature upto1300K

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While the aforementioned materials continue to underpin practical and commercial applications in thermoelectric power generation, notable strides have taken in the synthesis of new modern materials and the fabrication of material structures designed to enhance the performance of thermoelectric by reducing thermal conductivity

III. OBJECTIVES OF PROJECT WORK

Development of mechanical setup for heat energy recovery: The primary goal of this project is to design and construct a mechanical setup dedicated to the efficient recovery of heat energy. This setup will be instrumental in harnessing waste heat generated by various processes.

Utilization of Thermoelectric (TEC) Plates for Heat Energy Recovery: A key objective is the integration and application of Thermoelectric (TEC) plates within the heat recovery system. These TEC plates are pivotal in the converting the thermal energy differentials into usable electrical power.

Incorporation of Heaters with Temperature Control: To facilitate data collection at different temperature points, the project aims to incorporate heaters equipped with precise temperature controllers. These controlled heating elements are essential for maintaining and adjusting specific temperature conditions for experimentation and measurement.

Generation of Temperature-Voltage Graphs: The project also involves the collection of temperature and voltage data at various points during the heat recovery process. Subsequently, this data will be analysed and used to create graphical representations, specifically temperature versus voltage graphs. These graphs will serve as crucial visualizations of the relationship between temperature differentials and the electrical output of the TEC plates, underscores the extensive applications of this conversion system in various domains, including micro-scale waste heat utilization, such as in electronic chips and domestic gas-monitoring systems [2].

M. He, X. Zhang, K. Zeng, K. Gao: Their work centers on the recovery of waste heat from combined cycle processes, specifically within Rankine Cycles, and the internal combustion engines produces the high temperature exhaust gases. The study conducted experiment on a TOYOTA 8A gasoline engine to analyze the exergy and energy balance the waste heat in exhaust gases [5].

X. Gao, S. Juhl, M. Andreasen, S. Chen, S. Knudsen Koer: This research introduces a numerical model for an exhaust heat recovery system designed a Polymer Electrolyte Membrane Fuel Cell (HTPEMFC) stack for high temperature. The system incorporates thermoelectric generators situated within the walls of a fixed plate fin heat exchanger presented a numerical model of an exhaust heat recovery system for a high temperature polymer electrolyte membrane fuel cell (HTPEMFC) stack. They designed a Waste gases emanate from diverse sources, including vehicles, industrial processes, and heat generated from solid waste, among others. The overarching objective is to harness this waste heat and transform it into a useful form of energy. This necessitates the utilization of a system capable of converting heat into mechanical work. Furthermore, the choice of materials for Thermoelectric Generators (TEGs) holds significant importance when evaluating the energy and exergy of exhaust gases. This study delves into the analysis of a combined Thermoelectric enerator and Rankine Cycle (TEGORC) for exhaust heat recovery from Internal Combustion Engines (ICE). The authors calculated optimal best parameters for bottoming cycle using thermodynamic principles, taking into account the net power output and the ratio of volumetric expansion as objective functions. Factors influencing performance of the system and the size, such as the flow direction of TEG, TEG scale, high temperature, condensate temperature, evaporator pressure, efficiency of the internal heat exchanger (IHE), were examined. The choice of the fluid, R123, was made to avoid complications stemming from fluid decomposition [1].

IV. LITERATURE REVIEW

B. I. Ismail H. Ahmed. [2] This research focuses on the utilization of thermoelectric modules, with particular attention to performance parameters. The "figure of merit" (Z) is identified as a critical factor influencing the module behaviour of thermoelectric generator. The efficiency of these modules is fundamentally dependent on Z and the operating temperature difference. The paper fixed plate fin heat exchanger. The model employs a finite element approach, taking into consideration fluid properties, heat transfer process and the performance of the thermoelectric generator [6].

M. Strasser, R. Aigner, M. Franosch, G. Wachutka: This study is dedicated to miniaturized thermoelectric generators, with the primary goal of converting waste heat into less microwatts of electrical energy. To optimize the device, the authors emphasize the significance of materials with low thermal conductivity, which contributes to increased power output. The materials employed in this study include poly-Si and poly- Si-Ge [8].

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Component Specification:

(1) Thermoelectric generator

A Thermoelectric Generator (TEG) is a semiconductor-based electronic component designed to convert heat into electricity, leveraging the See beck effect. The experimental setup employs two TEGs connected in series. These TEG modules utilize bismuth telluride as the thermoelectric material and are engineered to operate efficiently at hot-side temperatures reaching up to 150°C. Notably, the TEG module generates a power output of 3.2 watts when exposed to a temperature difference of 100°C. These TEGs are ingeniously connected both thermally in parallel and electrically in series to amplify the voltage output.

