Designing a test rig which can simulate friction and wear in a steam environment

Designa en testrigg som kan simulera friktion och nötning i en ångmiljö

Lukas Nilsson

Faculty for Health, Science and Technology

Master of Science in Mechanical Engineering, Material engineering

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Supervisor: Mikael Grehk

Examiner: Pavel Krakhmalev

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Abstract

The aim of this master thesis is to find the most optimal design of a test rig. The test rig will manage to simulate a sliding contact in an environment which consists of high temperature and high pressure steam steam. This test rig could result in lowering friction and wear in applications which involve steam. This could increase the efficiency and reduce the cost for a company which will be more sustainable and beneficial for the environment.
Interviews, analytical calculations, simulations and a material selection were performed for the optimization of this test rig.
A pin on disk tribometer is utilized to simulate the sliding contact. The pin is transferred down on a rotating disk with the assistance of an applied load. The load is applied using dead weights as these weights are not excessively affected by the steam. This tribometer is placed in a cylindrical pressure vessel with rounded corners to achieve a kinder flow of steam. The closure function is in the shape of a half sphere to reduce the maximum stress. This shape is based on results from simulations with the use of FEM.
The disk is driven using a DC motor which is placed outside the vessel. The torque is therefore transferred from the motor to the disk using magnetic coupling.

Sammanfattning

Målet med detta examensarbete är att utveckla den mest optimala designen av en testrigg. Testriggen ska vara kapabel att simulera en glidande kontakt i en miljö som består av superkritisk ånga. Denna testrigg kan resultera i att minska friktionen och nötning i användningsområden som inkluderar ånga. Detta kan öka effektiviteten och minska kostnaden för ett företag vilket också är fördelaktigt för miljön.
Intervjuer, analytiska beräkningar, simuleringar och ett systematiskt materialval har använts för att optimera denna testrigg.
En pinne-skiva är den utvalda tribometern som ska utföra den glidande kontakten. Pinnen förflyttas ner på den roterande skivan med hjälp av pålagd last. Lasten är pålagd genom att använda vikter eftersom de inte påverkas alltför mycket av ånga. Tribometern är placerad i ett cylindrisk tryckkärl med avrundade hörn för att uppnå ett snällare flöde av fluiden.
Stängingsfunktionen har formen av en halvsfär för att minska den maximala belastningen.
formen av detta tryckkärl är baserad på simulationer utförda med hjälp av FEM.
Disken är driven genom att använda en DC-motor som är placerad på utsidan av tryckkärlen.
vridmomentet är transporterat från motor till disken med hjälp av en magnetisk koppling.

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Table of content

Introduction

Background

In the recent centuries since the industrial revolution there has been a lot of development when it comes to engineering achievements. This has been carried out without thinking of the consequences of the consumption of natural resources and the emission of greenhouse gasses. This led to the energy crisis in the mid 1970s which made it urgent to come up with solutions dealing with the preservation of energy which resulted in an awakening of using tribology in a green and sustainable way.[1] By using the science of tribology and decreasing the amount of friction and wear, there will be less waste heat which leads to a reduced energy and resource consumption.

This project will be executed by the interest of the company Invencon AB who is highly interested in this sort of design. The interest also covers other companies such as Ranotor AB and companies within the pulp and paper industry. Ranotor AB are working on a steam engine and how to find the best material combination in the cylinder which is in sliding contact with a piston. This would lead to an increased performance of this machine and increase productivity and reduce costs.

Aim

The aim of this project is to design a test rig that is able to simulate a sliding contact between two materials in an ambient steam environment.

Research questions

- What is the optimal design of a tribometer that can operate in a high pressure steam environment?

Delimitations

- This construction should withstand a maximum pressure of 100 bar and a maximum temperature of 450 °C.
- The diameter of the half sphere of the pin will be set at a diameter 10 mm and the diameter of the disk will be set at 100 mm.
- The project will not include a solution to generate the steam.

Theoretical framework

Tribology

Tribology is the science and technology of interacting surfaces in relative motion. It includes aspects such as friction, wear and lubrication. The study of tribology is important in many types of applications since it can lead to a reduction of costs for a company.[2] Money and time will be saved considering there will be less need for maintenance and replacement of components. On top of that it is beneficial for the environment with the reduction of energy consumption.[3] Tribological solutions are applied in a lot of different areas, including classical tribology which is mechanical components such as wheels and bearing and bio tribology which includes the biological system such as joints and dentistry. [4]

Friction

Friction is the tangential reaction that emerges when two elements are sliding against each other. The force resists the relative motion of one element over another, the elements could be both solid and fluid. There are mainly four types of friction, static, rolling, sliding and fluid friction. In this project, sliding friction will be studied. The coefficient of friction is defined by the friction force divided by the normal force of the body which makes the frictional force proportional to the normal force as portrayed in equation 1.[5][6]

$$\frac{F_N}{F_F} = \mu \qquad (1)$$

$F_N = normal\ force$

$F_F = friction\ force$

$\mu = friction\ coefficient$

The friction coefficients are divided into two different components, the adhesive and the ploughing component as portrayed in figure 1. The adhesive component is caused by an atomic attraction between the elements which result in elastic deformation and shearing of the element.

The ploughing component is the result of the difference between the hardness and the surface of the materials. This leads to plastic deformation on the material which is softer.[7]

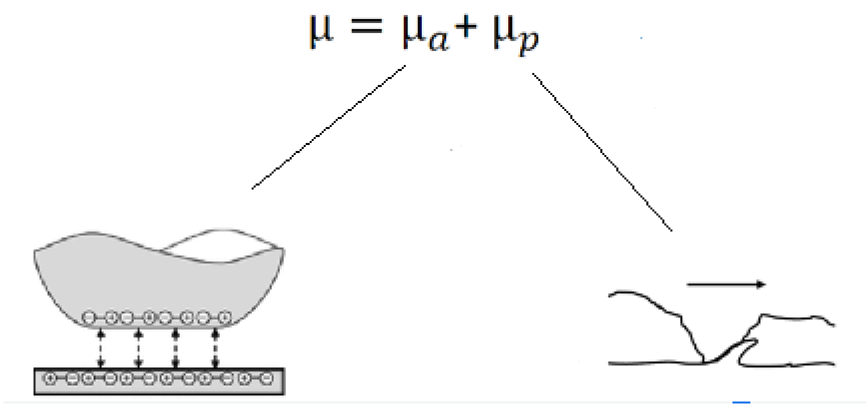


Figure 1: The two components of the friction coefficient

Wear

Wear is defined as removal of material when two surfaces are in contact and in relative motion relative to each other. Depending on the materials in contact, wear can be divided into different mechanisms. The main mechanisms are wear by the hard particles which includes abrasion and erosion and adhesion which includes sliding wear. [8]
In abrasion there are two-body abrasion and three-body abrasion. Two-body abrasion is when one of the surfaces has hard particles and removes material from the other surface.
Three-body abrasion is when hard particles are sliding between two surfaces.
In erosion, there is wear by hard particles striking the surface in the form of gas or liquid.
Sliding wear occurs when two materials are sliding over each other and depending if there is a ductile fracture or a brittle fracture the softer material will shear or crack.
By using the Archard equation 2 the total volume of wear per unit distance can be calculated.

$$Q = \frac{KW}{H} \qquad (2)$$

Q – *the total volume of wear debris per unit volume*
H – *the indentation hardness*
W – *the total normal load*
K – *a dimensionless constant of proportionality*[9]

As shown in the figure 2 wear is affected by different parameters such as load, sliding velocity and the interface temperature. The wear is more severe at high loads and high sliding velocity because this causes the tribological system to act adiabatic which means there is no transfer of heat. This leads to an increase in the interface temperature which additionally increases the wear.

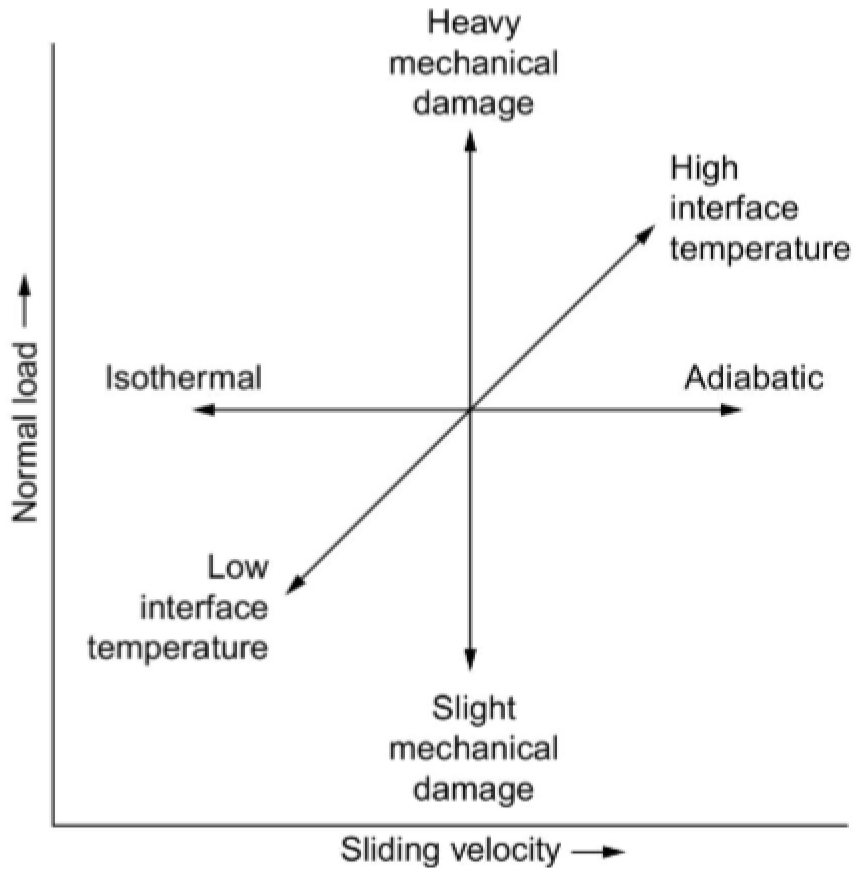


Figure 2: How different parameters affect wear

The atmosphere is a factor that could affect wear. If the system is exposed to moisture of certain gasses, it can promote corrosive and oxidative wear. An increase in temperature could lead to the formation of an oxide layer which can be protective if it can withstand the load. In the case of removal of the oxide layer the wear rate increases since the material underneath have been exposed to thermal softening.[10]

Thermal influence

When materials are exposed to a temperature and pressure above the critical point they behave differently compared to room temperature.
When material is exposed to high temperatures in tribological contact, thermal softening may occur. This causes the atomic vibrations and dislocations to increase which reduces the strength and stiffness of the material.

The high temperature leads to formation of an oxide layer and the higher the temperature the thicker the oxide layer. The sliding contact causes the oxide layer to fracture and wear debris is formed. The result is an exposure of the material underneath, since this material has been softened, it leads to an increased wear which is also known as oxidative wear which is shown in figure 3.[11]

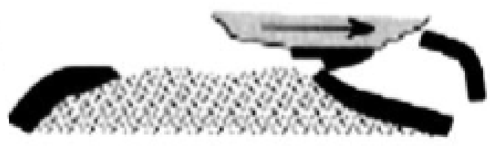


Figure 3: Portrayal of oxidative wear

When materials are subjected to stress at elevated temperatures, deformation could occur, even if the stress is below the yield strength. This is known as creep and it can be divided into three different stages, primary, secondary and tertiary creep. Primary creep is when the material starts to creep with a rapid rate which decreases over time. Secondary creep has a relatively uniform creep rate. Tertiary creep has an accelerated creep rate until the material breaks.[12]

The corrosion resistance of a material is dependent on parameters such as composition elements , grain size and pre-treatment of the material. Another important factor is the environmental conditions. When materials are subjected to steam, the steam can react to the surface of the material and cause corrosion which will lead to material degradation.[13] An increase in steam temperature causes the rate of corrosion to escalate and result in a brittle structure which could lead to cracking.[14]

At these extreme pressures and temperatures, electrical components such as strain gauges and motors get highly affected. The strain gauges measure applied forces by detecting changes in resistance which is affected by the amount of strain. In ideal cases, the resistance is only affected by the applied strain as portrayed in equation 3 where the length and cross section of the wire changes with increased strain.

$$R = \rho * \frac{l}{A}, \quad (3)$$

$l = length\ of\ the\ wire$
$A = cross\ section\ of\ the\ wire$
$\rho = resistivity$

Nevertheless, by increasing the temperature it could affect the strain in different ways. As portrayed in equation 4 how the resistivity is affected by the temperature.

$$\rho = \rho_0(1 + \alpha\Delta T), \quad (4)$$

$\alpha = coefficient\ of\ temperature$
$\Delta T = change\ in\ temperature$

An increase in temperature could cause the strain gauge to thermally expand which will be indicated as a change in strain.

