YRKESHÖGSKOLAN NOVIA

Design and Development of a Long Stroke Compressor

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BACHELOR'S THESIS

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Abstract

This thesis is done in collaboration with HUR Oy, which is a manufacturer of training equipment that uses air pressure as resistance. HUR had a problem with lubrication oil in the compressed air which the machines use was destroying the seals of the air cylinders used in the machines. Because of this HUR wanted to develop an own type of compressor that would use the same air cylinders that the training equipment use and therefore eliminate the need for lubrication. It became my task to design and develop a compressor accordingly to the specs that HUR had given me.

The result of this project was a ready planned product whit appurtenant drawings and calculations. The compressor will be set in production as soon as possible, and will be a part of HUR's product range.

Language: English Key words: Compressor, Pneumatics, Production

EXAMENSARBETE

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Titel: Design och Utveckling av Långslagig Kompressor

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Abstrakt

Detta examensarbete har gjorts i samarbete med HUR som är en tllverkare av träningsmaskiner som använder sig av tryckluft som motstånd. HUR hade problem med att tryckluften som maskinerna använder sig av innehöll små mängder olja från kompessorn som förstörde tätningarna i luftcylindrarna inne i träningsmaskinerna. Man ville därför utvecka en egen kompressor som skulle använda sig av samma luftcylindrar som själva maskinerna använder sig av, och därmed slippa behovet av smörjolja. Därför blev min uppgift att designa och utveckla en kompressor utifrån de krav som HUR ställde.

Resultatet blev en färdigplanerad produkt inklusive tillhörande ritningar och uträkningar. Kompressorn kommer att sättas i produktion så fort som möjligt och skall ingå i HURs produkt sortiment.

Språk: Engelska Nyckelord: Kompressor, Pneumatik, Produktion

OPINNÄYTETYÖ

Tekijä:	Lucas Manderbacka
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Päivämäärä: 5.1.2017 Sivumäärä: 31 Liitteet: 0

Tiivistelmä

Tämä opinnäytetyö on tehty yhteistyössä HUR Oy:n kanssa, joka on kuntolaitevalmistaja joiden laitteissa käytetään ilmapainetta vastuksena. HUR:lla on ollut ongelmia kompressorin voiteluun käytettävän öljyn kanssa, sillä öljy sulaatta tiivisteet niin että ne alkavat vuotamaan. Siksi HUR haluaisi kehittää oman kopressorin joissa käytettäisiin samoja ilmasylintereitä joita käytetään kuntoilulaitteissa, jonka avulla he pääsisivät eroon voitelusta kokonaan. Minun tehtäväkseni tuli juuri siksi kehittää ja muotoilla uusi kompressori HUR:in vaatimuksien mukaan.

Tuloksena on valmiiksi suunniteltu kompressori sekä siihen kuuluvat piirrustukset ja laskelmat. On tarkoitus että kompressori laitetaan tuotantoon niin pian kuin vain mahdollista.

Kieli: Englanti Avainsanat: Kompressori, Pneumatiikka, Tuotanto

Table of Contents

1 INTRODUCTION

This Bachelor's Thesis will process the design and construction of a long stroke piston compressor, the work will include drawings, calculations and cost calculations. The compressor is meant to replace the current compressors that HUR is using in their installations, but for a cheaper and more durable system.

1.1 Background

HUR is a manufacture of training equipment that uses air pressure as resistance. This system is very quiet and the machines have a very compact design. The air pressure that is built up by a compressor to approximately 8 bars, is stored in a tank hidden somewhere where it cannot be seen or heard. Every machine is then connected to this pressure reservoir and the machine automatically adjusts the pressure to the resistance that the customer has chosen. Once the pressure is reached the customer can train as long as he wants without any energy losses, the air-pressure is acting on a piston in an air cylinder that is connected to the arm that the customer is supposed to move for training. The machine itself has its own air reservoir to compensate for the increase and decrease of the volume because of the piston movement in the cylinder.

Over the years, HUR has discovered that some of the piston sealings made out of rubber inside the cylinders tend to start leaking after a couple of years of hard use. The cause for this was located to be the lubrication oil from the compressor. HUR has now come up with an idea to use the same air cylinders that are used in the machines to make a compressor that should be running at a very low rpm and be very quiet and without any need of lubrication.

1.2 Goal

There was one main task from HUR about this project and it was to design a ready product that can be used in HUR's own installations and also be sold as a product in HUR's stock assortment. Other than this, there was a need for an excel program that would calculate the specs for the compressor by choosing the right cylinders and rotating speed. This program would be useful for future development and was done in conjunction with all the calculations done when designing the compressor. The last one was to make a cost calculation on the final project. This was done through meetings with the sub suppliers and talking to the people responsible for the buying of additional parts at HUR.

Figure 1. *Picture of JUN-AIR 12-25 compressor (JUN-AIR, 2016)*

With my project, I am targeting the JUN-AIR Quiet Air 12-25, which is a two-piston multistage reciprocating compressor produced by the company Jun Air. This compressor is designed to be used in applications where low noise and a compact packaging is important. It is also designed to be very economical to use and have low maintenance costs. The compressor we are planning to build together with HUR has to be able to meet these standards or even improve upon them. Underneath are some technical data about the unit. (JUN-AIR, 2016)

- Noise Level: 48db (at 50hz)
- Displacement: 100 l/min (50hz)

- Max pressure: 8 Bar

(http://www.jun-air.com/product_overview_quiet_air.aspx)

1.3 Limitations

This project has been limited to the mechanical side of the compressor only. All the programming work and software will be done by another student who studies electrical engineering.

1.4 HUR

HUR is a company that produces training equipment for gyms and health facilities. The company was founded in 1989 and is now employing about 50 people in Kokkola and all togather about 80 people around the world. HUR is exporting about 90% of their products worldwide and their products are used in gyms and also in a lot of rehabilitation centers. It all started as a study at the Helsinki University of Technology about strength training, and the company has worked in a close relationship with the university ever since.

Figure 2. *Picture of the HUR Leg Extension Curl training machine (ABOUT HUR)*

The main thing that mkes HUR machines special amogst others is that all the training equipment uses compressed air as resistance instead of normal iron weights. The pros with this system is that you do not have any interference of inertia which means that you are able to do movements at any given speed and always have the same resistance. The machines are also very quiet and very easy to use.

Figure 3. *Picture of the HUR smart card circle. (ABOUT HUR)*

The newest models of the machines uses a smart card system, this means that you have your own card or RF identification which can be your phone or some other electronics that have your data stored for all the machines, and when the machine reads this data it automatically adjusts the resistance for you. The most common system uses 12 machines for all muscles placed in a circle so you can train your whole body within about 30 minutes. All the training information is afterwards stored on the card. When you are finished with your training you go to a main computer located near the training circle and from there you are able to see all the progress you have done during all your training sessions. All the data is also stored on your name and you can easily see all the improvements you have done since your first training. (ABOUT HUR)

(http://www.hur.fi/en/company/our-mission)

2 THEORETICAL BACKGROUND

In this chapter I am going to go through different types of compressors that could be used and list the pros and cons of each of these units, I will also explain the design of the target compressor and at the end I will talk about the design of my own unit.

2.1 Different types of compressors

There are three main compressor types on the market today, and these are used in a wide range of different equipment and machines. These three groups are: reciprocating air compressors, rotary screw compressors and the centrifugal compressor. Each of these have their pros and cons, and are more suitable than others in different applications. The reciprocating air compressor is the most common type for smaller compressors and is the cheapest one to build. The rotary screw is used in bigger compressors where there is a need of much higher airflow. The centrifugal compressor uses a turbine to compress the air and is used where huge quantities of pulse free air is needed.

