Feasibility Study of Thermoacoustic Lamina Flow Engine for Waste Heat Regeneration in Vehicles

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Abstract: - A small scaled model of the lamina flow engine is built to study the challenges associated with its fabrication and installation in vehicles and to approximate its production cost. The model engine produces 216mW at 0.6% efficiency using an aluminum hot tube. Subsequent experiments with different materials for the hot tube yields higher efficiency at the cost of higher production cost. A cost-efficiency relationship developed suggested a commercial thermoacoustic engine used in vehicles should be made at a production cost target of less than RM 7.85 (approximately 25USD) per percent efficiency.

Key-Words: - **Thermoacoustic, Lamina Flow Engine, Waste Heat Regeneration**

1 Introduction

In the coming decades, the greatest growth in the automobile population will occur in developing countries which can least afford clean technologies. The United Nations Fund for Population Activities estimates developing countries will be emitting 16.6 billion tons of carbon dioxide annually by year 2025, or about four times as much as developed nations due to the rapid rise in population. Hence, the development of a clean and cheap technology is imminent for the conservation of the environment

The research on Thermoaccoustic is promising as it has shown tremendous progress over the past decade and is slowly penetrating the commercial market especially in niche applications. In recent years, a Thermoacoustic Engine configuration called the Lamina Flow Engine gained popularity for its simplicity and its ability to function even using air as a working fluid at atmospheric pressure.

This research attempts to utilize this existing thermoacoustic technology to produce some useful energy from waste heat of an automobile and gauge whether it is economically feasible for mass production.

2 Availability of Waste Heat

The main engine of the vehicle can operates at temperature up to 1800 degree Celsius during an engine cycle. For this engine to be useful in driving the vehicle, it is required to run at high RPM. This means that the engine ejects the gas inside the combustion chamber even when it still has plenty of heat left. There are also various channels that the heat can escape from the engine without being fully utilize for example;

1) Conduction through the combustion chamber walls into the engine cooling system. This is usually via the radiator and its exposed pipe work.
2) Conductive transfer from the combustion chamber walls to the engine block exterior. This is also coupled with convective and radiative transfer to the engine surroundings.
3) Heat transfer from the exhaust gas to the exhaust system and subsequently to the environment.

Hatazawa et al, suggested as much as 35% of the thermal energy generated from combustion in an petrol engine is lost to the environment with most of it through the exhaust system. In Johnson's report, a total waste heat can range from 20kW to as much as 40kW for 3.0L petrol engine with a maximum output power of 115kW. This heat can be channel to the thermoacoustic engine, where it can be tap near the vicinity to the exhaust manifold or perhaps slightly further downstream at the catalytic converter.

This waste heat energy is more than enough to power all the electric and electronic systems in that particular vehicle. Further research by Hatazawa concluded that sufficient temperature and heating power is indeed available in the exhaust gas. However, capturing that waste heat proves a challenge. In his experiment, he only manage to obtain a thermal input 300W, at over 300 degree Celsius from a 3.0L Mazda engine running at 2600RPM with 35% throttle opening with his small scaled thermoacoustic heat engine.

3 Lamina Flow Engine

The main purpose of the Laminar Flow engine is to provide an external combustion heat engine of the upmost simplicity. By using working fluids at high temperature, this engine has a potential to reach very high efficiency and high power for the given weight and volume. The engine can be made simply with one side closed cylinder, a regenerator, and a piston.

This engine has a heated chamber that communicates with the cooled cylinder, and a working fluid in the engine volume undergoing compression and expansion by the movement of the piston in the cylinder. During its engine cycle, the cooled working fluid flows into the heated chamber during compression and subsequently heats within a time interval at the end of the compression. It then become heated and the working fluid flows from the heated chamber back to the cooled cylinder and rejects heat within a time interval at the end of the expansion.

With the working fluid pressure lowered during compression and higher during expansion, net work is produced by the piston. An effective time delay at the ends of the piston stroke is produced due to the sinusoidal motion of the piston.

The engine have no mechanical elements i.e. displacers, or valves, and pistons associated with its heated chamber. Also, as an external combustion engine, it can operate at high temperatures in the heated chamber limited only by available temperature resistant materials. Since the chamber walls do not need to be formed at close tolerances to accommodate pistons or the like this allows an engine of potentially high efficiency to be built to use any fuel or heat source

This engine essentially avoids the complex linkages required by Stirling engines. However, the processes still approximates the highly efficient Stirling Cycle, but with the benefit of eliminating the cranks, sliding seals or excess weight found in Stirling engines.

