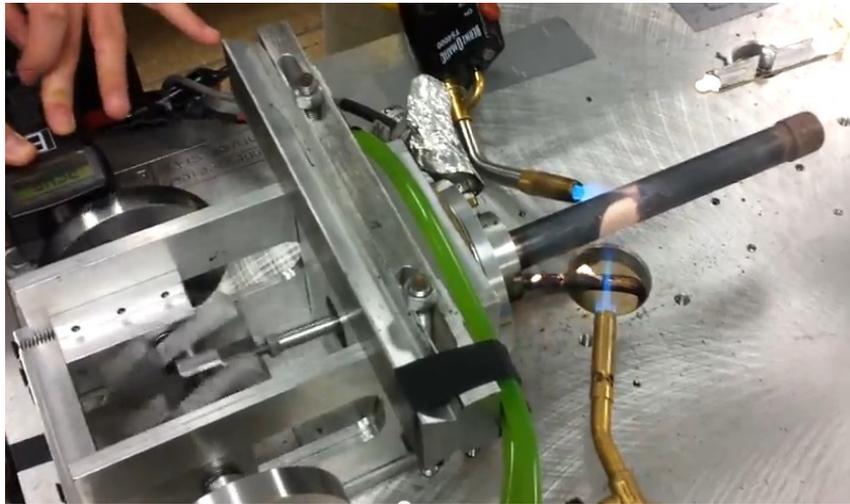


**ME 4444 Senior Design
Final Report
Group I**



Lamina Flow Heat Engine

Bobby Whitaker
Guilherme Araujo
J. Isaac Beasley
Nathan Payne
Vinicius Camara

Executive Summary:

The project scope was to build a cooling system using solar energy converted directly into mechanical energy through a heat engine. The goal of our project was to use a solar dish to heat the engine to run a compressor, which would run a typical compression refrigeration cycle consisting of a working fluid being compressed, cooled to room temperature, and then allowed to expand and cool, absorbing the heat from the air around it and carrying it away. This would eliminate several energy conversions found in typical solar panel to air conditioning systems, thus increasing the overall efficiency of the process.

The heat engine chosen was a thermal lag heat engine due to its simplicity and few moving parts. The design process began with the building of a small prototype called Prototype I. In order to confirm the engine could be replicated, it was then decided to build Prototype II using a modular design where a number of parameters would be variable, giving a better grip on the physics involved and range of data to be obtained via controls and monitoring system. After analyzing all the data, the design and building of the solar powered lamina heat engine would start, but as time grew short, Prototype II became the final design, being powered by torch and not the solar collector.

While being tested, Prototype II was successful, achieving rotations approaching 500 rpm and even generated small amounts of power. The Prototype II could serve as a test platform to research these engines in the future and to obtain a better idea of the physics behind it.

Table of contents

Executive Summary.....	2
Design Problem and Objectives.....	4
Design Documentation.....	8
Laboratory Test Results.....	17
Bill of Materials.....	19
Gantt Chart.....	20
Ethical Consideration.....	21
Safety.....	22
Conclusion.....	23
Acknowledgments.....	24
References.....	25

Design Problem and Objectives:

The project started with an ambitious design of building a Stirling engine, even though several groups before had not succeeded. Therefore, we decided to build a small engine as a test platform from which to design the final engine in case of failure and for better understanding as to why the others had failed. As a team, we never completed our final engine, but we prepared our smaller model so that it might become the final project. Due to time constraints, our Prototype II has become the final project. Prototype II was a successful engine because of its small, modular design. Because there is little published material on heat engines of this type, our mathematical model is limited in being able to assess only the general thermodynamic properties. We developed this second prototype as a bridge to the final project because of the complexity involved with the thermo acoustic, thermodynamic, and nozzle components being unknown to us. A scale model can be used to fine tune the software and model our engine in reality. Incremental changes can be made to understand how discrete changes affect the operation. The prototype was designed with the ability to change the physical parameters. We are able to rapidly change:

- Volume of the hot side collector
- Nozzle size
- Length of piston stroke or displaced volume
- Clearance volume at TDC (cold side volume ratios)
- Length of crank rod

Prototype II was built out of necessity for optimization. In our research, all available literature for large scale thermo acoustic engines was related to driving heat with sound. Using a thermo acoustic engine to drive a mechanical piston is a niche for which we were unable to find academic published research. Due to lack of quality information, Prototype II was built as a research platform to obtain data that we could not find otherwise. We had concluded that the overall geometry of the engine was significant to the operation of a thermo acoustic engine.

In our research, we discovered that there are multiple heat engines that are able to drive a piston, and each of them describe the physics of our heat engine. Depending on the source of publication, our heat engine has been described as a thermal lag engine and a thermo acoustic engine, as well as a lamina flow engine.