2.1.1 Reciprocating air compressor

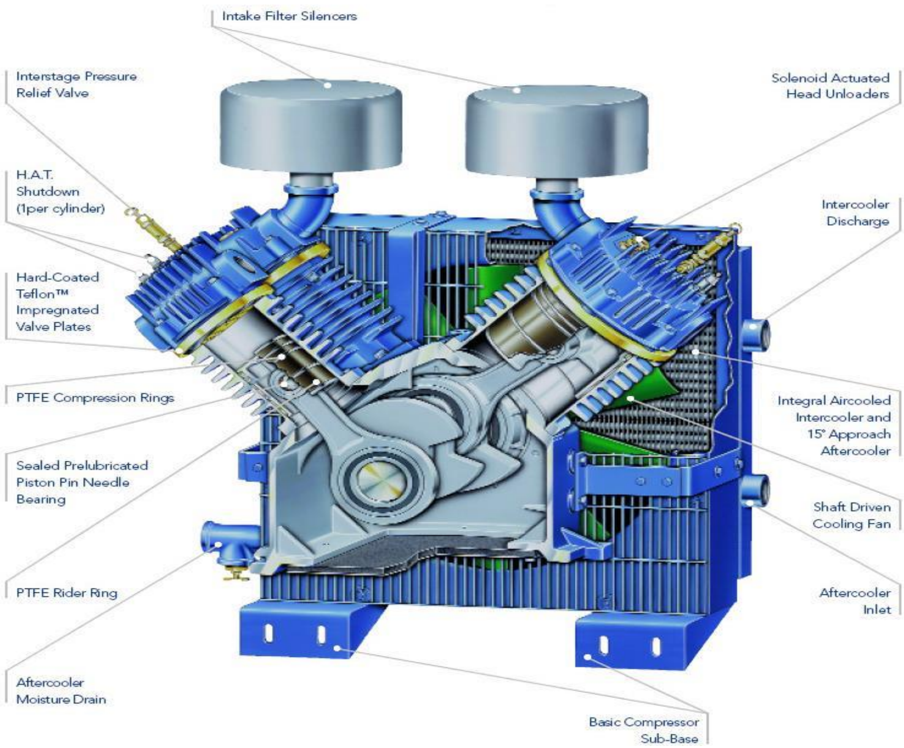

Figure 4. *Picture of a Reciprocating air compressor (Indotara, 2011)*

This is a type of a positive displacement compressor. This means that the pressure is increased by reducing its volume. These types of compressors often use a piston design, either working in single or multiple stages. If the compressor is multistage it means that the air is compressed in multiple stages to reach a higher pressure. These units are often constructed with one bigger piston that is used for the first stage of compression, which feeds a smaller one that compresses the air even further. This type of compressing is often used in smaller compressors were the need for airflow is quite small. Compressors of this type is used in a wide range of applications, and is the cheapest type to build, that is why almost every compressor for home use is a reciprocating type compressor.

2.1.2 Rotary screw compressor

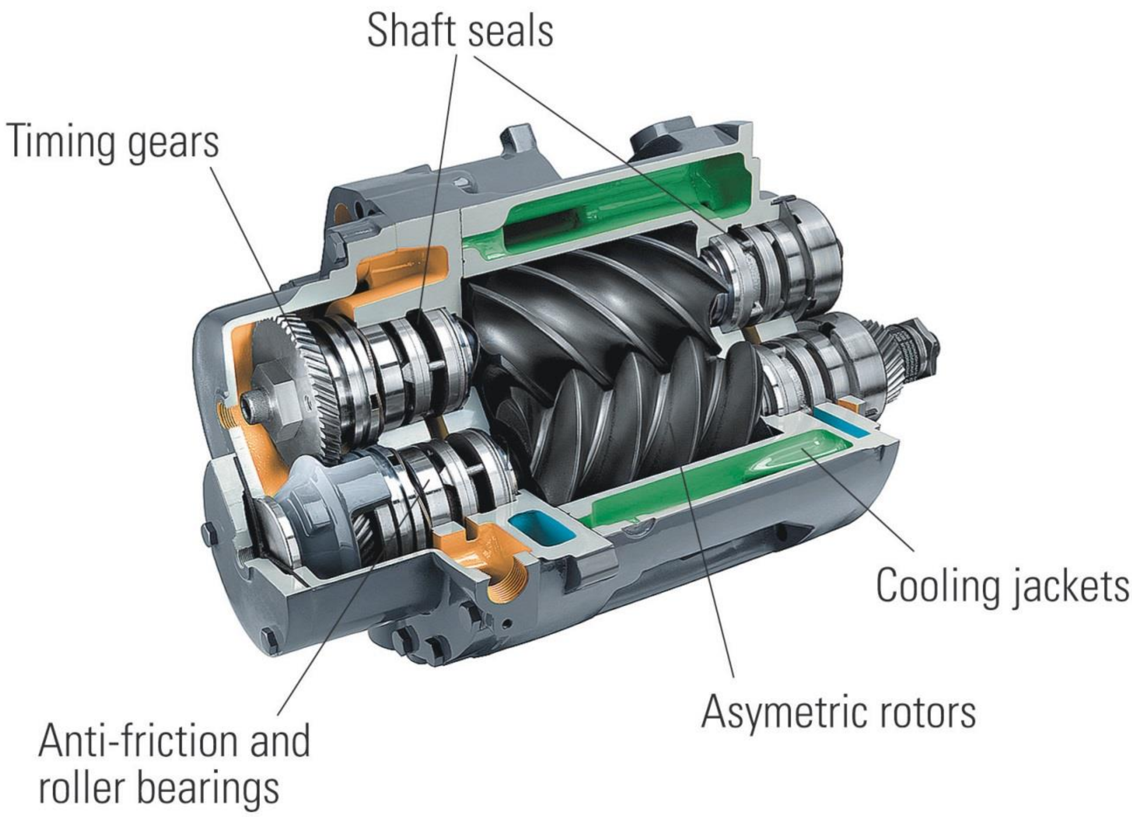

Figure 5. *Picture of a Rotary screw compressor (Indotara, 2011)*

The rotary screw compressor is also of positive displacement type, but use a screw instead of a piston. The most common types are helical or spiral lobe oil flooded screw air compressors. These compressors use screws that rotate and compress the air in between each other. These units are usually oil cooled internally, which assures that the air never exceeds high temperature and keeps the internal parts free from corrosion. The oil also has a sealing effect in between the screws. The pros with this system is the high flow capacity and smooth pulse free air output, there are also rotary screw compressors that are oil free by design. These units use specially designed air ends to be able to compress the air without oil in the compression chamber. The units also have a very long lifespan due to their simplicity and smooth operation.

2.1.3 Centrifugal compressors

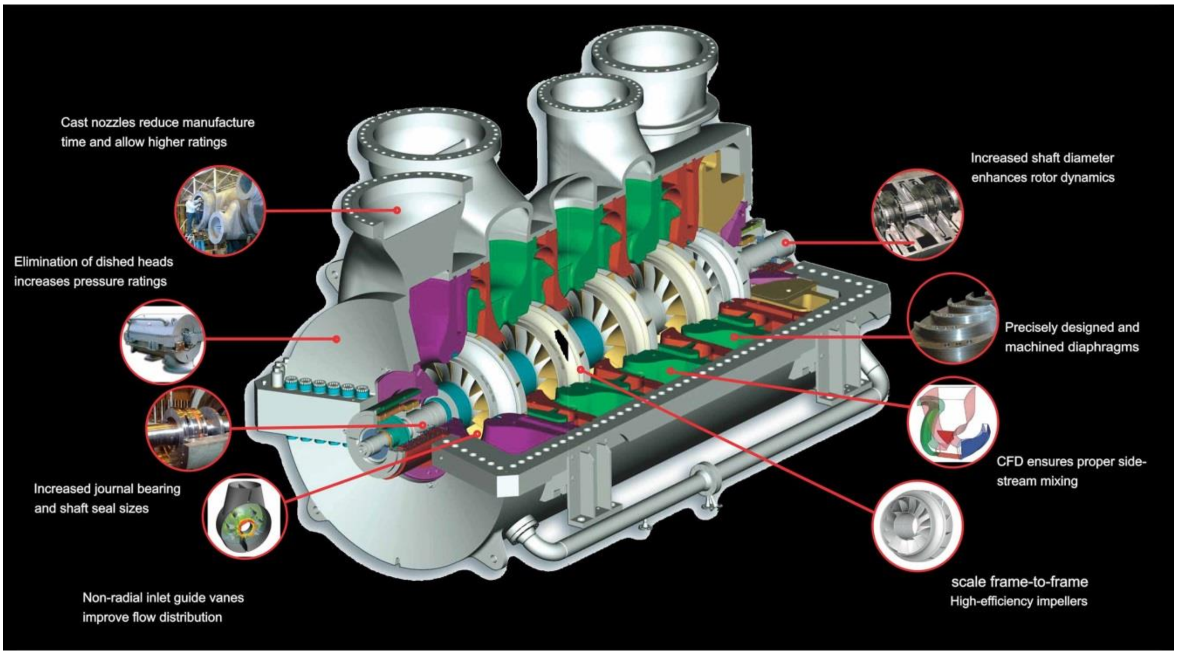

Figure 6. *Picture of a Centrifugal compressors (Yeganeh Rahavard Asia, 2016)*

This type of compressor is a dynamic compressor and uses a turbine or impeller that is spinning at high speed to compress the air. This is done by the angular momentum of the impeller. These units are used in applications where large quantities of pulse free air is required. The flowrate is controlled by adjusting the angle of the inlet vanes on the compressor, which will decrease the airflow. The advantage with this system is that the cooling and lubrication has no contact with the compressed air, which will guarantee oil free clean air.