3.1 Design and Configuration

The design of the model engine is an adaption of the design provided by Robert Sier (2002). Some simple modification were made to include a narrow aluminum passage for the hot heat exchanger and a galvanized iron housing for the cooling fluid (water) in the cold heat exchanger.

Designs of the model were done in Autocad and machined using the equipments available in Multimedia University Melaka Campus's mechanical workshop.

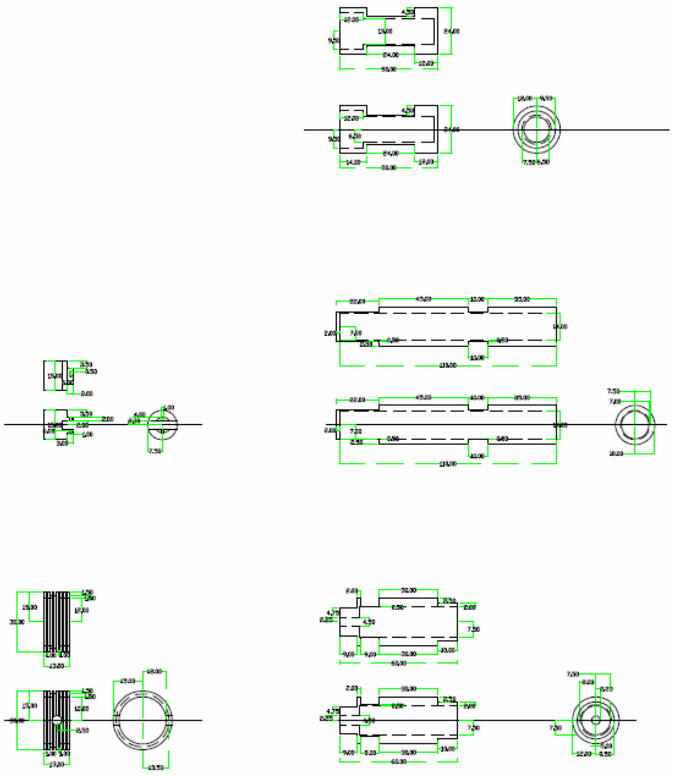

***Figure 1**: Parts of the engine: From top, clockwise (hot heat exchanger, resonant tube, power piston, cold heat exchanger, piston)*

4 Power, Efficiency and Hot Tube Material Test

A simple linear alternator, (taken from a Faraday Flashlight) is attached to the Lamina Flow Engine to quantify its power output. The figure below shows the experimental set-up.

Figure 2 *: Photo of the experimental set-up*

2.1 Results

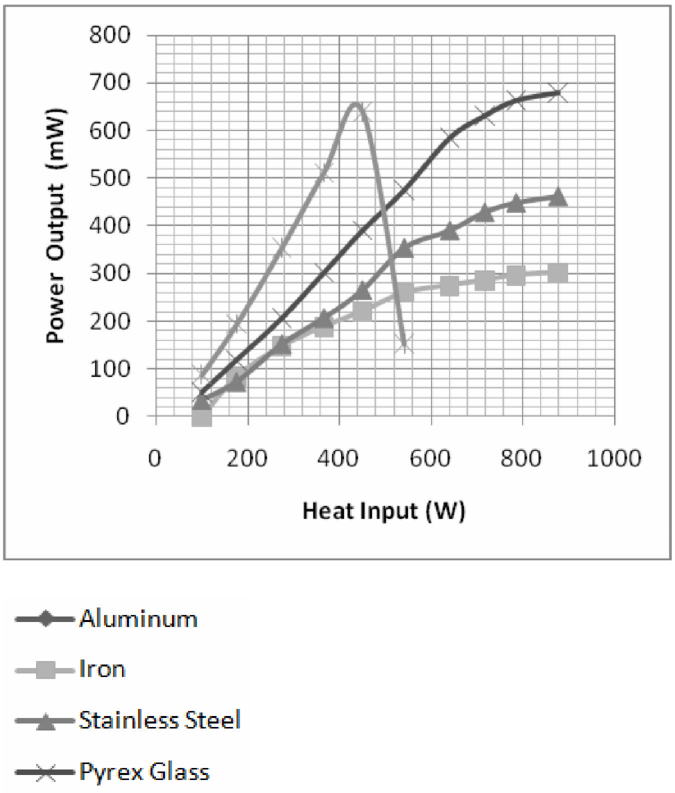

Figure 3 *: Graph of the engine power output of various resonant tube material versus heat input.*

