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Cover Page Footnote

I would like to thank my faculty advisor, Professor David Ibrahim, as well as all of the faculty of the Martin D. Walker School of Engineering at Olivet Nazarene University for their time, wisdom, and dedication to student success. I am grateful for all of the Olivet Nazarene University Honors Program faculty and their persistent commitment to my success. I would like to thank the Honors Program for financial support of this research. Lastly, I would like to thank my family for their continual support in every endeavor I pursue.

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ABSTRACT

Developing efficient thermoelectric generator systems to recover wasted thermal energy from automotive exhaust gasses has potential to improve engine efficiency and reduce carbon emissions. Due to their high thermal transfer efficiency, heat pipes have been used to assist thermoelectric generator systems in these applications. To aid in additional heat transfer, metal fins are often used with heat pipes to take advantage of extended-surface heat transfer. This paper proposes a thermoelectric generator system that employs metal foam as an extended-surface heat transfer aid used in conjunction with heat pipes. Three test conditions were simulated to evaluate the system performance in terms of maximum power output: one with heat pipes with no heat transfer aid, one with heat pipes and aluminum fins as a heat transfer aid, and one with heat pipes and metal foam as a heat transfer aid. The experimental results show that the power output of the system was lowest when using no heat transfer aid and highest when aluminum fins were used. Metal foam proved to be effective at increasing the power output but did not perform as well as aluminum fins. Metal foam helped increase the open circuit steady state voltage by 10.2%, whereas the aluminum fins increased the open circuit steady state voltage by 61.8%.

Keywords: thermoelectric generator, metal foam, heat pipes, waste heat recovery

REVIEW OF LITERATURE

Exhaust heat recovery systems are used to take advantage of otherwise wasted heat produced from an automobile's engine. In modern internal combustion engines only about 30% of the chemical energy in the fuel is converted into mechanical energy used by the automobile. The rest is turned into thermal energy. Though a portion of the heat is dissipated by the coolant, the majority of the heat is evacuated from the engine via the exhaust system. Harnessing this thermal energy and converting it into usable electrical power could allow for the removal of an automobile's alternator. This simple change would help reduce fuel consumption by reducing the parasitic load on the engine, which in turn reduces the amount of harmful CO2 gases released into the environment. Stobart et al. (2010) determined that such systems could increase fuel efficiency by as much as 4.7%.

Thermoelectric generators

One proposed method for capturing this thermal energy is with the use of thermoelectric generators. Thermoelectric generators consist of two metal plates separated by another metallic compound. As one side of the thermoelectric generator is heated, the temperature difference between the two metal plates increases. This temperature difference induces the flow of electrons in the material from the high temperature side to the low temperature side creating an electric potential, or voltage, which is then harnessed.

In recent years, automotive companies and independent researchers have been testing exhaust gas recovery systems utilizing thermoelectric generators. In the past decade BMW has developed and tested several prototypes. Their first tests, carried out in

2003, resulted in a maximum power production of 80 watts. A later attempt in 2006 resulted in production of 200 watts from a BMW 535i sedan. The same vehicle was equipped with an updated system two years later that was able to produce 300 watts. In 2011, the company tested a BMW X6 SUV equipped with a new system containing updated thermoelectric materials and an updated cooling system. At 125 km/h, the system produced 600 watts (Eder, 2011).

Other automobile manufacturers, including Ford, General Motors, Fiat, Renault and Chrysler have tested exhaust heat recovery systems as well. Tests were conducted on various size automobiles with varying results. General Motors was able to produce 230 watts from a system employed on a Chevrolet Suburban (Meisner, 2012). Renault Trucks was able to produce 350 watts from a truck with an 11 liter engine in 2011 (Champier, 2017).

Though automobile manufacturers have been investigating this technology for nearly two decades, it has yet to been implemented in a production vehicle. This suggests that current systems require further optimization in terms of performance and efficiency.

Heat exchangers

Automotive manufacturers are not the only ones interested in exhaust waste heat recovery. Academic researchers have been modeling and testing prototypes in an attempt to optimize heat exchanger and generator design. The optimization of heat exchanger efficiency is an area of intense interest due to the fact that available thermoelectric materials have inherently low energy conversion efficiencies, between 5 and 10% (Champier et al., 2017). Therefore, to obtain the most usable power from a thermoelectric system without developing new thermoelectric materials, one must use a heat exchanger with high thermal efficiency.