(Own Conclusion)

(http://www.engineeringtoolbox.com/air-compressor-types-d_441.html)

2.2 Design of the 12-25

The Junair 12-25 is a compressor of piston type using two pistons, one for low compression and one to further compress the air to about 8-10 bar. The compressor using short stroke and to be able to flow enough air it has to be spinning at a high speed, this creates a lot of unwanted friction in a small area that will lead to a lot of extra heat. Therefore, the unit has to be well cooled and lubricated. The oil that escapes with the air will then destroy the cylinder sealings within the training equipment.

To meet these requirements, we will be using a 3-phase ac motor rated at 0,55 Kw, which will drive through a bevel gear to reduce the crank speed to our desired level, and also make it possible for us to mount the engine between the cylinders to reduce space. Using these components and using some small technics with sound isolation will get the compressor well under the noise targets.

The 12-25 has a max flow of 100 l/min, however this unit is only recommended to run in 30% of the total time because of the risk of overheating. Therefor our unit should be able to flow about 33 l/min constantly to have the same mean airflow as the 12-25 unit and satisfy the airflow needs. Because HUR wants to make the compressor as cheap as possible they wanted to use the same standard air cylinders that HUR uses in their training equipment as the compressor cylinders. These should have a long stroke because we want an area as large as possible for the heat to escape from. After some time, we decided to use cylinders with a piston diameter of 50mm and a stroke of 200mm, this will give us a minimum crank speed of about 23 rpm to get us to the desired airflow.

The reciprocating air compressor was considered the best alternative for our application, this was mostly because of the simple design and cheap building cost. Also the small need for airflow and the small size dials out the reciprocating compressor as the most suitable.

(JUN-AIR, 2016)

(Own Conclusion)

(http://www.jun-air.com/product_overview_quiet_air.aspx)

2.3 Isentropic compression

The formula for Isentropic Compression will be used for calculating the torque that is applied on the crankshaft, because of the friction between the air molecules, the compression will generate heat that will further increase the pressure acting on the piston**.** Below is a copy from the

We begin our derivation by determining the value of a factor which we will need later. From the definitions of the specific heat coefficients, the specific heat at constant pressure **cp** minus the specific heat at constant volume **cv** is equal to the gas constant R:

cp - cv = R

and we define the **ratio of specific heats** to be a number which we will call **"gamma"**

gamma = cp / cv

If we divide the first equation by cp, and use the definition of "gamma" we obtain:

R / cp = 1 - (1 / gamma) = (gamma - 1) / gamma

Now we use the equation we have derived for the entropy of a gas:

s2 - s1 = cp ln(T2 / T1) - R ln(p2 / p1)

where the numbers 1 and 2 denote the states at the beginning and end of the compression process, **s** is the entropy, **T** is the temperature, **p** is the pressure, and "ln" denotes the natural logarithm function. Since there is no heat transferred into the cylinder and no other losses, the change in entropy is zero. Then the equation becomes:

cp ln(T2 / T1) = R ln(p2 / p1)

We divide both sides by "cp" and take the exponential function of both sides (this "un-does" the logarithms).

T2 / T1 = (p2 / p1) ^ (R / cp)

where the symbol "^" denotes an exponent. Now we substitute the expression for "R / cp" to obtain:

T2 / T1 = (p2 / p1) ^ [(gamma - 1)/gamma]

During the compression process, as the pressure is increased from p1 to p2, the temperature increases from T1 to T2 according to this exponential equation. "Gamma" is just a number that depends on the gas. For air, at standard conditions, it is 1.4. The value of (1 - 1/gamma) is about .286. So, if the pressure doubled, the temperature ratio is 1.219. The key point here is that we have a function that relates the temperature change to the pressure change during a compression process.

We can use the equation of state to derive the relation between the volume change and the pressure change. The equation of state is:

p * v = R * T

where **v** is, the specific volume occupied by the gas. If we substitute this expression for **T** into the temperature equation, we obtain:

(p2 * v2) / (p1 * v1) = (p2 / p1) ^ [(gamma - 1)/gamma]

Multiply both sides by (p1 / p2) to get:

v2 / v1 = (p2 / p1) ^ (- 1/gamma)

p2 / p1 = (v1 / v2) ^ (gamma)

The quantity **(v1 / v2)** is the ratio of the volume at state 1 and state 2 and is called the **compression ratio**. For **v2** less than **v1**, the pressure **p2** is greater than **p1**. With this equation, we can determine the change in pressure for a given compression ratio. And using the previous equation we know the change in temperature as well. The value of the compression ratio is a function of the design of the bore and stroke of the piston.

(https://www.grc.nasa.gov/WWW/K-12/airplane/compexp.html)

3 CALCULATIONS AND THEORY

In the calculations chapter I am going to explain all the calculations that have been done during the construction the compressor. First, I will go through all calculations needed for the torque calculations and after that I will continue with temperature calculations, and in the end I will finish with the cost analysis.

3.1 Piston location

One of the most important things about the machine was that it should be quiet and without vibrations. That is why it is really important to make the transactions of the forces which are produced as smooth as possible. This is done by making all the forces overlap each other. Because the compressor is designed to use two double acting air cylinders for each crankshaft revolution there will be four compressions for each rotation of the crankshaft. In the beginning the force acting on the crankshaft will increase slowly and then rapidly rise until the max pressure of about 8 bars is reached. It will then stay at the same force until the pressure is suddenly lost at once as the pressure is released. When the piston in the cylinder turns back the other way and begins a new compression of air the other way, it means that the pressure change in the cylinder can easily be calculated using the formula for adiabatic compression and the force is then calculated using the area of the piston used in the compressor. All these calculations were made in Excel where you are able to calculate the force acting on the crankshaft for each degree in the compression stage. This means that we can easily calculate the total torque on the crankshaft caused by the compression. By changing the angle between the two air cylinders we can smoothen out some unwanted torque peaks and this way get the smoothest operation combined with the lowest noise and the least wear on all the moving components.

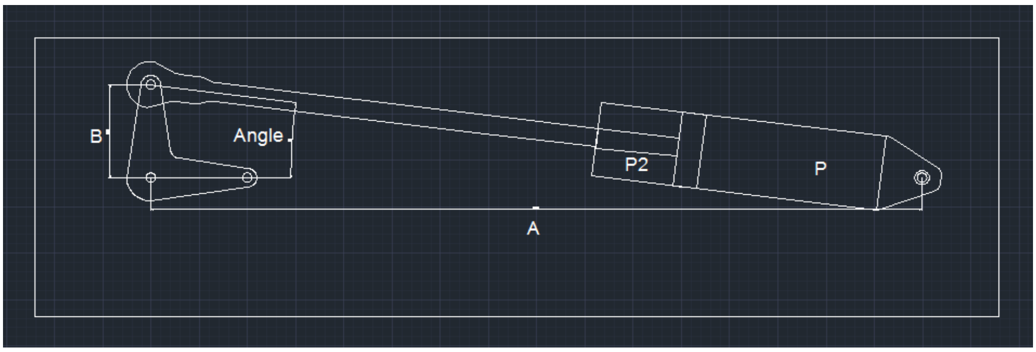

Figure 7. *Drawing of the compressor's rotating assembly.*

The first thing I had to pay attention to was the specs for the air cylinder that would be used in the compressor. In this case, it was a Festo 50/200 with a piston diameter of 50 and a stroke of 200mm. When we know what the cylinder specs are, it is important to measure the distance of the cylinder when it is totally decompressed and then add half of the stoke for the cylinder, in this case 100mm. This is what the distance between the attachment of the cylinder to the center of the crankshaft should be. When the crankshaft is constructed, it is important to take notice to some small errors in the manufacturing of the components so therefore the stroke of the system is limited to 198mm, which leaves a safe margin of 1mm to each side. This will guarantee that the piston will not reach the bottom at either end of its rotation. In the picture above this distance is marked with the symbol A. When we know what distance A is, it's possible to calculate the length of the cylinder at every angle of the crankshaft, this is essential when we need to know the actual position of the piston inside the cylinder. The formula for the length of the cylinder would in this case be:

$$\mathrm{Lc} = \sqrt{((A-(\cos\alpha * B))\text{^}2 + (\sin\alpha * B)\text{^}2)}$$

A and **B** are marked in the drawing above and the angle α is the angle between the line from center of crankshaft to the end of the crankshaft arms. When you are calculating the length in the bottom half of the rotation you need to subtract from the length **A** but when you are calculating in the top half you need to add to the distance **A.** When this length is subtracted by the length of the cylinder at the bottom, you will get the distance from the bottom to the place where the piston is located with this angle of the crankshaft. This gives us a length of 106,1 mm.