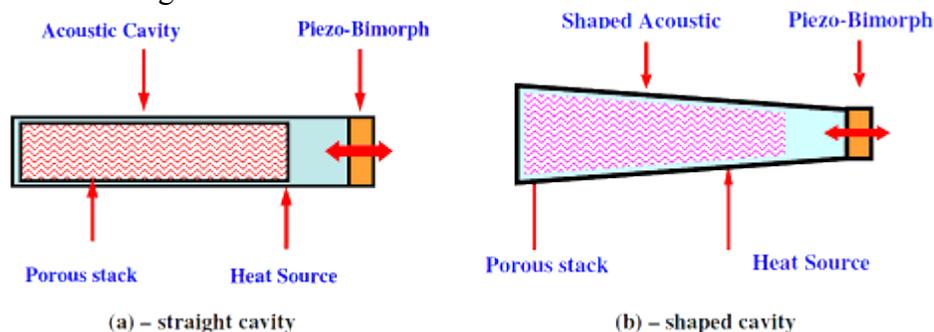


Figure 1

Most sources define a thermo acoustic engine as a variation of a pilot tube, where the temperature discrepancy across the stack (also referred to as a regenerator) causes a pressure wave in the form of a sound wave. A thermo acoustic engine using sound as the primary mover is known as an acoustic refrigerator. Most thermo acoustic engines excite a piezoelectric to generate electricity. In our engine, we are using the sound waves to heat and cool the air, and we are using the overall pressure change due to temperature change to drive the piston. To be precise, the standing wave is a function of both the geometry of the chamber and the temperature and the pressure of the working fluid. As the pressure changes with each stroke, we effect the harmonics of the standing wave. When tuned correctly, the pressure wave of the stack can assist in both cooling and heating the working fluid as the pressure changes due to the volume change due to the position of the piston. In our research, we were unable to find research that addresses how the pressure changes when accounting for both the volume change via the piston and the temperature changes via the thermo acoustic engine.

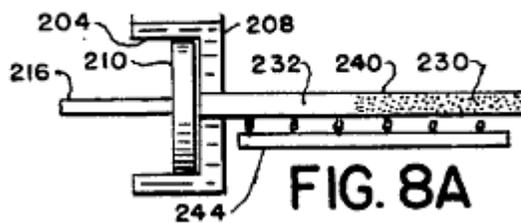


Figure 2

Most sources define a thermo lag engine as a modified Beta-Stirling engine. The engine works with both a compression and power stroke, and it is able to function without a displacer piston by delaying the rate that the working fluid is heated between the compression and power stroke.

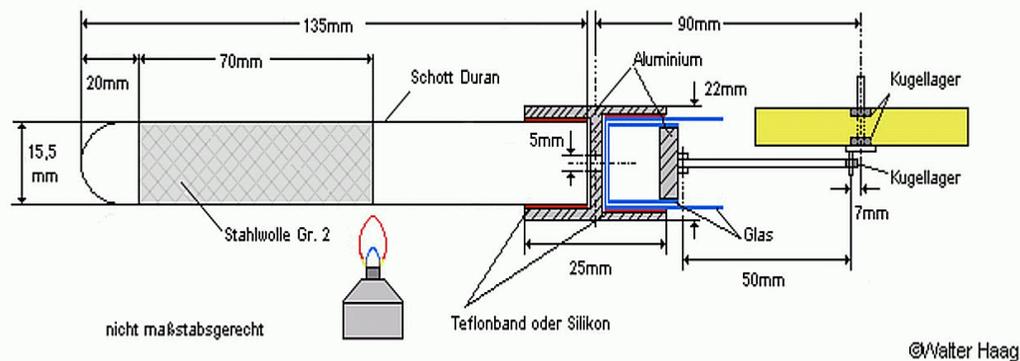


Figure 3 - Lamina flow engine

Most sources define a lamina flow engine as a modified thermo-acoustic engine with a nozzle dividing the two regions. The lamina flow receives its name because air moving through the nozzle does not become turbulent. Air moving through the nozzle into the hot chamber is directed toward the regenerator, while air moving through the nozzle into the cold side is cooled by the increase in velocity at the nozzle boundary. Our heat engine is based primarily on the lamina flow engine.

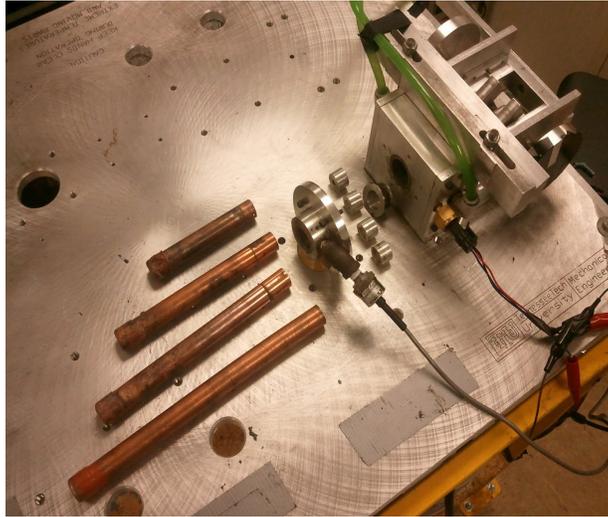


Figure 4 - Prototype II, exploded view with variable hot chambers and nozzles

That being said, our research illustrated that geometry and proportions of the engine is critical to its operation. As a team, we did not want to risk building a full scale model to discover it will not function on the account that geometrical proportions were off because our mathematical optimization faults.

