# Thermo-acoustic Engine for Electricity Production

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Bachelor´s thesis
May 2014
Mechanical and Production Engineering
Product Development

TAMPEREEN AMMATTIKORKEAKOULU
Tampere University of Applied Sciences

**ABSTRACT**

Tampereen ammattikorkeakoulu
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MÄKINEN, JUUSO & TUOMINEN, MARKO:
Thermo-acoustic Engine for Electricity Production

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This thesis is about a student project part that lasted from September 2013 to April 2014. The subject was to design and build a thermo-acoustic engine. Final goal of the project is to develop a cheap alternative for producing electricity in developing countries. The work was made in collaboration with Hannover University of Applied Sciences and Arts.

Thermodynamics and electromagnetic induction were applied in the project to create thermo-acoustic engines function. The engine was designed in Tampere, Finland and the prototype assembled both in Hannover, Germany and Tampere. The engine was tested during the project and finally heat energy was successfully converted into electricity. Biggest challenges in the project were creating the needed temperature difference between components and deciding the heat transfer method.

Project will be continued. Heat transfer for the engine is planned to be done with renewable resources such as solar power in the future. Development of the product will continue with tasks such as optimizing the engines materials, efficiency and usage of waste heat.

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Key words: thermo-acoustic, engine, design, development

**TIIVISTELMÄ**

Tampereen ammattikorkeakoulu
Kone- ja tuotantotekniikan koulutusohjelma
Tuotekehitys

MÄKINEN, JUUSO & TUOMINEN, MARKO:
Termoakustinen moottori sähkön tuottamiseen

Opinnäytetyö 60 sivua, joista liitteitä 12 sivua
Toukokuu 2014

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Tämän opinnäytetyön aiheena on syyskuusta 2013 huhtikuuhun 2014 kestänyt Tampereen ja Hannoverin ammattikorkeakoulujen yhteistyössä tekemä opiskelijaprojektin osa. Projektissa suunniteltiin ja rakennettiin termoakustinen moottori. Moottorin tarkoituksena on saada lämmöllä luotua aaltoliike, joka pyritään muuttamaan sähköksi. Projektin lopputarkoituksena on kehittää halpa vaihtoehto sähköenergian tuottoon kehitysmaissa.

Projektissa sovellettiin termodynamiikkaa ja sähkömagneettista induktiota termoakustisen moottorin toiminnan aikaansaamiseksi. Moottori suunniteltiin Suomessa, Tampereella ja suunnitelman pohjalta rakennettiin prototyyppi Hannoveriin, Saksaan sekä Tampereelle. Testeissä saatiin moottorin avulla onnistuneesti lämpöenergia muutettua sähköksi ja hohtodiodi välkkymään aaltoliikkeen tahdissa. Haasteita työssä olivat tarvittavan lämpötilaeron aikaansaanti sekä käytettävän lämmönmuodostustavan päättäminen.

Projekti jatkuu korkeakoulujen välillä. Moottorin lämmöntuonti pyritään tulevaisuudessa saavuttamaan uusiutuvilla luonnonvaroilla, kuten auringosta tulevan lämpösäteilyn avulla. Jatkosuunnitelmiin kuuluvat myös erilaisten materiaalin testaaminen, moottorin optimointi parhaan hyötysuhteen saamiseksi sekä erilaisten hukkalämpöjen käyttö moottorissa.

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Asiasanat: termoakustinen, moottori, suunnittelu, kehitys

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**ABBREVIATIONS AND TERMS**

| | |
|---|---|
| UAS | University of Applied Sciences |
| CAD | Computer aided design |
| 3D | Three-dimensional |
| $\Delta u$ | Internal energy |
| Q | Heat energy |
| W | Net work |
| $Q_H$ | Hot heat energy |
| $Q_C$ | Cold heat energy |
| p | Pressure |
| V | Volume |
| n | Amount of substance |
| R | Gas constant |
| T | Temperature |
| $\gamma$ | Heat capacity ratio |
| $C_p$ | Specific heat at constant pressure |
| $C_V$ | Specific heat at constant volume |
| emf | Electromagnetic flux |
| E | Induced voltage |
| N | Number of turns |
| $\phi$ | Magnetic flux |
| t | Time |
| $\varepsilon$ | Thermal efficiency |
| $\eta$ | Stirling process thermal efficiency |
| $T_H$ | Hot heat reservoir temperature |
| $T_C$ | Cold heat reservoir temperature |
| TDC | Top dead center |
| BDC | Bottom dead center |
| PVC | Polyvinyl chloride |
| HHX | Hot heat exchanger |
| CHX | Cold heat exchanger |
| ABS | Acrylonitrile butadiene styrene |

| | |
|---|---|
| DC | Direct current |
| LED | Light emitting diode |

## FOREWORD

Several negotiations were held with our consulting lecturers Prof. Harri Laaksonen and Prof. Matti Peltola from Tampere UAS and with Dr. Ralf Sindelar from Hannover UAS regarding what the thesis should include and how it should be improved. A physics lecturer Reijo Manninen from Tampere UAS was consulted for better knowledge of the thermo-acoustic engines background and he guided the research of the engines theory. Also the Tampere UAS lecturer Juuso Huhtiniemi gave information about rapid prototyping, machining equipment and the usability of the university facilities, laboratories and workshops.

The Process Energy and Environment Technics student Viktor Gyamfi from Hannover UAS was the third main member of this project who had personal interests in using this thermo-acoustic engine as a low-cost power source in developing countries. Jani Katajisto, the laboratory engineer from Tampere UAS, was working in Hannover for the whole time that this project took place and he was the main contact when asking about the engines needs and demands. The Finnish exchange students Janne Lindberg and Anssi Jaakkola helped with the engine electricsin Hannover and our former project manager and student Jani Grönlund gave tips about management and documentation during the project.

We very much appreciate all the help and effort gotten from the people mentioned above.

Juuso Mäkinen

Marko Tuominen

# 1 INTRODUCTION

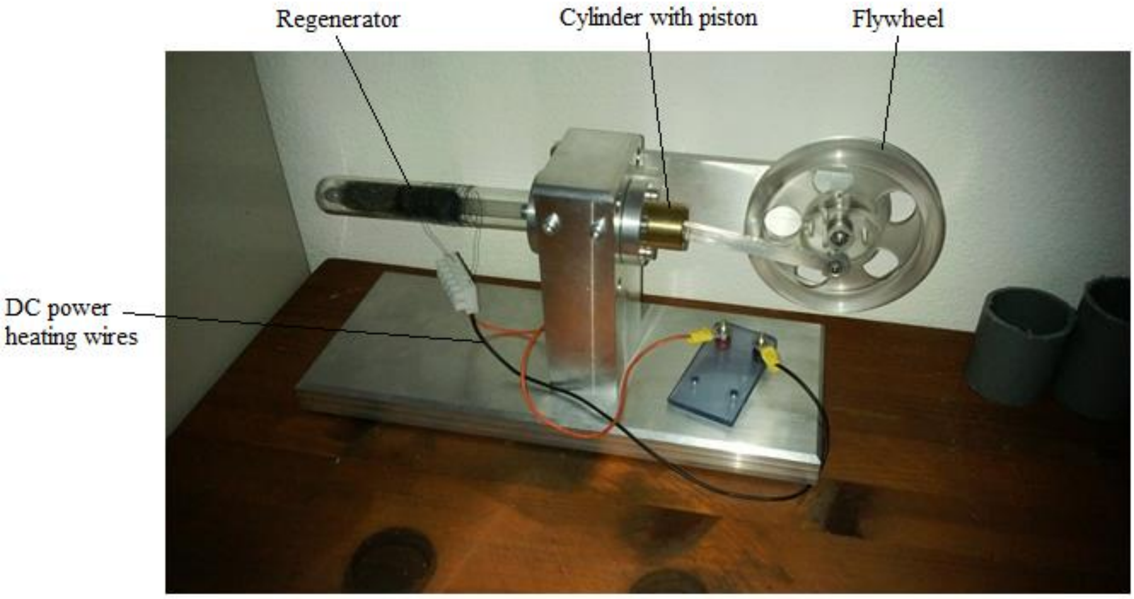
Main purpose of this thesis was to design and manufacture a thermo-acoustic pulse tube engine as an international university project. The project was arranged between two universities, Tampere University of Applied Sciences and Hannover University of Applied Sciences. Hannover UAS was the orderer of the project which was based on a previous year's thermo-acoustic engine project.

The final objective of this project was to manufacture the engine with a minimum budget, using low-cost parts and to be able to use this engine as a power source. Thermo-acoustic means that heat is transformed into sound and the sound wave is converted into mechanical energy. Design and testing took a long time and different heating systems were tried. The main objective during this part of the project was set to get the engine running and prove the working principle. Future plan is to design a heating system that uses possibly solar power. This will be made when the engine runs with any kind of heating device. Similar engines have been made before and some theses about this subject can be found in the literature and those engines were used as guidelines when starting this project.

# 2 BACKGROUND

## 2.1 Starting point

In a previous student project in 2012-2013 a standing wave thermo-acoustic engine was made (Picture 2.1.1). Tampere UAS was in charge of designing the parts and sending the CAD-drawings to Hannover UAS. The German project team then manufactured and assembled the parts and tested the proper usability of the engine. The Finnish project team 3D-printed the prototype, just to see how the parts fit and to learn and see 3D-printing in action. When this project was finished, an idea of a second thermo-acoustic engine project was presented and that it could be a subject for the bachelor's thesis.




PICTURE 2.1.1: A standing wave thermo-acoustic engine machined in Hannover UAS (Mäkinen, Tuominen 2013)

When planning the new project it was discussed to have people working on it, who already had some knowledge about thermo-acoustic engines. After stating this project as a possible subject for a thesis and that long distance working is not an issue, the personnel started to prepare their future tasks.

One primary statement was, that this thermo-acoustic engine should be made using cheap materials and possibly, recycled materials that are easy to find. A manual about the construction and assembly was ordered (Appendix 1.). This project will keep on going after this thesis is ready and the development process continues.

## 2.2 Collaboration

The project was arranged in international co-operation with the two universities. Tampere UAS is located in the city of Tampere. The university offers studies for 10 000 students in six educational fields (Tampere UAS 2014). Hannover UAS is located in Hannover and it has more than 7 000 students (Hannover UAS 2014). Tampere UAS and Hannover UAS do collaboration projects every year. Usually the Tampere UAS project participants study Mechanical and Production Engineering and they are usually responsible for the design, so often some if not all students are oriented in product development.

The German team visited Finland in February 2014 when Tampere UAS had an international week. Finnish team visited Germany in November 2013 and in April 2014. Small presentations about the engine were done in both schools during the visits. While the construction was tested to get running the Hannover UAS staff was briefly introducing the project for guests as a public relations act.

# 3 THEORY AND PHYSICAL BACKGROUND

> "A heat engine is a device that converts heat into mechanical work. Heat engines operate in a repetitive cycle of processes. Such an engine has some "working substance" that is returned to its initial state at the end of each cycle. Steam engines use water, while gasoline and diesel engines use a mixture of fuel and air." (Benson 1991, 411)

The subject of this thesis can be considered as a heat engine which works in a specific process cycle. In this case the working substance is air. Flowing substance transfers heat. Heat transfer on the other hand always involves energy transfer. The energy transfer can be used to induce electricity with mechanical movement produced by a piston or a membrane.

## 3.1 Thermodynamic laws

All the heat engines are based on the first and second law of thermodynamics. The first law of thermodynamics defines: "The internal energy of a system changes when work is done on the system (or by it), and when it exchanges heat with the environment." (Benson 1991, 377) The first law (1) shows that the internal energy $\Delta U$ of the system depends on the remainder of the heat energy $Q$ and the work done to or by the system $W$.

$$\Delta U = Q - W \qquad \text{(1) (Benson 1991)}$$

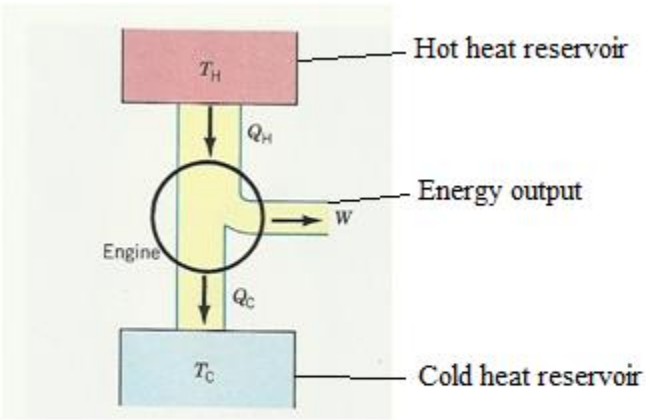
The net work done in the system can be calculated from the difference of the heat energy in the hot $Q_H$ end and the cold end $Q_C$ (2):

$$W = |Q_H| - |Q_C| \qquad \text{(2) (Benson 1991)}$$

The second law is a theory that has been stated in different ways but there is no mathematical form to prove it.

> "Heat flows naturally from a hotter body to a colder body; it does not flow spontaneously from a colder to a hotter body. According to the second law of thermodynamics perfect heat engines or perfect refrigerators are not possible." (Benson 1991, 409-412)

When heat flows from hot reservoir to the cold reservoir the system delivers energy and when flowing from the cold reservoir to the hot reservoir the system consumes energy (Picture 3.1.1).

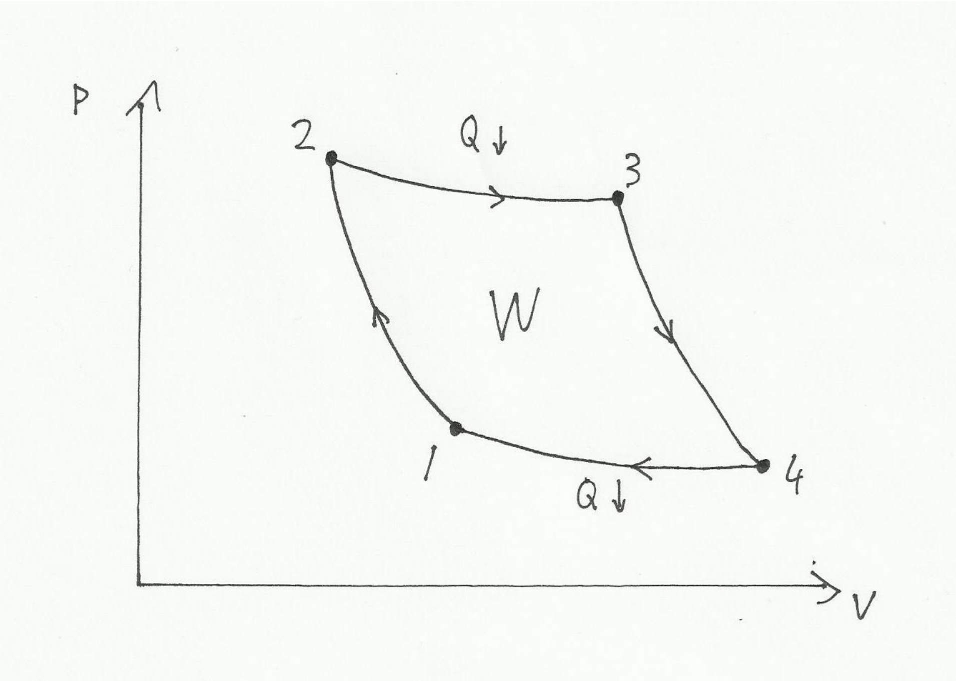



PICTURE 3.1.1: Simple model of a heat engines principle (Benson 1991)

The third law of thermodynamics is a statement that the absolute zero is not achievable and the so called zeroth law of thermodynamics states that if two system have the same temperature with a third system then all the systems are in a thermal equilibrium with each other (Tekniikan kaavasto 2000, 110). This means that they all have the same temperature (Manninen 2014).

### 3.2. Cyclic process

“Engines operate in cycles, in which the system-for example, a gas- periodically returns to its initial state.” (Benson 1991, 379) In a thermo-acoustic engine the heated air moves from the hot reservoir to the cold reservoir and cools down in the loop after which the whole process starts again. This thermo-acoustic pulse tube engine runs in a cycle which follows somewhat the ideal Carnot cycle (Picture 3.2.1).