3.2 Pressure calculations

Now when we know the piston location inside the cylinder at any given angle we are able to calculate the pressure caused by the adiabatic compression. This is done by using the formula for adiabatic compression.

$$P = \left(\frac{v1}{v2}\right)^{1,4} * sP$$

P is the pressure after our adiabatic compression, v1 is volume in the starting point, v2 is the volume at the end of our compression, the constant 1,4 is the isentropic constant, and sP is the starting absolute pressure usually about 1,013 mBar. We will start by calculating the volume at the beginning of the compression. First, we calculate the area of the piston and then take it times the full stroke of the cylinder, which in this case will be 200mm and will give us a total volume of 0,39 dm^3. Now we have to calculate the Volume at the end of the compression, and for this we need our piston calculations. We start by subtracting the length that the piston has travelled from the total stroke, this gives us a stroke of 93,9mm. When this is multiplied by the area of the piston it gives us a volume of 0,18 dm^3. After this we should have all the variables needed for the formula.

$$P = \left(\frac{0,39}{0,18}\right)^{1,4} * 1,013 = 2,99bar$$

Now when we know the pressure at any given angle of the crankshaft, we are able to calculate the force that the cylinder is generating. The cylinders that we will be using have a piston area of $20cm^2$, and because 1 bar equals 10N/ cm^2 we will get the force by multiplying the area with the pressure. In our case this gives us a force of 598N. On the graph below you can see the force created by the pressure in the cylinder for each degree of crankshaft turn. As you can see there is not much happening in the first 90 degrees, but after this the pressure rises quickly which makes the force increase. The reason why the force immediately stops at about 1600N is that the pressure is restricted to about 8 bar, this causes the force to stay at 1600N until the piston turns back the other way to start a new cycle.

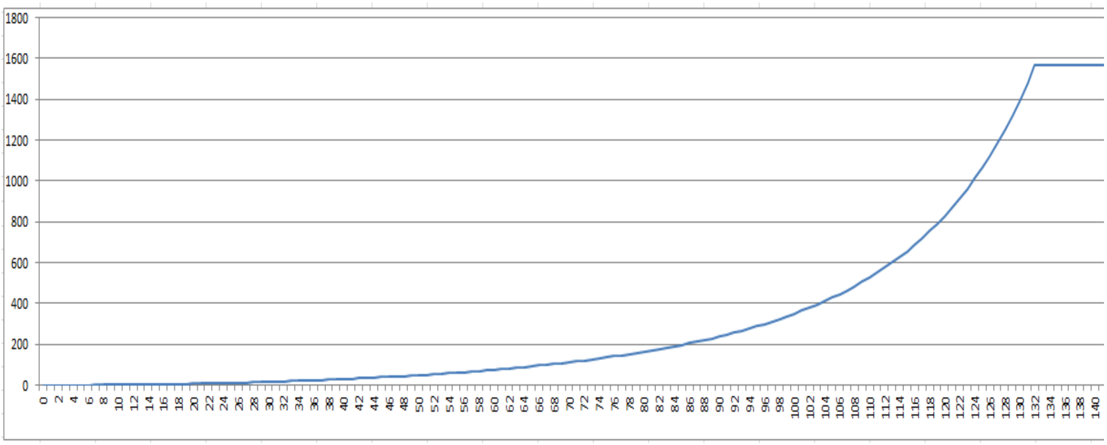

Figure 8. *Chart of Force produced by the piston in relation to crank angle.*

After this we are able to calculate the torque that is created on the crankshaft by the force from the cylinder. It is done by looking at the perpendicular force to the crankshaft. This is done with calculation below.

$$T = (sin\alpha * L) * F$$

T is the torque on the crankshaft, sinα is the angle between the cylinder axis and the axis from cylinder attach point to the rotating center of the crankshaft, L is the length from the rotating point for the crankshaft to the attach point of the cylinder, and F is the force produced by the pressure inside the cylinder. In our case the perpendicular distance is 99mm, which equals to 0,099m, to get the torque we have to multiply this distance by the force created by the cylinder, which was 598N. This equals a torque of 59,2Nm. Because our compressor will be limited to about 8 bars, we are interested to know what kind of torque will be produced on the crankshaft when the two cylinders are working together and what the optimal angle between these two cylinders are. To do this we need to make a model for one cylinder for a compression from start to finish and with a limitation of 8 bars of pressure. Then we take these models and space them at different angles and calculate the total torque produced on the crankshaft. The easiest way to do this is to make the calculations in Excel and simulate one crankshaft rotation and let Excel find the maximum and the minimum values. When this is done, we can make a graph of the values and see if everything looks alright.

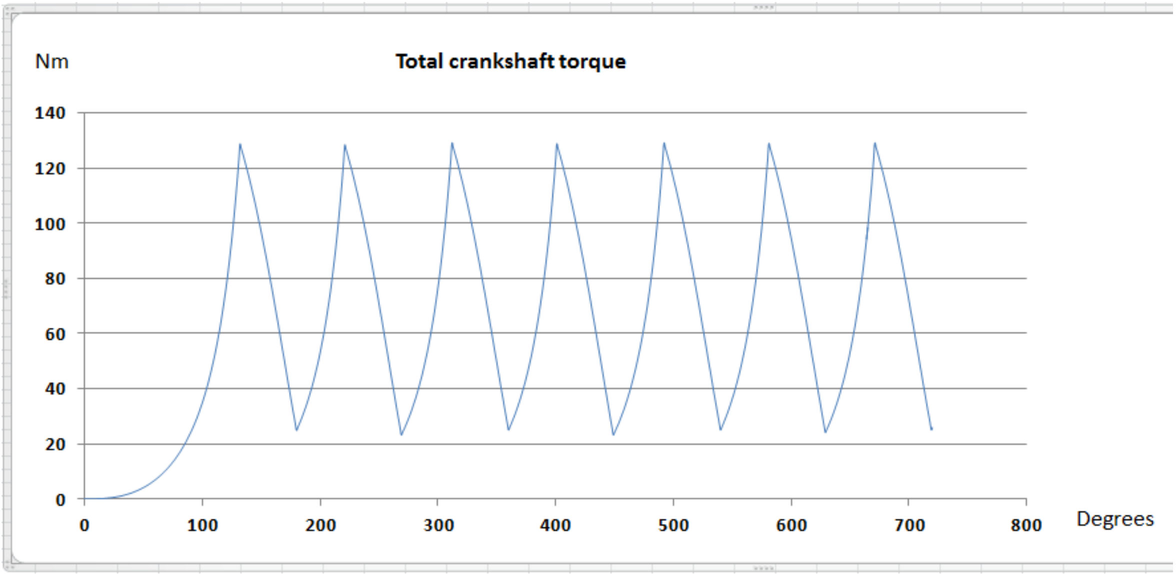

Figure 9. *Chart of the crankshaft torque I relation to the crank angle.*

On the graph above you can see that when the compressor is working against a maximum pressure of 8 bars, this gives us a varying in torque that range from 25Nm to about 127Nm. This is useful information because now we are able to choose the smallest possible bevel gear for our compressor and in that way, we are able to save a lot of money, because the bevel gears increase in price very rapidly when the size increases. One other thing that was discovered with these calculations was that the optimal angle between the cylinders is 90 degrees, this was discovered by calculating the total torque created by the cylinders and then spacing them with different angles. The smoothest operation was found at 90 degrees spacing.

3.3 Temperature

Heat caused by adiabatic compression is one thing that may give us problems if we don't pay attention to it. It means that there is no heat exchange with the outside world during the compression and the friction of the air will make it extreamly hot if the heat has no way to escape. In reallife you always have some degree of heatflow to the outside world, but since the compressions occuring inside our compressor are quite fast we can asume that there is not enough time for the heat to escape. This means that if no extra coolig is applied the sealing in the cylinder may be destroyed. To prevent this from happening, the compressor will be constructed as a box, and a small fan will be mounted at the top and draw fresh air around the working cylinders, which will help to keep the cylinders cool. The cylinder's large surface will also play a huge role for the cooling of the cylinders.