When choosing a material which for example a wire consists of, it is critical that the coefficient of temperature of the wire(α_t) is as low as possible as portrayed in equation 5. The coefficient of length expansion(a,b) should also be as similar as possible.

$$\alpha_t = \frac{c+k(a-b)}{k}, \quad (5)$$

$a = coefficient\ of\ length\ expansion\ of\ the\ material\ which\ the\ strain\ gauge\ is\ placed$
$b = coefficient\ of\ length\ expansion\ of\ the\ wire$
$c = resistance\ temperature\ coefficient\ of\ the\ wire$
$k = coefficient\ of\ temperature\ of\ the\ wire$
[15][16]

The motor consists of a magnetic circuit which is generated by a permanent magnet. By increasing the ambient temperature which the magnet is affected by, the magnet starts to demagnetize and can lose its magnetic strength which reduces the efficiency of the motor. Once the magnet has been demagnetized the process could not be reversed by reducing the temperature which means the motor could not be fixed.
To improve the insulation resistance of the motor, rewinding is used. An increase in temperature causes the winding to deform, which leads to the insulation wearing of, thus resulting in motor failure.[17][18]

Hertzian contact theory

Hertzian contact theory is a theory about mechanism of contact which is associated with the physicist Heinrich Hertz. This theory describes the contact between two elastic bodies.
Even if this theory can provide useful information it contains some limitations. It draws assumptions such as that the material exclusively behaves elastically and the material's surface does not contain any asperities, which does not reflect the reality of deformations and tribology.[19]
As shown in figure 4 there is a half sphere which is in contact with a flat surface where R is radius of the half sphere, d is the elastic deformation of the flat surface and r is the radius of the deformed surface. [20]
The maximum pressure can be calculated by using equation 6.

$$P_0 = \frac{2}{\pi}E^*\left(\frac{d}{R}\right)^{1/2} \quad (6)$$

$E = young's\ modulus$
$d = elastic\ deformation$
$r = radius\ of\ the\ deformed\ surface$

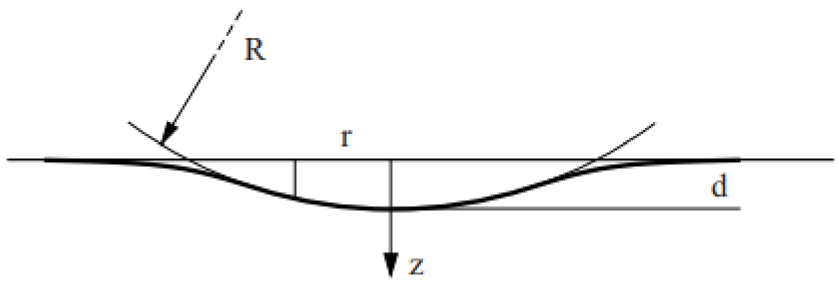


Figure 4: The result when an half sphere is in contact with a flat surface

Steam

Water has three physical states, ice, water and steam. Steam is the gas phase of water and it is created due to boiling or evaporation. When water is reaching its boiling point, it attains enough energy to overcome the forces which are holding them together. This makes them able to escape the liquid into the air above. [21]
The steam molecules are further apart from each other than water molecules, this makes the density of steam significantly smaller than the density of water.
As shown in figure 5 the boiling point of water is dependent on the pressure and by increasing the pressure, the amount of energy the water is able to carry increases.
Steam can exist in different states depending on the temperature and pressure and the different states of steam results in different tribological properties.
When the water is at its boiling point and reaches the state where water and steam can coexist it is called saturated steam. At this point the rate of water vaporization is equal to the rate of condensation. The properties of saturated steam include that the temperature can be easily and precisely controlled by the established pressure. It has on top of that a high heat transfer coefficient which requires a smaller surface area to transfer heat.
Another form of steam is unsaturated steam and this is the most common form of steam. It contains water droplets that have not yet been vaporized which means it contains a certain wetness. [22]
At temperatures above the critical point at the same pressure as the saturated steam, superheated steam is created. The superheated steam is particularly dry and has a lower density than the saturated steam at the same pressure. By using superheated steam the thermal efficiency will increase since it has a higher enthalpy and contains more energy per unit mass. This makes it especially suitable in drive applications such as turbines.[23][24][25]

The critical point of water occurs at a temperature of 374.15 degree celsius and a steam pressure of 220.64 bar. At this temperature the liquid and the gas have similar densities which makes it possible to go from gas to liquid without crossing any boundaries of phases. Since there are no boundaries between gas and liquid there is no surface tension.
The critical temperature is dependent on the attractions between the particles and the stronger the attraction, the higher the critical temperature.
The use of supercritical steam has increased in later years in for example supercritical steam generators where the benefits are high compressibility which means the size of the generator can be reduced compared to a subcritical boiler and still get the same result. Supercritical

steam has a higher efficiency which lowers the amount of fuel needed in a supercritical generator to generate the same heat energy.[26]

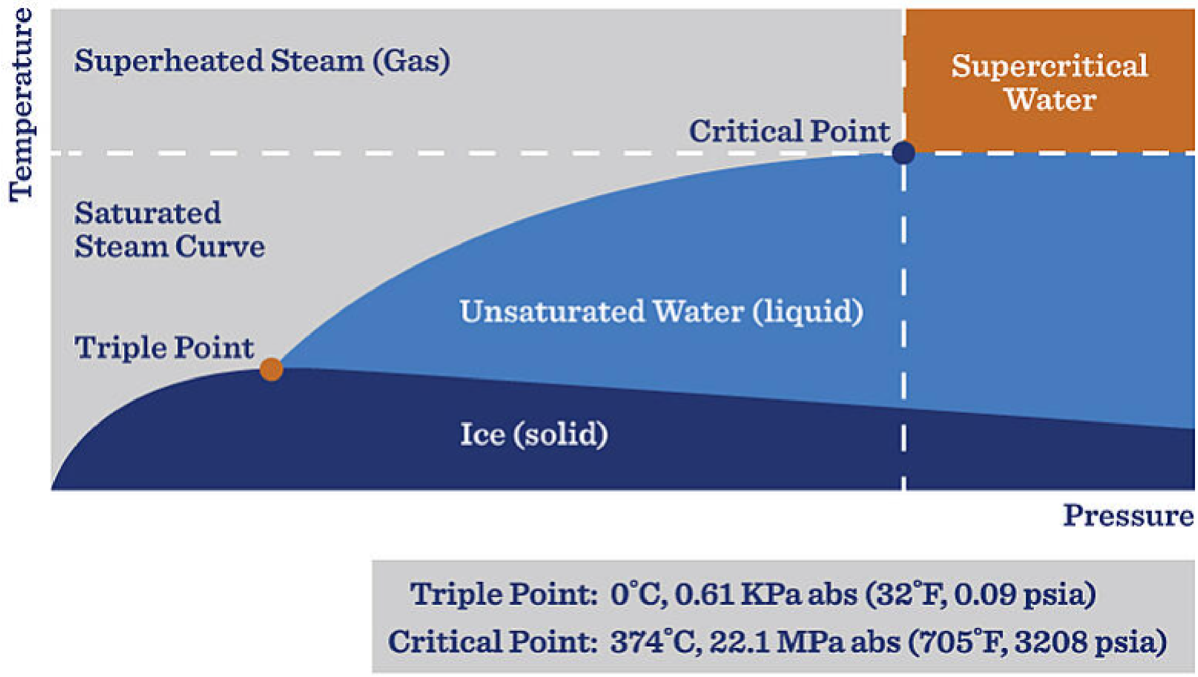


Figure 5: Different regions depending on the pressure and temperature

Pressure vessel

When designing a pressure vessel there are several important parameters to take into account. Firstly, the stress situation, if the vessel is thin or thick walled. As shown in equation 7 the pressure vessel is thin walled if the inside radius is more than 10 times greater than the wall thickness and thick walled if the ratio between the inside radius and wall thickness is less than 10.

$$\frac{R_i}{t} \geq 10 \; means\ thin\ wall \qquad (7)$$

$R_i = \; inside\ radius$

$t = \; wall\ thickness$

The contained steam pressure will act as stress on the pressure vessel. The pressure will act on the vessel as longitudinal stress and circumferential stress(hoop stress). Longitudinal stresses act in the axial direction of the cylinder while the hoop stresses act perpendicular to the axial direction of the cylinder which is portrayed in figure 6.[27]

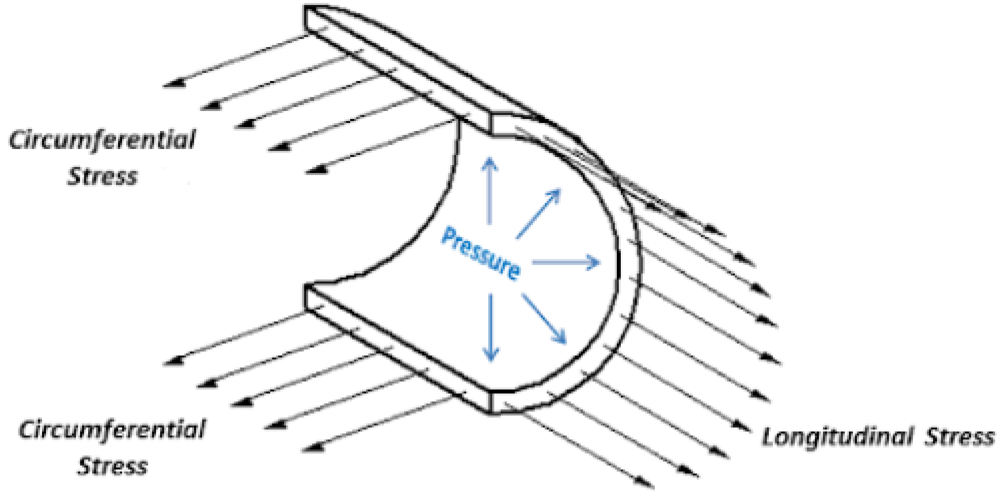


Figure 6: Portrayal of which direction the stresses act

When working with a thick walled pressure vessel, which is in the shape of a cylinder, the hoop stress is calculated by using equation 8 and the longitudinal stress is calculated by using equation 9.[28]

$$\sigma_{hoop} = P * \frac{r_o^2 + r_i^2}{r_o^2 - r_i^2} \tag{8}$$

$$\sigma_{long} = P * \frac{r_i^2}{r_o^2 - r_i^2} \tag{9}$$

$P = internal\ pressure$

$r_i = inner\ radius$

$r_o = outer\ radius$

Beam theory

The lever arm will be subjected to a force as portrayed in figure 7. There is a contact between the pin and the disk and the force originates from the rotation of the disk

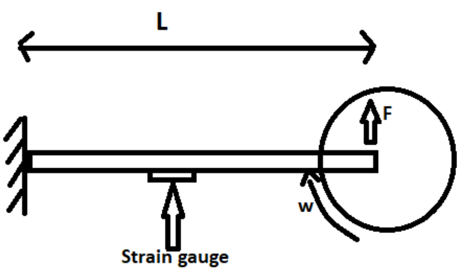


Figure 7: Portrayal of how the disk affect the beam

The force will cause the lever arm to bend. This will result in the fiber on the upper side to compress and the fibers on the lower side to strain. The curvature is calculated using equation 10:

$$\kappa = \frac{M}{EI} \qquad (10)$$

$M = momentum$
$E = young\ modulus\ of\ the\ material$
$I = moment\ of\ inertia\ by\ the\ cross\ section$

Pre-existing design

The current market consists of several designs of tribometers and several designs of pressure vessels however there is hardly any design that consists of a combined tribometer and pressure vessel.

A commonly used tribometer is portrayed in figure 8. This is a pin on disc apparatus where the disk is rotating creating a circular wear track on the disk caused by the pin. The load is applied using dead weights. The pin is attached to a lever arm and equipped with counterweights on the opposite side of the arm. [29]

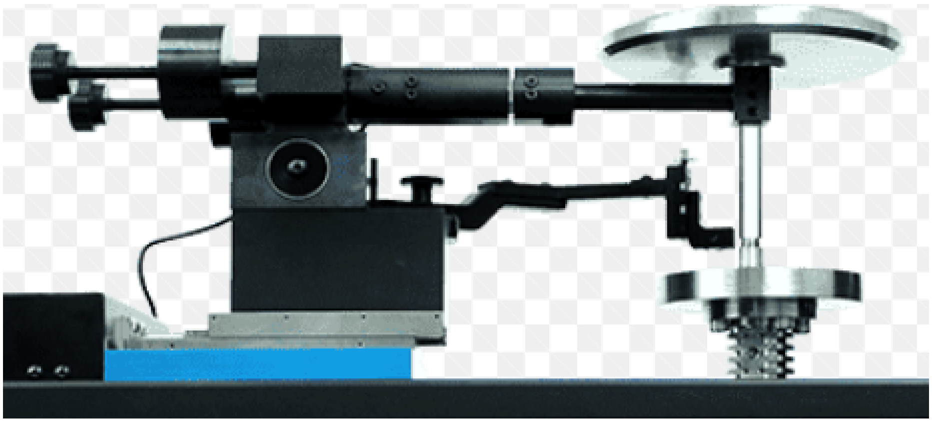


Figure 8: One commonly used tribometer

One existing design is a method where testing of polymers occurs under high pressure hydrogen. This is a design where a tribometer assembly is lowered down into a pressure vessel as portrayed in figure 9. The vessel consists of hydrogen with a pressure of 28 MPa. The tribometer is a ball/pin on disk apparatus where the ball/pin moves linearly with a sliding motion. The friction force is obtained using an in-line capacitor design load cell and the normal force using a loading arrangement.[30]