The geometry is important in the hot side of the engine because it defines the frequency that a standing wave operates. Because the standing wave helps pump heat in the hot chamber from the nozzle side to the other, we needed to be able to change the geometry in order to properly tune the hot chamber. Additionally, the diameter defines the ratio of heated surface to working fluid. Therefore, multiple pipes of various lengths and diameters were machined with the ability to easily interchange them.

The geometry is important in the nozzle because it affects the pressure and temperature between the two regions. A properly tuned nozzle can cool air as it enters the cold side and delay the heating since the engine has the ability to change out nozzle profiles quickly. The nozzle significantly affects the system by creating a pressure boundary between the hot and cold region, as well as cooling the air quickly by converting the gases internal energy into kinetic energy. The effectiveness of a nozzle is unique to the geometry of the engine; therefore, different nozzle configurations were tested for their effect.

On the cold side of the motor, the geometry and proportions of the crank mechanism define the compression ratio as well as the working fluid volume and surface area of the cold side. We recognized in our research that the surface area is important because it controls the rate of cooling. It is important to tune the heat transfer coefficients of both the hot and cold side, such that the working fluid expands and contracts such that we generate a net work output. It was decided that the stroke length should be adjustable, to ensure we could easily experiment with different compression ratios. It was also decided that the entire crank mechanism should be on a prismatic slide so we could adjust the volume of the cold side. Therefore, both the crank arm and the crank itself have been built as a prismatic slide such that the geometry could be adjusted quickly. Furthermore, the length of the crank rod between the crank and piston was seen as potentially being a factor, so it was designed to be adjustable.

The group started to build Prototype II shortly after the completion of our design analysis. Almost all of our parts were machined from standard aluminum stock or old parts salvaged from the machine shop in Brown Hall. The group decided our first project should be to fabricate the engine block since all our other parts depended on it. This contained the only cylinder as well as the water jacket for the cold side. Fabrication of the block went smoothly, so the group progressed to the hot side of our engine. Afterward, work progressed to the crank and crankcase. At this stage the flaws of the first design became apparent, which led to one of the first series of revisions. The slots on the sides were expanded to accommodate a larger and more robust sliding mechanism, giving a greater range of adjustability and durability. After building the crank mechanism, it proved to be far too unstable for the engine due to spacing of the mechanisms and the general lack of robustness of the shafts due to their small diameters, which led to a stiffness too low for the engine. This led to a major redesign of the crankshaft and its sliding mechanism. The new design moved supporting bearings further out on the shaft and increased the shaft diameters, increasing stiffness. The resulting design also improved the alignment of the crankshaft components, allowing more force to be transferred to the flywheels and less into vibration, increasing overall efficiency.

During the fabrication process, part of team also began to design and build the controls and monitoring system. A thermal and pressure sensor would be located on both sides of the engine. Then connected to an Arduino microprocessor board. Then would be used as the data acquisition system to output values to a computer, which plotted the values using Matlab. This system would have monitored the pressures and temperatures in the two sides of the engine, as well as the engine speed and power. From this, the computer would have been able to output the engine's pressure vs. volume graphs as well as calculate the theoretical power and overall and Carnot efficiencies. This would have enabled the engine to be analyzed in real time. An interface was programmed to communicate between the Arduino and Matlab. The system was flawed in having a significant latency between reads that only a few points of data could be gathered and plotted per stroke. Programing the sensors directly into the national instruments equipment in the lab solved the latency problem, but this was completed at late date, due to focus on the motor by the group.

The solar dish was also retrieved during this time and brought to the lab for clean up and evaluation. The original fabricators reported that the dish was still coated in a protective film which, upon removal, would reveal the mirror finish of a reflective covering used to coat the dish. This final step would have taken place just before tests commenced to protect the covering as long as possible. With this addressed, work began to design a stand for the dish and mount for the motor on the dish. However, as time grew short, it was decided the engine would be run on propane or butane gas torches instead for its initial tests and all resources should be moved to finishing the engine itself, and work on the dish was temporarily suspended. It was never resumed due to the time constraint.

Detail Design Documentation:

Prototype I was built during the second and third week of the semester. The Prototype consisted of a glass beaker courtesy of Clement's halls chemistry supply closet, a coat hanger, copper coated steel wool, a small bearing, a milled aluminum piston, a tea light candle, and scrap components in the shop. During testing, the best run consisted of the piston oscillating a partial stroke of about 60 degrees of the full crank cycle. Although the run was short, it proved that we successfully built an engine that exhibited the properties of a thermal lag engine. A unique property of a thermal lag engine is that it has two power strokes, unlike most engines which have a power and compression stroke. The fact that the engine was oscillating proved that the engine had two power strokes. Further testing with greater sources of heat shattered our test beaker.



Figure 5 - Prototype I

As a group we concluded that the reason why Prototype I was not successful was due to our dimensions and tuning of the engine. The models on which we based Prototype one exclusively used a graphite piston. Further research showed that the surface friction coefficients between Aluminum and glass are typically between 0.5 and 0.7, friction coefficients between glass and graphite are typically 0.1 or less. The final conclusion is that Prototype I would have been functional with the addition of a graphite piston, better crank mechanism, and better volume ratios.