PICTURE 3.2.1: The ideal Carnot cycle (Mäkinen 2014)

The Carnot process cycle consists of four phases. All the equations representing different phases of the heat engine process cycle are simplifications or modifications of the ideal gas law (3). The equation states that the system pressure $p$ multiplied by the volume $V$ is the same as the product of the amount of substance $n$, the gas constant $R$ and the system temperature $T$.

$$pV = nRT \quad \text{(3) (Tekniikan kaavasto 2000)}$$

First phase 1-2 in the cycle is the isentropic compression (4). In the first phase the pressure and temperature rises while the air volume in the system drops. Because the volume drops the membrane in the engine moves to the bottom dead center. The equation states that the relation of the pressure and volume depend on the heat capacity ratio γ which is constant for ideal gas. The ratio can be calculated from the difference of specific heat capacity at constant pressure $C_p$ and constant volume $C_V$ (5).

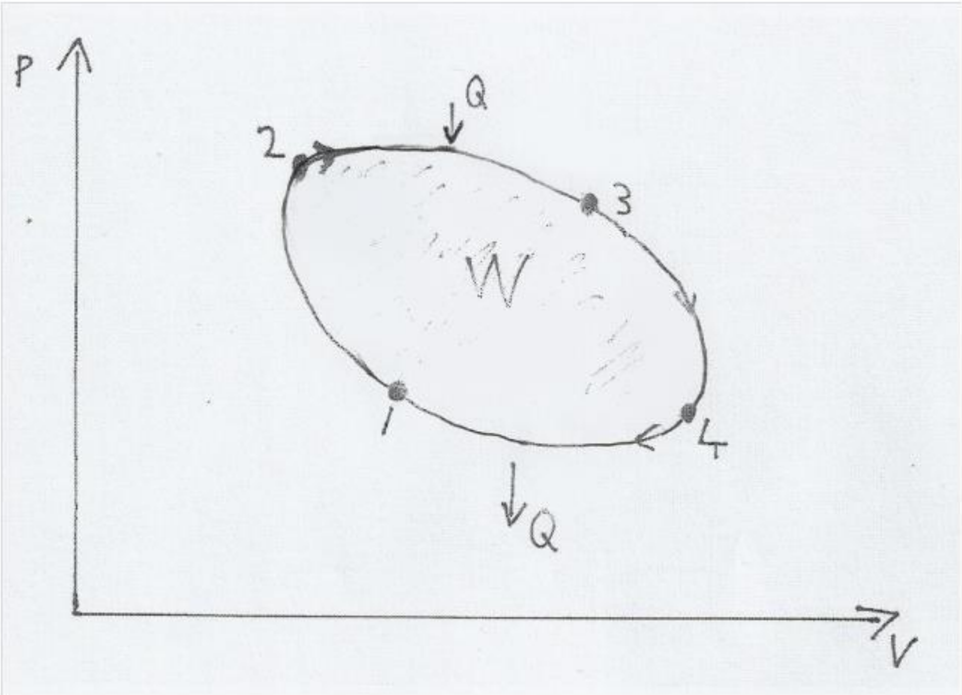
$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} \quad \text{(4) (Tekniikan kaavasto 2000)}$$

$$\gamma = \frac{C_p}{C_V} \quad \text{(5) (Tekniikan kaavasto 2000)}$$

The second phase 2-3 is the isothermal expansion (6). The pressure in the system drops at the same time as the air volume rises which makes the membrane go up. The temperature in the system does not change.

$$p_1V_1 = p_2V_2 \quad (6) \text{ (Tekniikan kaavasto 2000)}$$

During the phase 3-4 the volume rises more and the phase 1-2 is reversed while the pressure decreases and the temperature does not change. This is called the isentropic expansion and the engine membrane rises to the top dead center. The phase 4-1 of the cycle is the isothermal compression. Pressure starts to increase while the volume decreases because the temperature stays the same. The air compression moves the membrane down. This phase completes the cycle and the process starts again. The work $W$ in the system is harnessed into use as it moves the membrane. The net work done during the process can be calculated of the area inside the cycle diagram. In phase 2-3 heat is brought into the system and in the phase 4-1 there is heat transfer out of the system. The real process cycle is never exactly like the ideal cycle as it has more elliptical and less efficient form (Picture 3.2.2). The phases are not so clear because of energy loss during the process.




PICTURE 3.2.2: The realistic Carnot cycle (Mäkinen 2014)

### 3.3. Thermal efficiency

The basic idea of system efficiency $\varepsilon$ is the benefit divided by the price. The thermal efficiency (8) for a heat engine can be calculated as the quotient of the net work $W$ done by the system and the hot reservoir heat energy $Q_H$:

$$\varepsilon = \frac{|W|}{Q_H}$$ (8) (Tekniikan kaavasto 2000)

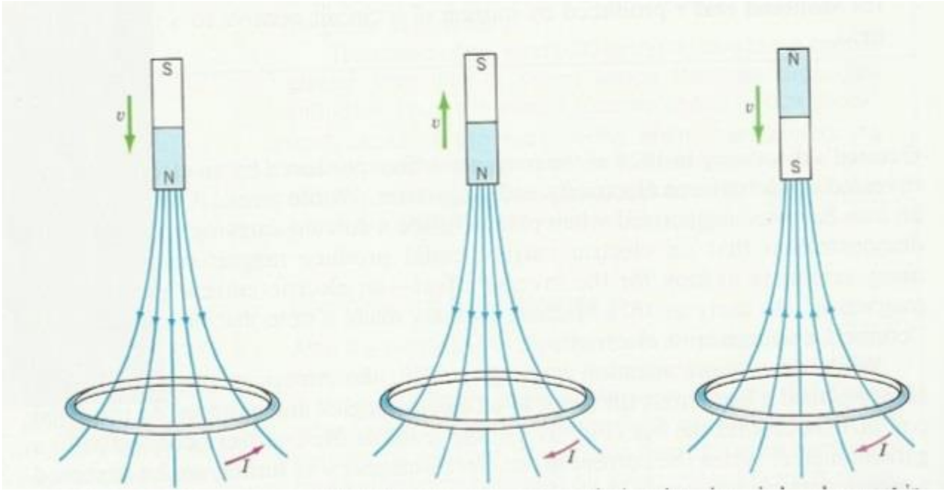
The work and heat given by the system are agreed to be negative. However, efficiency is always positive so that is why absolute values are used. The efficiency is always less than one (Inkinen & Tuohi 1999, 458). In all processes where heat is transferred only in hottest and coldest temperature $T_H$ and $T_C$, the heat energies and temperatures react the same way (Inkinen & Tuohi 1999, 460) (9).

$$\eta = 1 - \frac{T_C}{T_H}$$ (9) (Naddaf 2012)

The engine efficiency equation does not consider heat loss during the process so realistic achieved efficiency is about half of the calculated (Naddaf 2012, 6). For example a car engines running follows an Otto process. Otto cycle’s efficiency can be calculated as any heat engines efficiency and the figure calculated is around 60 percent and the real car engines efficiency is around 30 percent (Manninen 2014).

### 3.4 Electromagnetic induction

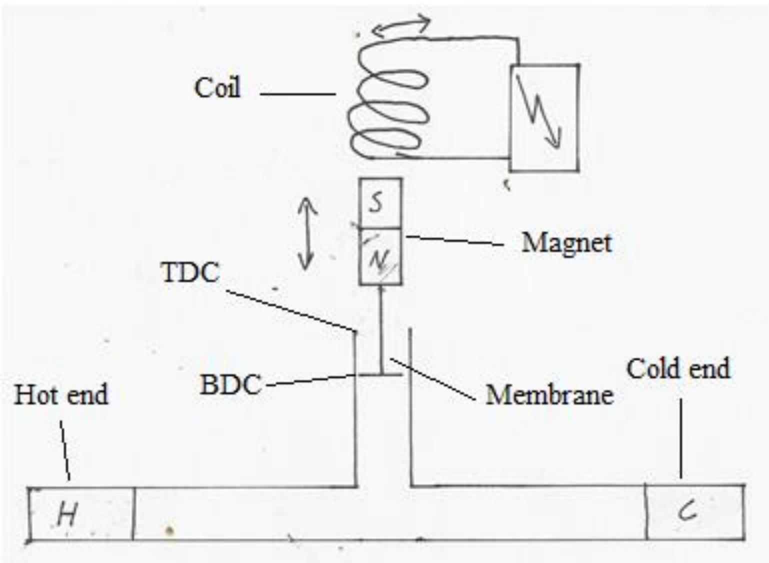
> “A current is induced (generated) in the coil when the magnetic field through it changes. The term electromagnetic induction encompasses two phenomena. The first involves a current that is induced in a conductor moving relative to magnetic field lines. The second involves the generation of an electric field associated with a time-dependent magnetic field.” (Benson 1991, 617) (Picture 3.4.1)




PICTURE 3.4.1: Current induction to a loop by moving magnet (Benson 1991)

The only mechanical movement in the engine is in the membrane which produces the electricity output. The membrane is moved by the energy that comes out of the side branch while the heat moves from the hot end to the cold end. The magnet attached to the membrane produces current by electromagnetic induction when the membrane is moved by the air pressure (Picture 3.4.2).

> "Faraday stated that the induced emf in a circuit is proportional to the rate at which magnetic field lines cross the boundary of the circuit. This Faradays law shows that the induced emf along any closed path is proportional to the rate of change of magnetic flux trough the area bounded by the path". (Benson 1991, 620)




PICTURE 3.4.2: Heat engine converting heat energy to electricity by induction (Mäkinen 2014)

The direction of the induced current depends on the position of the magnet and which way it moves compared to the inductor coil. When the north pole of the magnet moves ahead toward the coil the induced current moves counterclockwise from the magnet point of view. Correspondingly when the magnet moves away from the coil the current flows clockwise. Same thing is generalized as Lenz's law (7): "The effect of the electromagnetic flux is such as to oppose the change in flux that produces it." (Benson 1991, 621) The induced voltage $E$ depends of the number of turns $N$ multiplied by the change of the magnetic flux $d\phi$ during the change of time $dt$:

$$E = -\frac{Nd\phi}{dt} \qquad \text{(7) (Benson 1991)}$$

## 3.5. Solar power

More than two billion people around the world who live in the remote and rural areas of developing countries have no access to electricity. (Score project UK) Within an hour the sun radiates more energy to the Earth than the whole mankind consumes in a year. (Inkinen & Tuohi, 1999, 424) Solar power is a possibility to make the pulse tube engine running with renewable resources. The sun provides enormous amounts of heat that could be converted into electricity. After the engine is working properly, next step is to discover the best way to harness the heat coming from the sun and provide the temperature difference for the engine.

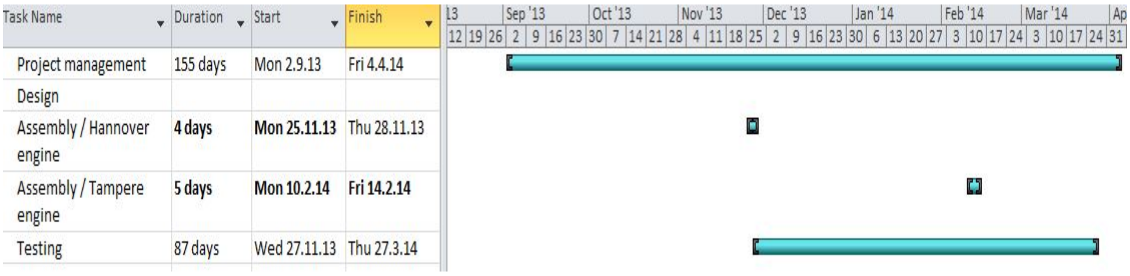
A cheap replacement for a solar panel might be a concave base wrapped in aluminum foil or painted to reflect sunlight for the hot heat exchanger to create useful hot reservoir. Solar power input with components made from scrap yard findings would able the engine be built everywhere in the world with low costs.

## 3.6 Thermo-acoustic engines component solutions

The thermo-acoustic engine designed and assembled in this project works with the heated steel pipe as a hot reservoir and in some cases the copper pipe and coil as the cold reservoir and the air flow phenomenon creates a continuous sound wave pulse inside the loop made from the PVC-pipe. The heat reservoirs form the engine component called the regenerator. The possibility of electromagnetic induction is used to convert the pulse into voltage. In this project a loudspeaker was used for the output source. The loudspeaker with the magnet and coil inside was mounted to the engines output side branch. When the sound wave pulse hits the loudspeaker membrane the magnet and the coil together induce electricity. The benefits of this engine are the possibility to produce electricity with renewable resources and the loudspeaker membrane being the only mechanically wearing part in the structure.

# 4 TASKS

There were four separate tasks in the project which consisted of the phases that the engine was built in (Picture 4.1). The project management was handled to make everybody work efficiently for the same goal and all the practical things to go smoothly. Tasks changed while the project went forward. Secondt task was to design a vision for the engine structure. The design was updated several times to consider different component options. The third task of the project was to assemble the construction of the engine based on the design and when the engine was assembled the testing was started to make the engine run like planned. Since this was a prototype, a lot of product development was done to get the best configurations together.



| Task Name | Duration | Start | Finish |
| --- | --- | --- | --- |
| Project management | 155 days | Mon 2.9.13 | Fri 4.4.14 |
| Design | | | |
| Assembly / Hannover engine | 4 days | Mon 25.11.13 | Thu 28.11.13 |
| Assembly / Tampere engine | 5 days | Mon 10.2.14 | Fri 14.2.14 |
| Testing | 87 days | Wed 27.11.13 | Thu 27.3.14 |

PICTURE 4.1: The four main tasks of the design team

## 4.1 Project Management

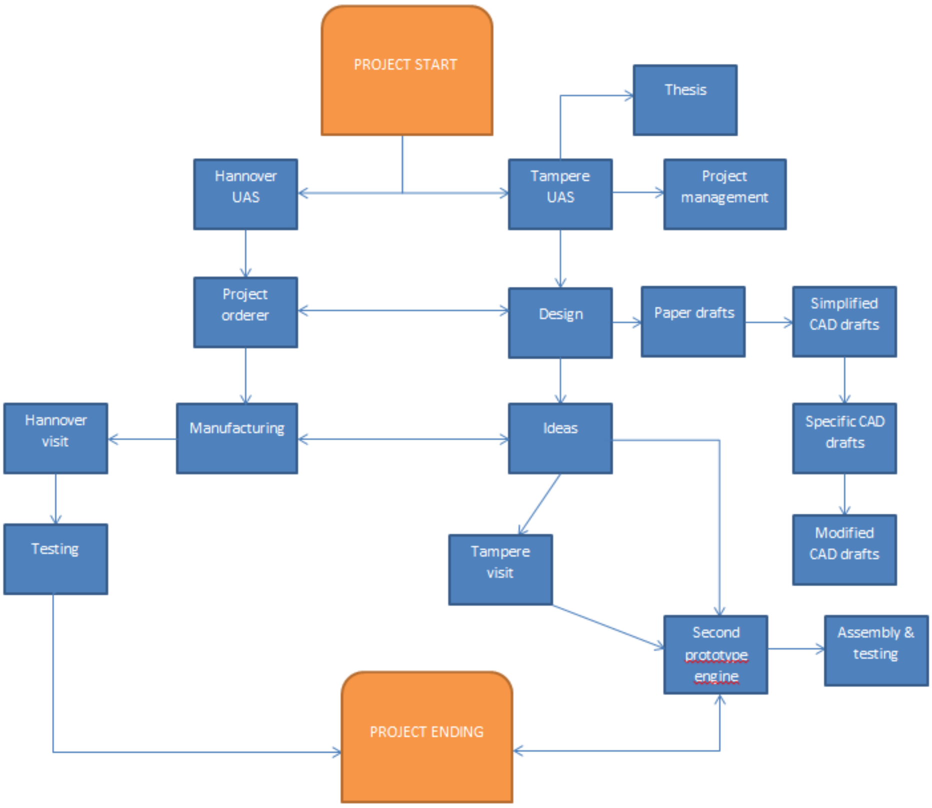
Project management through the autumn 2013 and spring 2014 included mostly sharing tasks and information (Picture 4.1.1). The design, construction and electrical duties together with orders, purchases and funding were organized to support each other and fit the schedules. When the personal tasks were finished all the personnel were guided to co-operative tasks. Meetings needed to be arranged as well as the team visits. The databases were Tampere UAS network and personnel’s own computers and memory devices. Memos of the conferences were sent all personnel during the project.