Besides the the heat created by the compression of the air, there are two other main components in the compressor that also create heat. The first one of them is the electric motor, this unit with its rated power of 0,55kw only has an efficiency of about 90%. It means that 10% of the energy used by the motor will escape as heat, which equals a heating power of 0,055kw. The second component in the system that creates heat is the bevel gearbox, wich has an efficiency of about 95%. This type of gearbox have some advantages but also some drawbacks, one of the advantages is that it is possible to mount the engine in the middle in between the two cylinders, which saves space. The second advantage is that the wormgear is able to rotate the helical gear but the helical gear is not able to rotate the worm gear, this means that even if the power to the engine is cut in the middle of a compression, the cylinders will stop and stay in the position they had at the time the power was cut of even if the cylinder are full of air.

Except the torque on the crankshaft there is still one thing that we are interested to know, and it is the temperature created by the adiabatic compression. If this temperature is too high the sealings inside the cylinder may get damaged. To be able to calculate this we have to use the formula for adiabatic compression, and calculate the compression ratio or what the volume after compression will be if the pressure after compression is 8bars. When we look at the calculations we will see that the pressure will reach 8 bar at 0,156 dm^3. With this information, we are able to calculate the temperature by using the formula below.

$$T = \mathrm{sT} * \mathrm{rC}^{0,4}$$

T is the temperature after compression, sT is the starting temperature in kelvin, and rC is the compression ratio. The compression ratio can be calculated from the volume change, $0{,}39dm^3/0{,}156dm^3$, which gives us a compression ratio of 2,5:1. Now we are able to calculate the temperature after compression, this gives us a temperature of 430kelvin, which is equal to 157$°C$. This shows why it is important to have good cooling for the cylinders to make sure that the heat has somewhere to go and will not be able to destroy the components. In reality the air will never reach this temperature as long as the cylinders themselves are kept cool. Now when we know how much heat is generated by the compressor, we are able to estimate the heating power of the system by calculating the heating power from the compression and the power from the engine and gearbox. First, we will calculate the heating power of the adiabatic compression. For this we need the specific heat value for the air, which is 1,0035 $J * g * K$ and the mass of the air that is getting heated. This can be calculated using the volume of air that the compressor is flowing per minute, which is 33 l/min at 23rpm. This gives us a flow of 0,55 l/s. When we take this times the density of the air, which is 1,225 kg/m^3, we will see that this equals to a mass airflow of 0,67 g/s. The last thing we need to know is the temperature difference between the beginning of the compression verses in the end of the compression. We assume that the starting temperature is 22 ℃. This gives us a temperature difference of 135K. We have everything we need to know to calculate the heating power of the compressor, and the formula we are going to use is:

$$SHV * Delta\, T * M$$

This gives us a heating power of 0,090Kw. If we add this to the heat created by the engine 0,055Kw and the gearbox 0,02475Kw we will end up with a total heating power of about 0,169Kw. With this information, we can choose the right cooling fan for our compressor. If we assume that all of the cooling air will reach the max temperature of the component, then we will only need a really small fan, but it is really difficult to know if the components receive enough cooling, so we had to do a temperature test to see how much cooling was needed.

3.4 Cost calculations

		1 Series	10 Series
		€	€
Material (s235)		33	29
Machining			
	Cutting(laser)	25	13
	Bending	30	15
	welding	20	12
	Paint (powder)	50	19
Machining total		125	59
Gearbox + Accessories		400,136	363,76
Engine (0,55KW/3000)		109,725	99,75
Cylinders (Festo 50/200)		65,96	65,96
Accessories		50	50
Assembly		15	15
Total price / piece(ALV 0)		923,821	741,47

Figure 10. *Table of cost calculation for the compressor.*

One of the most important things with the compressor was to keep the price down. This was also one of the most difficult tasks with the project. As you can see from the cost calculations above, there is one thing that stands for more than half of the cost, and it is the gearbox, which we should be able to cut a lot of cost from in the future by ordering large quantities. One option when trying to decrease the gearbox price would be to decrease the torque that is being developed, this could be done by changing the 50mm in diameter cylinders for some smaller 32mm ones. This would allow us to buy a smaller gearbox with a lower torque rating, which is much cheaper and would also reduce the size of the whole package. All the material work for the machine will be done by Oy Hiltop Ab, which is a sub-supplier company that supplies all the parts for HUR and is specialized in laser cutting and bending. As you are able to see from the picture the machinery and material costs will decrease relatively to the quantity. The air cylinders and all the supporting pneumatic parts will be supplied by Festo, which is a big manufacturer of pneumatic components. HUR is buying about 200 cylinders a month from Festo and therefore have a big discount on these parts. If we in the future would find a need for more airflow there is a possibility to get more heat resistant air cylinders from Festo. The cylinders that are used today are rated at a maximum of 80℃ but there is a possibility to get cylinders which are rated up to 120℃. This would give us a possibility to increase the rotational speed, and by that gain more airflow. However, this would also create an increase in costs.

4 TESTING

In the testing chapter I am going to go through all the tests that were done during the development of the compressor, including temperature testing and airflow testing. I am also going to talk about all the equipment that was used.

4.1 Temperature measurement

When air is compressed the internal friction of the air will make it really hot. Depending on the surrounding material, temperature and outside cooling the temperature can vary a lot. The higher the compression ratio, the higher the temperature of the compressed air will be. If the mass of the air is increased, the heating effect of the compression will also increase. One of the biggest concerns we had about this type of compressor was the fact that it might get too hot under continuous operation before we got up to our desired airflow. If the compressor is run only at short periods of time there is no need for extra cooling, because all the heat created will be absorbed by the surrounding material, such as the cylinders, the engine core, and the frame of the compressor. But if the compressor will be run for extended periods of time the surrounding components will get hot and will not be able to absorb any more heat. Therefore, it is important to run the test for a really long time at maximum load and make sure that the temperature increase has stopped before the test is declared done.

4.2 Equipment used in the test

To be able to do an accurate temperature mesurement on the compressor we needed a small sensor that would give a reliable result. For this task we chose the LM235. It is an analog output termistor type temperature sensor that has an operating temperature range from 40℃ to 125℃ and has an accuracy of (+/-) 3℃. The sensor outputs an linear current from 0,4mA to 5m. The curve for the sensor can be seen on the graph below.

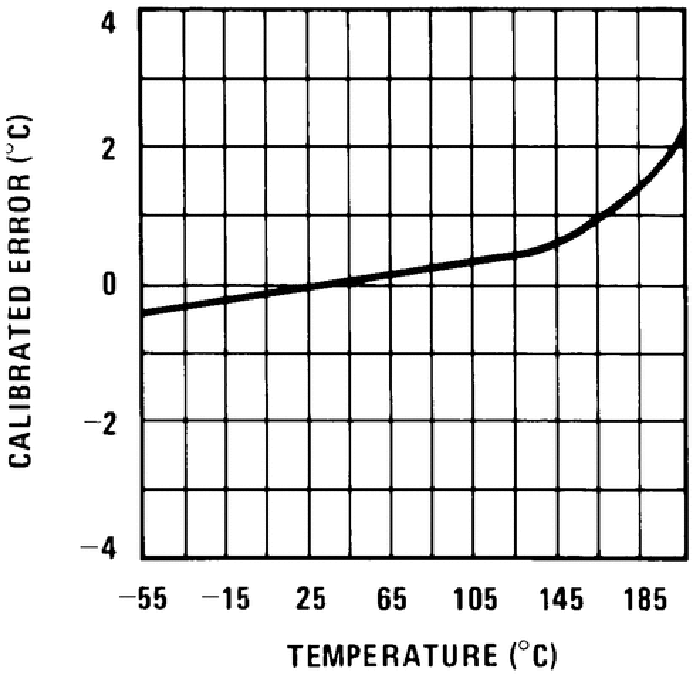

Figure 11. *Graph for the LM235 temperature sensor.*

4.3 The test

We decided to do the temperature test on a prototype that HUR had built a few years ago, with open cylinder and engine without external cooling equipment. The prototype used two 50/200 air cylinders that were mounted to a 1 phase 0,37kw engine with a rotation speed of 1500rpm. This engine was mounted to a gearbox with a gearing of 100:1. This gave a rotation speed of 15rpm. Our goal was to reach an airflow of 40l/min and the plan was to swap out the old engine and change it for a three-phase engine and start with low speed and slowly dial it up until we reached our maximum allowed temperature using a frequency converter. But, we had a spare 3 phase engine with a rotational speed of 3000rpm, which we knew would get us close to our airflow goal, so we changed the engine and did our first test without a frequency converter. The temperature sensor model LM235 was mounted on our prototype at the end of the cylinder where we assumed would be the hottest spot. The pressure was cranked up to 10bars and the temperature measurements were started. In the beginning the temperature rose quickly as expected and after some time the temperature increase slowed down and came to a stop at a mean temperature of 57 degrees Celsius. The rotational speed which led to this temperature was 29 rpm and an airflow of 42 l/min. This temperature was achieved after little over two hours of testing. It was done in a closed room with no airflow that could cool the compressor and with an ambient temperature of 20°C. We did 15 of these tests to be sure to get the most accurate results as possible. When all the tests ware done, we assumed that if the compressor only reached a temperature that was 80% of the maximum temperature without cooling, like it did during our testing, there would only be need for a small fan that would transport all the heated surrounding air away. Therefore, we chose a small fan and mounted it at the top of the compressor to support the cooling. With additional cooling capacity in the future, there is a possibility to increase the airflow of the compressor so that it could be used in bigger installations.