Prototype II was built during the remaining weeks. It was designed in a way that we could change the engine parameters such as stroke length, cold side volume, hot side volume, regenerator material and nozzle type. After initial tests with the engine, some of the components had to be changed for new versions due to problems, including undesirable dynamics or damages caused by the heat addition.

In the images below we can see some of the interchangeable components used to vary the engine parameters.

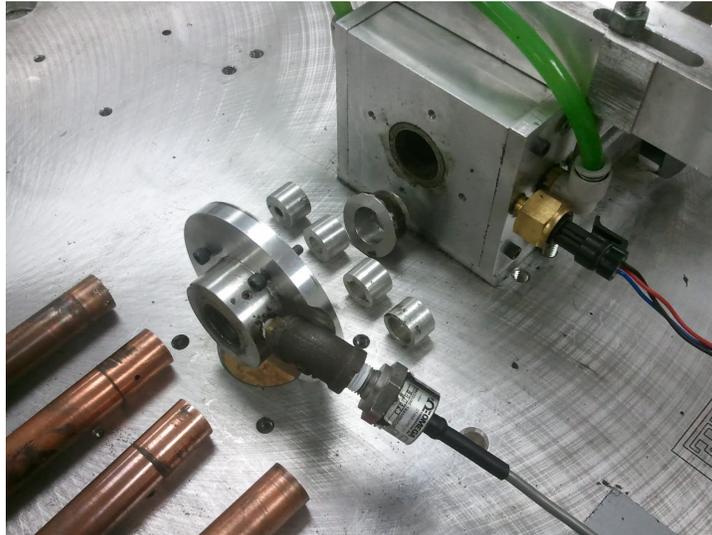


Figure 6 - Exploded assembly showing the various modular components of the engine. In the end, we had 4 nozzles and 4 lengths of copper pipe.



Figure 7 - The 4 nozzles were cut the inner diameters of $\frac{5}{8}$, $\frac{1}{2}$, $\frac{3}{8}$, and $\frac{1}{4}$ inches. Where the outside diameter let us use the nozzle in the hot side and cold side using the adapter seen in figure 9.



Figure 8 - Engine block without nozzle adapter Figure 9 - Engine block with nozzle adapter

The first parameter described here is the interchangeable nozzle. We machined several diameters of nozzles with the objective of varying the velocity of the fluid when moving from one chamber to another, and as well the fluid movement profile in each case.

Additionally, because the nozzle acts as the divider between the hot and cold sides, it was unknown if it would be beneficial to keep the nozzle warm in the hot side, or to keep it cool by placing it within the cold chamber where it would be cooled by the water jacket. Prior to starting the Prototype II fabrication process, the team debated whether the nozzle should be placed in the cold side cylinder or hot side cylinder and how it would affect the engine's performance. A conclusion to this debate was to develop the adapter with a the nozzle in the hot side, and an adapter to place the nozzle inside of the cold side as seen in figures 8 an 9.



Figure 10 - left: capped hot chamber; right: hot chamber with slug (aluminum part)

The Hot side consisted of a copper pipe, originally, the idea was to create a single copper pipe that would have an aluminum slug that would slide into the copper pipe to adjust the length of the hot side chamber. The slug had its diameter dimension changed to better fit the hot side cylinder - PII-EBA-104. The slug had the advantage that we could permanently seal the tube to the adapter, and make incremental changes to the length, but eventually it became too hard to slide it or remove it from the chamber. By this time, having trouble changing the slug position, we had concluded that the ability to adjust the incremental length was not significant, and a series of permanently capped pipes was fabricated.



Figure 11 - Different types and sizes for hot chambers

Additionally, it was unknown if the existing hot side was too small or too large, to prove the hypothesis, a series of smaller diameter tubes were cut. Because the adapter plate had been machined to the specs of the copper pipe, the nozzle was sacrificed and used as an adapter for the pipe. This was a rapid modification because the ID of the nozzles were cut to the OD of the pipe.

Another important interchangeable component was the regenerator. Multiple types of steel wool were used inside of the hot side. A coarse copper coated wool was used in addition to three separate steel wools.



Figure 13 - From left to right: copper wool, then steel wool from coarse to the most fine one

Between the adapter plate and engine block, an insulating gasket was added. The intention of this device was to maximize the temperature difference between the two sides, by preventing heat conducting from the hot side to the cold side of the engine. Originally, a polyurethane gasket was used, which deformed under the heat. A secondary gasket was made out of a fiberglass composite. Those two types of insulating gaskets are shown in figure 12. As a note, two fiberglass gaskets were made to accommodate the cold side nozzle adapter. Pictured above is the cold side nozzle adapter. (figure 9)



Figure 12 - Left: Polyurethane insulation; Right: Fiberglass insulator

During the process of machining the parts for Prototype II, changes were made in the engine block frame's thickness. It was a slight dimension change in order to use sheets of material available in the market as well as in the Brown Hall's machine shop. Also, one of the two design types of engine block frame B - part number PII-EBA-101-2 - was not machined, making the fabrication process easier, faster and more efficient. Instead engine block frame A was machined two times to fulfill the engine block frame B need, also the engine block design was adjusted to fit the new changes. This decision was only possible due to the non-critical need of the engine block frame B part.