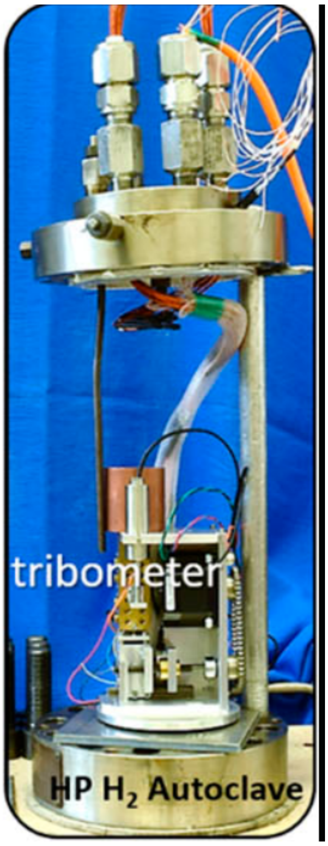


Figure 9: Tribometer inside a pressure vessel

Another design is a rotary tribometer which operates up to a pressure 15 MPa of CO_2. The pressure chamber is split in the middle where the upper part is pneumatically moved in a vertical direction as portrayed in figure 10. The load in this case is applied by means of a servo controlled ball screw actuator. This apparatus is designed to be flexible due to operating with different types of adapters such as a ball on disc and a sliding four ball assembly.[31]

Figure 10: Apparatus where the pressure vessel consists of an upper and lower part

Literature study

Designing of the vessel

When designing a pressure vessel it is important to consider all factors that could affect the safety of the vessel during its lifespan. According to standard AFS 2016:1, there are parameters that need to be specially observed when dimensioning a pressure vessel to achieve the acquired mechanics. For example, there is the inner and outer pressure as well as the surrounding and working temperature.
The calculating pressure must not be lower than the maximum pressure of the vessel which is 100 bar and the stresses that affect the vessel must be in the certain margins of safety. The calculating temperature must not be lower than the maximum temperature which is 450 °C. The vessel is acquired to handle the upcoming reaction forces and momentum which can be managed by choosing the correct types of fundament and mountings.
Over time there are certain mechanisms that could occur which are critical to include and try to predict when it comes to the choice of material. In this kind of vessel the components inside are exposed to high temperatures and loads over a long period of time thus increasing the possibility of creep and fatigue. Since the pressure comes from steam another important factor is corrosion which will be important when choosing material.

Safety

The pressure vessel must be designed so it does not put the user in any danger. According to AFS 2016:1 the vessel must include a function which informs the user if the vessel is safe to open or not. If the vessel is not safe to open there must be a function that prevents this. It must as well include some sort of safety valve that assures that it does not exceed the maximum pressure of 100 bar.

To ensure the safety of the user, inspections must be made regularly and inspections are only possible if the vessel is designed accordingly. The internal parts must if necessary be capable of being replaced and therefore, the vessel must have the suitable size to gain access to these parts.
The vessel must include an opening and shutting function thus gaining access to the internal parts nevertheless this function must not lead to any damage on the inside.
To make these inspections possible the vessel must on command be able to be emptied from the high pressure steam. This will additionally make it possible to clean and maintain the vessel. This lowers the possibility of hazardous effects such as chemical reactions and corrosion.
To ensure a safe clearance and filling, the vessel must be equipped with suitable parts, not creating an unstable flow of the fluid or exceeding the wanted pressure.
The vessel must contain safety equipment which is manufactured and constructed for its purpose. This equipment should include a solution for which the pressure does not during a

prolonged period of time exceed the maximum pressure and this short term overpressure can not exceed more than 10 % above the maximum pressure.
The vessel should additionally contain a solution which measures the temperature.

The highest stress for which the vessel must be able to handle in drift, is the maximum pressure and the maximum temperature multiplied with the coefficient 1.25 or the stress which comes from the maximum pressure multiplied with the coefficient 1.43.

PS*V diagram

This diagram includes fluids whose steam pressure at the highest temperature exceeds more than 0.5 bar plus the atmospheric pressure. As shown in the diagram it contains different modules for different regions of PS*V-values. The different modules are shown in figure 11 for each region.

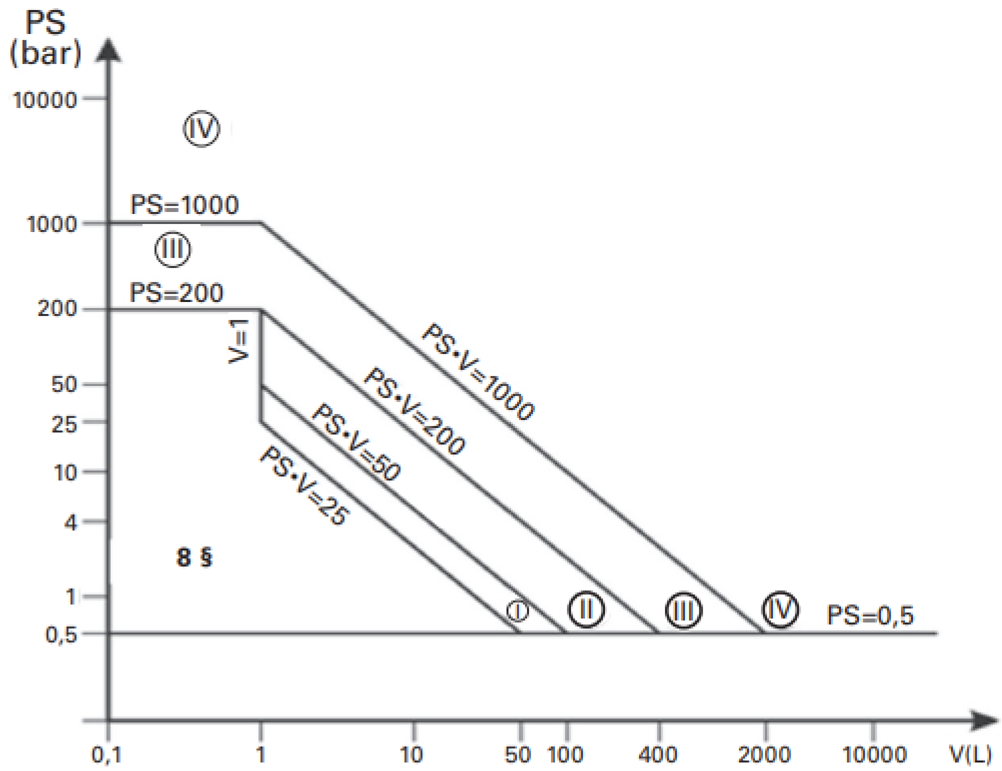


Figure 11: Diagram where the pressure of fluids exceed 0.5 bar plus the atmospheric pressure

I	=	**Module A**
II	=	**Modules A2, D1,E1**
III	=	**Modules B(construction type) + D, B (construction type) + F, B(production type) + E, B(production + C2, H**
IV	=	**Modules B(production type) + D, B (production type) + F, G, H1**

Figure 12: The regions and their correlating modules

Depending on the pressure(bar) and volume(L) it will be linked to different regions and these regions correlate with different modules as seen in figure 12. Since the pressure is at 100 bar and the volume at approximately 22 liters the pressure vessel correlates to region III. Therefore the modules in region III are required to be followed if this kind of vessel is to be constructed and manufactured and these can be found in the standard of AFS 2016:1.

Choice of material

The material which will be used must be suitable for its purpose and its expected life span. Therefore it must follow the following requirements. The material must have a high fatigue strength and high creep strength thus increasing the life span. The material must be ductile enough thus preventing any brittle fracture. It must be chemically resistant against the containing fluid and must not be affected over time by processes such as corrosion and thermal expansion.
On top of that it must be able to handle the negative effects that could occur while different materials are joint together.
[32]

Tribometer

This project includes a simulation of friction and wear and the choice of tribometer is a pin-on-disk apparatus. This tests materials which are tested in pairs. One of the materials is a pin with a radiused tip which is positioned perpendicular to the other material, which is in the form of a disk. The pin moves vertically with the assist of a load, while the disk rotates which results in a circular sliding path on the disk, which is shown in figure 13.
The critical parameters are the applied load on the pin, the velocity of the disk, the number of revelations and the conditions of the environments such as ambient pressure.
The disk is holded by a chuck which rotates with the help of a motor. The pin is stationed to a specimen holder which is attached to a lever arm. To prevent vibrations which affect the measurements, the lever arm must be part of steady construction.

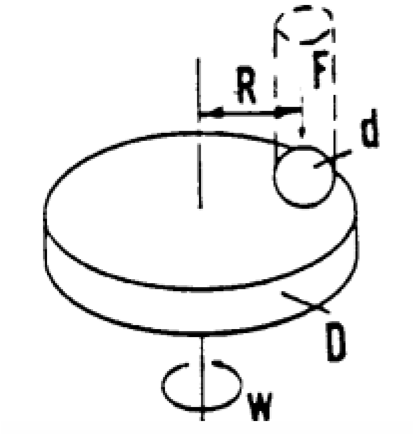


Figure 13: Portrayal of a pin-on-disk tribometer

Procedure of using a tribometer

To achieve accurate measurements there are certain things to take into account. The specimen should be cleaned and there must not be any dirt or foreign matter on the specimen. The disk must be fixed perpendicular to the axis of resolution and the pin must be fixed perpendicular to the disk.

It is important to specify the materials which are being tested and the only requirements which are required is being able to resist the stresses by not breaking or flex excessively. The dimension of the specimens must as well be in a certain range. According to the standard ASTM G99, the diameter of the pin commonly ranges from 2 to 10 mm. The disk has a typical diameter range of 30 to 100 mm and a thickness of 2 to 10 mm. The surface roughness is usually 0.8 µm or less. The report of specifications should include material type, dimensions, form, processing treatments, surface finish and specimen preparation procedures.

Before starting the procedure the desired values of the critical parameters must be set. To select the right load, the load is firstly applied prior to starting the motor. This takes place to understand when the pin gets in contact with the disk. To get the desired velocity of the motor, it is started when the pin and disk is out of contact and adjusted to get the desired velocity. At this stage the load and velocity is set and it is time to set the number of revolutions and the test can begin.
When the test has started it should not be restarted or interrupted.
When the test is clear new specimens can be tested for comparison to obtain sufficient results.

Simulate wear

To measure the wear, the dimension of the specimen must be measured to the nearest 2.5 µm when measuring the volume. When weighing the specimen it must be measured to the nearest

0.0001. Both the pin and the disk are weighed and measured before and after. The measurements are compared to calculate the volume and mass loss.
The volume loss of the spherical pin is calculated using equation 11 assuming there is no significant disk wear.

$$Pin\ volume\ loss\ =\ (\pi h/6)[3d^2/4\ +\ h^2] \tag{11}$$

Where:

$h\ =\ r\ -\ [r^2\ -\ d^2/4]^{1/2}$

$d\ =\ wear\ scar\ diameter$

$r\ =\ pin\ end\ radius$

The volume loss of the disk is calculated using equation 12 assuming there is no significant pin wear.

$$Disk\ volume\ loss\ =\ 2\pi R[r^2 sin^{-1}(d/2R)\ -\ (d/4)(4r^2\ -\ d^2)^{1/2}] \tag{12}$$

Where:

$R\ =\ wear\ track\ radius$

$d\ =\ wear\ track\ width$

The volume loss can as well be calculated by using the mass loss and convert it to volume by using equation 13:

$$Volume\ loss,\ mm^3\ =\ \frac{mass\ loss,\ g}{density,\ g/cm^3}\ *\ 1000 \tag{13}$$

If wear occurs in the form of transfer of material from one specimen to the other these equations can not be used since there is no removal of material from the system.

Simulate friction

When simulating the friction the friction coefficient is what is desired. To obtain the friction coefficient the law of friction(1) is used as shown below.

$$\frac{F_N}{F_F}\ =\ \mu \tag{1}$$

$F_N\ =\ normal\ force$

$F_F\ =\ friction\ force$

$\mu\ =\ friction\ coefficient$

According to ASTM G99 the friction coefficient should be reported when available.
The normal force is obtained directly from the adding weights which is proportional to the mass of the weights which regulates the load. The friction force is measured by using a friction force system such as load cell or a strain gauge. The relation between these measurements is what decides the friction coefficient.
[33]

Methodology

Interview

This project includes having an understanding about different subjects such as tribology, steam and pressure vessels.
To achieve this and ease the process, two interviews were held. Both interviews were semi structured interviews which means that they were performed with a flexibility between the interviewer and the interviewees but still under a structured manner. They were performed according to GDPR which means they were anonymous and their names will not be mentioned in this text.
The first interview was held in person with an expert in tribology and material science, who had a lot of experience of using a tribometer. Because of this, the interview revolved mostly about the usage of a tribometer, what is important to take into account and critical moments.
The second interview was performed on zoom with a person who possesses a lot of experience involving working with supercritical steam and steam engines. Therefore the interview mostly was about the design of the pressure vessel and the impact that occurs because of the extreme steam pressure.