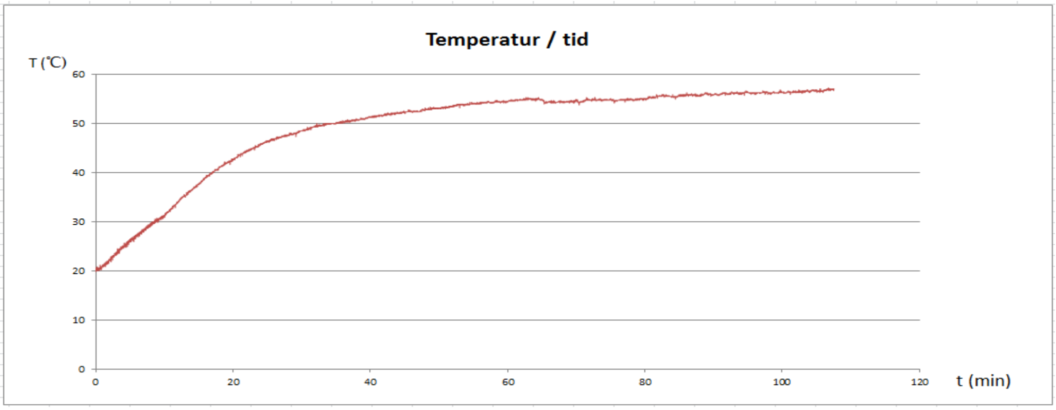

Figure 12. *Graph for the temperature in relation to time.*

The fan that was chosen for the compressor is a 120mm, 230v and 20w of power. This unit has a flow of 52l/min which equals to about 0,063 kg/s of airflow. The small unit is very cheap and really efficient, and should also be very reliable.

4.4 Airflow testing

To know what the actual airflow need was, we had to test this at an actual gym. The test was done by mounting a reley switch which was connected to a computer that registered when the compressor at the gym was on. The compressor at the gym had an airflow of 50 l/h and an air reservoir of 20 l. The unit worked in a pressure range from 8-10 bars, it let the pressure drop until 8 bars and then it took the pressure up again to 10 bars. By calculating the times the compressor had been active during the day of testing and knowing the volume of the air reservoir we could estimate the needed airflow. During our day of testing, the compressor had been active only 4 times, by taking this times 20 l and then by 2 for the pressure from 8-10 bars we could calculate that the needed airflow was about 160 l, which equals about 4 minutes of production for our unit.

5 DESIGN AND CONSTRUCTION OF THE HUR COMPRESSOR

In this chapter I am going to explain what has been done to the design and construction of the compressor. I am going to break down the compressor in smaller categories and explain the details.

5.1 Detailed construction

The key elements for the construction are that it should be very durable and stand the test of time, and at the same time it should be made as cheap as possible to assure that HUR will get a profit as big as possible for every compressor they sell. S235 was considered the best alternative for this construction. This is a construction steel with a tensile strength of 235Mpa. Some of the inner parts would use galvanized steel to remove the need for painting, and the casing would use the S235 coated with powder paint, and some of the outer parts would use veneer to give the compressor a more sophisticated furniture look. HUR had their own thoughts about how the compressor should be constructed and this was with the engine and bevel gearbox in the middle and two cylinders on each side. This is the most compact construction and also the simplest way to do it. All the metal parts will be drawn in Autocad and then cut into shape with a laser cutter. After this, some of the edges need to be bent and some of the holes need to get threads. Next, some of the parts that need paint will get painted and the other parts will go straight to HUR for assembly.

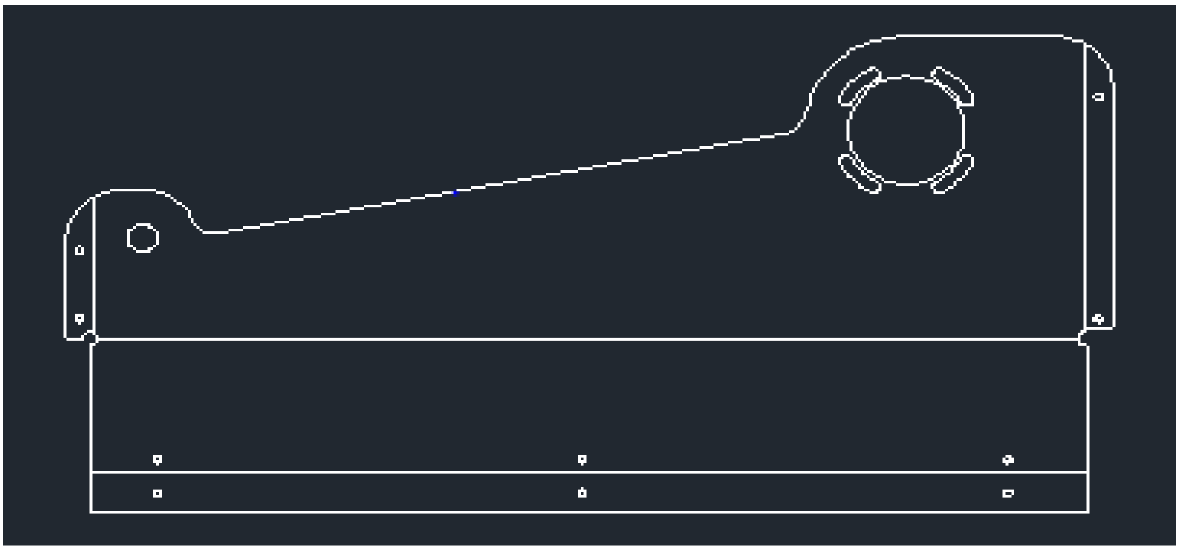

Figure 13. *Drawing of the frame of the compressor.*

The frame which is seen on the picture above will be made of galvanized s235 2,5mm as mentioned, and will be the main component that adds the strength and rigidity to the construction. At the left, we see the attachment points for the cylinders and on the right, we see the holes for the gearbox. All the extra lines that are seen on the picture are bending lines, where the sheet is suppose too be bent. In the middle, we have the main bending point, which adds the most rigidity, it will be bent 90 degrees outwards. The holes that are seen on the bottom and on each side of the picture will get 6mm treads so that we are able to attach the casing to the frame, all of these will also be bent 90 degrees outwards. Two of the parts will be made and one will be the mirror image to the other one. The gearbox will then be mounted in between these two plates, as seen in the picture below.

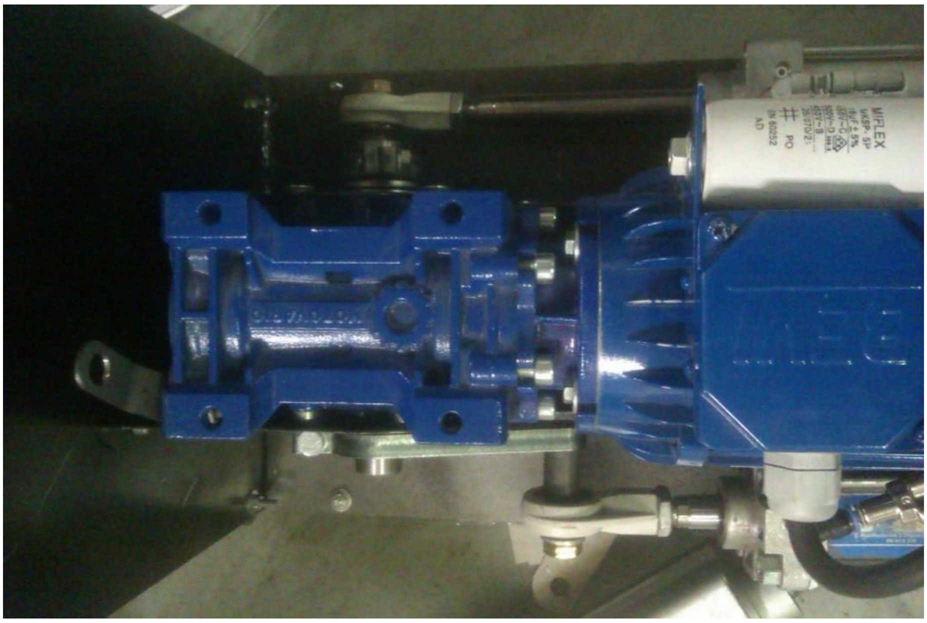

Figure 14. *Picture of the bevel gear used in the prototype.*

The cylinders will be mounted on the outer side of these pars with one end attached to the frame on a bearing and with the other side attached to the crankshaft, which will be attached to the gearbox. The attach point for the cylinders was changed from the prototype to be put as near as possible to the bending point for the sheet. This adds extra rigidity and will prevent the compressor from rocking as the forces change from one side to the other. This is why the crankshafts rotational center and the attach point of the cylinders sits at a slight angle. When the compressor is working, it will see constant change in forces between 0 and 400N from side to side. This will put a lot of stress on all the components and we have to make sure that the construction stays together even after many years of hard work.