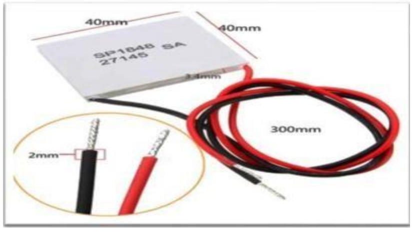

Fig.2 thermoelectric generator

- Model: SP1848-27145
- Operating Temperature Range: -40 to 150°C
- Cable Length: Approximately 20cm
- Principle Utilized: See beck effect
- Primary Material Composition: Bismuth telluride Dimensions: 40mm x 40mm x 3.4mm
- Merit (Z): Ranging from 2.5 to 3.0 × 10^-3 W/°C Bismuth telluride-based TEG modules were chosen for their cost-effectiveness and ready availability.

1. HEAT SOURCE AND HEAT SINK:

A heat source represents a heat-producing object or entity. A heat sink, on the other hand, serves as an element designed to adeptly absorb and efficiently dissipate heat generated by another object through direct thermal contact.

2. ALUMINUM HEAT SINK:

In the current research, a flat back-type aluminium heat sink is the cooling medium of choice. This heat sink design incorporates a series of cooling fins that benefit from an air cooling system. The aluminium heat sink's cold-side temperature is meticulously maintained at ambient room temperature, typically hovering between 26 to 30°C. Impressively, the aluminium heat sink boasts 25 heatdissipating fins spanning a considerable area of 70mm x 80mm, and these fins exhibit a slight thickness of 0.5mm. The experimental setup incorporates two of these aluminium heat sinks. The rationale behind choosing aluminium heat sinks lies in their exceptional thermal conductivity, widespread availability, cost-effectiveness, lightweight build, and their seamless compatibility with the TEGs. In cases where the electrical output from the TEG alone proves insufficient to power the load, a booster circuit comes into play. For this purpose, a straightforward Joule Thief circuit is employed, featuring a round ferrite toroid, a 1K resistor, and an NPN transistor. This circuit effectively boosts DC voltage to meet the necessary requirements, albeit with an efficiency rating that typically falls within the 70% to 80% range.

Voltage boosting is meticulously monitored through the use of a digital multimeter.

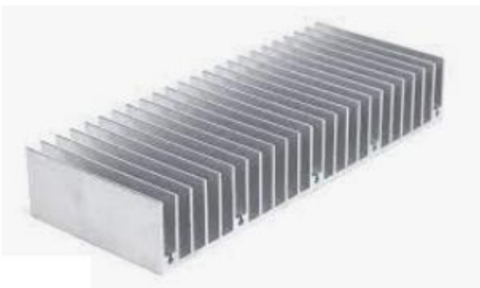

Fig.3 Aluminium heat sink

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3. MULTIMETER:

Ensuring the ongoing monitoring of the system's performance is of paramount importance to the experiment. In this regard, a total of three multimeters are strategically positioned across different junctures within the circuit. The first multimeter is connected immediately after the TEG module to diligently monitor the resultant output voltage. The second multimeter is positioned following the booster circuit, serving the critical function of monitoring booster voltage. Lastly, the third multimeter is strategically connected in proximity to the load, enabling the meticulous monitoring of the electric current flowing throughout the circuit. The chosen multimeters are of the DT830D digital type, featuring a DC voltage range of up to 200 V, maintaining an accuracy level of ±0.5%. Simultaneously, the DC current range spans from 200 mA to 10 A, maintaining accuracy levels of ±1.2% and ±2.0%, respectively.

4. TEMPERATURE CONTROLLER:

The temperature controller module incorporates an array of crucial components, including a temperature sensor, keys, an LED display, and a relay, in addition to requiring a stable DC 12V power supply. Functioning as a highlyaffordable and top-quality thermostat controller, it ensures the system consistently maintains the desired set temperature or closely approximates it.

5. HEAT PASTE:

Heat paste represents a viscous fluid substance characterized by properties reminiscent of grease. Its inherent nature increases the thermal conductivity of the thermal interface, expertly filling the minuscule air gaps that can emerge due to surface imperfections, such as those arising from less- than-perfectly flat or smooth surfaces. This heat paste is diligently applied to both junctions of the TEG, facilitating the smooth transfer of heat. It is particularly noteworthy that this heat paste boasts impressive thermal conductivity while concurrently maintaining its electrical insulating properties. In the context of this experimental setup, a silicon-based compound with a white hue is selected for its remarkable ability to withstand temperatures as high as 150°C.