Project management was started in the summer 2013 by making the first schedule for the project. The schedule was completed during the project. The first conferences were about sharing the information and duties of the project. The project deadline was decided to be until the end of March (Table 4.1.1). It was stated that the ideal goal was to get the basic structure of the engine working by any heating method necessary until the deadline.

TABLE 4.1.1: Preliminary project schedule (Mäkinen, Tuominen 2014)

**TIMETABLE**

| Week | Phase |
|---|---|
| 43 | Skype-meeting: Information, ideas, our dutys in the project |
| 44 | Project planning, SKM, materials, construction ideas, schedule update |
| 44-47 | Project planning (Transferring new thoughts to drawings, construction etc.) |
| 46 | Dr. Sindelar in Finland |
| 47 | First version possibly ready |
| 48 | Mäkinen and Tuominen in Hannover |
| 49-51 | Changes and updates if needed |
| 52-1 | Christmas holiday |
| 2- | Project finishing and thesis writing |
| 7 | Katajisto and Gyamfi in Tampere |
| End of March | Last visit in Hannover (Mäkinen & Tuominen) and project closing |

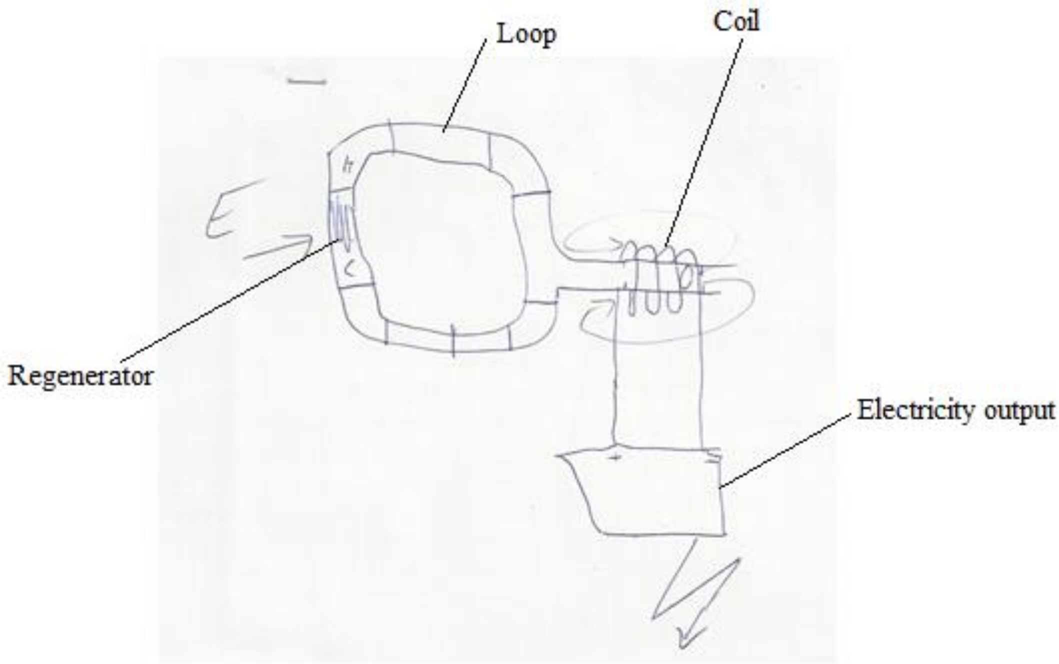



PICTURE 4.1.1: Flowchart of the whole project (Tuominen 2014)

The time from September until December 2013 was agreed to be used for updating the ideas for the engines materials and improving the design in order to develop the product. In week 7 2014 a new engine was built in Tampere for testing. Presentations for interested people and groups were arranged and when the parts were preordered the most important thing about managing was to focus the resources efficiently.

### 4.2 Design

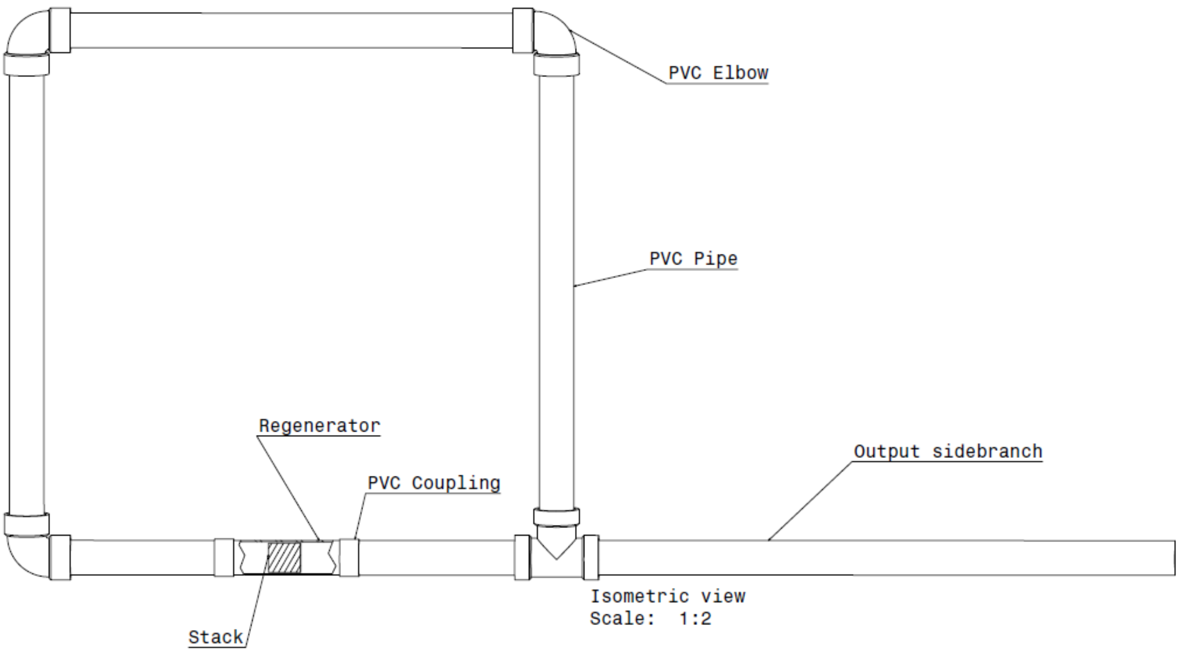
Design work started by defining the possible materials and construction ideas simply drafted on paper (Picture 4.2.1). The draft included the pulse tube engines loop in which the sound wave was planned to move. A hot heat reservoir and a cold heat reservoir were drafted to the input and an induction coil to the engines output side branch.




PICTURE 4.2.1: Draft of the pulse tube engines basic structure (Mäkinen 2014)

First CAD-design for the engine (Picture 4.2.2) was a simple draft just depicting the basic construction of the loop. There was one side branch for the electrical output. Regenerator was a simple glass tube with a stack of steel wool inside and it needed more design. The whole construction was coupled with PVC-fittings. The project group was discussing whether the engine was going to use standing or travelling wave. The travelling wave was stated more efficient and that is why it was pursued. Travelling wave system brought the need of a side branch with which to optimize the frequency of the engine air flow. The first prototype was decided to have only one regenerator and when the construction starts to work it is possible to add more regenerators.

The engine was built using PVC-pipes and -fittings. When the design was being made, it was necessary to use real looking parts. Dassault Systémes 3D Content Central had a wide range of different products from different companies. The parts listed in 3D Content Central were compatible with CATIA so the parts were taken from there. Using ready parts gave the advantage to see exactly how the engine would look like and it was very helpful when listing the parts in the bill of material (Table 4.2.1).



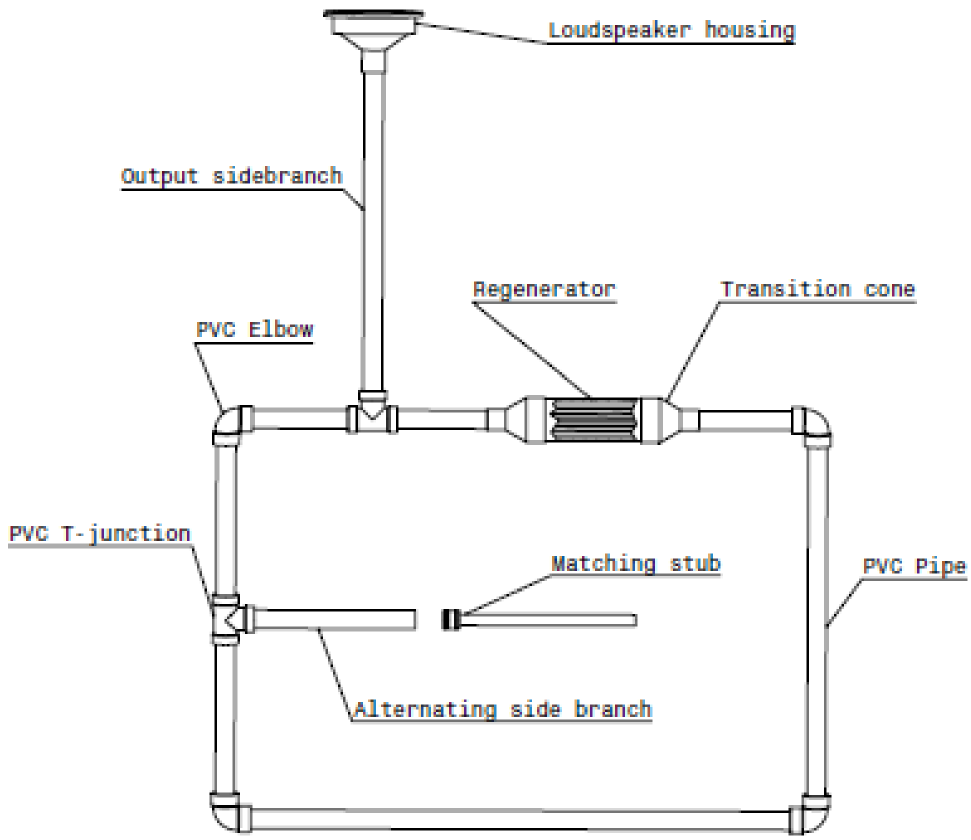

PICTURE 4.2.2: First CAD-model of the PVC-loop structure, the regenerator and the output side branch (Tuominen, Mäkinen 2014)

TABLE 4.2.1: First bill of material (Tuominen, Mäkinen 2014)

| | | |
|---|---|---|
| **Bill of Material, Thermoacoustic engine/Piping** | **6.11.2013** | |
| **First prototype** | | |
| | | amount |
| 1 | 2 inch 90-degree elbow | 4 |
| 2 | 2 inch PVC Tee | 1 |
| 3 | Self designed PVC-pipes (OD=50mm, ID=46mm, L=750mm) | 3 |
| 4 | Self designed PVC-pipes (OD=50mm, ID=46mm, L= about 275mm) | 2 |
| 5 | Self designed glass tube regenerator | 1 |
| 6 | Piece of steel wool as a stack | 1 |
| 7 | 2 inch coupling socket | 2 |
| 8 | Adhesive tape/glue for the fittings | |

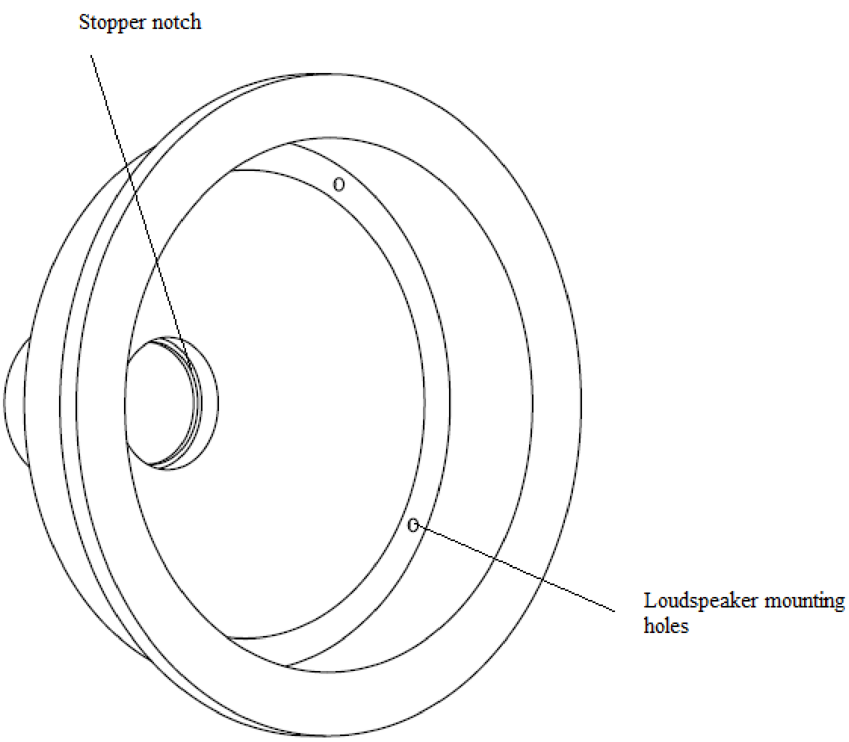
A wider regenerator with small steel pipes inside it was originally designed for the CAD-draft (Picture 4.2.3) but while testing the conclusion was that any wider regenerator was not needed. All testing was done with a single steel pipe HHX and copper pipe

CHX. The PVC-pipes ordered had inner diameter of 46 millimeters and outer diameter of 50 millimeters. The engine loop has two side branches and the first side branch is the alternating side branch. It has a sealing piston inside and by moving the piston there is a possibility to try different frequencies of the vibration caused by the pulse inside the loop. The other side branch is the more important one because it has the electricity output loudspeaker in the end of it.




PICTURE 4.2.3: First final CAD-construction with the loop, loudspeaker housing, regenerator and the side branches (Tuominen, Mäkinen 2014)

A thermo-acoustic engine has a piston-like mechanism that transforms the pressure difference into electricity. When planning this projects energy conversion the piston was replaced with a loudspeaker. The loudspeaker needed to be mounted onto the system and it needs to have a tight fit so that the air cannot escape. A housing for the 8-inch loudspeaker was designed for the Hannover engine (Pictures 4.2.4). Another housing was designed and rapid prototyped for later use in Tampere UAS (Appendix 1.) The housing has a tube with a small notch inside so that the PVC-pipe can be pushed inside the tube all the way up to the notch. The notch acts as a stopper so that the PVC-pipe is pushed in the right place. The housing has a cone shaped design because not only does it hold the loudspeaker in place but it also acts as an adapter. The purpose of this cone is to change the diameter of the output so that the air inside is hitting the whole surface area of the membrane. The loudspeaker has a collar with four holes in it that is being used to attach the loudspeaker into the speaker box. This same collar was used to attach the loudspeaker into its housing.




PICTURE 4.2.4: CAD-model of the loudspeaker housing (Tuominen, Mäkinen 2014)

About five meter loop length and around 46-50 millimeter pipe diameter were agreed for the experimental setup. Next important part was the regenerator which was intended to be built with as low costs as possible. The stack inside the regenerator was agreed to be steel wool in the first prototype.

> “The stack serves two purposes. It’s an accelerator, causing air molecules to speed up as they move through the small openings. It also serves as insulator, to keep the hot side hot and the cool side cool (Ferris 2009).”

Length of the side branch for the loudspeaker was set to 960 millimeters and for the fine tuning alternator to 450 millimeters. The bill of material was updated in order to get the needed parts ordered in Hannover (Table 4.2.2). The power supply was decided to be electric in the first prototype. Also the alternating side branch with the piston was designed.