Figure 14 - Left: Redesign crankshaft; Right: Old crankshaft

Again, working on the Engine Block Frame A - fabrication. It was decided to change how the crank-slide mechanism would be connected to the engine block frame A. The crank-slide mechanism was considered unstable, having short range, and also it was too short to be reasonable tapped. Now, the crank-slide mechanism position would be defined by sliding it and using set screws, instead of using long bolts and nuts. The Engine Block Frame A design was only changed to fit the new mechanism.



Figure 15 - Left: Old crank-slide; Right: Redesigned crank-slide

The first assembly attempt and friction test showed us a problem in the crank-shaft mechanism and piston rod. The crankshaft was bending mainly because of its play in the bolts and single bearing on each side of the crank. The variable piston rod wasn't fully locked, which means the piston was turning in the cylinder axis and making the whole mechanism stop and stick. A major redesign was needed on the parts crank-slide, crankshaft, piston rod connector, new piston rod design, and new component in the crank-shaft mechanism holding part number PII-EBA-103-3. The solution proposed was increasing the crank-slide length and adding two bearings on each crank-slide instead of one, PII-EBA-103-2 was entirely redesigned now having a counterweight and defining the engine's stroke, and PII-EBA-103-3 assuming the previous PII-EBA-103-2 role as a connector between crankshaft and piston rod. The new piston rod proposed consisted of two components, one male and female threaded solid rods (holding PII-EBA-108-1 and PII-EBA-108-2 part numbers) instead of two males rods and a coupler nut. The new design was still variable and easier to lock.

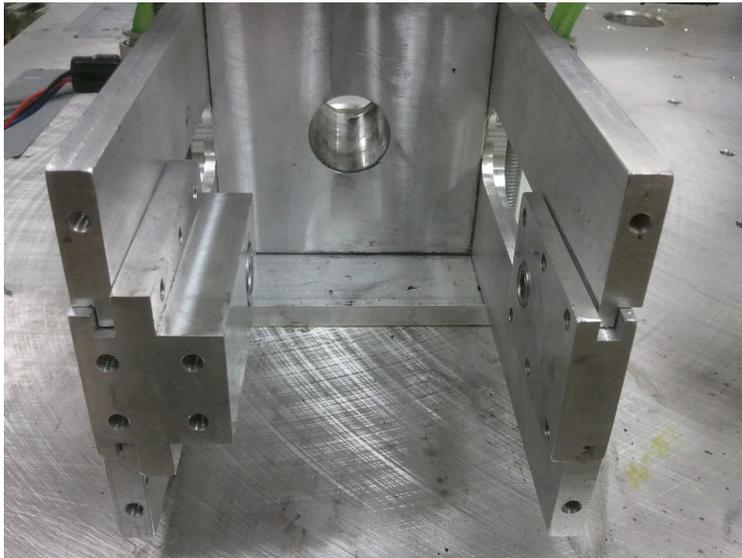


Figure 16 - Engine block assembly, on the left hand new crank-slide compared to the old one on the right

It's important to note that this major design change went smoothly because of the modular design of the engine. The new crank mechanism was designed to work with the existing slotted support sides. Additionally, the new crank mechanism was designed to work with the existing piston rod and flywheels. Although the crank had to be re-machined, no other significant modifications were made.



Figure 17 - Piston rod, on the left old piston rod compared to the new one on the right

It was decided that the piston rod was far too heavy for our engine, the original piston rod consisted of two eye-bolts and a tapered coupler. It was purchased as it was the smallest size available to us on McMaster-Carr. The original crank rod weighed 120.5grams, our slimmer aluminum variant weighed 26.4 grams.



Figure 18 - Aluminum piston and graphite piston (black)

Two identical pistons were machined, one out of aluminum and the other graphite. The aluminum weighed 33.2 grams and the aluminum weighed 21.7 grams. Although the graphite piston is lighter, the primary reason for machining the graphite piston is that graphite to aluminum surface friction that's seven times less than aluminum to aluminum. This is largely due to the fact that as the graphite piston breaks into the wall of the motor, itself lubricates itself with grapheme. Furthermore, we noticed that the graphite was superior in holding compression.