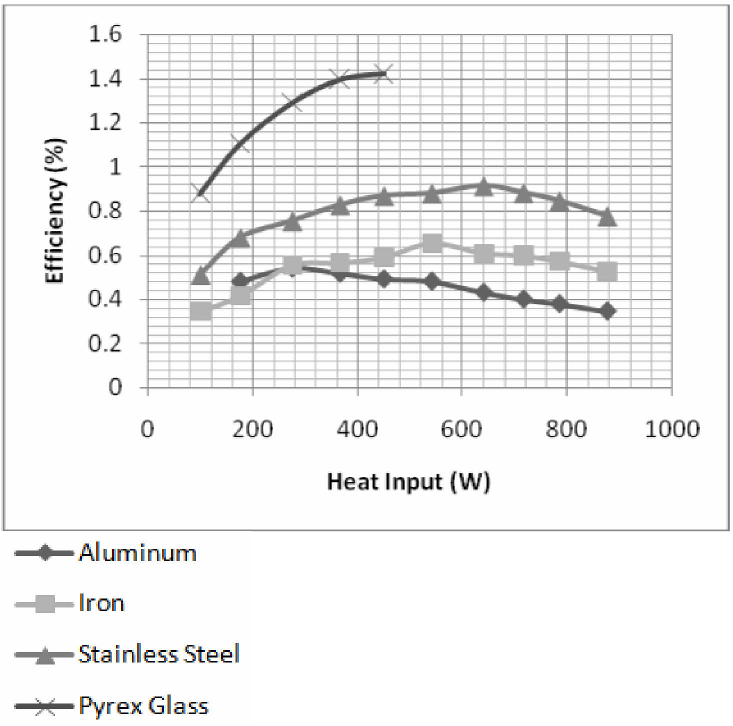

Figure 4 *: Graph of the engine efficiency of various resonant tube material versus heat input.*

From the graph, clearly, the Pyrex Glass Resonant Tube yields the best efficiency. After some researching, it is found that the efficiency of the engine decreases in ascending order of the material's thermal conductivity.

Material	**Thermal Conductivity (W/(mK)**	**Maximum Efficiency**
Aluminum	250	0.49
Iron	80	0.65
Stainless Steel	16	0.91
Pyrex Glass	1.005	1.42

A high thermal conductivity in the resonant tube allows rapid transfer of heat from the hot heat exchange across the tube. This heat is then transferred to the regenerator which is in physical contact with the walls of the tube. This results into a drop of temperature gradient along the length of the stack. With less temperature difference on the both end of the regenerator, the efficiency drops

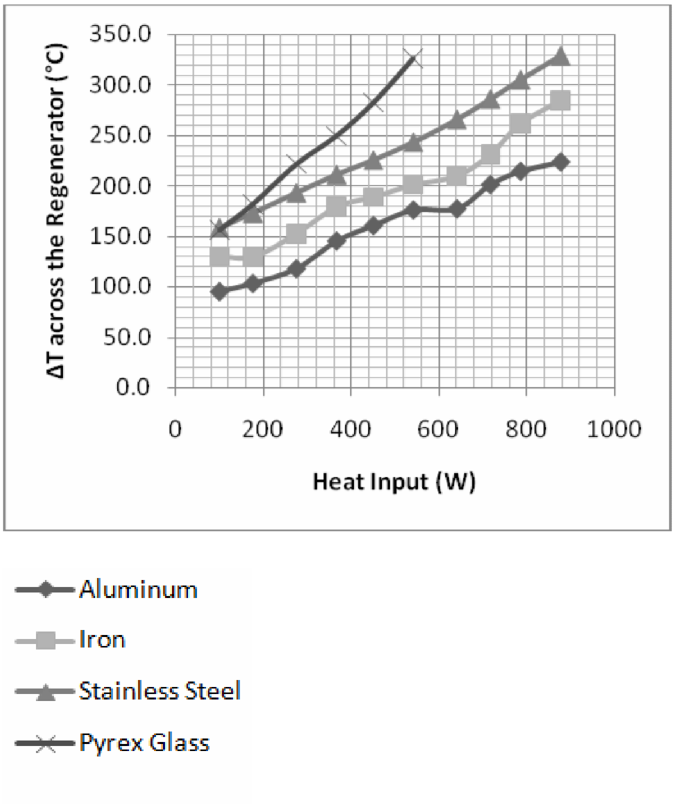

***Figure 5** : Graph of the temperature difference across the regenerator of various resonant tube material versus heat input.*

Though pyrex tube provides the best result, it is has a few drawback that limits its utilization in thermoacoustic engine. The operating temperature is limited to 514°C as it will start to expand out of shape and soften beyond that temperature. In this experiment, the pyrex tube cracked at 60% valve opening, resulting in a sudden drop in the induced current. In less a minute, the engine stop working completely. As the exhaust gas can reach up to 700°C, this material is not suitable for operation at this extreme temperature.