TABLE 4.2.2: First complete constructions bill of material (Tuominen, Mäkinen 2014)

| | | |
|---|---|---|
| **Bill of Material, Thermoacoustic engine/Piping** | **13.11.2013** | |
| **First prototype** | | |
| | | amount |
| 1 | 2 inch 90-degree elbow | 4 |
| 2 | 2 inch PVC Tee | 2 |
| 3 | 2 inch PVC Pipe | 7 meters |
| 4 | Self designed glass tube regenerator 110mm Diameter | 1 |
| 5 | Transition cones Stainless steel | 2 |
| 6 | Adhesive tape/glue for the fittings | |
| 7 | Thermal buffer tube Stainless steel L=178mm Diameter=110mm | 1 |

## 4.3 Construction and assembly

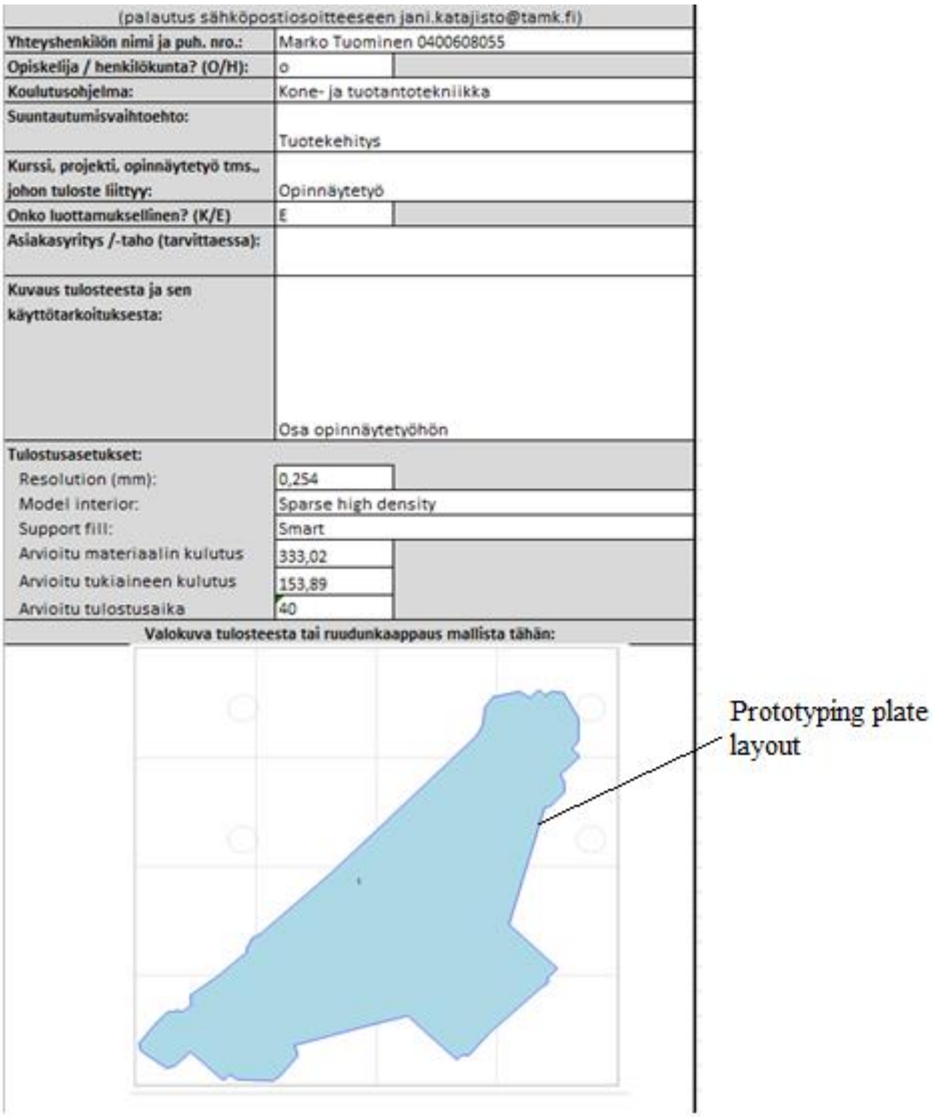
While assembling the first prototype the cooling was going to be made with copper pipe and coil (Appendix 1.). An alternating side branch piston was designed for either machining or rapid prototyping. The piston had two grooves with o-rings on them to keep the piston still with friction. There was an option to machine the whole piston or only the end with separately assembled rod on it (Picture 4.3.1).

PICTURE 4.3.1: Alternating side branch piston machined from plastic with a separate metal rod (Gyamfi, Katajisto 2014)

The loudspeaker housing was produced by rapid prototyping in Tampere with Stratasys Dimension Elite -machinery. Rapid prototyping is widely used in product development, because it is easy to create small scale prototypes from which the designers can see if the design is going to work or not (Table 4.3.1). In this project product development played a large role. First the design of the housing was converted as a Standard Tessellation Language-format (STL) with CAD-program to get the 3D-model in a form that the rapid prototyping machinery could work with. The converted data was given to the printer program and the program calculated the need of material and fitting the part to the printing plate (Picture 4.3.2). When the material was checked, plate assembled and the printer started the machine would calculate the estimated prototyping time. Printing material was ABS plastic and the printing process took about forty hours to complete. (Picture 4.3.3) After the cover part was finished the component was separated from the plate, the support material was removed and the component was cleaned and ready to be picked up for the assembly (Picture 4.3.4).

TABLE 4.3.1: SWOT-chart of rapid prototyping (Mäkinen 2014)

| Strengths | Weaknesses |
|---|---|
| -Speed<br>-Precision<br>-Easiness | -Expensive<br>- Products somewhat fragile (available also metal RP)<br>- Big machinery but only small products |
| **Opportunities** | **Threats** |
| - Straight from CAD to STL and ready part<br>- Prosthetic applications | - Small chance of printing errors |



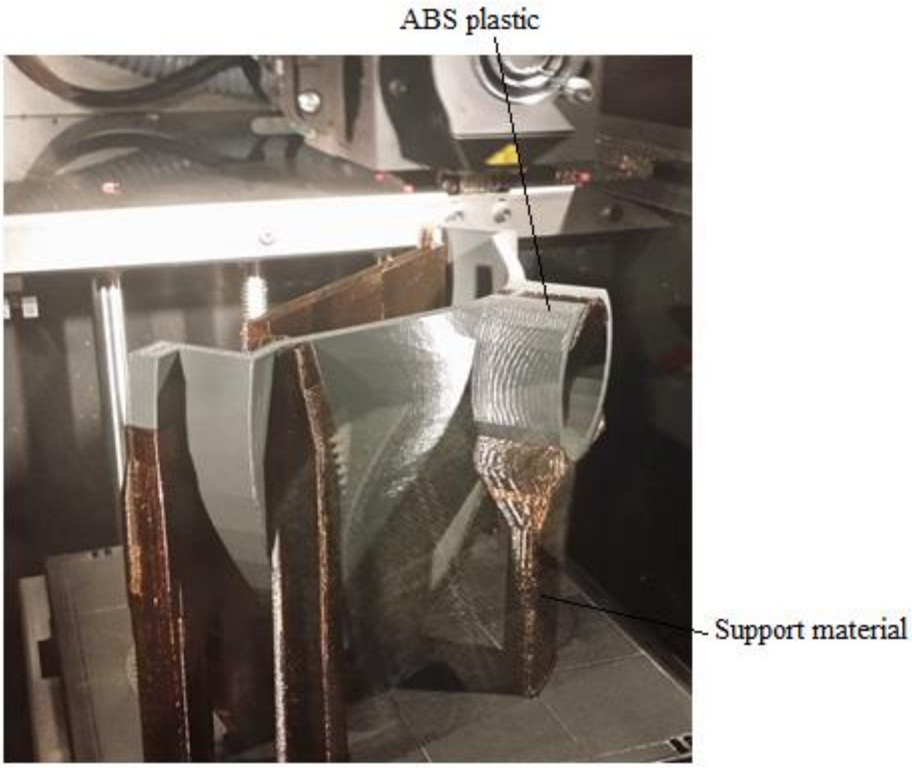
(palautus sähköpostiosoitteeseen jani.katajisto@tamk.fi)

| | |
|---|---|
| Yhteyshenkilön nimi ja puh. nro.: | Marko Tuominen 0400608055 |
| Opiskelija / henkilökunta? (O/H): | o |
| Koulutusohjelma: | Kone- ja tuotantotekniikka |
| Suuntautumisvaihtoehto: | Tuotekehitys |
| Kurssi, projekti, opinnäytetyö tms., johon tuloste liittyy: | Opinnäytetyö |
| Onko luottamuksellinen? (K/E) | E |
| Asiakasyritys /-taho (tarvittaessa): | |
| Kuvaus tulosteesta ja sen käyttötarkoituksesta: | Osa opinnäytetyöhön |
| Tulostusasetukset: | |
| Resolution (mm): | 0,254 |
| Model interior: | Sparse high density |
| Support fill: | Smart |
| Arvioitu materiaalin kulutus | 333,02 |
| Arvioitu tukiaineen kulutus | 153,89 |
| Arvioitu tulostusaika | 40 |

Valokuva tulosteesta tai ruudunkaappaus mallista tähän:



PICTURE 4.3.2: Loudspeaker housing STL-file transferred into rapid prototyping program (Tuominen, Mäkinen 2014)

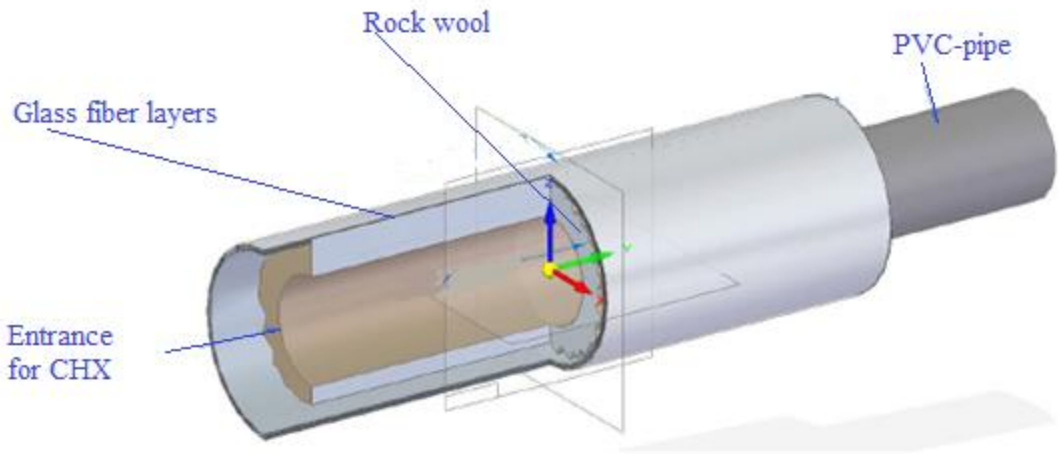



PICTURE 4.3.3: The Hannover engines loudspeaker housing in rapid prototyping (Tuominen, Mäkinen 2014)

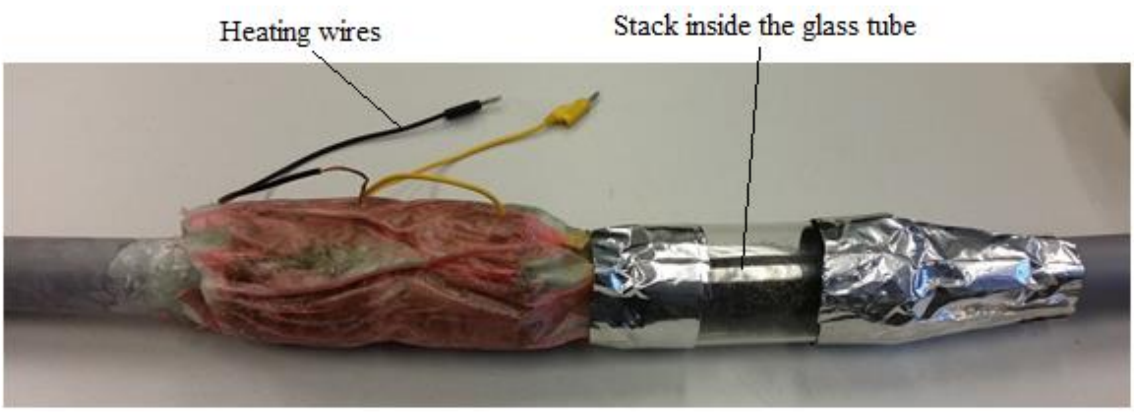

PICTURE 4.3.4: The loudspeaker mounted in the rapid prototyped housing (Tuominen, Mäkinen 2014)

For the first assembly the regenerator steel and copper pipes were gotten from a scrap yard free of charge. A copper coil inside the plain copper pipe as a cold heat exchanger was designed and ordered to have flowing water inside the coil to cool the regenerators cold end. When testing, the copper pipe cooling was used without the coil which was not delivered yet. Hot heat exchanger was first heated with the power supply by heating directly the steel wool stack inside the steel pipe.

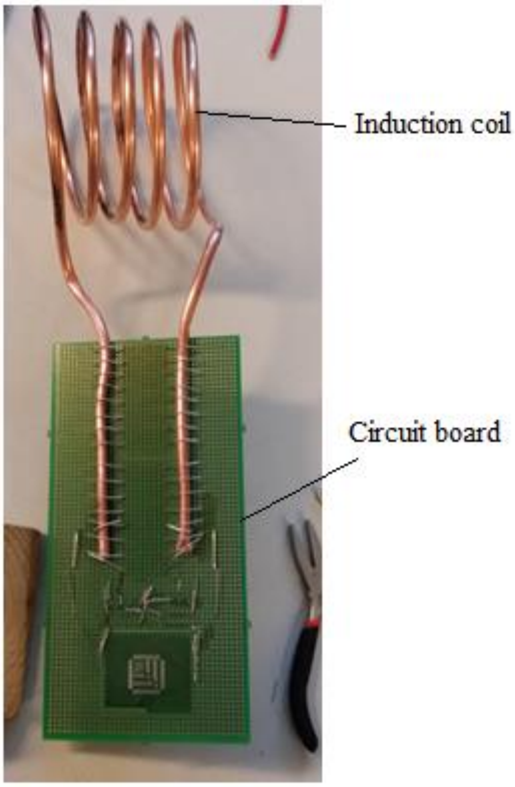
During testing an idea of the next versions regenerator from glass fiber with stone wool insulation came up (Picture 4.3.4-5). Glass fiber construction would be easy to assemble and disassemble and it would prevent possible heat loss well. An induction heater was soldered and the idea was to use this heating system with the glass fiber regenerator (Picture 4.3.6). However, these applications were not tested in this part of the project but they are available when the project continues forward.