V. EXPERIMENTAL SETUP FOR WASTE HEAT RECOVERY

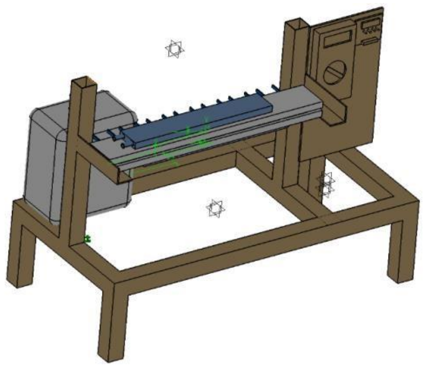

Fig.4 Experimental Setup For Waste Heat Recovery

WORKING PROCEDURE OF THE SETUP

The primary inquiry guiding this investigation revolves around the comparative analysis of power output across various models of Thermoelectric Generators (TEGs). To address this fundamental question, a systematic working procedure has been devised, and the overarching goal is to glean insightful findings through a series of coherent steps. These findings will be instrumental in achieving the following objectives

- **Comparative Assessment of TEG Performance:** The core focus of this endeavor is to meticulously evaluate and compare the performance of different TEG models. By subjecting these TEGs to a battery of tests, we aim to discern the variations in their power output. Through these tests, we intend to draw comparisons that will elucidate the distinctive characteristics of each model concerning its power generation capabilities.

- **PERFORMANCE-PURCHASE PRICE CORRELATION:**

A crucial aspect of this investigation is to draw a connection between the performance of the TEGs and their respective purchase prices. By examining the relationship between power output and cost, we seek to uncover whether higher-priced

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TEGs necessarily deliver superior performance. This analysis will provide valuable insights for potential buyers or researchers looking to optimize their investments in TEG technology.

- **VALIDATION AGAINST SUPPLIER DATASHEETS:**

To ensure the integrity of our findings, we will rigorously validate the results obtained through experimentation against the supplier datasheets for each TEG model. This validation step is essential to confirm the accuracy of the information provided by the manufacturers and to maintain the highest standards of research rigor.

- **POWER GENERATION AND TWO-POLE CHARACTERISTICS:**

Beyond merely measuring power output, this investigation also delves into the underlying characteristics of the TEGs. In addition to quantitative data, we aim to explore the two-pole characteristics of these TEGs, shedding light on their behavior in different operating conditions. This deeper understanding of the TEGs' performance attributes will contribute to a comprehensive assessment of their capabilities. In conclusion, the working procedure of this setup adheres to a structured approach that encompasses testing, analysis, comparison, and validation. The ultimate aim is to furnish a comprehensive understanding of the TEGs' performance, their cost-effectiveness, and how well these attributes align with the information provided by the suppliers. This endeavor promises to yield valuable insights and facilitate informed decision-making for those engaged in TEG technology research or utilization.

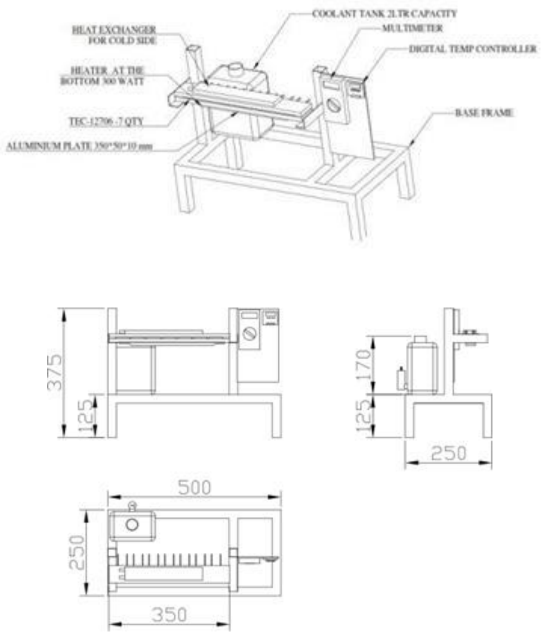

Fig.5 CAD Design For Waste Heat Recovery

In our experimental setup, we have incorporated a 250-watt heater, which serves as the primary heat source for our investigation. To ensure precise control over the temperature, a Temperature Controller has been deployed, allowing us to set and maintain the desired temperature conditions with accuracy. The electrical output generated by the Thermoelectric (TEC) plates is measured using a Digital Multimeter, enabling us to quantitatively assess the electricity produced by these TEC plates.

Our setup has been meticulously designed to facilitate heat energy recovery up to 12 volts. To achieve this goal, we have connected six TEC plates in series, capitalizing on their combined output to reach the desired voltage level. This arrangement optimizes the conversion of heat into electricity and ensures that the recovery process is efficient and effective.

As we progress with our experimentation, we will chart our findings by creating graphical representations in the form of temperature versus electricity produced. These graphs will provide a visual depiction of the relationship between temperature differentials and the electrical output generated by the TEC plates. Such graphical data will be instrumental in comprehending the performance characteristics of the TEC plates and how they respond to varying temperature conditions

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VI. RESULTS AND CONCLUSION

In this chapter, we present the outcomes and draw our conclusions based on the experiments conducted using the test rig. Our primary focus has been on the analyzing the waste heat recovery from exhaust gas of an Internal Combustion Engine (ICE). The results obtained from these experiments shed light on effectiveness the waste heat recovery system and provide valuable insights into its performance and potential applications.

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