Functional specification

A functional specification is a document where all requirements are converted into functions. This guarantees that nothing is forgotten when generating ideas and since it is described as functions, it could lead to another way of thinking which can generate new and different ideas.
To define all the functions in a clear way, they are described with a verb and a substantive. Additionally they are graded those prioritizing the functions which decides which requirement the customer finds most important and what's critical to include. If there are any limitations of the function, that is also defined. [34]

Requirement specification

The purpose of a requirement specification is to create a document where all requirements are collected and specified. These are requirements given by the customer, that comes from including standards and various other sources. The requirements must be easy to follow and have a clear structure. This is used in the product development phase where it is used to check what has been done and what is next to do. Furthermore it makes sure that all requirements will be fulfilled. [35]

Risk analysis

A risk analysis is used to identify all the potential risks. By identifying the risks and making yourself or the group more aware of the situation lead to an increasing chance of preventing them. The risks are graded by probability and consequence thus creating a resulting risk value. To reduce the possibility of any of these risks happening a recommended action is included. This should be performed in the early part of the stage which increases the probability of reducing or preventing the risks. The complete risk analysis is placed in appendix A.[36]

Concept generation

The generation of concepts was performed using a criteria matrix. The criterias which were the most critical, containing different solutions were written down along with their possible solutions. Concept generation is a method where its purpose is to generate new ideas and look for brand new solutions to achieve the most optimal product design.[37]

Calculation of friction force through a strain gauge

By using beam theory which is mentioned in the theory section, a strain gauge can be utilized to obtain the friction force (F_f) as portrayed in figure 15. As portrayed in figure 14, a strain gauge is placed on the outer side of the beam. The value obtained by the strain gauge is how much strain the outer side of the beam is exposed to. There will occur torque in the beam however this can be neglected since the force is relatively small and won't affect the strain measurements.

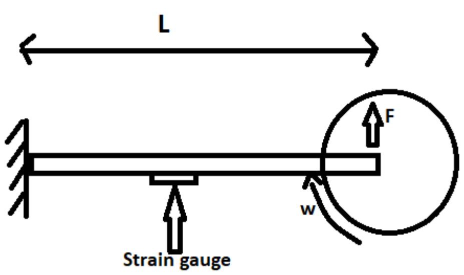


Figure 14: Placing of the strain gauge

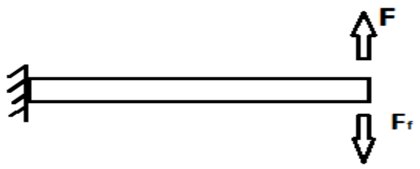


Figure 15: Portrayal of the friction force

$$M = F * L \quad (15)$$

$F = force, L = length, M = momentum$

Since the force(F) will cause the beam to bend as portrayed in figure 16 a curvature radius(ρ) can be calculated equation 17 and 18. The young modulus(E) in equation 17 is acquired from the chosen material and the moment of inertia(I) is calculated using equation 16 since the cross section is circular as portrayed in figure 17. The momentum(M) is calculated using equation 15.

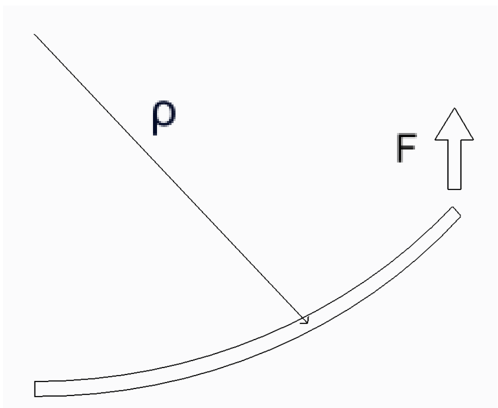


Figure 16: Curvature caused by the force

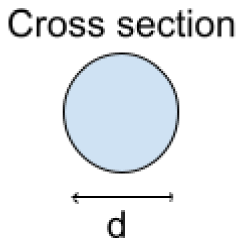


Figure 17: Cross section of the beam

$$I = \frac{\pi d^4}{64} \quad (16)$$

$$\kappa = \frac{M}{EI} \quad (17)$$

$$\kappa = \frac{1}{\rho} \quad (18)$$

$I = Moment\ of\ inertia$

$d = diameter$

$\rho = curvature\ radius$

$E = young's\ modulus$

[38]

The curvature radius is used to obtain the relation between the original length(L) and the new length of the outer side of the beam which is equal to the strain. This is executed by calculating the relation between outer circumference and central circumference of the circle in figure 18 using the curvature radius(ρ) and the thickness of the cross section(h).

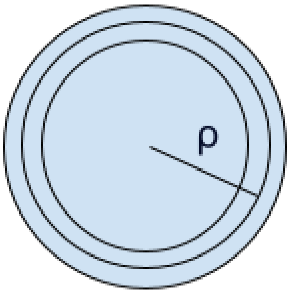


Figure 18: Circumference using the curvature radius

Circumference of the outer circle is portrayed in equation 19:

$$(\rho + \frac{h}{2}) * 2 * \pi \quad (19)$$

Circumference of the central circle is portrayed in equation 20:

$$\rho * 2 * \pi \quad (20)$$

The resulting strain is portrayed in equation 21 which is the relation between outer circumference and central circumference.

$$(\frac{(\rho+\frac{h}{2})*2*\pi}{\rho*2*\pi}) = \textit{the value obtained by the strain gauge} \quad (21)$$

Material selection

The material is selected with the assistance of the material selection program Granta EduPack. The materials were chosen by plotting 4 separate plots. Each with one parameter on the x-axis and one on the y-axis. The materials who fulfilled the requirements were marked in each plot. Afterwards they were evaluated to find the most suitable material which were the materials that fulfilled the requirement in every plot.

Dimensioning of pressure vessel

The inside volume is dimensioned by developing a large enough volume to fit each component. The vessel is thick walled and the thickness is calculated considering the design factor, the internal pressure, the chosen material and the magnetic coupling.
By using what has been written in the theory section under “pressure vessel” which can be applied for cylindrical vessels.

Dimensioning the thickness regarding the magnetic coupling

When using magnetic coupling the air gap should be as small as possible to increase the efficiency of the coupling. By decreasing the air gap, it leads to a higher magnetic flux density and increases the torque transfer efficiency. However a larger air will result in a higher tolerance for misalignment. Another important factor is the pull out torque which is the maximum amount of torque which could be transferred using the magnetic coupling. The pull out torque decreases with an increasing air gap.[39]

FEM-analysis

The finite element method(FEM) is a method where an object is divided into numerous elements which are connected at points called nodes. The physical state of the object is described using partial differential equations which is solved using a finite element analysis. The result of this is only an approximate solution.[40]
This method is an efficient way to reduce time in the process of developing a product. This is because there are less physical prototypes and all the components can be optimized as early as in the design phase.
This is used to simulate the mechanics of critical components such as the pressure vessel. The magnitude of deflection and the resulting stress will be simulated to assure the component is correctly designed.

Design development

Requirement specification

In appendix B , there is a compilation of all requirements received from customers, standards and myself. The aim of this project is to fulfill all these requirements and design a tribometer accordingly.

Functional specification

A functional specification has been made which can be found in appendix C. In this functional specification, practically all requirements have been converted into functions where they have been divided from how they should be prioritized. This is a benefit when time becomes a factor and prioritization is required.

Concept generation

A concept generation is made where the different criterias are the functions that have different solutions and are different in the concepts. The solution for the remaining functions remains the same throughout the concepts. This concept generation can be found in appendix D.

Concept 1

As portrayed in figure 19 this concept is a pin on disk tribometer where only a part of the pin and the disc is placed in the pressure vessel. High pressure seals are used to allow translational movement of the pin and rotational movement of the apparatus that holds the disk. This is used to not cause any leaks of pressure and this allows the volume of the pressure vessel to get as small as possible. Dead weights is used to apply the load which can be regulated by adding or removing the weights. The normal force is obtained by converting the load of the dead weights to a force.
The friction force is obtained using a strain gauge which is placed on the lever arm that converts strain to a force. The disk is driven by a DC motor which is placed below the pressure vessel to not be affected by the steam.

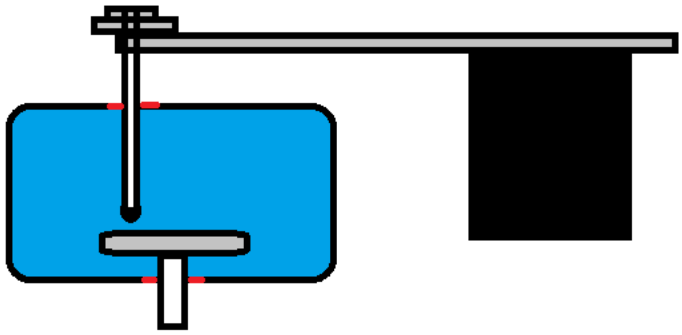


Figure 19: Concept 1

Concept 2

This is a concept which has a similar construction of the tribometer however in this concept, the entire tribometer is placed inside a pressure vessel. The DC motor is the sole component which is placed on the outside since it is optimal to not place a motor in a high pressure environment. The torque from the motor is transferred to the disk through a magnetic coupling. This prevents the possibility of leaks since the vessel is fully isolated.
The load, the normal force and the friction force is calculated in the same way as concept 1 however in this case the dead weights and the strain gauge will get affected by the steam. The strain gauge consists of some protection as an encapsulation. This pin holder will manage to change the angle of the pin allowing the whole pin to be utilized. There is an additional weight on the right side of the lever arm as portrayed in figure 20. This is a counter weight which stabilizes the tribometer.

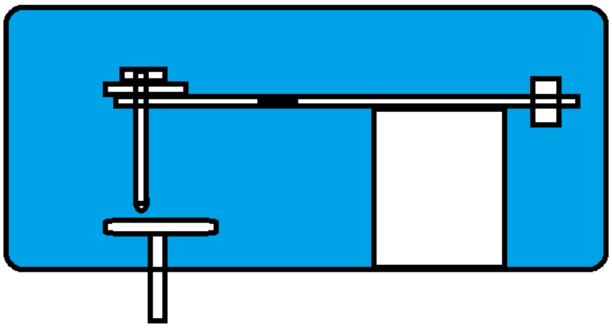


Figure 20: Concept 2

Concept 3

This concept includes a lowering of the tribometer apparatus into the pressure as portrayed in figure 21. This is a pin on disk tribometer where the pin is pressed down using a pneumatic actuator which is utilized to regulate the applied load. The disk is driven with an AC motor that is placed underneath the pressure vessel. As in concept 2, a magnetic coupling is used to transfer the torque from the motor to the disk. The normal force is converted using the pneumatic actuator and the friction force using a strain gauge.

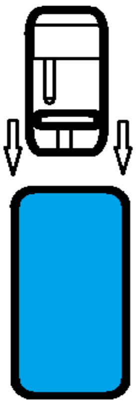


Figure 21: Concept 3

Concept 4

This is a concept which is similar to concept 3 when it is lowered down . It is a pin on disk tribometer which utilizes a piezoelectric actuator to linearly press the pin down and this force is equal to the normal force. As all other concepts the DC motor is placed underneath the vessel and seals are used to allow rotation without any pressure leaks. As portrayed in figure 22 a strain gauge is placed on the pin to obtain the strain which is converted into a force.

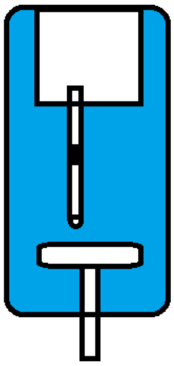


Figure 22: Concept 4

Concept evaluation

In the concept evaluation, the concepts are rated according to critical criterias to achieve a clear evaluation of the concepts. The concepts are rated from 1 to 5 and judged by the total score. The concepts are judged with respect to criterias as practicality, usability, requirement fulfillment, safety, maintenance, weight and sustainability. The concept evaluation can be found in appendix E.
Concept 2 achieved the highest total score and will be the concept which is chosen and will be developed further.

Final design

Figure 23 portrays the final design of the tribometer which is executed by using the CAD program CREO. It is a pin-on-disk tribometer where the applied load is regulated by alternating between different amounts of dead weight which is placed right above the pin holder. The pin holder additionally has the function of regulating the angle of the pin by 45 degrees.
The disk is placed in a three- jaw chuck where it is stuck. Different sizes of the disk can be used since the jaws can be adjusted using a lock key.
The disk rotates by using a DC motor which is placed on the outside of the vessel. The motor is connected to the chuck using magnetic coupling which can transfer torque through the wall of the vessel using magnetic fields.
The friction force is simulated using a strain which is placed on the lever arm. It registers the amount of strain and converts it into a friction force. This is described in more detail in the methodology section.
There is a counter weight placed on the end of the lever arm to stabilize the tribometer and this can be screwed in or out to match the applied load.