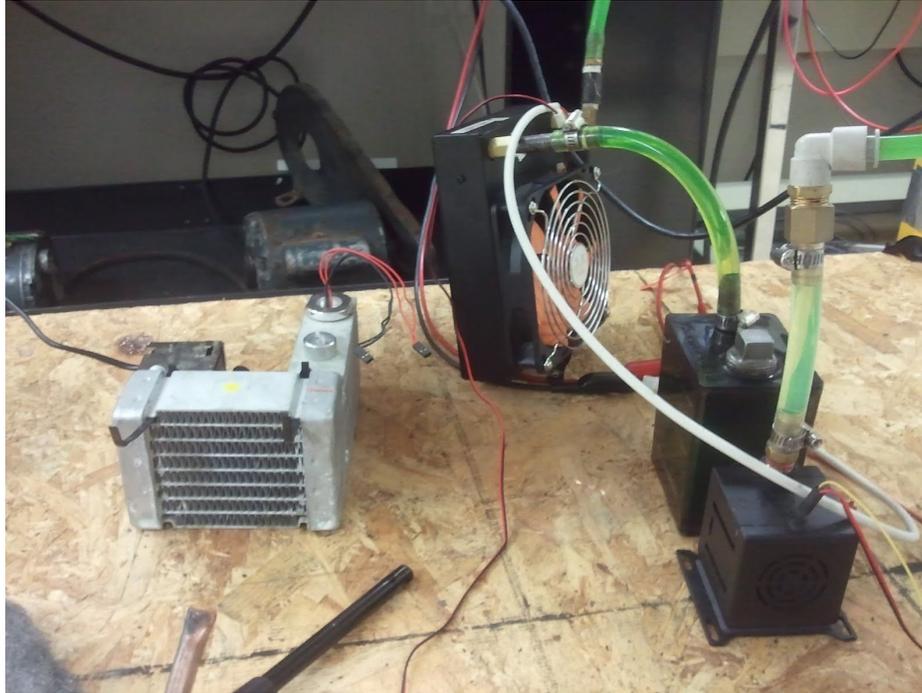


Figure 19 - Both pump and cooling devices used

We were surprised with the amount of heat moving through the water jacket. After a test run, wall temperatures inside the wall of the cold side were typically between 120° F and 130° F. We removed the coolant pump (left) and replaced it with one of larger capacity (right), we noticed temperatures now between 110° F and 125° F. This change resulted in noticeable improvement with the engine.

Laboratory Test Plan and Results:

The first stage of testing involved changing its variable parameters (piston rod length, stroke, hot chamber volume, nozzle profile, crankshaft position and steel wool quantity). That is the main reason why the engine was chosen to be a modular design. During the first stages, the challenge was to find a configuration that would cause the motor to run on its own. As a test method, a pulley was mounted to the test platform behind the flywheel. A controlled weight attached to a string was wound around the crankshaft. As the weight would fall, it would exert a controlled torque until the weight hit the floor. The photo tachometer would measure the RPM, and the experiment was repeated multiple times to calculate the average maximum speed.

Hot Side Parameters	Nozzle Parameters	Cold Side Parameters	Misc	Average Maximum RPM.
Copper tube #2	Hot Side, 3/8"	Short crank, max cold volume	No heat	854.8
Copper tube #2	Hot Side, 3/8"	Short crank, max cold volume	MAPP Gas, Radiator Off	882.05
Copper tube #2	Hot Side, 3/8"	Short crank, max cold volume	MAPP Gas	955.4
Copper tube #2	Hot Side, 3/8"	Short crank, max cold volume	Propane	911.2

Table 1

Table 1 shows a table for a single configuration. The RPM was always measured before heat was added for every configuration as a control for the friction of the crank, as the RPM increased, it was a sign that the heat engine was assisting the motor. As an average with this set up, the control RPM was typically around 880 RPM. For most configurations, the engine would begin running on its own once the Average Maximum RPM began exceeding 1750 RPM.

Lab View setup was configured to read the pressures inside the hot and cold chamber.

