Characterization of Fractal Heat Exchangers Applied to Thermoelectric Waste Heat Recovery

Keywords: Waste heat recovery, Fractal heat exchanger, Thermoelectrics

Motivation

Growing global energy demand has resulted in a major effort for energy conservation research. In the United States, the transportation sector is responsible for 28 percent of the nation's total energy consumption [1]. Thermodynamic analyses of transportation vehicles show that less than 1/3 of vehicle fuel energy is used for operation, and the rest is released to the environment in the form of waste heat. Recovering some of this waste heat, as stated in a NSF/DOE program solicitation, has the potential to improve vehicle efficiencies by 5 percent and thus reduce the amount of total energy consumed [3].

One viable option for the recovery of low-grade exhaust waste heat from vehicles is the direct conversion to electricity using thermoelectric generators (TEGs). Previous research has shown that TEGs can produce enough power to replace the vehicle alternator, which will reduce the load on the engine and increase vehicle efficiency. TEG technology has feasible applications in over-the-road vehicles, which use a substantial portion of energy in the transportation sector.

A TEG operates like a thermocouple. It uses the Seebeck effect to generate power from a temperature difference maintained on either side of the module. Though TEGs have been studied periodically throughout the past century, global trends toward energy conservation have led to a renewed interest in the topic. Recent thermoelectric material studies have shown exponential increases in thermoelectric efficiencies, and the possibility of achieving 20 percent efficiency. Though thermoelectric material research has increased, a proportional increase in TEG heat transfer research has not been substantiated. A major challenge for thermoelectric waste heat recovery in vehicle applications is the optimization of heat transfer through the TEG while minimizing backpressure on the engine, which reduces engine efficiency.

Objective

The objective of the proposed project is to study the power gain from a thermoelectric waste heat recovery device that incorporates a fractal heat exchanger design. Power gain is defined as the power generated from the heat transfer through the TEG minus the power loss from the engine due to the effects of backpressure.

Fractal patterns are common in nature, especially in flow networks such as rivers and blood vessels. In biomimetics, which is adapting nature's optimized processes to engineering solutions, heat exchangers made with fractal patterns take advantage of lower pressure drop and higher rate of heat transfer through the system due to increased surface area. An extensive literature survey has shown that though most research in fractal heat exchangers has been at the microscale, because fractal patterns are scale invariant, fractal heat exchangers can also be studied at the mesoscale. In fact, Meyer [2] experimentally validates a mesoscale Koch island fractal heat exchanger. The results show a 250 percent increase in heat transfer with only a 6 percent increase in pressure drop when compared to a rectangular duct of the same cross sectional area. My proposed project seeks to further investigate the effects of mesoscale fractal heat exchangers when applied to thermoelectric vehicle waste heat recovery systems.

Hypothesis

If effective vehicle waste heat recovery is related to increased heat transfer and lowered pressure drop, then a fractal heat recovery system will show a positive power gain.

Research Plan

The proposed research plan is composed of two parts: heat exchanger construction and experimental design. First, to construct the fractal heat exchanger, a fractal duct must be developed using a variety of techniques such as extrusion, welding, and drilling. Then, a flow path must be constructed to direct hot gas of varying temperatures through the fractal duct. The gas will mimic engine exhaust and the varying temperatures can demonstrate a range of drive cycles. The next step is to provide a cold sink for the thermoelectric modules. To do this, the thermoelectric modules should be sandwiched between the fractal duct and liquid coolant ducts fitted to the fractal shape. The coolant ducts should operate counter flow of the hot gas in order to maximize heat transfer. Finally, the constructed heat exchanger should be held together with insulated brackets in order to thermally isolate the system.

The important parameters to measure in the proposed research project are temperature, pressure, flow rate, and power. To measure the temperatures of the system, thermocouples should be placed at the inlet, outlet, and surface of both the fractal and coolant ducts. The pressure drop across the fractal duct can be measured with a differential pressure and the results can be used to find the corresponding engine power loss. To measure flow rate, meters should be placed at the inlets and outlets of the fractal and coolant ducts. Finally, readings should be taken using a variety of techniques to measure the power output of the thermoelectric modules. All of the measurements in the experiment will be used to characterize the heat flux, backpressure, and power gain from the thermoelectric waste heat recovery system.

Broader Impacts

Results from this project have the potential for large societal impact by addressing both the United States' reliance on foreign oil and environmental concerns. Major findings in the proposed research study could help mitigate US energy consumption and thus reduce harmful environmental impacts. Another important impact is the broad dissemination of the proposed study's results. My communications strategy will not only consist of technical aspects published in literary journals, but it will also incorporate presentations to policy makers involving projected impact. The combination of these two communicative aspects will encourage others to improve upon my results and allow policy makers to make informed decisions on energy policy.

During my graduate studies, I plan to conduct research at the Massachusetts Institute of Technology (MIT). This institution is home to leading TEG and heat transfer researchers, and is considered one of the best graduate institutions for engineering. One unique aspect about MIT is that they have a thermoelectric waste heat recovery student organization. Through this organization I will look to coordinate outreach activities such as tours and high school presentations to inspire the next generation of researchers. Also during my time there, I will encourage undergraduate students to become involved with my research as there are countless other studies to run with the experimental setup. I will take on a mentor role with these students because I have seen first hand from my experiences the positive impacts of mentoring. The combined aspects of education at all levels and TEG's exciting potential impacts is why I have chosen to obtain an advanced degree and pursue a career in the field of energy research.

References

1. Energy Information Administration, "Energy consumption by sector," *Annual Energy Review*, 2008.
2. J.P. Meyer and H. van der Vyver, "Heat Transfer Characteristics of a Quadratic Koch Island Fractal Heat Exchanger," *Heat Transfer Engineering*, 2005.
3. Program Solicitation, "NSF/DOE Partnership on Thermoelectric Devices for Vehicle Applications," June 2010.