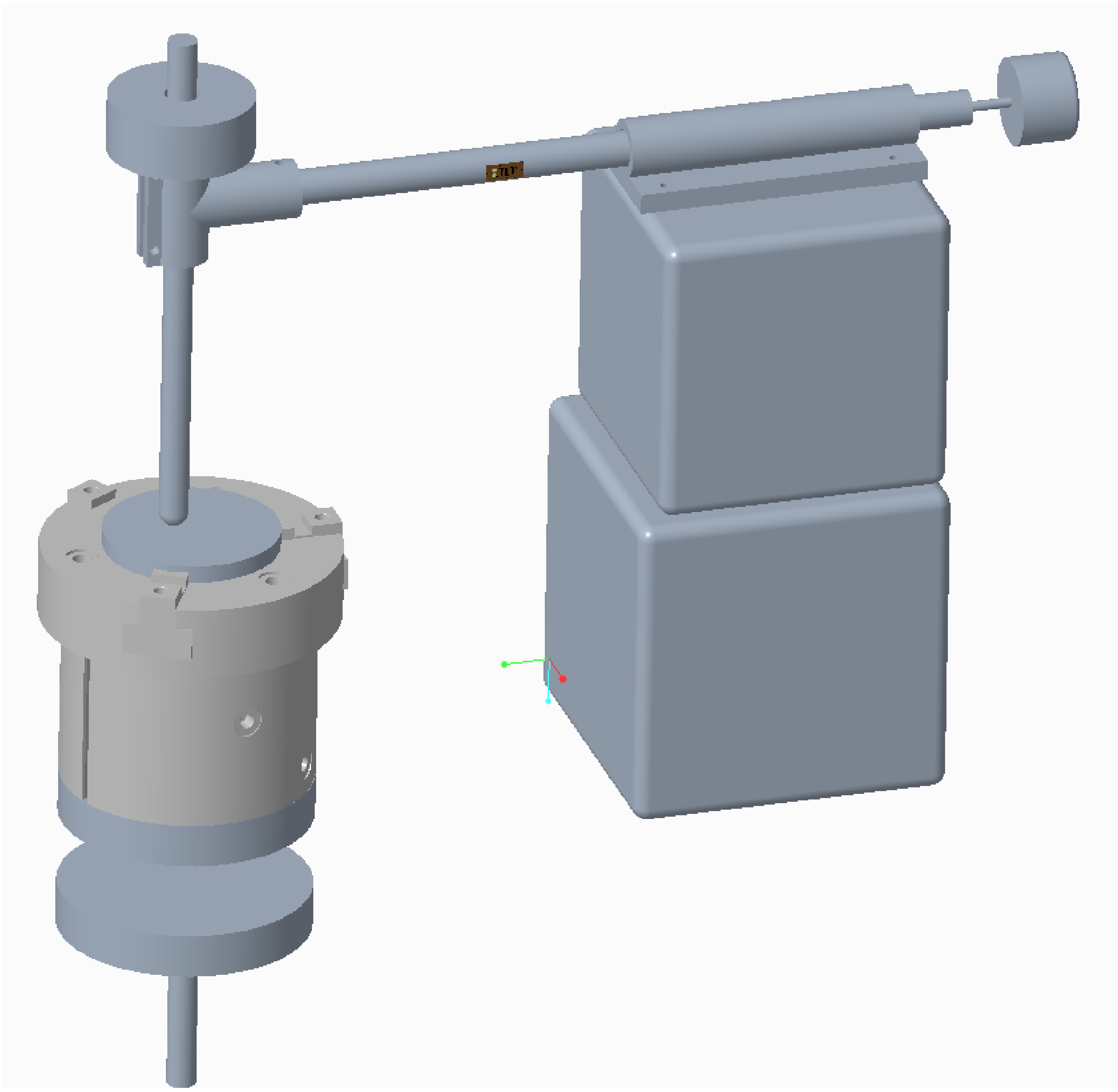


Figure 23: The final design on the tribometer

Figure 24 portrays the final design of the pressure vessel. It is a cylindrical vessel with a flat bottom. It has a closure function on the top which can be used to change and maintain components. A safety valve is connected to the vessel thus controlling the maximizing pressure by lowering it, if it exceeds.

The vessel is connected to a steam generator through a pipe where the steam is being controlled using a ball valve. A high pressure solenoid valve is attached to the pipe which has the function of shutting down the flow of pressure in the case of detecting any danger.

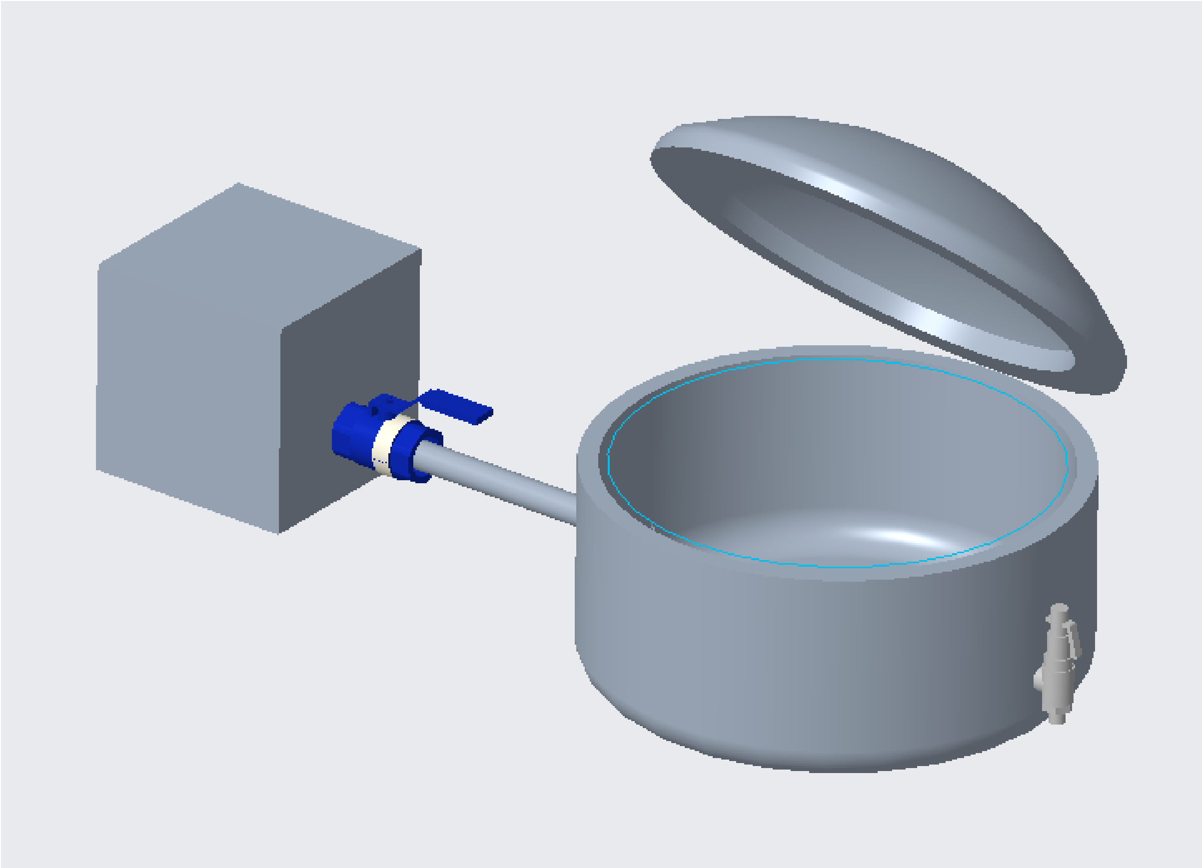


Figure 24: Final design of the pressure vessel

Figure 25 portrays the combined pressure vessel and tribometer. The tribometer is placed inside the vessel where accurate tribotest will be made in an environment of high temperature and high pressure steam.

The temperature is measured using a resistance temperature detector(RTD) and the pressure is measured using a bourdon tube. The velocity of the disk is measured using a speed controller which is connected to the motor.

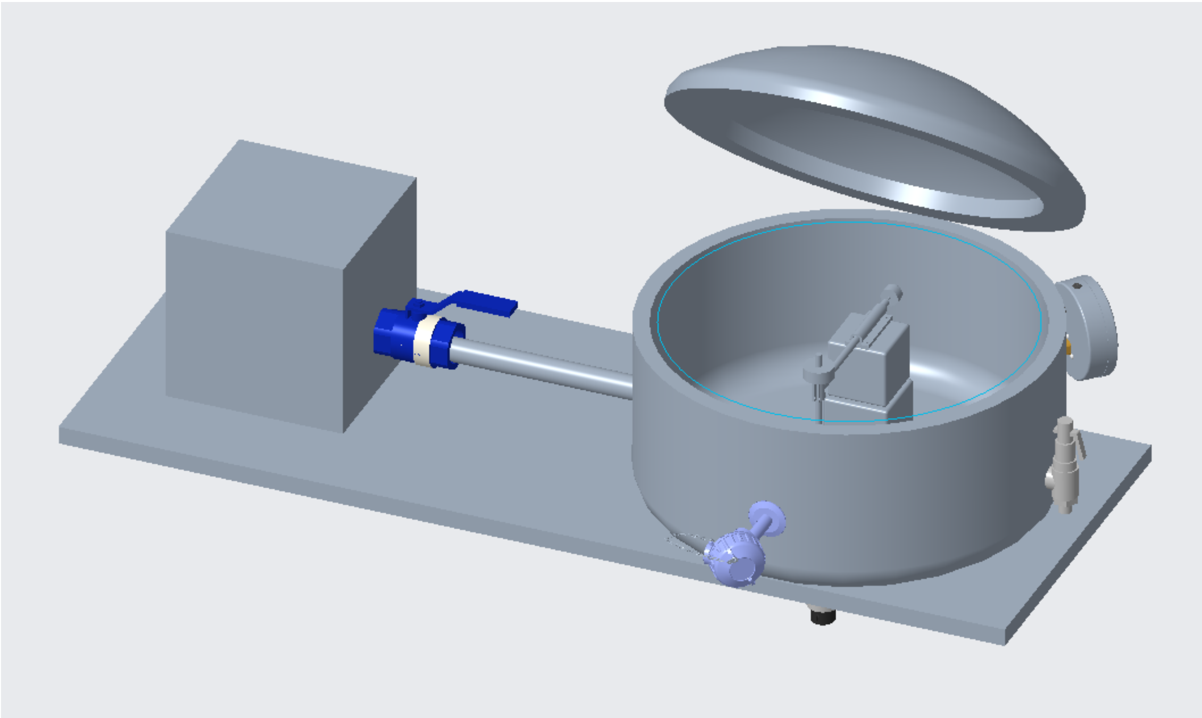


Figure 25: Final design of the tribometer and pressure vessel combined

Machine elements

Available machine elements

Steam distribution system

Piping system

To transport steam from a steam generator to the pressure vessel, a high pressure steam piping system is required. Since there is high pressure steam in the pipes, they should not be too long since the friction in the pipes could cause the pressure to drop excessively. Loops, bends and offset should not be considered. [41]
The steam always flows from a region with high pressure to a region with low pressure, therefore a pressure drop can be utilized to increase the flow of steam in the system. The pipe consists of insulation to minimize the energy losses and improve the efficiency of the system. Carbon steel(ASTM A106) is a common material for pipes in steam applications and will be able to handle the pressure and temperature using correct dimensions. The pipe has a diameter of 40 mm and wall thickness of 10.16 therefore able to manage a steam pressure over 100 bar with a temperature of 450 degree celsius.[42] [43]

Ball valve

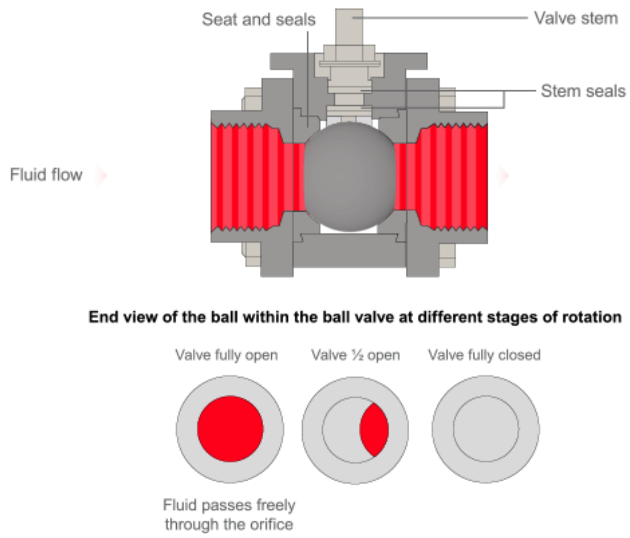
A ball valve shown in figure 26a is a valve which consists of a spherical ball between two sealing rings. The valve is fully opened when the ball is aligned with the pipe ends and fully closed when the ball rotates 90 degrees.
This ball valve is used to allow the fluid to flow through or close the passage of flow. It is placed where it can safely and easily be shut off which in this case is close to the steam generator.[44]

Shut down valve

To ensure safety for the user the vessel is equipped with a shut down valve. This stops the flow of the fluid in the case of detection of a dangerous event. To check if the valve is capable of operating on demand or has the necessary performance of safety, the valve is tested by measuring the safety integrity level(SIL). This is either executed with a proof test which is a manual test where all possible failure modes are tested. This could as well be tested with a diagnostic test which is an automated on-line test that will detect the percentage of the failure modes. [45]
Figure 26b portrays a high pressure solenoid valve which will be used to shut down the flow of pressure. It can handle the required pressure of steam and is easy to maintain and clean.

Safety valves

In this sort of pressure vessel, there is a possibility of overpressure and this could be caused by several reasons. One is heat input which is an energy form that causes vaporization and thermal expansion thus increasing the pressure. The other energy form is an increase in pressure that comes directly from a higher pressure source.
The rate which pressure is reduced by is called the revealing rate and it is according to the standard API STD 521 only affected by one a single cause since two unrelated failures is not so common and does not to be taken into account.
Since all outlets on the vessel will be blocked it is required that the pressure relief device has at least the same capacity as the pressure source.[46]
The valve portrayed in figure 26c is a safety valve made out of stainless steel. This valve has a full nozzle and will be connected through flanges. It can handle both the pressure and temperature of the steam.