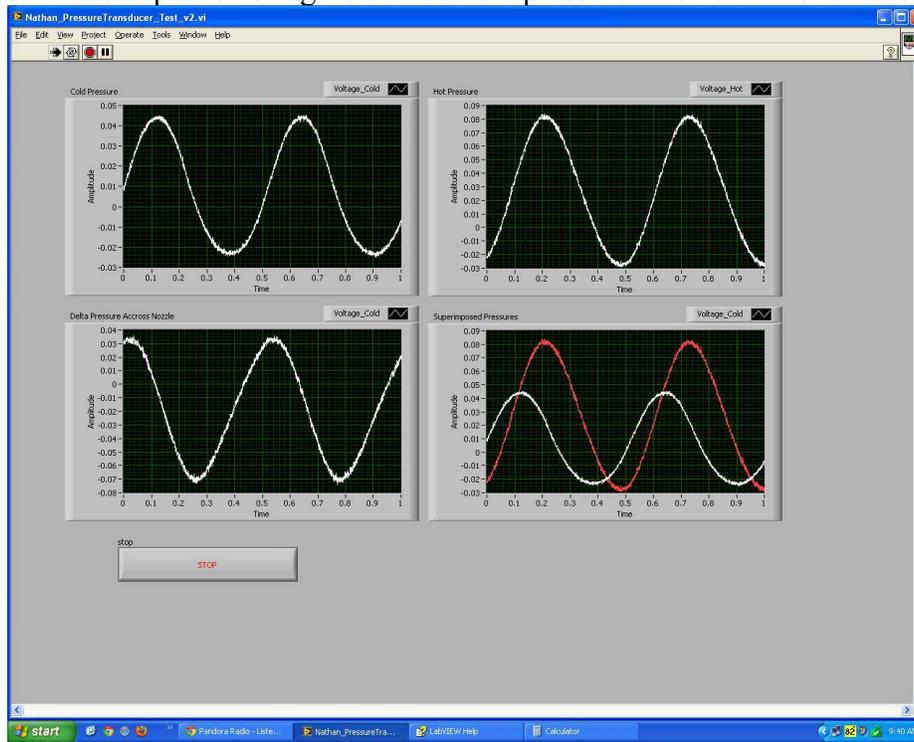


Figure 21 - Pressure sensors output

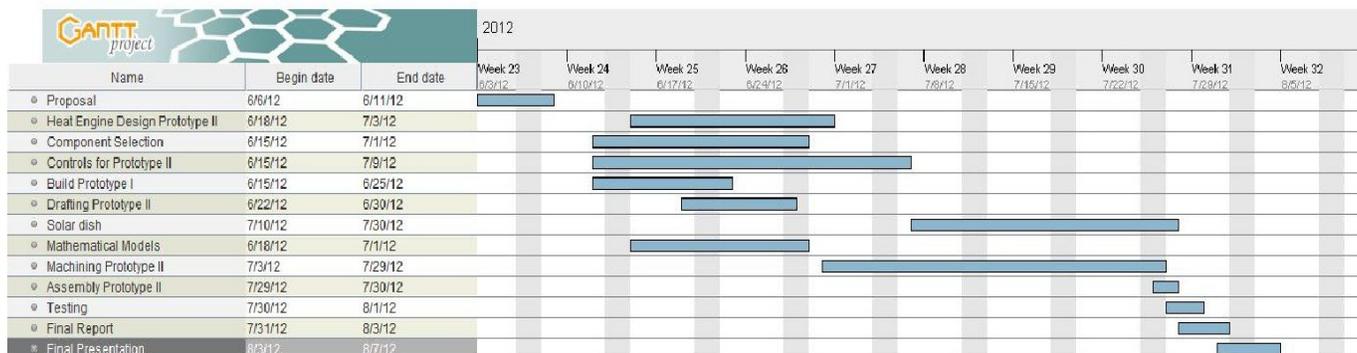
Our highest RPM was obtained with our medium grit, filling half the length of the hot chamber and lightly packed as not to inhibit the movement of air. The second longest hot chamber (9.5 inches long), crankshaft at its lowest BDC position, the widest nozzle (5/8 inch). Also, the engine has worked better using the MAPP torch as heat source, giving higher rpm than when using propane. We were able to obtain a steady 500 rpm. A small DC electric motor working as a generator was connected to Prototype II crankshaft to check how many Voltages the engine could generate.

Our best output was the same setup with the longest hot chamber, Prototype II was able to generate 0.2V, .1A while rotating about 100 rpm.

Bill of Materials

Name	Part Number	Qty	Unit	\$ cost	Details
Allen FH M5x0.8 50mm	92125A228	1	Pkg 25	\$10.92	McMaster-Carr (Needed 2)
Allen FH M5x0.8 35mm	91294A218	1	Pkg 50	\$9.90	McMaster-Carr (Needed 20)
Allen FH M5x0.8 20mm	93395A310	1	Pkg 25	\$6.45	McMaster-Carr (Needed 6)
Allen Setscrew M5x0.8 12mm	91217A175	1	Pkg 100	\$2.96	McMaster-Carr (Needed 6)
Nut for M5 bolts	90695A037	1	Pkg 100	\$2.78	McMaster-Carr (Needed 2)
Bearing OD:12mm ID:6mm W:4	7804K112	2	Each	\$7.67	McMaster-Carr
Sleeve Bearing	6391K403	2	Each	\$0.84	McMaster-Carr
Coupler Nut	90268A032	1	Each	\$6.92	McMaster-Carr
Graphite rod 1.5"	9121575	1	Each	\$75.47	McMaster-Carr
Solid Rod End - Male threaded	3798K48	2	Each	\$6.52	McMaster-Carr
Engine block	PII-EBA-100	1	Each	\$0.00	Make
Engine block frame A	PII-EBA-101-1	1	Each	\$0.00	Make
Engine block frame B	PII-EBA-101-2	1	Each	\$0.00	Make
Crank Slide	PII-EBA-102	2	Each	\$0.00	Make
Crank-Shaft End	PII-EBA-103-1	2	Each	\$0.00	Make
Crank-Shaft Center	PII-EBA-103-2	1	Each	\$0.00	Make
Pin	PII-EBA-104	1	Each	\$0.00	Make
Piston	PII-EBA-105	1	Each	\$0.00	Make
Engine block base	PII-EBA-106	1	Each	\$0.00	Make
Flywheel	PII-EBA-107	2	Each	\$0.00	Make
Male solid rod threaded	PII-EBA-108-1	1	Each	\$0.00	Make
Female solid rod threaded	PII-EBA-108-2	1	Each	\$0.00	Make
Plate - Crankslide connector	PII-EBA-109	1	Each	\$0.00	Make
Generator mount	PII-EBA-110	1	Each	\$0.00	Make
Shaft locker	PII-EBA-111	2	Each	\$0.00	Make
Nozzle holder	PII-EBA-112	1	Each	\$0.00	Make
Polyurethane gasket	PII-EBA-200	1	Each	\$0.00	Make
Nozzle 1	PII-EBA-201-1	1	Each	\$0.00	Make
Nozzle 2	PII-EBA-201-2	1	Each	\$0.00	Make
Nozzle 3	PII-EBA-201-3	1	Each	\$0.00	Make
Hot chamber connector	PII-EBA-202	1	Each	\$0.00	Make
Hot chamber	PII-EBA-203-1	1	Each	\$0.00	3/4 copper pipe (Have)
Hot chamber	PII-EBA-203-2	1	Each	\$0.00	3/4 copper pipe (Have)
Hot chamber	PII-EBA-203-3	1	Each	\$0.00	3/4 copper pipe (Have)
Hot chamber	PII-EBA-203-4	1	Each	\$0.00	3/4 copper pipe (Have)
Hot chamber	PII-EBA-203-5	1	Each	\$0.00	3/4 copper pipe (Have)
Copper Cap	PII-EBA-203-6	5	Each	\$0.52	3/4 copper pipe cap (local hardware store)
Slug	PII-EBA-204	1	Each	\$0.00	Make
Setscrew setting ring	PII-EBA-205	1	Each	\$0.00	Make
Pressure Sensor	PII-PS	2	Each	\$35.00	EBAY
TOTAL COST			52 Pcs	\$218.06	