Fin-plate heat exchangers

The most common heat exchanger design in exhaust heat recovery applications is a variation of a fin-plate heat exchanger. Exhaust gas flows into the heat exchanger where it encounters internal fins and plates that direct the gas towards the outside surface of the system. The heat from the exhaust gas increases the temperature of the outside surface of the heat exchanger, which then heats the hot-side surface of the thermoelectric generator. This general design is widely used because it theoretically allows for the transfer of a high percentage of the heat present in the gas.

Su et al. (2014) conducted a simulation and experimental study on the thermal optimization of a heat exchanger used for an exhaust heat recovery thermoelectric system. The study analyzed three fin-plate heat exchangers with varying internal design structures. The goal was to achieve even thermal distribution across the outside surface of the heat exchanger, which would be in contact with the hot-side surface of the thermoelectric generator. The internal designs utilized a fishbone-like structure, an accordion-like structure, and a random structure. Using computer software, each design was modeled and the heat transfer efficiency was simulated. Each system was then applied to the exhaust system of a four cylinder engine. The computer simulations suggested the accordion type design would provide the most even distribution of heat, and prototypical tests confirmed this hypothesis. The accordion-like structure produced a 3.5% and a 6.5% higher average temperature than the fishbone-like structure and random structure, respectively.

Liu et al. (2016) completed a multi-objective optimization of a heat exchanger for an automotive exhaust thermoelectric generator. The heat exchanger was a variant of a fin-plate heat exchanger. The system utilized internal fins with varying orientations. The study was conducted to evaluate thermal properties and pressure properties of the gas as it flowed through the system. The study had four optimization targets: average temperature, temperature gradient in longitudinal direction, temperature gradient in transverse direction, and average static pressure drop through the system. Throughout the study, five parameters were optimized: fin length, fin height, fin thickness, fin angle, and interval distance. Sixteen computer-aided models with variances in some or all of the five parameters were created and simulated. The simulations revealed the intricate correlation between all five parameters, though internal fin height had the greatest effect (34%) on thermal flow to the surface of the thermoelectric generator.

Fin-plate heat exchangers are the most common heat exchanger used in exhaust heat recovery systems with thermoelectric generators. Their large surface areas allow for significant thermal energy transfer from the exhaust gas to the external surface. The large external surface also allows for easy mounting of the thermoelectric modules. However, fin-plate heat exchangers have disadvantages. Even with an optimized design it is extremely difficult to achieve even temperature distribution over the surface of the heat exchanger. Also, the internal fins increase the back pressure of the exhaust gas, which decreases engine efficiency (He, 2017). Due to these disadvantages researchers are investigating other ways to raise heat exchanger efficiency.

Heat pipes

Heat pipes provide another solution for increasing heat exchanger efficiency. They are generally very efficient and have high thermal conductivity. Recently, research has been conducted regarding heat pipes being used in exhaust heat recovery systems. Cao et al, (2018) analyzed the performance of heat pipes in this application. Several parameters were tested to achieve an optimized state, including the depth of the heat pipes, the angular position of the heat pipes, and the use of fins to aid in heat transfer. Notably, the addition of fins increased the output by 43%. In this experiment, in the systems optimized state, 81.09 volts were generated from 36 thermoelectric modules. This equated to a thermoelectric power generation efficiency of 2.58%. Remeli et al. (2016) tested a similar system that used heat pipes to heat and cool the thermoelectric generator. In this test, 62 aluminum fins were also used to aid in heat transfer. Modeling showed that the prototype had the capability of recovering 1.345 kW of waste heat, yet, it only generated 10.39 watts of electricity, equating to a 0.77% conversion efficiency.

Metal foam

Metal foam is a porous material made by injecting gas into liquid metal. Metal foam can be made from nearly any metal including aluminum, copper, silver, gold, nickel, etc. Metal foam can vary greatly in pore size and density.

Bai et al. (2017) conducted a numerical investigation on the performance of a thermoelectric generator system employing a heat exchanger externally wrapped in metal foam. The heat exchanger was a simple cylindrical device, with a radius not much larger than that of the automotive exhaust pipe. The heat exchanger had no internal fins or plates. The exterior of the heat exchanger was octagonal and each side was covered with metal foam. An identical heat exchanger without metal foam was also tested so the results could be compared. The researchers also varied the thickness and porosity of the foam in order to optimize the design. The results showed that the use of metal foam increased temperature and distributed heat more evenly across the external surface where the thermoelectric modules were mounted. The tests also concluded that the system utilizing metal foam had an increased power output by 170%, compared to the system without metal foam.