Portrayal of a ball valve
(a)

Portrayal of a shutdown valve

(b)

Portrayal of a safety valve

(c)

Figure 26: The valves of the construction

Magnetic coupling

A magnetic coupling is a machine element which can transfer torque from one shaft to another without a physical connection. This works due to magnetic fields. This is commonly used in applications where the fluid is required to not escape into the atmosphere. [47]
Figure 27 portrays a magnetic coupling which can handle temperatures in the range of -50 to +500 degree celsius and pressure in the range of 0 to 500 bar. It will be made in stainless steel and can handle a torque in the range of 50 to 5400 Ncm.

Figure 27: Portrayal of a magnetic coupling

Chuck

A chuck has the function of holding the revolving disk. The chuck in figure 27 is a three-jaw chuck which is the most commonly used chuck and will be used for the final design. It has one hole for a chuck key which has the function of tightening or loosening the grip. Since there is only one hole, all jaws move dependly with each other.[48]
It will be made of the same material as the pressure vessel. This is the material that according to granta EduPack and the material selection process that can handle supercritical steam most optimally.

Figure 28: Portrayal of a three-jaw chuck

Dead weights

The load will be applied and measured through the use of dead weights. The load will be increased by adding weights and reduced by removing weights. They will be placed directly above the pin holder resulting in as accurate normal force as possible. The normal force will be proportional to the applied load. Dead weights are used since this is the solution which gets affected by the steam the least.

Motor

The chuck will rotate with the help of a motor and a motor is a device that converts electrical energy into mechanical energy.
The choice of motor is either an AC motor or a DC motor. An AC motor is powered by alternating current and they are divided into two types, asynchronous and synchronous.
An AC motor consists of, as shown below in figure 29b, a stator which has multiple windings. The stator is connected to an AC supply which generates a magnetic field. The rotor consists of closed loops of conductors which generates current because of the magnetic field. This results in a revolving and since the rotor is attached to an output shaft, this shaft starts to rotate.
The benefits of an AC motor is that it requires less maintenance compared to the DC motor, additionally it is more cost-effective.

A DC motor is powered by direct current. There are two types of DC motors, a brushed motor and a brushless motor however the basic principle is as shown below in figure 29a. A conductor is placed in a housing of a magnet which generates a magnetic field. The conductor carries a direct current which is supplied by a DC source. This causes a mechanical force moving perpendicular to the magnetic field and in the direction of the current. The benefits of a DC motor is high precision and control when regulating the speed and it provides a constant torque over a wide range of speed. This is highly beneficial in this sort of tribometer since it is important to control the velocity of the motor to get accurate measurements. [49][50]

The relation between power, torque and angular velocity of a motor is as shown in the equation 22:

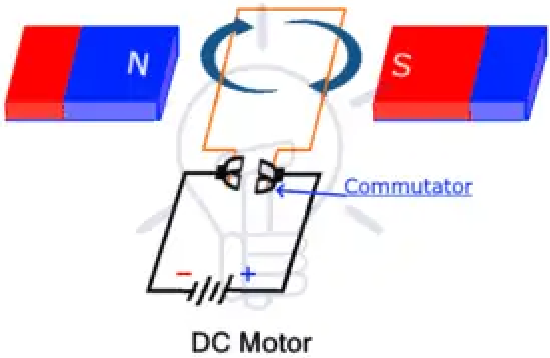
$$P[W] = Mv * \omega[Nm/s],\ P = \frac{Mv * n * \pi}{30} \quad (22)$$

$Mv = \ torque$

$\omega = \ angular\ velocity$

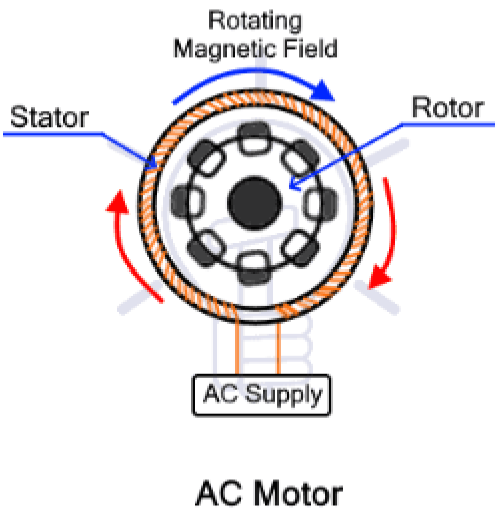
$P = power$

$n = \ number\ of\ revelations$



How a DC motor works

(a)



An AC motor and its components

(b)

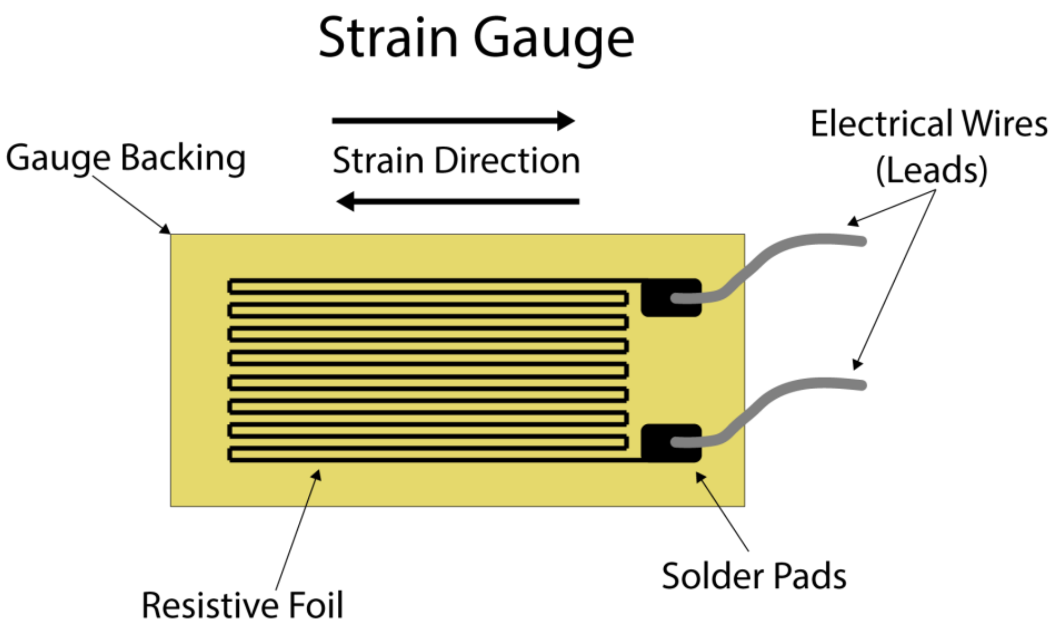
Figure 29: Portrayal of a DC and AC motor

Load cell

A load cell is a device that converts a mechanical force to an electrical signal which can be recorded by the user. The most common load cell is strain gauge load cell. This type of load cell consists of a strain gauge which is portrayed in figure 30a, which is positioned inside the housing of the load cell as shown in figure 30b. The strain gauge has the function of turning the applied load into electrical signals. When a load is applied to the strain gauge, the wire deforms which causes the resistance to change. This change of resistance is measured and converted into digital values using a digital meter.
The resistance of the wire(R) is measured using equation 23: [51]

$$R = \rho * \frac{l}{A}, \tag{23}$$

$l =$ *length of the wire*
$A =$ *cross section of the wire*
$\rho =$ *resistivity*



Portrayal of a strain gauge

(a)

Portrayal of the housing of the load cell

(b)

Figure 30: The strain gauge and its housing

This can be used to calculate the friction coefficient. By using a strain gauge load cell to measure the applied force on the pin, the normal force is obtained since they are equal. However in this case the normal force will be obtained from the applied dead weights. This is preferred since the number of machine elements inside the pressure vessel should be reduced if possible.
To calculate the friction coefficient, it is required to obtain the friction force. This is possible utilizing beam theory mentioned in the theoretical framework. By placing a load cell on either or both sides of the lever arm that is exposed to deformation, the strain is measured and converted into the friction force portrayed in the methodology section.

The strain gauge will be placed in the lever arm and therefore be exposed to supercritical steam. To ensure the strain gauge measurement does not get affected by the steam an encapsulation gauge can be used. This is a product that could operate in harsh environments such as high temperature and high pressure. As seen in figure 31 it consists of a flange and an environmentally resistant metallic tube which is the sensing part of the product. The tube also consists of the encapsulated gauge and an insulator. The involved material used in the gauge should result in some heat and corrosion resistant material.

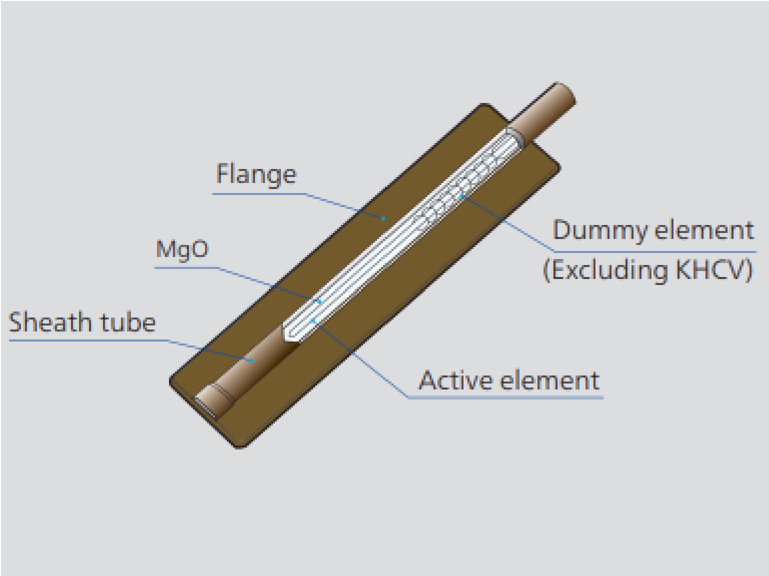


Figure 31: Portrayal of a encapsulated strain gauge

Temperature compensation

Since strain gauges are sensitive devices that get affected by changes in temperature, it is important to compensate for these temperature variations. The thermally induced strain(ε_T) is expressed with equation 24. As portrayed in figure 32, β_g is the linear expansion coefficient of the resistive element and β_s is the linear expansion coefficient of the measuring object.[52]

$$\varepsilon_T = \frac{\alpha}{Ks} + (\beta_s - \beta_g) \quad (24)$$

$\alpha = Resistive\ temperature\ coefficient\ of\ resistive\ element$
$Ks = gage\ factor\ of\ strain\ gauge$

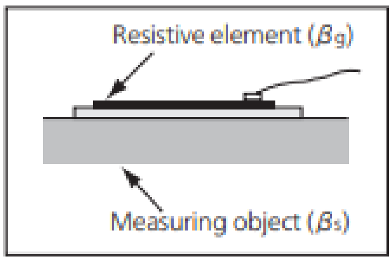


Figure 32: A strain gauge placed on an object

Measurement tools

The purpose of this apparatus is to achieve accurate measurements which can be compared with measurement from another material combination. Therefore it is critical to keep track of the different parameters such as temperature, steam pressure and the velocity of the disc. This is managed using tools of measurement.