Another drawback lies on its fragile nature, as pyrex glass can shatter with physical shocks and vibration that associated with the typical nature of transportation. Also, sudden cooling and temperature change will cause the tube to crack almost instantaneously, making this material much more susceptible in the harsh operating environment of a vehicle. (unless it is modified or protected by other materials to adapt to such environment)

Among the four material tested, the next best choice is using stainless steel, for it best balanced out durability, cost and efficiency.

5 Target Production Cost

The cost-efficiency relationship is developed based on the public expectation and demand of a automotive waste heat regenerator. From the result of a survey conducted by the author, an overwhelming majority of the participants in this survey wants to reduce their fuel consumption to save cost (85.8%) and to reduce greenhouse gasses to the environment (79.6%). Among the methods suggested to them, adding a device that reduces fuel consumption was preferred (70.4%) over driving slower (52.6%) and using lower engine capacity (CC) cars. (68.4%)

This hints that a device that can recoup some power (in a sense, fuel) from waste heat will enjoy a fair demand from the public. In addition, the public is willing to pay up an average RM 362.90 ringgit to pay for such device with the expectation of RM 33.95 ringgit savings of fuel per month.

Given the following parameter:

Current Petrol Price: RM 1.80/liter,
Average annual distance driven per car : 17862 km,
Average fuel consumption of a car : 12.75 km/ liter
Energy Content per liter of petrol : 32.0 MJ/liter
Average waste heat from car exhaust system :35% of Fuel Consumption

The economic value of the regenerator's efficiency 1.36% per RM saved a month. Factoring this into the public's expectation, a production cost target of **RM 7.85 / percent efficiency** should be achieved before the thermoacoustic heat engine device can penetrate into the commercial market.

Generally, if a successful regenerator is available, consumers will want to see such device implemented as a stock car product (84.8%), ready to be used upon purchased rather than as an additional device purchased later on individually.

With 489,269 vehicles being produced in Malaysia alone in 2009, this opens the possibility of such device to be manufactured in huge numbers; allowing production cost of the engine to be reduced through economics of scale.

6 Conclusion

The model created successfully generated a small amount of electrical energy (less than 1W) and further research can be conducted to increase its power capacity and efficiency. However, even with using the cheapest material and simplest design, the model cost about RM 108, where the bulk of the cost comes from the fabrication process. Coupled with its low efficiency, it fell far short from the target production cost of RM 7.85/ percent efficiency.

Though, with bulk purchases and increase production number, the figure could be reduces as much as 70% due to economics of scale.

Even if the efficiency of the Thermoacoustic Heat Engine improves significantly, there are a number of major obstacles to overcome before it can be implemented successfully on an automobile.

Extracting the waste heat from the exhaust system

Both direct and indirect heat transfer method have drawbacks which prevents a significant heat exchange between the exhaust gas and the working fluid inside the hot tube.

A direct heat transfer method will result in some blocking the flow path of the exhaust stream, causing the car's main engine has to push against a higher back pressure. This subtracts power from the engine cylinder and ultimately reduces the efficiency of the main engine. An indirect heat transfer method requires more contact area to ensure greater rate of heat transfer, with creates a bulkier system. Also as the exhaust stream is unrestricted, huge portion of the gas flows past the heat exchange area without transferring much of its useful heat

Low Power Density

A typical modern internal combustion engine in a car has a power density higher than 75kW/L while a thermoacoustic heat engine that utilize an external heat source, is much lower. With the general expectation of 10%-30% efficiency, the engine would need to have an output capacity of at least 5kW for waste heat regeneration applications in a vehicle.

To date, there are very few efficient thermoacoustic heat engines that reach this capacity efficiently. Furthermore, a typical 30% efficiency, 100W engine already weight more than 13.9kg. Installation of such bulky and heavy equipment will be problematic in terms of space constrain and also increase the fuel consumption of that particular vehicle.

With high public expectation and demand, it will be extremely difficult for the Thermoacoustic heat engine to penetrate the commercial market. As of the present, the application of this technology in automotive waste heat energy regeneration is not feasible given its limited performance capacity and high production cost per efficiency

Nevertheless, its physical simplicity, with relatively few parts should warrant more research to further improve the thermoacoustic heat engine. As more and more research funds and experts pouring into this field, perhaps another feasibility study few years down the road might yield a positive result.

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