Gantt Chart



Tasks List

Name	Begin date	End date	Resources
Proposal	6/6/12	6/12/12	
Heat Engine Design Prototype II	6/18/12	7/4/12	
Component Selection	6/15/12	7/2/12	
Controls for Prototype II	6/15/12	7/10/12	
Build Prototype I	6/15/12	6/26/12	
Drafting Prototype II	6/22/12	7/1/12	
Solar dish	7/10/12	7/31/12	
Mathematical Models	6/18/12	7/2/12	
Machining Prototype II	7/3/12	7/30/12	
Assembly Prototype II	7/29/12	7/31/12	
Testing	7/30/12	8/2/12	
Final Report	7/31/12	8/4/12	
Final Presentation	8/3/12	8/8/12	

Ethical Consideration:

One of the principal goals of our project was to compose research data on this type of heat engine. Our reason for building Prototype II was the lack of publication, and we wish to release our information to the public.

Because the project can be considered a success, we are broadcasting videos and reports of our project to sources such as facebook and youtube. We feel that this is the best method of communicating to other individuals seeking information about thermo acoustic engines. Furthermore, We have communicated that all our work is associated with Tennessee Tech, ME4444 program. We feel that we are assisting in building a positive public image of our campus. As a note, none of our videos with personnel have been uploaded without the consent of all individuals in the video.

Safety and Hazards Analysis:

The safety of personnel and property was taken in account while building Prototype I and Prototype II as well as running test in both engines. While in the machine shop machining both engines, the safety equipments and procedures were fully applied to meet the machine shop requirements and the team's perspective.

The possible threats while running tests on Prototype II of moving parts and high temperature parts were overcome. The engine was fixed on a stand with an engraved caution warning sign. As far as a heat source, the MAPP torch and propane torch were in good condition and considered reliable. We had discussed the threats of such devices with Chris and Jeff, who agreed that the hand held torches are already used in the machine shop, and are safe for indoor use given fresh air flow is sufficient. As a precautionary, windows in the senior design labs were left open during operation, and the fire extinguisher was removed from the wall and placed near our testing platform. Furthermore, the test platform was cleared before tests. The exposed crank mechanism did present a hazard, and we chaperoned and instructed guest on how to deal with the engine when it was running.

The major and primary safety issues related to building both prototypes and later testing Prototype II were diminished and overcome.

Conclusions:

Our final conclusions are that the engine worked best with Copper tube #3, the second to the longest of our tubes, the $\frac{5}{8}$ We attached a small DC motor to function as a generator which recorded an output of 0.2V, .1A while rotating at about 100 rpm. This resulted in our engine generating a confirmed impressive 20,000,000 nanoWatts, equivalent to a dwarf winter white Russian hamster running in a wheel at about 125 RPM. Compared to the industrial average of 0.02 Megawatts of heat output of the MAPP gas Torch, we've obtained about a 0.01% total system efficiency. The work output of our Heat engine is equivalent to a Syrian hamster in a wheel. That being said, Dr Hoy was impressed and believes we deserve a C+.

We would like to give a special word of appreciation to:

Mr. Jeff Randolph and Mr. Chris Mills, who proved indispensable in the fabrication, machining, and obtaining resources for our project.

Dr. Meenakshi Sundaram and Dr. Darrell Hoy, our class instructors who helped and encouraged us throughout our project.

Dr. Michael Baswell and Dr. Ahmed Elsayy who graciously donated our solar collector dish.

Dr. Michael Allen and his prior senior design group that let us have the engine test stand and gave us encouragement and insight.

Dr. Corinne Darvennes, Dr. Sastry Munukutla, Dr. Stephen Idem, Dr. Jie Cui and Dr. Robert Craven who offered their knowledge and expertise to help us gain understanding of the project in theoretical sense.

References:

- [1] Fox, Robert W., Introduction to Fluid Mechanics, 6th ed., 2010
- [2] Mechanical Engineering at Virginia Tech, HOT, Release 2.6.1
- [3] Los Alamos National Laboratory Delta-EC Release 6.3b11
- [4] John C. Weatley, The Natural Heat Engine, Los Alamos science Fall 1986
- [5] Peter L Tailer, “Thermal lag machine” Patent 5,414,997. May 16,1995
- [6] Alexander Loh Wenk Keen, Dr. Dirk Rilling “Feasibility Study of Thermo acoustic Lamina Flow Engine for Waste Heat Regeneration in Vehicles” University of Melaka.