Temperature sensor

A temperature sensor is a device that converts input data which is the temperature of the surrounding environment into electronic data. There are two sensors that operate in the acquired range of temperature, thermocouples and a resistance temperature detector(RTD). Thermocouples have a wider range of temperature compared to the RTD. However the RTD which can be seen in figure 33 has a better accuracy than thermocouples which makes it more suitable for this project. [53]
A resistance temperature detector consists of a wire wrapped around a ceramic or a glass core. The accuracy and repeatability is decided by the choice of wire material. This material includes exclusively high purity conducting metals such as platinum, nickel and copper. These materials have an accurate resistance/temperature relationship which means that the electrical resistance changes as a function of temperature. [54]

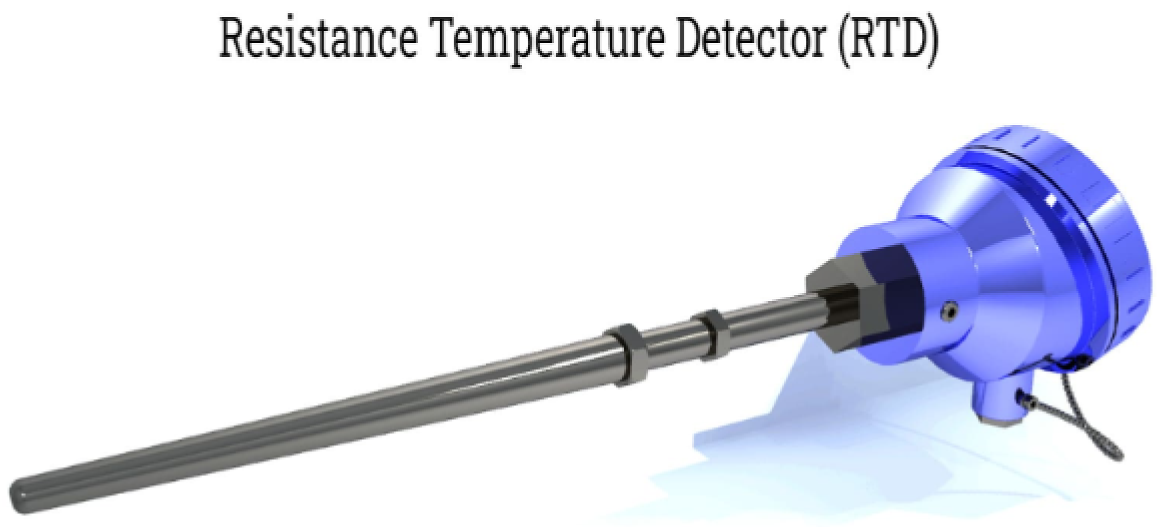


Figure 33: Portrayal of a resistance temperature detector

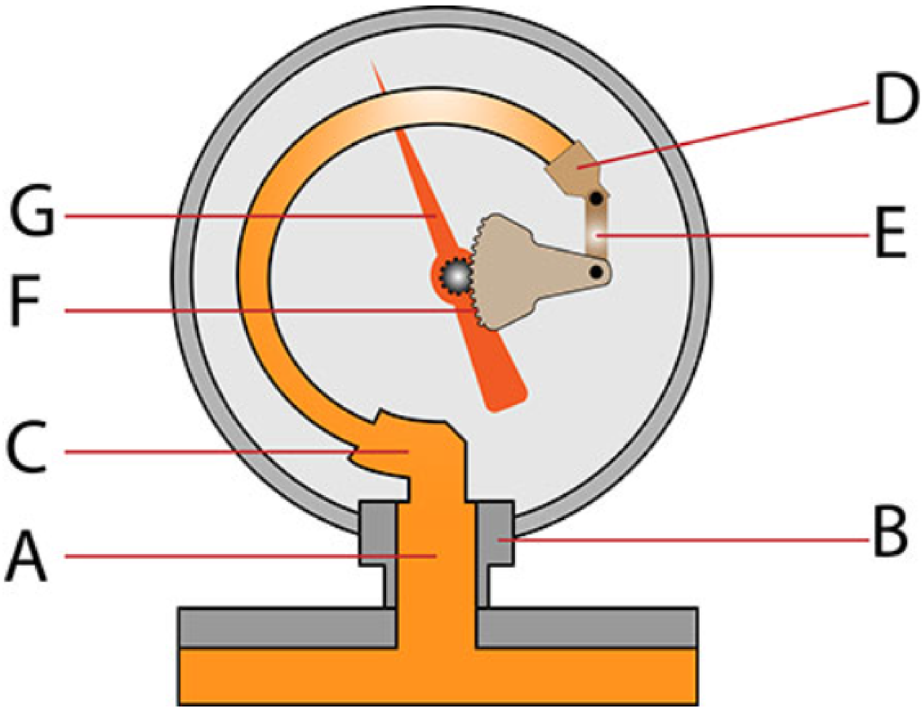
Pressure gauge

A pressure gauge has the function of measuring the pressure of a fluid within a system. This is critical to ensure the system is consistent and that there are no leaks.
A pressure gauge consists of a sensor that registers the pressure and converts it to an electrical signal. This can be observed on a dial as portrayed in figure 34a. The sensor consists of a pressure-sensitive element which deforms under pressure. This is connected to a measure mechanism and converted into readable measurements.

The most commonly used pressure gauge is the bourdon tube pressure gauge and this gauge measures pressure relative to the atmospheric pressure. A bourdon tube consists of a flattened thin-wall closed-end tube in the shape of a C as seen in figure 34b. The pressure is distributed

into the tube through an inlet pipe. As the pressure enters the tube the oval cross section becomes more circular and the tube starts to straighten up. The free end of the tube is attached to links and gears which cause the indicator on the dial to rotate clockwise when pressure increases and counter clockwise when pressure decreases. The indicator is at 0 when there is no pressure since the tube has returned to its original shape.
A bourdon tube is usually made of stainless steel, brass or monel.[55]

A dial which portrays the pressure
(a)



How an bourdon tube works
(b)
Figure 34: Portrayal of a bourdon tube

Speed controller of a DC motor

To control and measure the speed of a DC motor a speed controller can be utilized as seen in figure 35. Specifically a closed loop control system which controls the speed and since it is a closed loop it simultaneously provides feedback in form of the speed. The speed is proportional to the supply voltage, therefore by increasing the voltage the speed increases.
To get the acquired speed, two tasks are done simultaneously. The speed is measured and compared to the desired speed. Consequently an appropriate voltage is supplied. [56][57]

Figure 35: A DC motor speed controller

Manufactured components

These components are required to be manufactured since they do not exist on the market or they will be specially made for each tribotest.

Pin

The pin consists of one of the materials that is to be tested. So this component will be specially made for each test, however all pins will be cylindrical and consist of a half sphere at the end of it. This pin will be attached to the pin holder and will be pressed down into the disk.
According to ASTM G99 the typical pin diameter ranges from 2 to 10 mm where the included half sphere on the tip of the pin has a similar diameter. Since materials have different properties the dimension will be adjusted accordingly by the user.[33]

Disk

The other material that is to be tested is in the form a disk which also will be specially made for each test. The disk will be attached to the chuck and rotated by the assistance of a motor. According to ASTM G99 the typical disk diameter ranges from 30 to 100 mm and the thickness ranges from 2 to 10 mm.[33] The dimension will differ by the chosen material and will be decided by the user.

Pin holder

The pin holder has the function of holding and stabilizing the pin. The pin holder will be manufactured to grip the pin whatever the size of the diameter. It is attached to the lever arm and will have the function to regulate the angle of the pin. The angle will be maximum 45 degrees in reference to the pin being vertically placed. This will result in utilizing the entire half sphere of the pin thus extending the lifespan of the pin which results in less waste and is beneficial for the environment.

Pressure vessel

The pressure vessel is designed to withhold the fluid and be large enough to fit the tribometer including the possibility of maintenance and change of components. The vessel will be cylindrical with a flat bottom and containing corners resulting in better flow of the fluid. The top will be able to open using a closure function as portrayed in figure 36 to make the tribometer available for the user. The vessel has an inner diameter of 300 mm and a wall thickness of 5 mm. This was calculated using the equation in the theory section under "pressure vessel". A design factor of three and titanium with a yield stress of approximately 900 MPa were used to obtain this wall thickness. The vessel has a height of 300 mm from the bottom to the opening at the top.
The vessel should be preheated before introducing the steam. This reduces the thermal stress which acts on the vessel, it results in a better temperature distribution throughout the vessel and it reduces the risk of condensation which could damage the internal of the vessel.

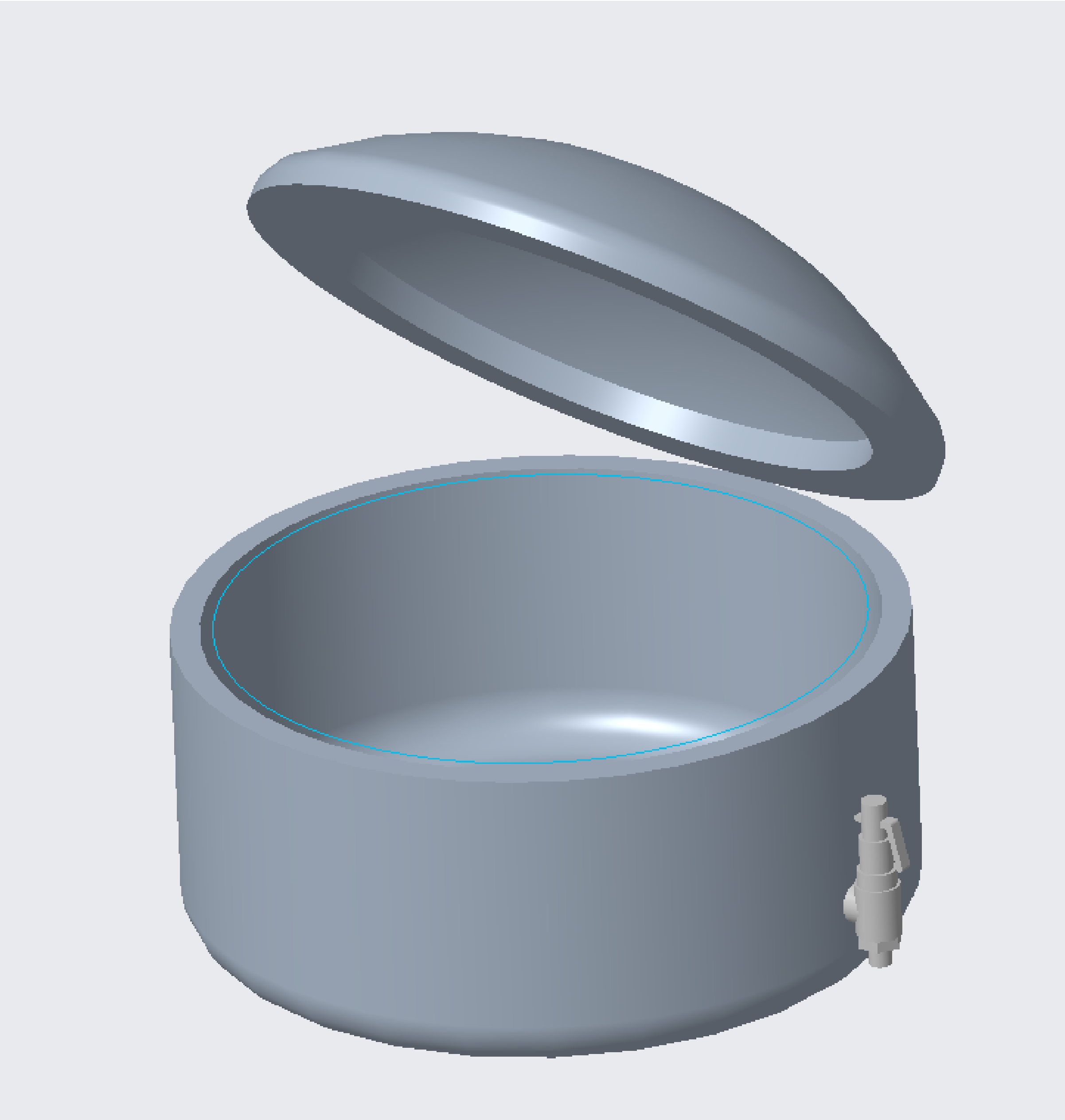


Figure 36: The pressure vessel

Result

Interview

Interview 1

This interview portrayed the importance of several important topics. most notably how important it is to keep track of your parameters. These parameters include load, velocity, temperature and steam pressure. These are critical to keep track of to achieve accurate measurements.
One other factor that could affect the accuracy of the measurement is the contact between the pin and the disc. If this contact is not controlled no conclusion can be made from these tests. The distance from the center of the disk to the position of the pin is important as well when determining the velocity of the disk.
When starting the test, the pin will cause a circular wear pattern. Since the pin probably will move in the same track there is a possibility of remaining wear particles in the track which could affect the measurements. This is an important factor to be aware of.
The pin holder should contain a function to regulate the angle of the pin since it means the entire can be utilized and cause less waste.
Since the pressure vessel contains high temperature and high pressure steam, the fewer machine elements inside the vessel the better. Since it is possible to measure the wear afterwards outside the pressure vessel, it is more optimal for this kind of apparatus.
To make sure the test reflects the conditions of reality, several tests should be made and compared. This will result in a better overall picture of the test procedure.
Another important factor is the steam affected screws. They should consist of a corrosion resistant material or consist of an oxidizing agent to prevent oxidation. Examples of these materials are stainless steel or a nickel based alloy.
The contact between the disk and pin will result in a generated pressure according to the hertzian contact theory mentioned in the theory. The disk must rotate with a constant velocity to achieve usable measurement, therefore it is important to oversize when choosing a motor. Otherwize it could lead to the disk slowing down by the contact pressure.

Interview 2

As mentioned in interview 1, there should be as few machine elements as possible in the pressure vessel. This results in as few machine elements as possible being affected by the steam which is desired.
It is beneficial to design the vessel with as low volume as possible since it could simplify the construction process due to less modules that are required to be followed which is mentioned in the literature study.
The corner of the vessel should be rounded consequently creating a kinder distribution of pressure.

The pressure vessel should contain one solution to introduce the steam into the vessel and one solution to automatically transport out the steam if the pressure gets too high and a safety hazard. It should as well consist of a seal that allows for rotation for example the disk which motor is placed outside.
Since the temperature will be as high as 450 degree celsius, an awareness of the thermal expansion of the including components must exist.

Material selection

With the assistance of the material selection program Granta EduPack an optimal material could be selected. This material will be used for the pressure vessel as well as for some of the components inside the vessel. It was selected with respect to six properties which are critical in this material selection. Another important property is that the material must be para- or diamagnetic for the magnetic coupling to work.

4 plots were made with one parameter on each axis.
Plot 1 includes the thermal expansion coefficient on the Y-axis which is optimal to be as low as possible since an expansion of the components could affect the measurements. The X-axis consists of the durability to fresh water which is required to be excellent since the components will be exposed to corrosion due to the steam. The best material is marked with a box as portrayed in figure 37.

