Waste Heat Recovery from an Internal Combustion Engine

Design Team
Josh Freeman, Matt McGroarty, Rob McGroarty
Greg Pellegrini, Ming Wood

Design Advisor
Professor Mohammed Taslim

Abstract
A substantial amount of heat is dissipated from all internal combustion engines (I.C.E). This waste heat is a potential source of usable energy and currently there are few and limited devices that harness it. This project focuses on the first phase of a three phase plan to develop a device to convert this thermal energy into usable kinetic energy. Several thermodynamic cycles were researched as potential methods for heat removal. Analysis and comparison of each method yielded Stirling cycle as being the most ideal candidate. Initial designs were modeled and compared to determine which would yield the most power output from the device. After refining initial design concepts, an analytical model was created in Simulink to simulate the design and to help determine optimal aspects. With the prototype design complete, construction of the device has begun and a testing plan has been outlined to run the device on a testbed.

For more information, please contact m.taslim@neu.edu.
The Need for Project

Internal combustion engines dissipate significant thermal energy, which can be converted via a waste heat recovery device into usable kinetic energy. There currently exist similar devices in large scale applications, but none in the automotive field. All I.C.ES run on the Otto cycle and require a combustible fluid to operate, of which 20% of its chemical energy goes toward propulsion. Roughly half of the remaining energy is removed from the system as heat via the exhaust stream without doing any usable work. Development of a device to harness this wealth of thermal energy into usable kinetic energy could increase the overall vehicular efficiency thereby reducing fuel consumption, which will save the consumer significant money in the long term. Current waste heat recovery devices are typically found in large scale applications such as cargo ships and manufacturing plants, but not in smaller scale applications, specifically automotive. Automotive devices like the turbocharger and supercharger increase the engine’s power, but can have negative effects upon its performance. This leaves a void in the automotive market for a waste heat recovery device that yields a more efficient vehicle.

The Design Project Objectives and Requirements

Design Objectives

The primary end objective is to design a device capable of harnessing the waste thermal energy present in a common vehicle’s exhaust stream and return an appreciable amount back to the vehicle system in the form of usable kinetic energy. For the first of three planned project phases, a prototype was designed around a testbed, mimicking a scaled down automotive environment, which is shown in Figure 2. The purpose of this prototype is to gauge the feasibility of producing a necessary amount of power while conforming to a certain subset of the overall project design requirements.

Design Requirements

The primary requirement of the device is to produce enough usable kinetic energy to mitigate parasitic loses on the engine, which includes the power needed to run the AC compressor, various pumps, and alternator. This adds up to roughly 7% of the engine’s horsepower. Final device requirements include a payback period of less than 5 years and a sale price of approximately $500 a unit. The device needs to fit within the confines of the vehicle it is housed in without severely altering the vehicle’s design or components.
The specific design objectives for the phase I prototype are based on these overall design requirements. The prototype is designed to occupy a space envelope of approximately one cubic foot, cost under $1500 dollars to manufacture, possess a factor or safety of at least 1.5 for all components when subjected to maximum operation forces, and provide the freedom to alter select components for various testing studies.

**Design Concepts Considered**

Three thermodynamic cycles were explored as methods of heat removal. A device using the Stirling cycle was ultimately chosen over one based on a Rankine cycle or thermoelectric materials due to a multitude of factors. From here, four initial design configurations were analyzed. Each design consisted of two cylinders pairs placed around the exhaust pipe from an internal combustion engine, a regenerator linking the cylinders in each pair, and a power transmission with a flywheel. The main differences between them were the mechanism used for power transmission and the Stirling configuration utilized.

**Power Transfer Concepts**

In two of the four initial designs the pistons were connected to a crankshaft, much like in a typical I.C.E. The two remaining designs connected the pistons to a swashplate as the means of power transfer. A swashplate consists of a shaft connected to a disc mounted at an angle. As the pistons go through their linear motion they slide across the surfaces of the angled disk which causes the shaft to rotate. The two swashplate designs had a horizontally mounted flywheel, while the designs using a crankshaft had a vertically mounted flywheel.