PICTURE 4.3.5: Breakout view of the glass fiber regenerator



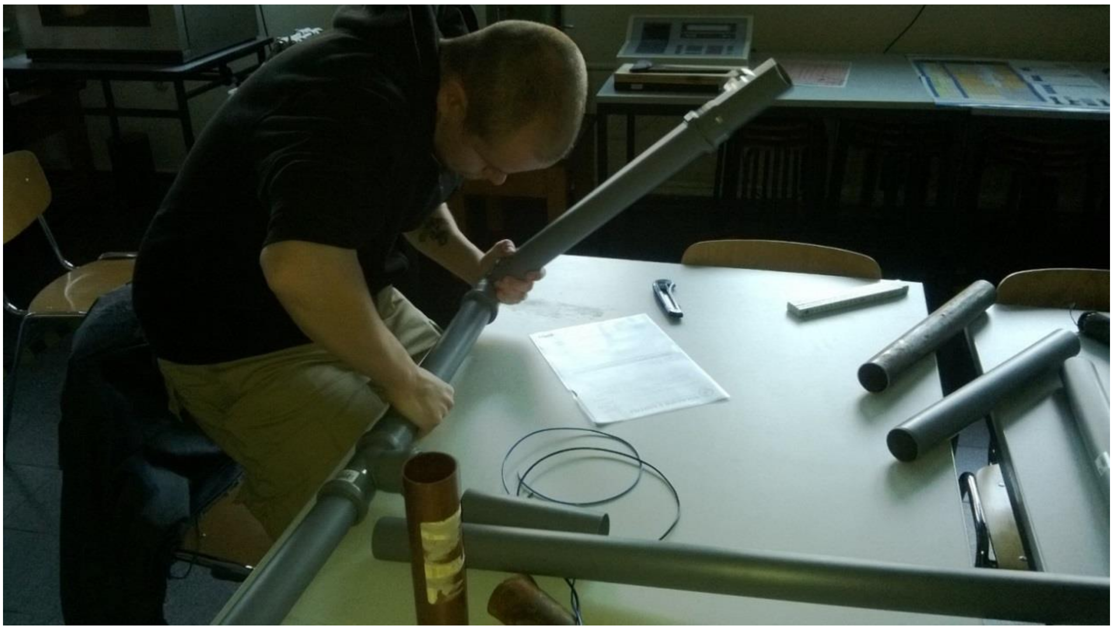

PICTURE 4.3.6: Glass fiber regenerator mounted in glass tube with foil in Tampere UAS (Tuominen, Mäkinen 2014)



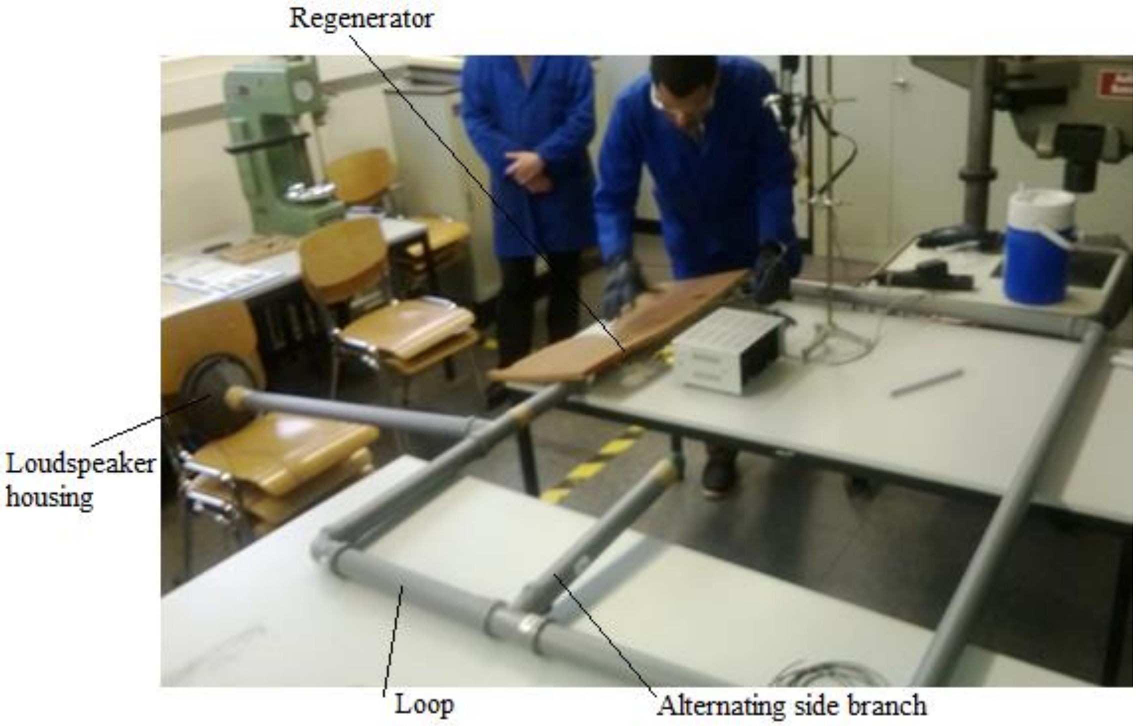

PICTURE 4.3.7: Soldered induction heater (Tuominen, Mäkinen 2014)

## 4.4 Testing

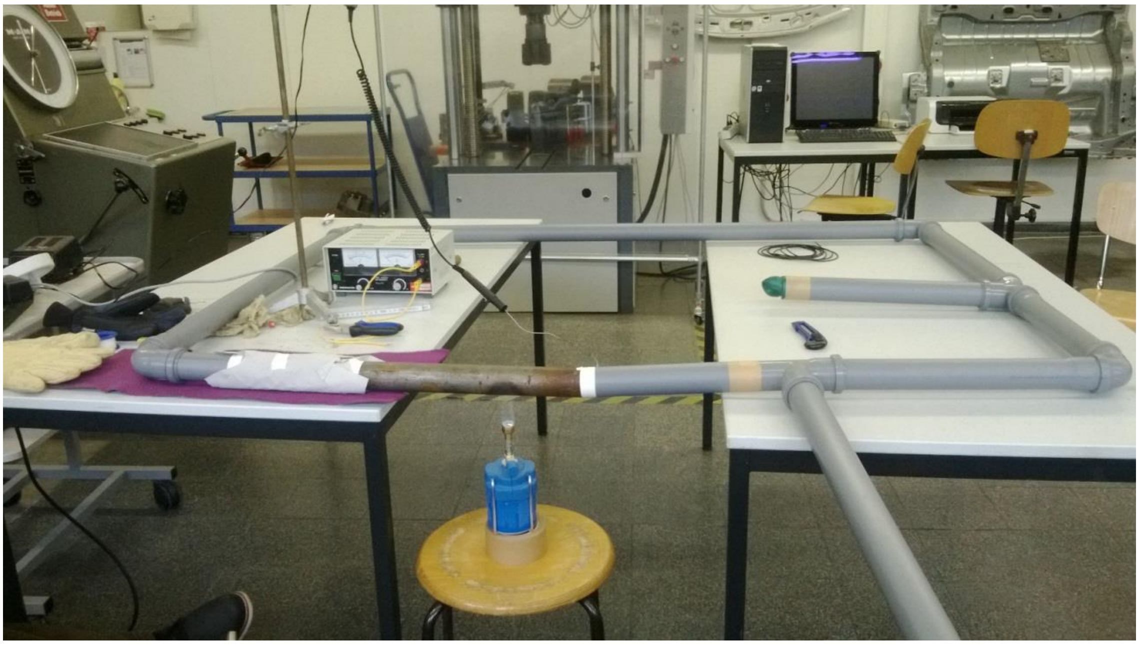
The engines first prototype was assembled in November 2013 and the engine had its first trial run (Picture 4.4.1). Electrical heating, gas burner and cooling by dry ice were applied (Pictures 4.4.2-4). The most important thing in running the engine is to get around high enough temperature difference on as small distance as possible.



PICTURE 4.4.1: Assembling the first engine (Tuominen, Mäkinen 2014)




PICTURE 4.4.2: Engine testing with DC power supply heating and dry ice cooling (Tuominen, Mäkinen 2014)



PICTURE 4.4.3: Engine testing with gas burner heating and dry ice cooling (Tuominen, Mäkinen 2014)


PICTURE 4.4.4: Engine regenerator in the testing facilities Hot and cold reservoir sealed with teflon tape (Tuominen, Mäkinen 2014)

The engine did not start with the first try and because of the power supply melting down and too poor temperature difference in the regenerator, a gas burner was applied for the next trial. Testo 901 -thermometer was used to get temperature data from inside the steel pipe. However, the data was not reliable because the thermometer might have measured the steel pipes temperature instead of the air temperature inside the pipe and that may be why the measured temperature was very high and still there was no movement on the output membrane.

A test for data measurement was made shortly after the engine was assembled for the first time. The engine was heated with a gas burner and in lack of dry ice the cooling was made by pouring water to the cold heat exchangers copper pipe (Picture 4.4.5). The measurement proved that the air temperature difference was not enough for creating a travelling wave pulse. (Table 4.4.1)

PICTURE 4.4.5: Engine testing with gas burner heating and water cooling (Tuominen, Mäkinen 2014)

TABLE 4.4.1: Measurements of testing the regenerators reservoir temperatures (Mäkinen 2014)

**Measuring the temperature difference with different matching stub lengths**

| T,hot/C | T,cool/C | ΔT/C | MS piston depth/mm |
|---|---|---|---|
| 22 | 35 | 13 | 390 |
| 18,9 | 32 | 13,1 | 305 |
| 21 | 76 | 55 | 225 |
| 20 | 75 | 55 | 80 |

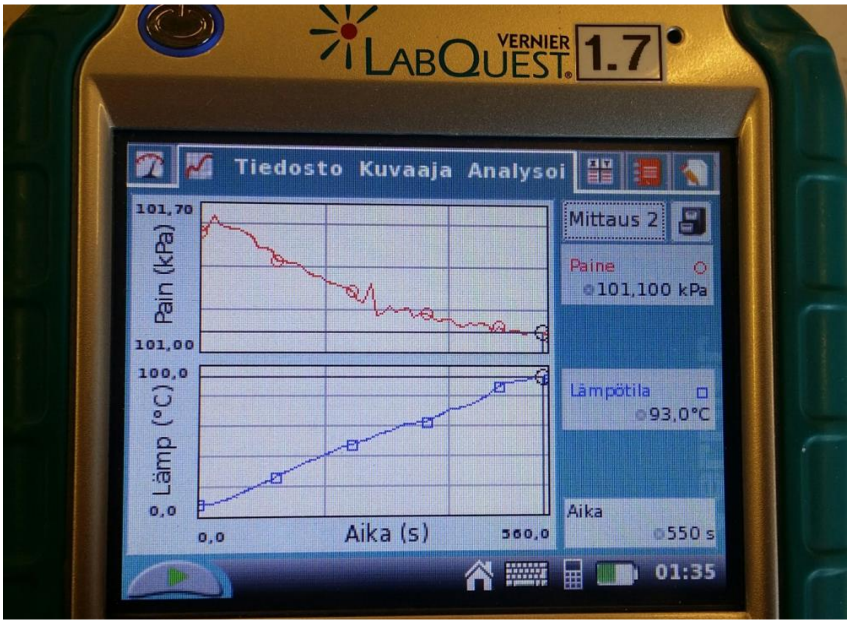
In order to test the output of the loudspeaker the membrane was moved mechanically to have a working output when the other construction becomes ready (Pictures 4.4.6-7). The loudspeaker induction was stated usable because moving the loudspeaker membrane by hands the oscilloscope showed an induced voltage. For further testing a new power supply was ordered to replace the broken one. A fuse was assembled in the power supply to prevent similar equipment loss by overheating the supply.

PICTURE 4.4.6: Tampere engines loudspeaker mounted to its housing (Tuominen, Mäkinen 2014)

PICTURE 4.4.7: Testing the loudspeaker induction with a Fluke-oscilloscope (Tuominen, Mäkinen 2014)

Same time as the loudspeakers electricity induction was tested the pulse applications were tested separately. The heat engine structure was simplified in a T-shape and measured the heating and pressure in a closed structure (Pictures 4.4.8-9).


PICTURE 4.4.8: Heating and measuring the T-junction structure (Tuominen, Mäkinen 2014)



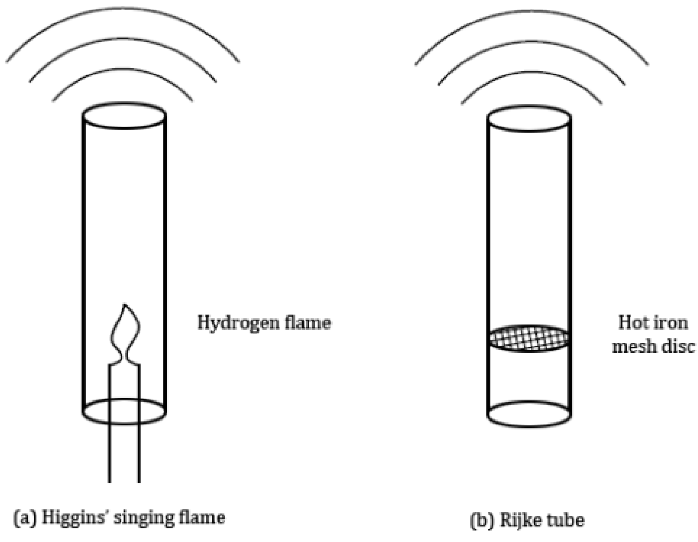

PICTURE 4.4.9: Measuring the T-junction structures temperature and pressure (Tuominen, Mäkinen 2014)

Since the equipment measured data only once per second there was no way to get results to resemble a cyclic process working on a frequency around 60 Hz. There was a detectable pressure drop while heating the closed structure. The change of the pressure was discovered controversial with the isochoric gas law. (10)

$$p_2 = \frac{p_1 T_2}{T_1} \tag{10}$$

The results were not usable as they came out because they were unexpected. The pressure and temperature sensors and the LabQuest-data logger are mostly used in educational purposes and they may present inaccuracies. The T-structures ends were sealed with plain rubber balloons and that is why volume variation was possible in the system circumstances. The equipment and testing conditions probably caused the surprising results. However, the test gives perspective about how accurate measuring devices are needed to get reliable data of the subject. When useful data is gathered from the engine it can be used together with the scientific theory for calculations and optimization.

Design teams second visit to Hannover was made for more testing and project closure. The Rijke tube principle was tested in both Tampere and Hannover. A steel wool stack was mounted to a plain steel pipe and the open pipe started to whistle when heat was brought to it from below (Pictures 4.4.10-11).

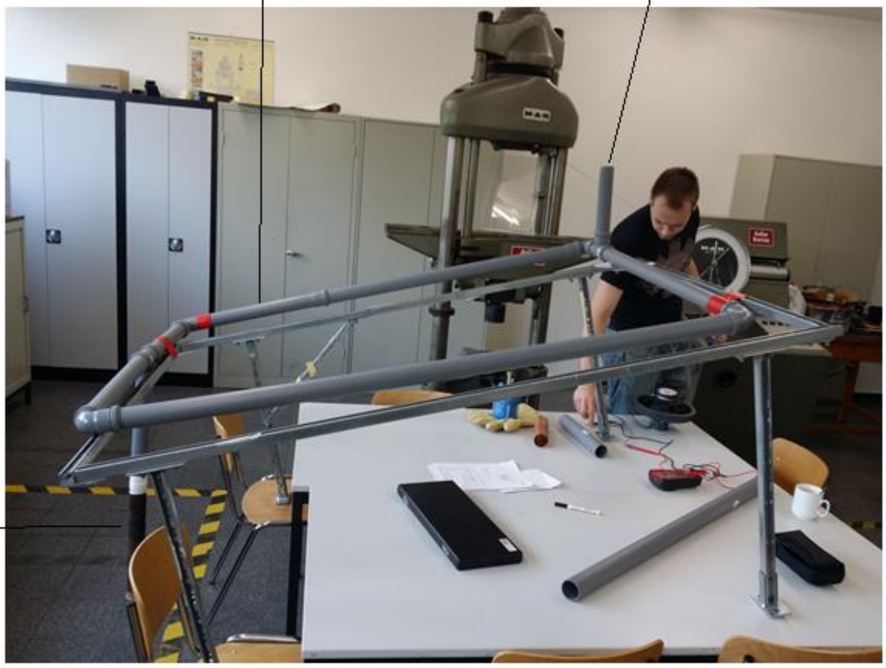



PICTURE 4.4.10: Example of a Higgins' singing flame and Rijke tube (In't panhuis 2009, p. 2)

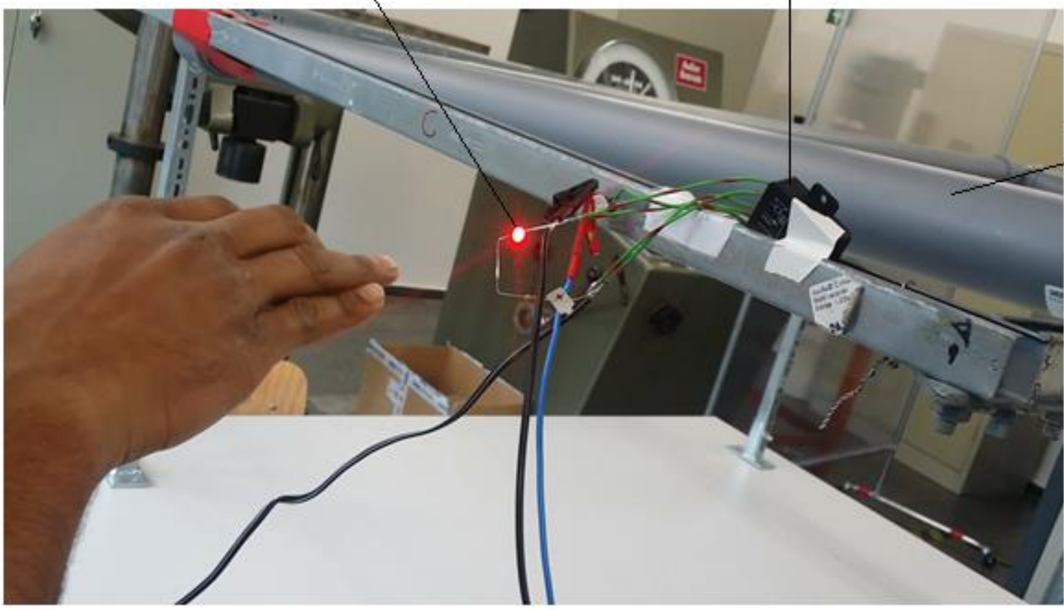
PICTURE 4.4.11: Rijke tube principle testing (Tuominen, Mäkinen 2014)

An idea came up to mount the loudspeaker over the steel tube and measure if any current can be gotten from the sound through the loudspeaker. Some milliamperes were gotten and then the same method was tried with the whole engine structure. The steel tube was in the alternating side branch and the output side branch was open. The sound went through the whole engine (Picture 4.4.12).