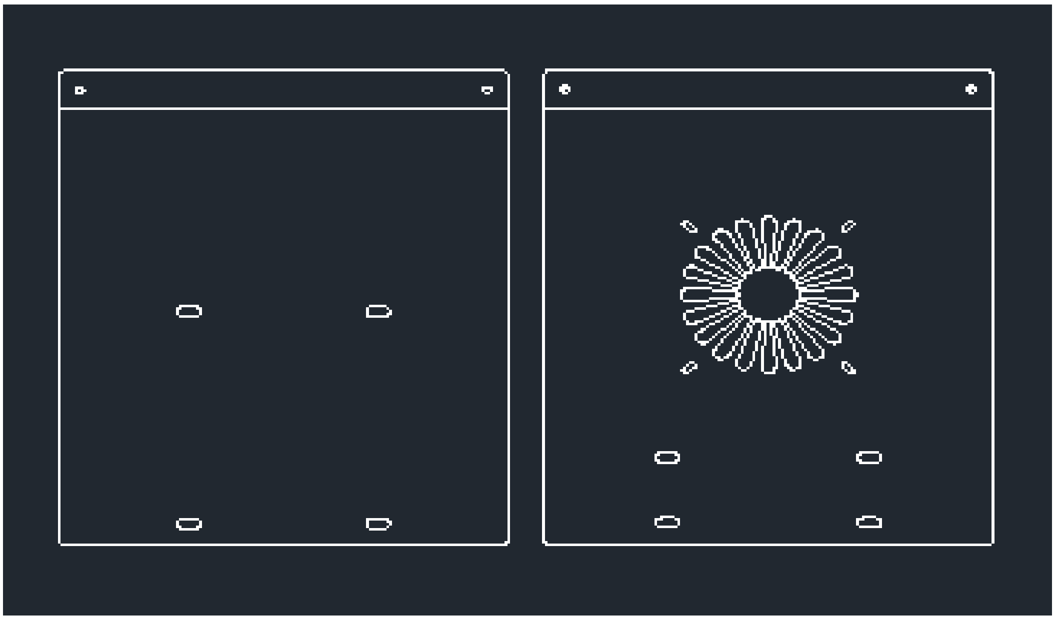

Figure 15. Drawing of the end plates for the compressor.

On the second picture you can see the top and the bottom of the compressor. The top plate will be fitted with the cooling fan that will draw cool air in from the side and create an airstream by the cylinders and gearbox. These two plates will be mounted after the frame is applied and will also help with rigidity. These will be made out of 1,5mm thick s235 and be powder painted.

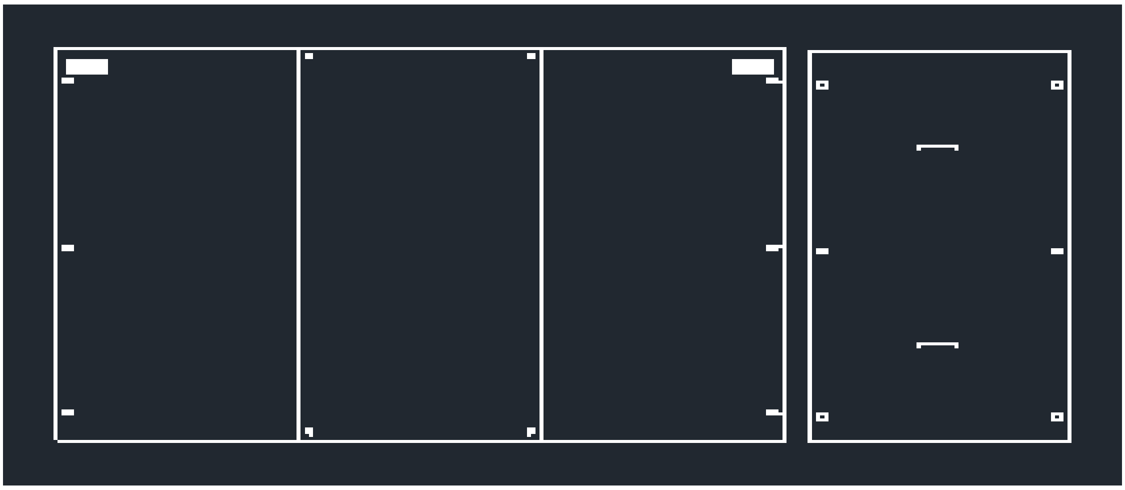

Figure 16. Outer covering for the compressor.

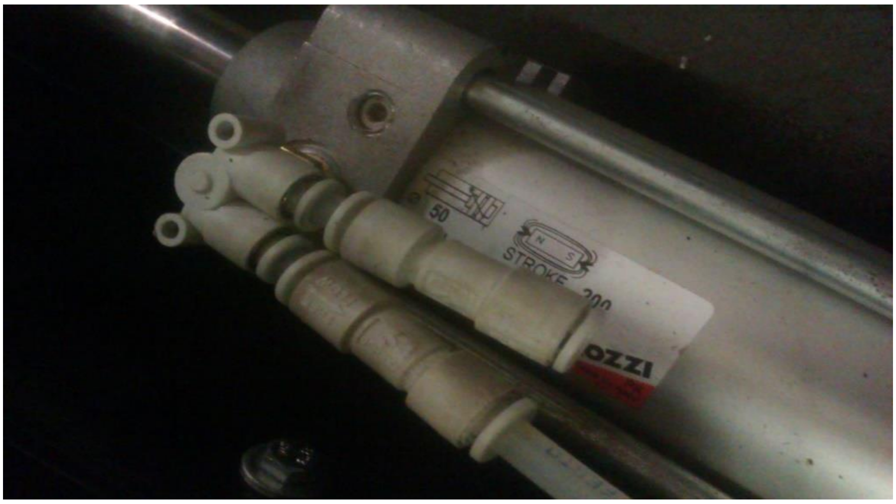

Figure 17. Drawing of the bottom plate and the sides of the casing.

In figure 18, you can see all the four sides of the compressor. The part on the left, which is the biggest part in the construction will be made out of 1,5mm thick s235 and be bent two times so that it will cover 3 sides. On the top of the picture you see the airinlets for the cooling air, which will be located on the bottom sides of the compressor. On the right of the picture you can see the last sheet that will be covering the last side of the compressor. This side will also be fitted with the airreservoir that will fit between the frame under the engine and gearbox. Both these parts will be screwed to the frame.

On the picture below you can see the arrangement for the crankshaft, with both cylinders spaced 90° apart as this was tested to be the angle that gives the smothest torque on the crankshaft. You are also able to see the attachment of the gearbox, which sits inbetween the frame and connecting both of the halves together.