Based on the results of the aforementioned research, it is clear that the addition of aluminum foam increases the heat transfer between the flowing heat source and the outside environment. Similarly, the aforementioned research also concludes that the addition of aluminum fins to a system utilizing heat pipes increases the heat transfer between the heat source and the heat pipes. My study aims to compare the two heat transfer aids (aluminum fins and aluminum foam) when used in conjunction with heat pipes in an exhaust gas waste heat recovery system. This study tests the heat transfer efficiency for thermal electric generation from a system using heat pipes with no heat transfer aid, a system using heat pipes and aluminum fins, and a system using heat pipes and aluminum foam.

This lends further credibility to the use of such systems being employed in vehicles that utilize internal combustion engines. This research creates baseline from which new studies can be conducted to improve these types of systems. Ultimately, the goal of this research is to aid in the creation of a system that will allow for the elimination of a vehicle's alternator, greatly improving fuel efficiency and reducing carbon emissions.

METHODS

To study the detailed parameters of the proposed thermoelectric generation system, an experimental test rig was built. A forced air kerosene heater producing 50,000 Btu with a volumetric flow rate of 175 cubic feet per minute was used to simulate the flow of automotive exhaust gases. The forced air heater was coupled to a four inch diameter metal duct through a series of reducers. This test rig is pictured in **Figure 1**.

Figure 1: Automotive exhaust heat simulation device. A forced air kerosene heater coupled with metal duct was used to simulate an automotive exhaust system.

As shown in **Figure 2**, four 150 mm long, 8 mm diameter copper heat pipes were positioned 30 mm apart and inserted halfway into the duct so that the ends were positioned in the center of the duct. The other end of the heat pipes were inserted into a 150 mm x 50 mm x 12.7 mm aluminum block, seen in **Figure 3**.

Figure 2: Heat pipe positioning in duct. Four heat pipes were separated by a distance of 30 mm and inserted 7 6mm into the metal duct.

Figure 3: Heat pipe positioning in aluminum block. The opposite ends of the four heat pipes were inserted into an aluminum block.

The hot side of three thermoelectric generators (TEGs) were attached to the face of the aluminum block. The cold face of the TEGs were then attached to another identical aluminum block with four identical copper heat pipes positioned 30 mm apart inside of the block. These heat pipes were left open to the ambient air to act as a heat sink and keep the cold side of the TEGs at a relatively constant temperature.

Three 40 mm x 40 mm x 3.4 mm, Bismuth Telluride (Bi_2Te_3) thermoelectric generators were used in each test. The thermoelectric generators were clamped between the two aluminum blocks. Due to its conductive nature, polysynthetic silver thermal paste was used between the faces of the thermoelectric generators and the aluminum to increase heat transfer.

The experiment was run three times with slight variations. In the first test, there was no heat transfer aid used in conjunction with the heat pipes. The heat pipes in the duct were directly exposed to the hot forced air. In the second test, sixteen rectangular aluminum fins, made of 6101 alloy and measuring 150 mm x 12.7 mm x 1 mm were placed onto the heat pipes that were inserted into the duct. Each fin was separated by a distance of 2 mm. These fins are pictured in **Figure 4.** The fins were used to aid in heat transfer. In the third test, these fins were replaced with a rectangular aluminum foam block measuring 150 mm x 50 mm x 12.7 mm. The aluminum foam had a relative density of 10 to 12%, 20 pores per inch (PPI), and was processed from 6101 alloy. Again, the aluminum foam was used to aid in heat transfer. **Figure 5** shows the heat pipes inserted into the aluminum foam block. **Figure 6** shows the aluminum foam block inserted into the metal duct.

Figure 4: Metal fin positioning. The four heat pipes were placed through holes in sixteen aluminum fins

Figure 5: Aluminum foam positioning. The heat pipes are inserted into the aluminum foam block.

Figure 6: Heat pipe and aluminum foam positioning. The aluminum foam and heat pipes are inserted similarly to the initial test with only heat pipes. The test conducted with aluminum fins was identical as well.

Three data sets were recorded from each test. First, the open-circuit steady-state voltage for each system was recorded using a digital voltmeter. The open-circuit steady-state voltage is the voltage produced by the circuit after the heat pipes have reached their maximum heat transfer potential, transferring a steady amount of heat to the aluminum block and therefore to the hot side of the thermoelectric generators. The time taken for each system to reach the open-circuit steady-state voltage was also recorded. The temperature at the center of the top surface of the aluminum block was recorded using an infrared thermometer. Using the open-circuit steady-state voltage and the amperage of the system, the power production of the system was found.