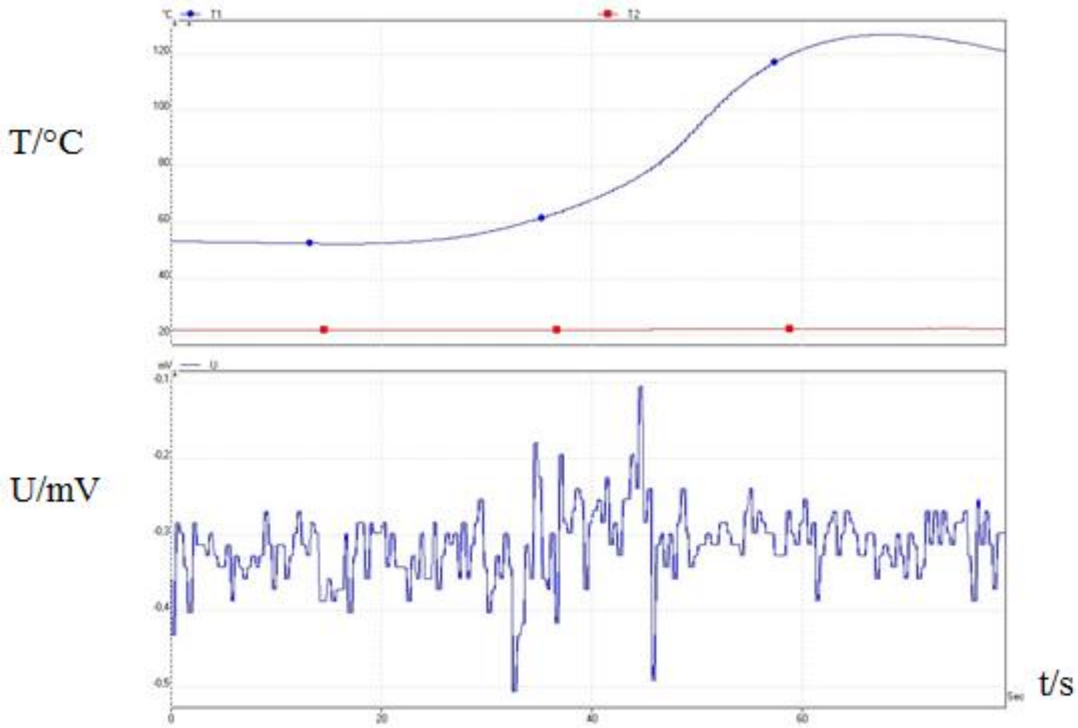
The final test configuration was built using a LED, an amplifier and resistors. The amplifier was used to amplify the voltage that was gotten from the engine. The test was successful because when heating the steel tube the loudspeaker produced enough current and voltage through the amplifier to get the LED flickering (Picture 4.4.13). Pico TC08 -data logger was used to record temperatures from the hot and the cold end. Temperature from the hot end was measured from the steel pipe and the temperature from the cold end was measured just before the loudspeaker. Voltage and current were measured from the loudspeaker and they rose related to the heat transfer (Picture 4.4.14).




PICTURE4.4.12: Testing the side branch input in Hannover (Katajisto 2014)




PICTURE 4.4.13: Amplified LED reacting to the thermo-acoustic pulse (Katajisto 2014)




PICTURE 4.4.14: Data logger-measurements of the side branch input (Katajisto 2014)

### 4.5 Safety matters

When considering the safety matters before assembling the engine in Hannover the first thing that came up was being cautious with the engine construction and possible high air pressure flowing in the loop. Even though too high air pressure was unlikely it had to be considered. While testing the engine the PVC-fittings and couplings had only insulation rings holding them together to prevent too high pressure development. Teflon tape was used to attach the regenerator's steel and copper pipes with each other and the PVC-loop in order to get easy access to the steel wool stack for adjustments and measuring. The tape in the first assembly trial was enough to keep the parts together but would give up in case of high heat and air pressure.

Jackets and eyeglasses needed to be used while applying the dry ice to cool down the systems cold heat exchanger. Pipe was covered and nobody was allowed to touch it with bare hands. Regenerators steel pipe was insulated from the wires of the power supply with teflon tape. Insulation was there to prevent any electrical shocks by conduction to the steel pipe. When moving from electrical heating to the gas burner it was important to be cautious with the burner flame. Melting of the electrical supply was an example of a hazardous possibility in laboratory working environment.

While testing the other version of the engine in Tampere University of Applied Sciences in week 7 2014 an electrical induction heater was soldered together from the ordered parts. While testing the heating it was important to be cautious and keep everybody from burning themselves when discovering the high temperature that was applied from the heater. Early in the soldering phase a vacuum was used so that nobody would inhale any fumes and that the testing facility air condition was kept as required. For the same reason a separate steel pipe was heated outdoors to test the regenerators basic principle and the acoustic sound.

# 5 CONCLUSIONS

## 5.1 Research and working methods

Research of the information during the project was retrospective. Old available information was used as much as possible to get a ready known usable structure. In order to get information, different thesis literature both Finnish and foreign were studied. However the whole groups testing methods where rather prospective. When the engine was tried to get running the group used a great quantity of testing to get wanted results (Kaatiala 2014). Physics literature helped to find the right scientific theory.

## 5.2 Tasks

Theory and background is a very important part of creating something new. When starting the project the members should gather all the information and theory possible to make the design work easier. Smaller amount of testing time might have been needed in this project if the team had had a better theoretical awareness from the beginning. Maybe that way there would have been better results with the engine with less time spent on the large quantity of testing. The project will be only partly finished in March 2014 so there is an opportunity for the members to continue working with this subject but the Finnish design team needs to reconsider the option later in the spring and summer 2014.

On a product development project there are certain needs and risks in the project management process. When looking at the table of nine fields of information many things point out to be exactly like mentioned in the table (Picture 5.2.1). Most important thing in the management was to arrange all the resources while students' own studies. There is always a limited amount of time to use. The most important thing in work life projects is always making the product profitable so the purchases and other expenses need to be well considered.

Picks from nine fields of information:

- Fitting resources together
- Time
- Costs
- Human resources
- Communication
- Risks
- Purchases

PICTURE 5.2.1: Project managements fields of information (M. Peltola 2013)

Project management was fluent despite many obvious risks that were met during the management process (Picture 5.2.2). Management projects usually tend to expand. When the project gets bigger it is more difficult to handle. When people try something new for the first time it does not quite work like expected so different applications need to be varied as in this project. A document for continuing the project was written and there was mentioned the need of clear project management and personnel especially named for that purpose (Appendix 3.).

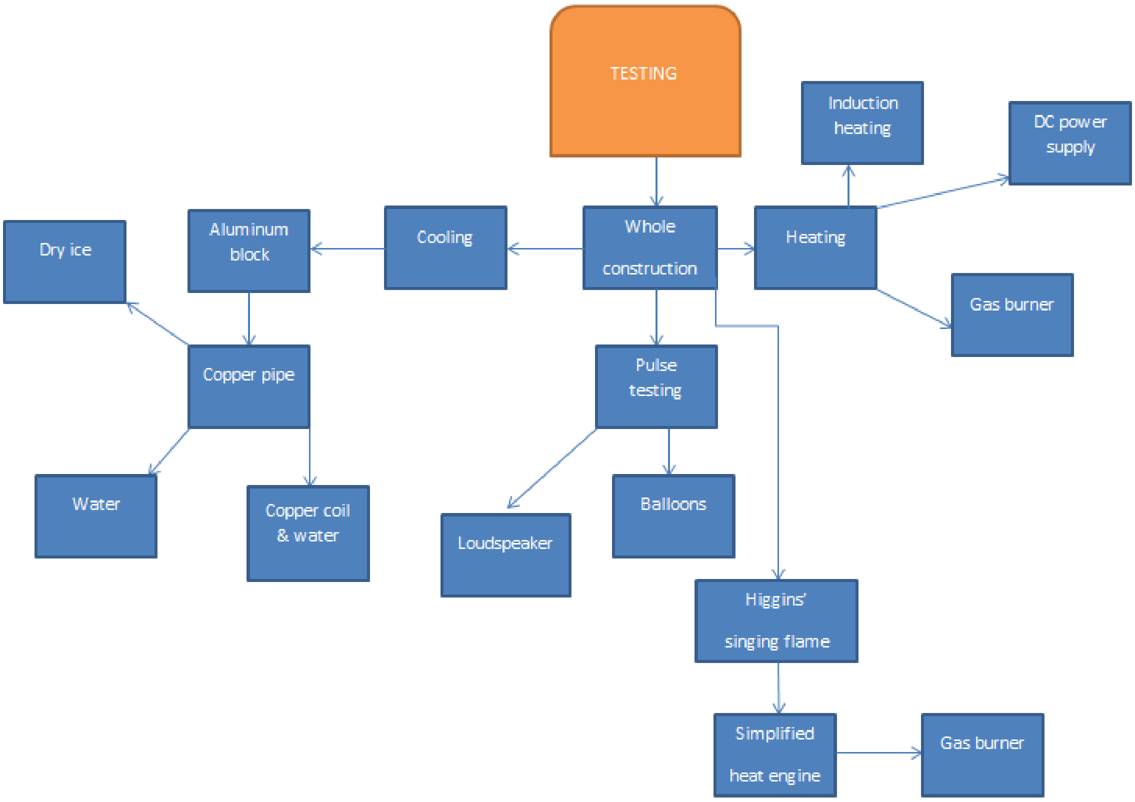
Obvious risk examples

- Size of the project
- First try of a solution or technology
- Lack of clear project management process
- Lack of project management structure
- Little experience of the project manager
- No clear owner or commitment
- Little amount of resources and skills
- Rush

PICTURE 5.2.2: Project managements risk examples (M. Peltola 2013)

There needs to be someone in control and having a clear vision of the big picture and possibly able to make big decisions. In this project so far there has been no specified management so a large amount of time has been spent on arranging things among all own tasks of personnel. All these things emphasize when there are only three active project members working at the same time and all the members are students in the middle of their studies. Ideal for continuing members might be one group for coordination and correspondence, one group for testing and measuring and one or two groups for construction of new setups.

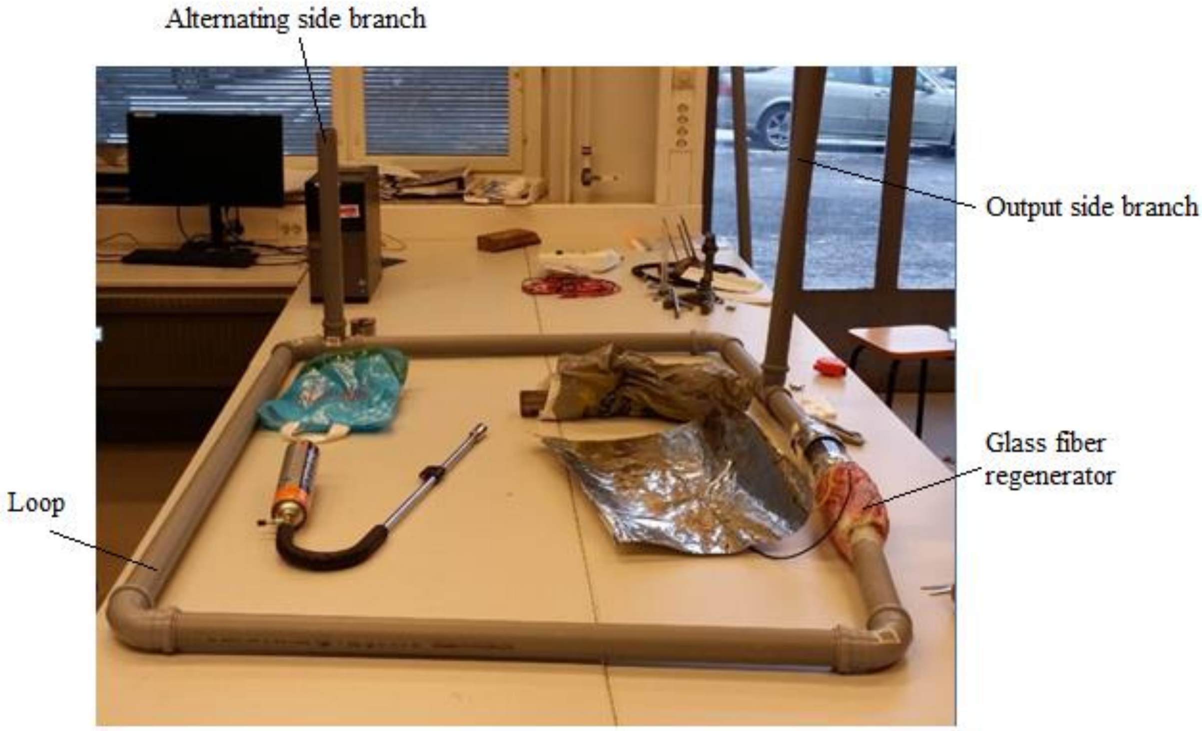
The construction of the engine is easy so regardless of the small amount of time to assemble the engine as a group the structure was put together and tested several times with different setups. After the first concrete prototype of the engine was assembled in the autumn 2013 in Hannover the team tested the gain of the temperature difference. In the beginning there was too much concentration and effort for the cold heat exchanger since heating the air up is easier than cooling it down. Several different setups were needed to accomplish results that show progression in the project and achieving the electric output with sound from heat (Picture 5.2.3). This gives a good basis for continuing the development as the side branch input application started working and the basic principle of the thermo-acoustic engine was proved.




PICTURE 5.2.3: Flowchart of testing setups (Tuominen 2014)

## 5.3 Continuation

Another pulse tube engine loop was assembled in Tampere for the new project recruits to work with (Picture 5.3.1). Now that the engine works with some modifications there is demand for more development to make it running like originally planned with the alternating piston side branch and closed loop regenerator.




PICTURE 5.3.1: Second engine assembled in Tampere (Tuominen, Mäkinen 2014)

More testing with professional equipment gives chance to create a real process cycle diagram. From the diagram or equation (2) the engines output energy and efficiency can be calculated. Next the membrane movement harnessed to induce voltage will give information of the possible power of the electricity output. After the engine works with the original structure it needs be optimized. When the engine performance is optimized it is easier to commercialize (Laaksonen, Peltola 2014). Thermo-acoustic engine can be made with lower costs than solar panels. This is because these engines do not have many parts and those parts can be found for example in a scrap yard.

> “Sound waves are longitudinal waves characterized by density or pressure fluctuations. Audible sound, that our ears can detect, ranges in frequency from about 20 Hz to 20,000 Hz." (Benson 1991, 339)

> “The sound is part and parcel of those pressure waves, though it doesn’t serve a useful purpose. In the same way that heat is a waste product of an internal-combustion engine, sound is a waste product of the thermoacoustic engine. Controlling that sound is part of the design challenge” (Ferris 2009).