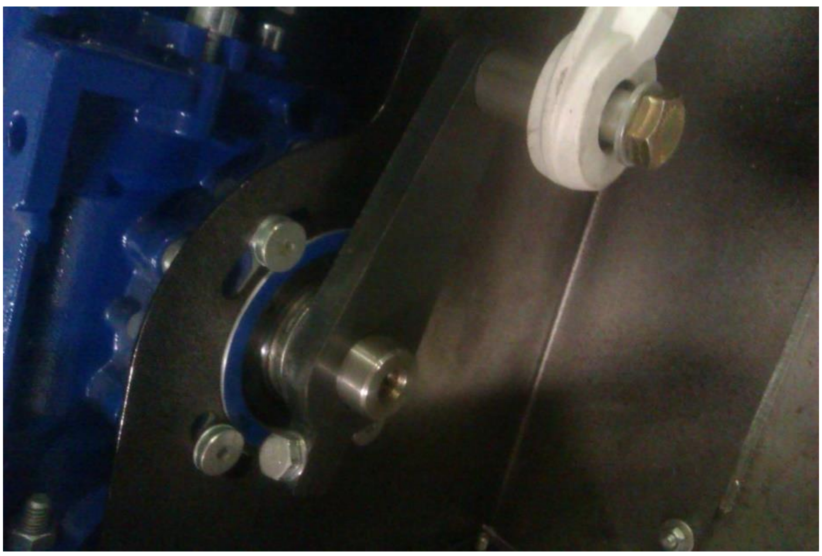

***Figure 18.** Picture of the crankshaft.*

5.2 Assembly

As mentioned, the compressor will be assembled side by side with the other HUR training equipment, and special notice have to be taken to assure that the compressor is as easy as possible to assemble. Therefore, as few as possible of the parts in the construction will be welded, which gives the assembler more room to work around the machine and makes it easier to pull all the cables and air tubes in the compressor. One man will be responsible for each machine from start to finish of the assembly, which assures that all the machines are assembled in the same way and an even quality can be guaranteed.

5.3 Accessories

There are a lot of small accessories that are needed for the compressor to work properly among these are all the valves, the pressure switch and the fan. The prssure switch in the compressor has the task to stop the compressor when the maximum desired pressure is achived, and start the compressor when the minimum pressure is achived. The value between these is called the threshold value, usually this is about 2 bars on most compressors. This value will stop the compressor from stopping and starting all the time if the pressure is on the limit of the activation pressure. The pressure switch also has to unload all the cylinders from pressure. This is done by mounting a one way valve on the inlet to the air tank which assures that no pressure is able to escape back to the cylinders. After every stop the pressure switch then opens a valve that lets the air that is trapped between the cylinders and the inlet one way valve out thus unloading the cylinders. This assures that the compressor is able to start its work from zero load with no risk of burning the engine. Other parts used in the compressor is the cooling fan , this fan is coupled to the same pressure switch which always turns the fan on when the compressor is running. The valve arrangement on the compressor is very simple and only consists of one way valves, a one way valve is a valve that only accepts an airflow in one desired direction, and will shut immediately if the air wants to go in the other direction. With two of these mounted on every cylinder end and one at the inlet of the air reservoair makes a total of 9 valves per compressor. The use of only one-way valves make the risk of failure much lower and the design much cheaper. On the picure below you can see the construction of a one-way valve.

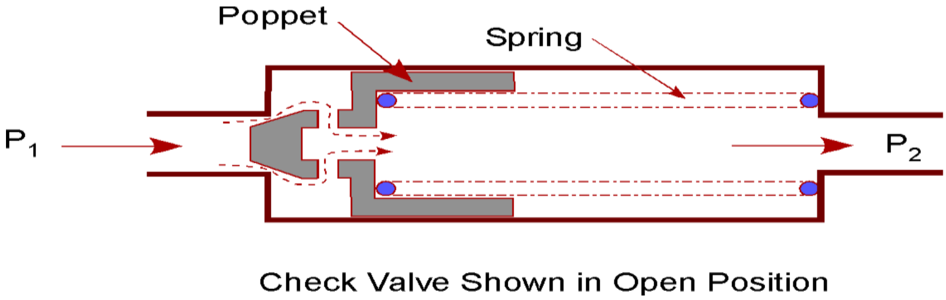

Figure 19. *Explanation of a one-way valve. (Design Aerospace, 2013)*

6 RESULT DISCUSSION

The result of this project is a new product that HUR can use in their own installations or sell as an independent product. This work also includes calculations that are necessary for the development of a cost effective and durable product. With the use of the excel program HUR is able to shortly calculate the number of cylinders needed and what the best combination of gearbox and cylinder would be. This program could be completed with prices for the components which would make it very useful tool. With all this research done in this thesis HUR can easily develop the compressor without making any bigger mistakes, and without the need of trial and error methods.

Input

Amount of cylinders	4
Rod radius (dm)	0,1
Cylinder radius (dm)	0,25
Stroke (dm)	2
Rotational speed (Rpm)	45
Length from Cylinders to crankshaft centre (dm)	3
Atmospheric pressure (bar)	1,013

Air density (Kg/M^3)	1,2
Specific heat value (J/g/℃)	1,005
Max pressure (bar)	10
Starting temperature (Celcius)	22

Output

Airflow (l/min)	64,998
Rotational speed (Rps)	0,75
Heating power (Kw)	0,34915
Max temperature (K)	562,397
Max temperature (celcius)	289,247
Volume/ Cylinder (l)	0,3925
Total Cylinder Volume (l)	1,4444

***Figure 20**. (Calculator tool for cylinder airflow in Excel)*

The Excel program that is used for the cylinder calculations can be seen on the picture above. The program was ordered by HUR as a part of the project, because it was very important that there would be a possibility to improve upon the compressor in the future, and a program of this kind would make this a lot easier. The program uses all of the calculations made for the compressor to make a tool that will make it easier to put together a combination off different parts and quickly see the outcome. The tool takes to account the dimensions of the construction to calculate the optimal smooth operation. The tool makes it is easy to see what happens with the torque and total airflow if the cylinders are changed. It will also draw a graph of the force created by the pressure and also the torque. This Program has been a very efficient and useful tool when different possible combinations have been gone through, and will most likely be used frequently in many years to come to find the best possible solutions. The program can also be improved in the future if there is something that is considered useful and is still missing from the current program.

6.1 Final discussion

In the discussion, I am going to talk about the project in general, what went well and what could have been done better. I will also compare the result of the project with the purpose.

The project has been very interesting and I have learned quite many new things about pneumatics. Sometimes in the beginning, there was a lack of communication with the company and the project was kind of missing it`s red string. But the issues were sorted out quite quickly after the start. The biggest concern about the project was lack of time, with this kind of project that needs a lot of communication and physical attendance at the company one day a week is not enough, especially when the company that you do the project for is about 2 hours away by car. This led to a lot of dead time when I was not able to work on the project because of lack of instructions and answers for critical questions. These problems had to be sorted out on weekends and led to a lot of problems because the company was usually closed during the weekends. The things that went good were all the calculations for the rotation assembly and also the cost calculations. It was because these could be done on my free time without the involvement of the company.

With this newly developed compressor HUR is able to end their dependency on other manufacturer’s compressors, they are able to cut the price for their training equipment packages or get a bigger deposit for their machines. They are also able to have a compressor that is customized for their needs. In the future, there are plans to implement a system to the compressor that measures the operating time, temperature and pressure and then adjusts the operation for maximum possible efficiency. This model will be online all the time and the information would be possible to follow in reality from anywhere in the world. This would make it possible for HUR to see how effectively their machines are being used, because the airflow need is direct proportional to the usage of the machines. There are also some plans to make a unit that only uses steel in the frame construction, with the outer panels made of plywood. This design would be much more sound dewing and would therefore make for a more silent unit. The plywood would also give the unit a much more sophisticated look that would fit in with HUR’s living room styled gyms and it could also be placed among the machines with no need to hide it away. This would make it very useful at installations where it is hard to find a place to hide the unit. The first manual units will be installed in the region, so it will be easy to follow their operation and have a replacement unit ready if there would be some problems or struggle with the new machinery. The compressor will be continuously improved over time to make a product that is flawless and as efficient as possible in the end.

After all, when you compare the final result of the project with the task, it all came out quite well, everything what was asked for was fulfilled and the company itself was satisfied.

LIST OF SOURCES

ABOUT HUR

http://www.hur.fi/en/company/our-mission

(Read 5.5.2016)

Indotara 2011, Pengertian Air Compressor

http://www.indotara.co.id/pengertian-air-compressor&id=114.html

(Read 2.12.2016)

Isentropic compression

https://www.grc.nasa.gov/WWW/K-12/airplane/compexp.html)

(Read 12.2.2017)

JUN-AIR 2016, Quiet air

http://www.jun-air.com/product_overview_quiet_air.aspx

(Read 3.11.2016)

The Engineering ToolBox, Reciprocating, rotary screw and rotary centrifugal air compressors

http://www.engineeringtoolbox.com/air-compressor-types-d_441.html

(Read 17.11.2016)

Yeganeh Rahavard Asia 2016, Centrifugal Compressors

http://yeganehrahavardasia.com/Products/centrifugalcompressors.aspx

(Read 19.12.2016)