RESULTS

The results of the experimentation can be seen in Table 1. The results show that the addition of a heat transfer aid increased the surface temperature of the aluminum block, therefore, increasing the temperature of the hot side surface of the TEGs and the temperature gradient between the hot and cold side surfaces of the TEG. This increase

TABLE 1: TEST RESULTS

Test Conditions	Volts	Watts	Power Density (W/m^2)	Time to Reach Steady State (Min:Sec)	Aluminum Block Temperature (°C)
Heat Pipes	2.93	1.54	321	7:36	11.3
Heat Pipes and Aluminum Fins	4.74	3.11	648	7:19	20.7
Heat Pipes and Aluminum Foam	3.23	1.85	385	8:22	15.1

in temperature gradient lead to an increased electrical power output.

The results show that in both instances, the addition of an extended surface heat transfer aid increased the open-circuit steady-state voltage. The addition of aluminum fins increased the voltage by 61.8%, while the addition of aluminum foam increased the voltage by 10.2% over the base test with no heat transfer aid.

The addition of aluminum fins also reduced the time for the system to reach open-circuit steady-state voltage, compared to the system with no heat transfer aid. However, the addition of aluminum foam increased the time for the system to reach steady state by a considerable amount.

The increase in power density is representative of the increase of temperature, and therefore, voltage. Again, the addition of aluminum fins resulted in the highest power density, generating 648 W/m2. The addition of aluminum foam resulted in the second highest power density, yielding 385 W/m2. These results indicate that aluminum fins are a better heat transfer aid than 10% density, 20 PPI aluminum foam when used in conjunction with heat pipes that are exposed to hot, rapidly flowing air.

DISCUSSION

This study assessed the performance of an automotive exhaust heat recovery system utilizing thermoelectric generators, aluminum foam, and heat pipes. The results concluded that the addition of aluminum foam to the system was effective at increasing open-circuit steady-state, as well as power density. However, the addition of aluminum foam was not as effective at increasing these factors as the addition of aluminum fins. The amount of heat transferred to or from extended surfaces, like fins or porous media like metal foam, is, among other factors, related to the amount of exposed surface area. In this study the fins and metal foam were made from the same material, meaning they share the same intrinsic properties that effect heat transfer such as specific heat and thermal conductivity. The considerable differentiating factor between the fins and the metal foam was the exposed surface area. Predictably, the additional surface area of the fins lead to greater heat transfer.

It should be noted that this study tested one very specific variation of aluminum foam: 10-12% relative density, 20 PPI, processed from 6101 alloy, measuring 150 mm x 50 mm x 12.7 mm. Metal foam is largely variable in relative density, PPI, material, and size. As seen in Bai et al. (2017), variance in these factors lead to a variance in heat transfer effectiveness. A sample of metal foam with a higher relative density would have a greater exposed surface area and would lead to greater heat transfer. The optimization of these factors could be an area for future research.

It should also be noted that this study only tested the influence of the addition of aluminum foam on the electrical power output of the system. Though this is a significant factor in an automotive exhaust waste heat recovery, there are other factors that must be analyzed as well. One specific factor to consider is pressure drop within the exhaust system. As explained in Cao et al. (2018), significant pressure drop within the exhaust system has adverse effects on engine performance and efficiency. In an exhaust waste heat recovery system like the one tested, the electrical power output and effect of pressure lost must be weighed to optimize the system. Metal foam is known for its ability to transfer heat well while minimizing pressure drop in a system. Though the addition of metal foam in this experiment was not as effective as the addition of aluminum fins in terms of increasing electrical power generation, it may prove beneficial in reducing pressure drop in the system. The optimization of pressure drop and electrical power output could also be an area for future study.

The optimization of thermoelectric generator systems to recover wasted thermal energy from automotive exhaust gasses can improve engine efficiency and reduce environmentally harmful carbon emissions. In an attempt at optimization, a new system was created using thermoelectric generators, heat pipes, and aluminum foam. The electrical power produced from this system was compared to existing systems utilizing thermoelectric generators and heat pipes, as well as existing systems using thermoelectric generators, heat pipes, and metal fins. The results showed addition of aluminum foam increased heat transfer, but not as well as the addition of metal fins. The results show promise for systems utilizing metal foam, however, further testing will be needed to achieve optimization.

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