**Stirling Configuration Concepts**

Two designs used two pistons per cylinder pair (alpha configuration) while the other two had one piston and one displacer per cylinder pair (gamma configuration). The gamma configuration, shown in Figure 3, uses a displacer to move the working fluid back and forth through the device. In the alpha configuration, shown in Figure 4, one cylinder per pair was set to be the hot side, meaning it operated at a higher temperature. This hot side cylinder obtained its higher temperature by being in contact with the exhaust pipe. The other cylinder was placed away from the exhaust pipe to keep it at a lower
temperature, thus making it the cold side. The gamma configurations had a hot and cold side within the cylinder housing the displacer, meaning that one end of the displacer cylinder needed to be heated by the exhaust pipe and the other end cooled either by flowing ambient air or a water jacket.

**Recommended Design Concept**

The final design is comprised of four cylinders driving a crankshaft, all mounted to a custom support with the hot side submersed in the exhaust flow.

**Design Description**

The prototype design uses the alpha configuration with the cylinders 90° offset from each other and the pistons connected to a crankshaft assembly between them, much like a V engine in automobiles. The cylinders are submersed in the exhaust stream and have fins attached to their exterior to maximize heat transfer. The cold side cylinders have a similar set up except the cylinders are exposed to flowing ambient air.

The regenerators linking the cylinder pairs are made of ½” copper piping and have a pressure gauge to monitor the system as well as a safety blow off valve. These pipes are stuffed with copper wool to increase the temperature differential.

The crankshaft is made of custom machined aluminum parts in order to minimize its weight. The pistons from each cylinder pair connect to a single crankshaft throw. At one end of the crankshaft is a flange and flywheel, while the opposite end has a pulley which is used to connect the crankshaft to a generator via a belt to measure the system output power.

**Analytical Investigation**

A simplified model of the prototype was created in Simulink to model and run simulations. By changing individual aspects of the analytical model and running simulations the optimal design of the prototype could be developed. These aspects include the effects of dead volume, number of fins, engine speed, and system pressurization on engine performance. Some of the results from these studies are shown in Figures 4 and 5. A Computation Fluid Dynamics (CFD) simulation was also run to analyze the backpressure to the I.C.E from the cylinders in the exhaust stream, which found a negligible pressure loss of 0.1 PSI. An image from this simulation is shown in Figure 6.
Individual parts were also analyzed in Solidworks to determine whether they would be able to withstand the expected maximum operation forces. Static loads were applied to critical components to mimic the dynamic forces acting at a single moment in time, as shown in Figure 8. The static loads applied were equivalent to the force from the system pressurized at 50 psi, or roughly 481 lbf. All components were required to have a factor of safety of at least 1.5.

**Key Advantages of Recommended Concept**

The key advantages of the prototype design include high heat transfer, delivery of power, and ease of manufacturing. By submersing the hot side and cold side cylinders into the exhaust and air flow respectively and adding fins, the design allows for the highest level of heat transfer as well as temperature differential. The orientation of the pistons/cylinders make the 90° offset inherent in the design, simplifying the crankshaft design. Components for this design were selected based on ease of manufacturing and materials available.

**Financial Issues**

The production cost of the prototype design is $1200, but this value is expected to lower for the final mass-produced device. Initial cost estimates of the prototype design were under $1000 for parts and materials. With design reconfigurations the final cost to produce the Phase 1 prototype inflated to approximately $1200. This increase in cost can be attributed to ordering materials in low volume, bending certain design decisions to meet safety requirements and accommodate a limited on-site manufacturing capability. Cost for a mass-produced device can be expected to be much lower with a goal of $500.

**Recommended Improvements**

The design process will continue to the next phase where the design is to be scaled to automobile environment and the power output of the device will be improve. Development of initial prototype design serves as a conclusion to Phase I of the overall project. The next project phase would be to scale design for use in an actual automobile environment, mostly through use of improved manufacturing techniques and material choice. Optimal methods for delivering the kinetic output energy in the automobile (accessory powering, direct flywheel hook-up, etc.) would need to be investigated to maximize benefits of the waste heat recovery device and meet payback period and cost requirements for commercial implementation.