When commercializing a product, appearance is as important as functionality. The current thermo-acoustic engine is quite big and noisy so if resizing and using some kind of muffler does not have a bad effect on the performance making those improvements would be useful. PVC-pipes are cheap but appearance wise they are not very appealing. The aesthetics might improve if the engine was made from a different material. This provides a challenge, because the new materials should still be as cheap as PVC. Rapid prototyping is an easy way to manufacture parts such as the housing for the loudspeaker. It is still quite expensive method so other application for the housing should be considered.

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# APPENDICES

Appendix 1. Assembly manual

**Juuso Mäkinen** **Assembly manual**

**Marko Tuominen**

Mechanical and Production Engineering

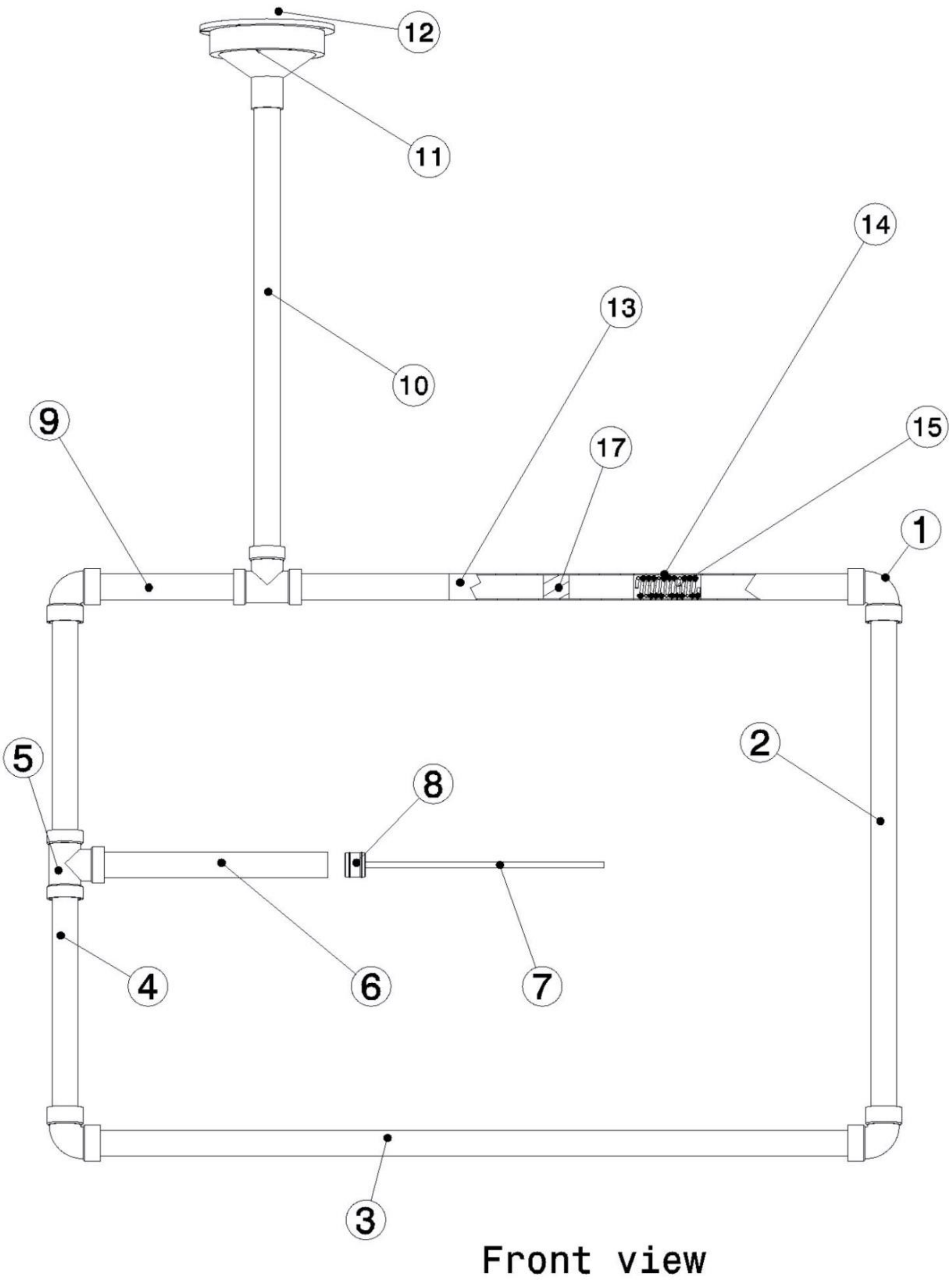
Product Development 15.5.2014

Tampere UAS

**Assembly of the thermo-acoustic engine with DC heating**

Part list:

1. PVC-elbow Qty= 4pieces
2. PVC-pipe approx. 1000 mm Qty= 1 piece
3. PVC-pipe approx. 1500 mm Qty= 1 piece
4. PVC-pipe approx. 500 mm Qty= 2 pieces
5. PVC T-section Qty= 2 pieces
6. PVC-pipe approx. 450 mm Qty= 1 piece
7. Piston rod Qty= 1 piece
8. Piston with O-rings= 1 piece
9. PVC-pipe approx. 350 mm Qty= 3 pieces
10. PVC-pipe approx. 920 mm Qty= 1 piece
11. Loudspeaker housing Qty= 1 piece
12. Loudspeaker Qty= 1 piece
13. Steel pipe approx. OD= 50 mm Qty= 1 piece
14. Copper pipe approx. OD=50 mm Qty= 1 piece
15. Copper coil
16. Insulation tape in the regenerator sealings
17. Steel wool stack 1 piece

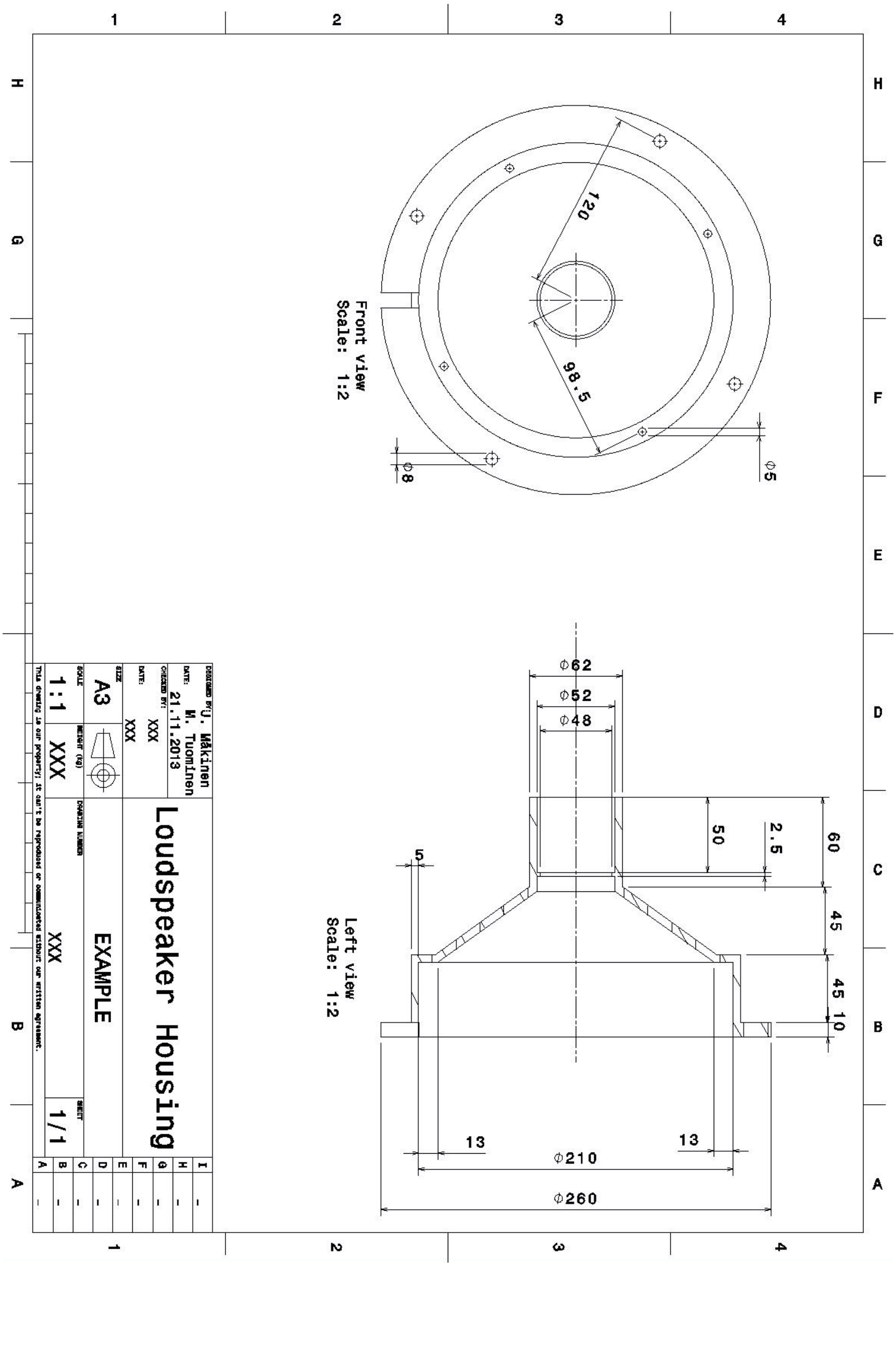


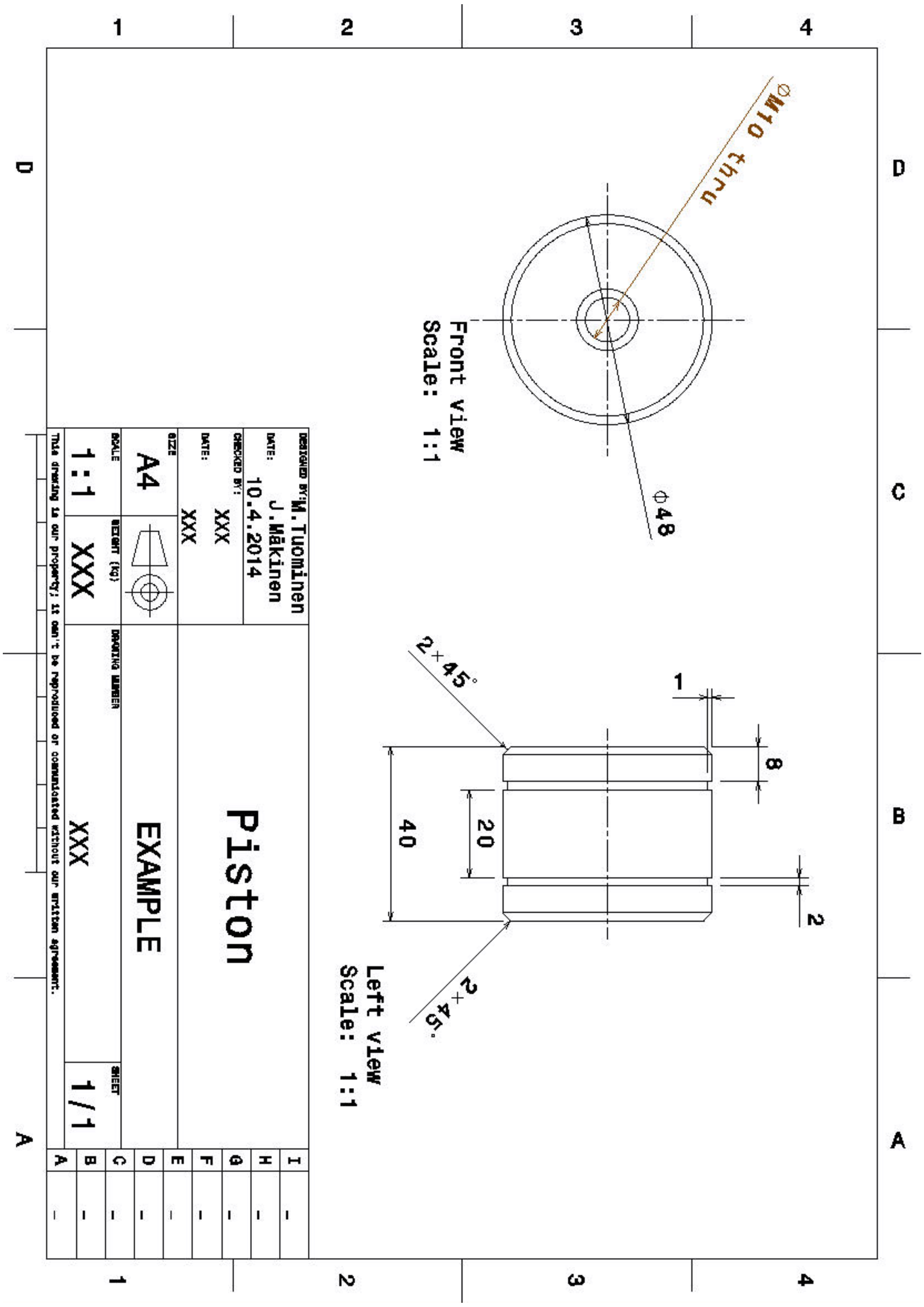

Front view
Scale: 1:5

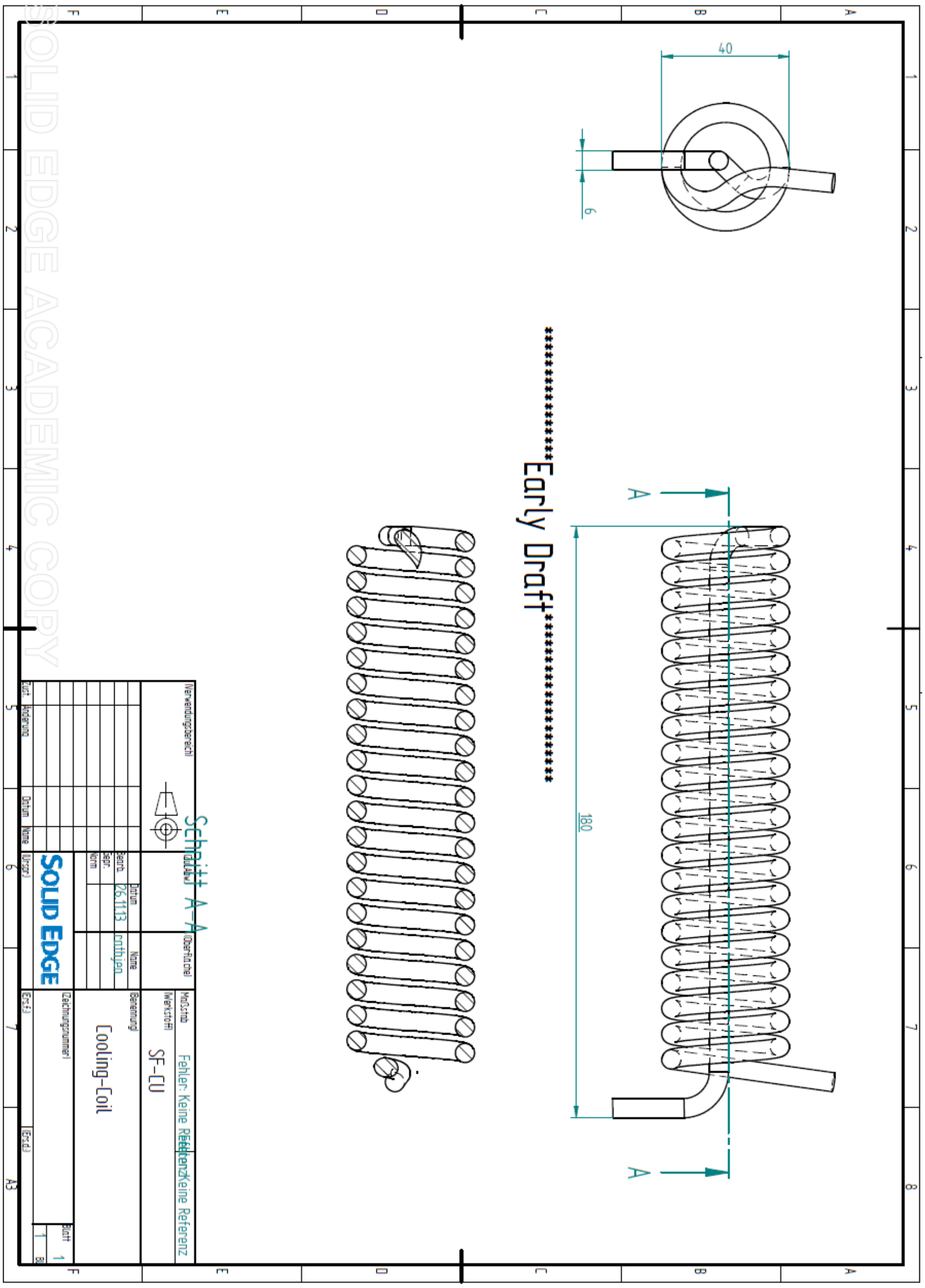
**Assembly Instructions:**

- Start the assembly by attaching two PVC-elbows (1) to each end of a PVC-pipe approx. 1000 mm (2).
- Next, attach a 1500 mm long PVC-pipe to one those elbows. (3)
- Attach a third PVC-elbow to the free end of this 1500 mm pipe to form a U-shape.
- To this elbow, attach one PVC-pipe with a length approx. 500 mm. (4)
- Next, attach one PVC T-section (5) and another 500 mm PVC-pipe.
- To the middle outlet of the PVC T-section, attach the side branch PVC-pipe that has a length approx. 450 mm. (6)
- Insert the piston (8) with O-rings to the side branch.
- Attach the fourth PVC-elbow to the free end of the second 500 mm long PVC-pipe.
- Next, attach one PVC-pipe with a length approx. 350 mm (9) to the elbow and another PVC T-section after it.
- To the middle outlet of this T-section, attach another side branch PVC-pipe with a length approx. 920 mm. (10)
- To this side branch attach the loudspeaker housing. (11)
- Insert the loudspeaker (12) into its housing and bolt it onto place.
- Attach another 350 mm pipe to the T-section that was mentioned earlier.
- Hot heat exchanger consists of two components. Ø50 mm steel pipe (13). Steel wool stack (17) goes inside the Ø50 mm steel pipe.
- The Cold Heat Exchanger consists of a copper pipe (14) with a copper coil inside (15).
- Attach the Hot Heat Exchanger to the Cold Heat Exchanger with insulation tape (16).
- Attach the Cold Heat Exchangers other end with insulation tape to the third PVC-pipe that has a length approx. 350 mm.
- Attach this last PVC-pipe to last PVC-elbow that is available and you have a closed loop.

**NOTICE! PVC-PIPE DIMENSIONS ARE APPROXIMATE AND HAVE SOME EXTRA LENGTH TO WORK WITH.**


Loudspeaker Housing
EXAMPLE
DESIGNED BY: U. Mäkinen
M. Tuominen
DATE: 21.11.2013
CHECKED BY: XXX
DATE: XXX
SIZE A3
SCALE 1:1
WEIGHT (kg) XXX
DRAWING NUMBER XXX
SHEET 1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.
Front view
Scale: 1:2
Left view
Scale: 1:2
120
98.5
Φ8
Φ5
Φ62
Φ52
Φ48
50
2.5
60
45
45
10
5
13
13
Φ210
Φ260


Front view
Scale: 1:1
⌀M10 thru
⌀48
Left view
Scale: 1:1
2×45°
2×45°
1
8
2
40
20
DESIGNED BY: M.Tuominen
J.Mäkinen
DATE: 10.4.2014
CHECKED BY: XXX
DATE: XXX
SIZE A4
SCALE 1:1
WEIGHT (kg) XXX
Piston
EXAMPLE
DRAWING NUMBER XXX
SHEET 1/1
This drawing is our property; it can't be reproduced or communicated without our written agreement.


40
6
180
A
A
Early Draft
Schnitt A-A
SF-CU
Cooling-Coil
Fehler: Keine Referenz
SOLID EDGE
SOLID EDGE ACADEMIC COPY

Appendix 2. Future tasks

**Juuso Mäkinen** **Future tasks**

**Marko Tuominen**

Mechanical and Production Engineering

Product Development 15.5.2014

Tampere UAS

**Tasks for the next phases of the thermo-acoustic engine project**

Depending on if the engine works with the originally designed structure or not:

- More testing and ideas to get it running and when it does:
- Optimizing the engine when it is running.
- Efficiency can be calculated and enhanced.
- Reduction of heat input on the HHX (Hot Heat Exchanger).
- Construction of the CHX (Cold Heat Exchanger) with high temperature gradient.
- Testing of different lengths and densities when using steel wool as a stack for the regenerator.
- Optimizing the distance between hot and cold area to stabilize the wave.
- Testing of different sizes and materials on the regenerator e.g. glass tube.
- Testing a variety of different size loudspeakers and materials for the housing (Rapid prototyping is too expensive for use in developing countries).
- Building a device for demonstrative issues to visualize the output energy.
- Building a solar heating system (reflectors).
- Qualifying the effect of the position of the piston inside the matching stub.
- Testing of different geometrics and lengths than single loop for better use of space in the set-up area.
- Thinking of solutions for use of waste heat (cooking etc.).
- Measuring other physical values depending on modifications.

- Aim of all modifications should be to position the parameters into operating ranges that support specified applications.

**Long term issues:**

- Thermo-acoustic engine as a cooling system (reversing the heat engine process cycle)

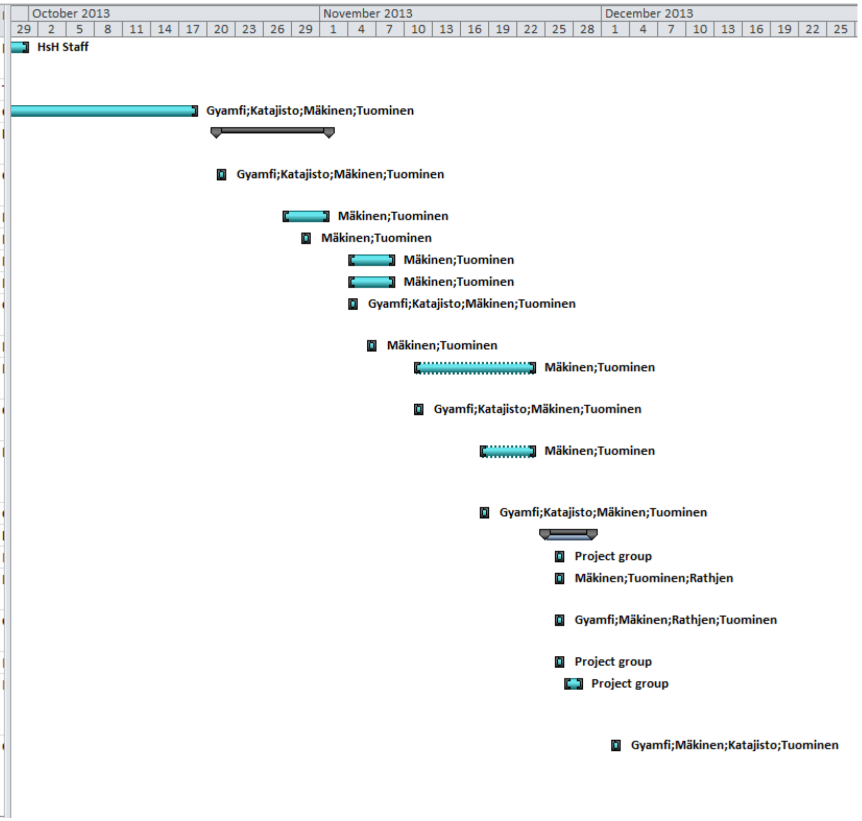
- Clear team management, ideal would be one group for coordination and correspondence, one group for testing and measuring and one or two groups for construction of new components.

- Consideration how to commercialize the engine.

- How much of the parts can be taken from scrap yard or by sponsors in cheap price or even free of charge. This affects straight to the profit.

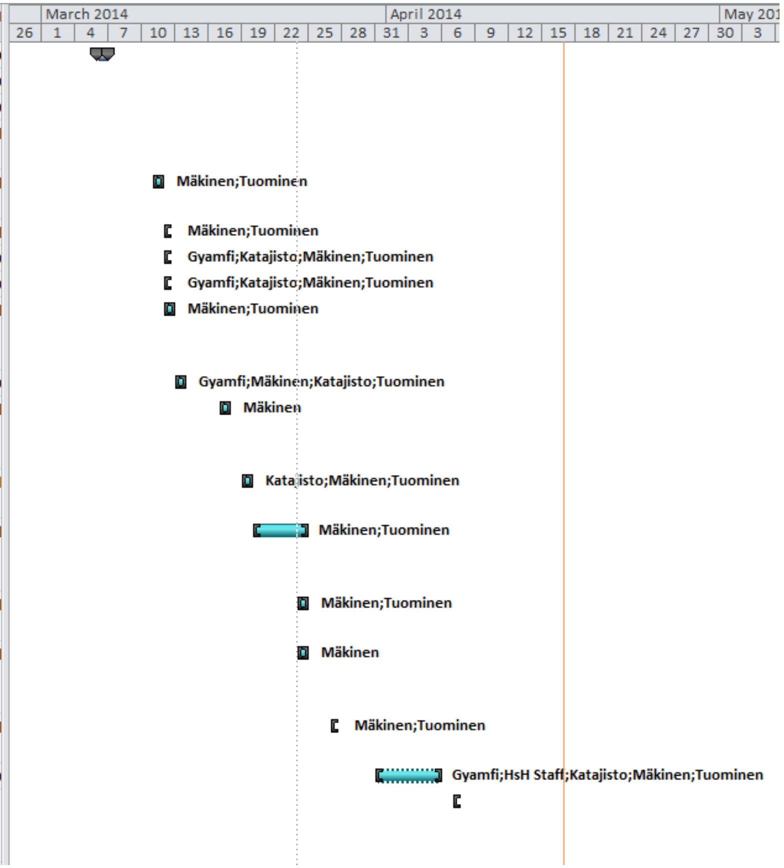
Appendix 3. Project plan

| Task Name | Duration | Start | Finish |
|---|---|---|---|
| Recruiting project members | 109 days | Wed 1.5.13 | Mon 30.9.13 |
| First schedule | 5 days | Mon 2.9.13 | Fri 6.9.13 |
| Gathering information | 30 days | Mon 9.9.13 | Fri 18.10.13 |
| **Actual start of the project** | **10 days** | **Mon 21.10.13** | **Fri 1.11.13** |
| First SKM/Introduction | 1 day | Mon 21.10.13 | Mon 21.10.13 |
| Materials/Solutions | 5 days | Mon 28.10.13 | Fri 1.11.13 |
| Modified schedule | 1 day | Wed 30.10.13 | Wed 30.10.13 |
| Design | 5 days | Mon 4.11.13 | Fri 8.11.13 |
| First hand-drawn drafts | 5 days | Mon 4.11.13 | Fri 8.11.13 |
| SKM/Experimental setup, regenerator ideas | 1 day | Mon 4.11.13 | Mon 4.11.13 |
| First prototype design | 1 day | Wed 6.11.13 | Wed 6.11.13 |
| Changes before regrouping | 11 days | Mon 11.11.13 | Sat 23.11.13 |
| SKM/Changes, Financing RP | 1 day | Mon 11.11.13 | Mon 11.11.13 |
| Rapid prototyping of the Hannover engine housing | 6 days | Mon 18.11.13 | Sat 23.11.13 |
| SKM/Changes, Safety | 1 day | Mon 18.11.13 | Mon 18.11.13 |
| **Regrouping in Hannover** | **5 days** | **Mon 25.11.13** | **Fri 29.11.13** |
| Meeting | 1 day | Tue 26.11.13 | Tue 26.11.13 |
| Design of the cooling coil | 1 day | Tue 26.11.13 | Tue 26.11.13 |
| Ordering of the regenerator parts | 1 day | Tue 26.11.13 | Tue 26.11.13 |
| First engine assembly | 1 day | Tue 26.11.13 | Tue 26.11.13 |
| Testing the engine/Gathering data | 2 days | Wed 27.11.13 | Thu 28.11.13 |
| SKM/Glassfibre regenerator, Piston design, Loudspeaker testing | 1 day | Mon 2.12.13 | Mon 2.12.13 |



| Task Name | Duration | Start | Finish |
|---|---|---|---|
| **SKM/Proceeding** | **1 day** | **Tue 7.1.14** | **Tue 7.1.14** |
| Later regroups in Tampere and | | | |
| Deadline until the end of March 2014 | | | |
| Recruiting continuers | | | |
| SKM/Proceed as agreed | 1 day | Thu 16.1.14 | Thu 16.1.14 |
| Briefing with consulting teachers | 1 day | Mon 20.1.14 | Mon 20.1.14 |
| SKM/Regrouping in Tampere | 1 day | Thu 30.1.14 | Thu 30.1.14 |
| Physics research/Thermodynami Heat engine | 1 day | Thu 30.1.14 | Thu 30.1.14 |
| Test facilities, Meetings, Facility Access rights, Part orders for Tampere engine | 5 days | Mon 3.2.14 | Fri 7.2.14 |
| SKM/Parts ordered, Testing, Hannover regroup around week 13 | 1 day | Thu 6.2.14 | Thu 6.2.14 |
| **Regrouping in Tampere** | **5 days** | **Mon 10.2.14** | **Fri 14.2.14** |
| Meeting, Assembly of Tampere engine | 1 day | Tue 11.2.14 | Tue 11.2.14 |
| Testing the Tampere engine | 2 days | Wed 12.2.14 | Thu 13.2.14 |
| Induction heater soldering | 2 days | Thu 13.2.14 | Fri 14.2.14 |
| Presentation | 1 day | Fri 14.2.14 | Fri 14.2.14 |
| **SKM** | **1 day** | **Thu 20.2.14** | **Thu 20.2.14** |
| Rapid prototyping of the housing in Tampere engine | 3 days | Thu 20.3.14 | Sun 23.3.14 |
| Access rights | | | |
| Consulting teachers will keep in touch | | | |

| Task Name | Duration | Start | Finish |
|---|---|---|---|
| **SKM** | **1 day** | **Thu 6.3.14** | **Thu 6.3.14** |
| Documentation | | | |
| Testing ideas | | | |
| Testing before the project closure | | | |
| Briefing with consulting teachers | 1 day | Tue 11.3.14 | Tue 11.3.14 |
| Documentation | | Wed 12.3.14 | |
| Commercialization | | Wed 12.3.14 | |
| Product Development | | Wed 12.3.14 | |
| Meeting with former manager/Project management | 1 day | Wed 12.3.14 | Wed 12.3.14 |
| SKM/Documentation/Co | 1 day | Thu 13.3.14 | Thu 13.3.14 |
| Physics research/Process cycle, Induction | 1 day | Mon 17.3.14 | Mon 17.3.14 |
| SKM/Documentation, Regroup in Hannover | 1 day | Wed 19.3.14 | Wed 19.3.14 |
| Rapid prototyping of the Tampere engine housing | 3 days | Thu 20.3.14 | Mon 24.3.14 |
| Physics research/Whole theory | 1 day | Mon 24.3.14 | Mon 24.3.14 |
| Physics research/Process cycle, testing equipment | 1 day | Mon 24.3.14 | Mon 24.3.14 |
| Engine testing day in Tampere | | Thu 27.3.14 | |
| Regrouping in Hannover | 6 days | Mon 31.3.14 | Sat 5.4.14 |
| Project closure documentation and tasks | | Mon 7.4.14 | |



Appendix 4. Thesis responsibilities

**Juuso Mäkinen** **Thesis responsibilities**

**Marko Tuominen**

Mechanical and Production Engineering

Product Development 15.5.2014

Tampere UAS

**Thermo-acoustic Engine for Electricity Production**

This document is written to clarify the responsibility areas between the writers of the thesis text “Thermo-acoustic Engine for Electricity Production ” to able the assessors to give separate evaluations.

Mr. Mäkinen’s responsibilities in the report were the projects theoretical background, physics research and documentation of the design work.

Mr. Tuominen’s responsibilities in the report were the documentation of the engine construction and testing.

Documentation concerning the project management and conclusions has been done in co-operation with each other.