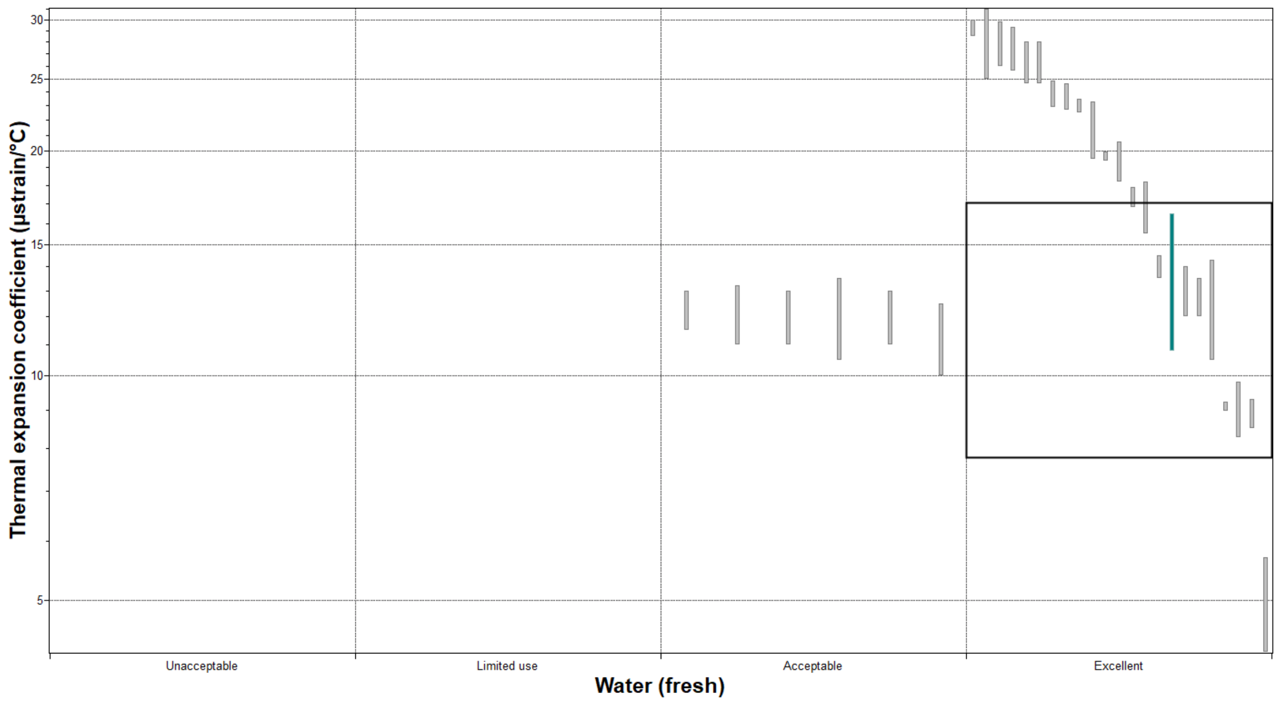


Figure 37: Plot 1 with durability to fresh water on the x-axis and thermal expansion coefficient on the y-axis

Plot 2 includes the parameters of maximum service temperature on the Y-axis and melting point on the X-axis which must exceed the maximum temperature of the steam which is 450 degree celsius. The most suitable material is marked with a box as shown in figure 38.

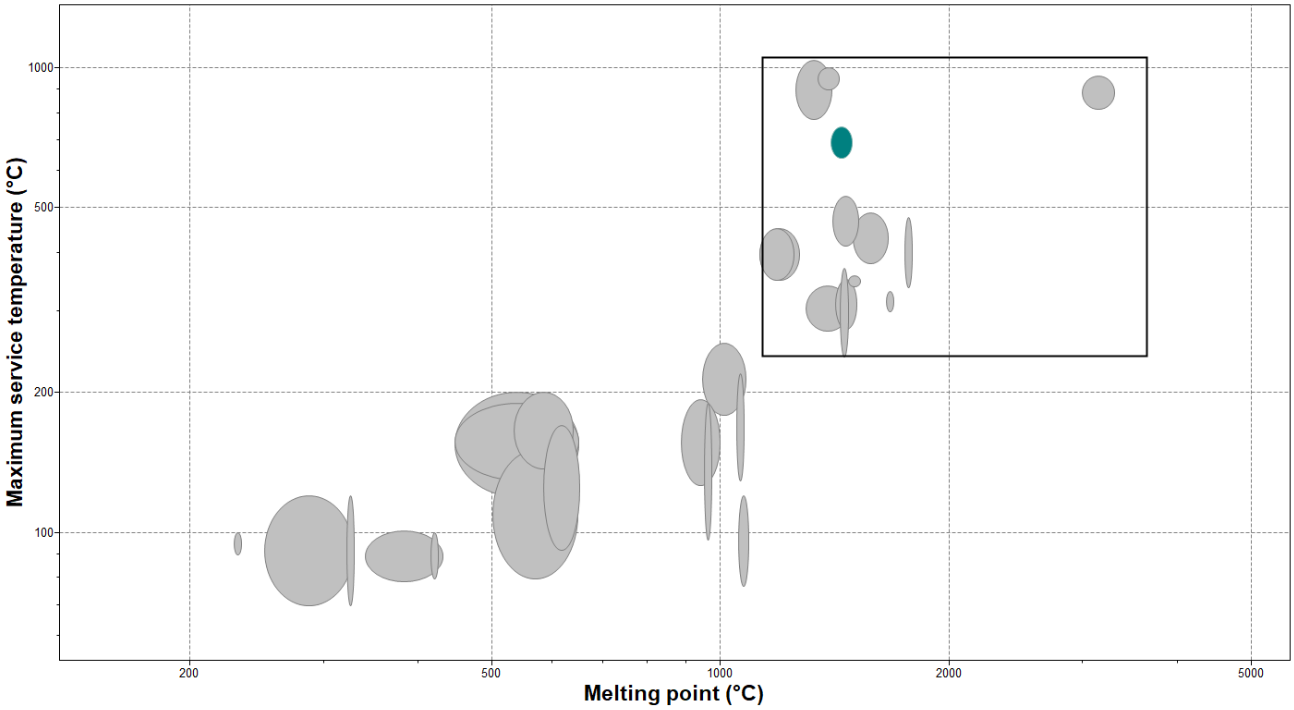


Figure 38: Plot 2 with melting point on the x-axis and maximum service temperature on the y-axis

Plot 3 involves price on the Y-axis since it is optimal for the material to be cheap. The X-axis consists of fatigue strength at 10^7 cycles which is an important factor since the test is running for a long period of time. Figure 39 shows the best material in this plot.

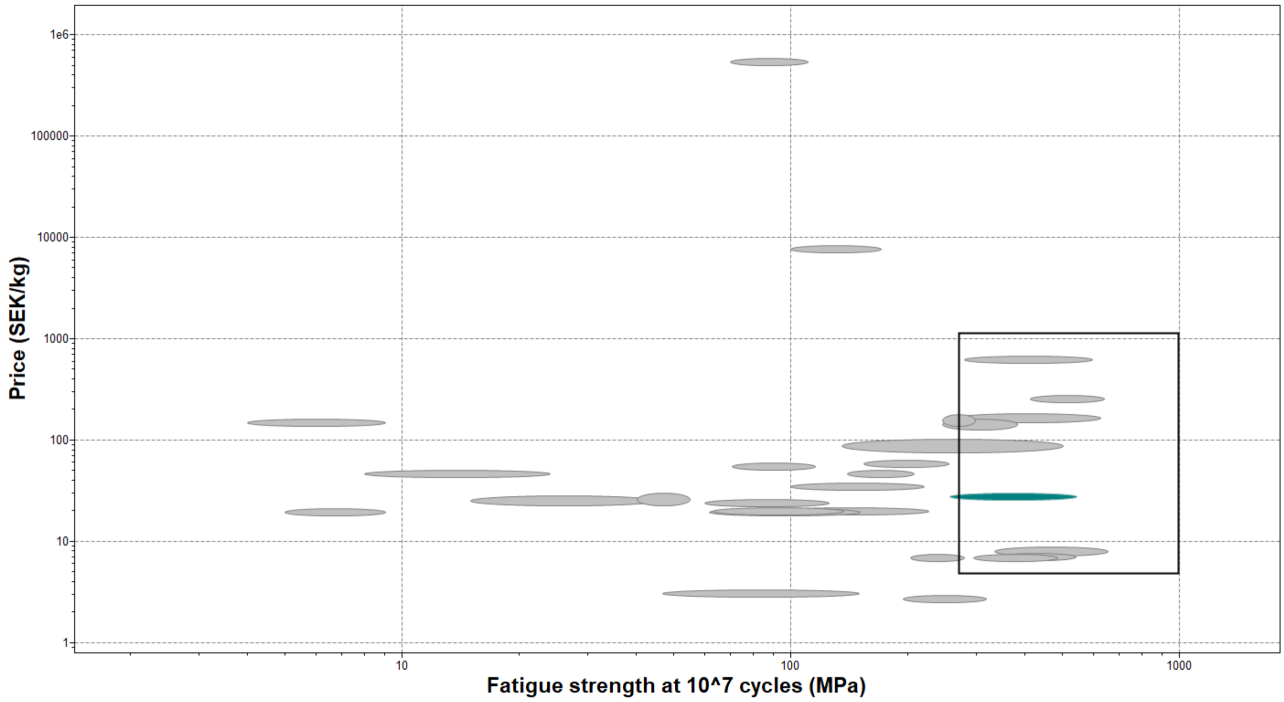


Figure 39: Plot 5 with fatigue strength at 10^7 cycles on the x-axis and the price on the y-axis

Plot 4 portrays which materials are the most environmentally friendly. The Y-axis includes the CO2 footprint and the X-axis includes the amount of embodied energy. Both these parameters should be as low as possible therefore the best materials belong in the bottom left region of the plot as shown in figure 40.

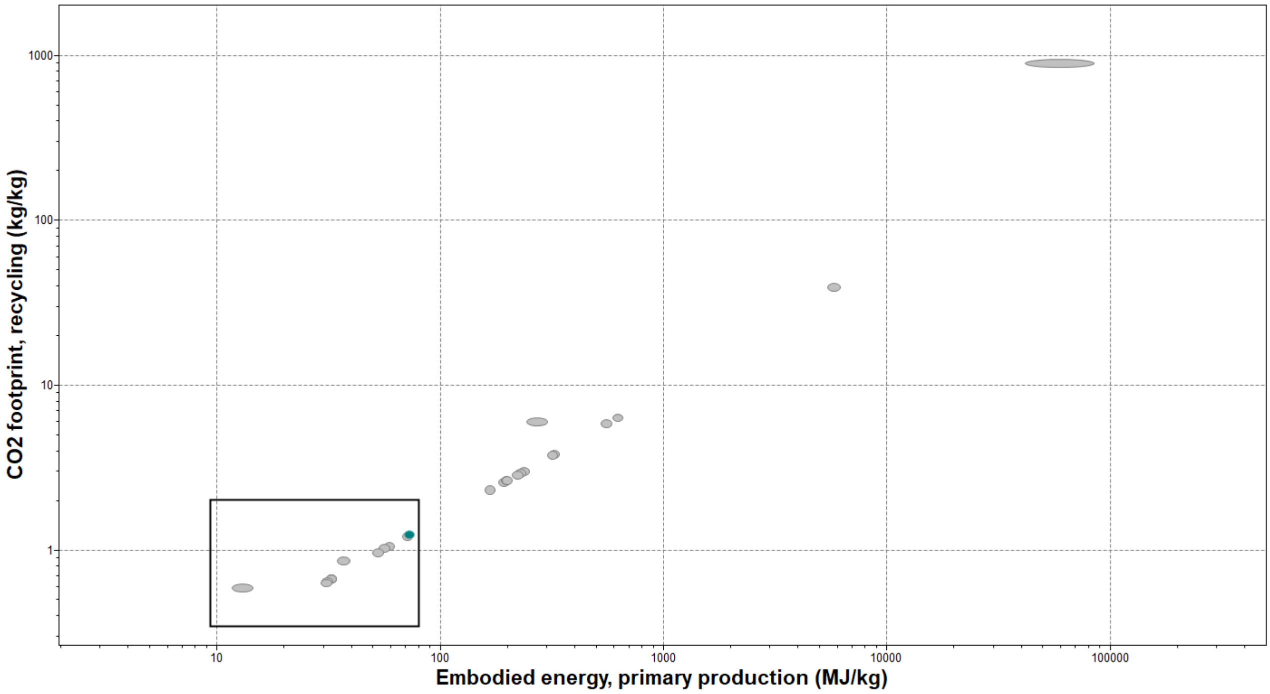


Figure 40: Plot 4 with embodied energy on the x-axis and CO2 footprint on the y-axis

The only material which is included into each one of the marking boxes in the plots is stainless steel. This material fulfills all requirements and parameters and is the resulting material which the components and machine elements will consist of. Other candidates which proved to be suitable materials are nickel based superalloy and titanium.

FEM-analysis

As portrayed in figure 41, 42 and 43, a FEM-analysis was performed on the pressure vessel by placing an internal pressure of 10 MPa and placing a boundary condition at the bottom. The result is portrayed in table 1.

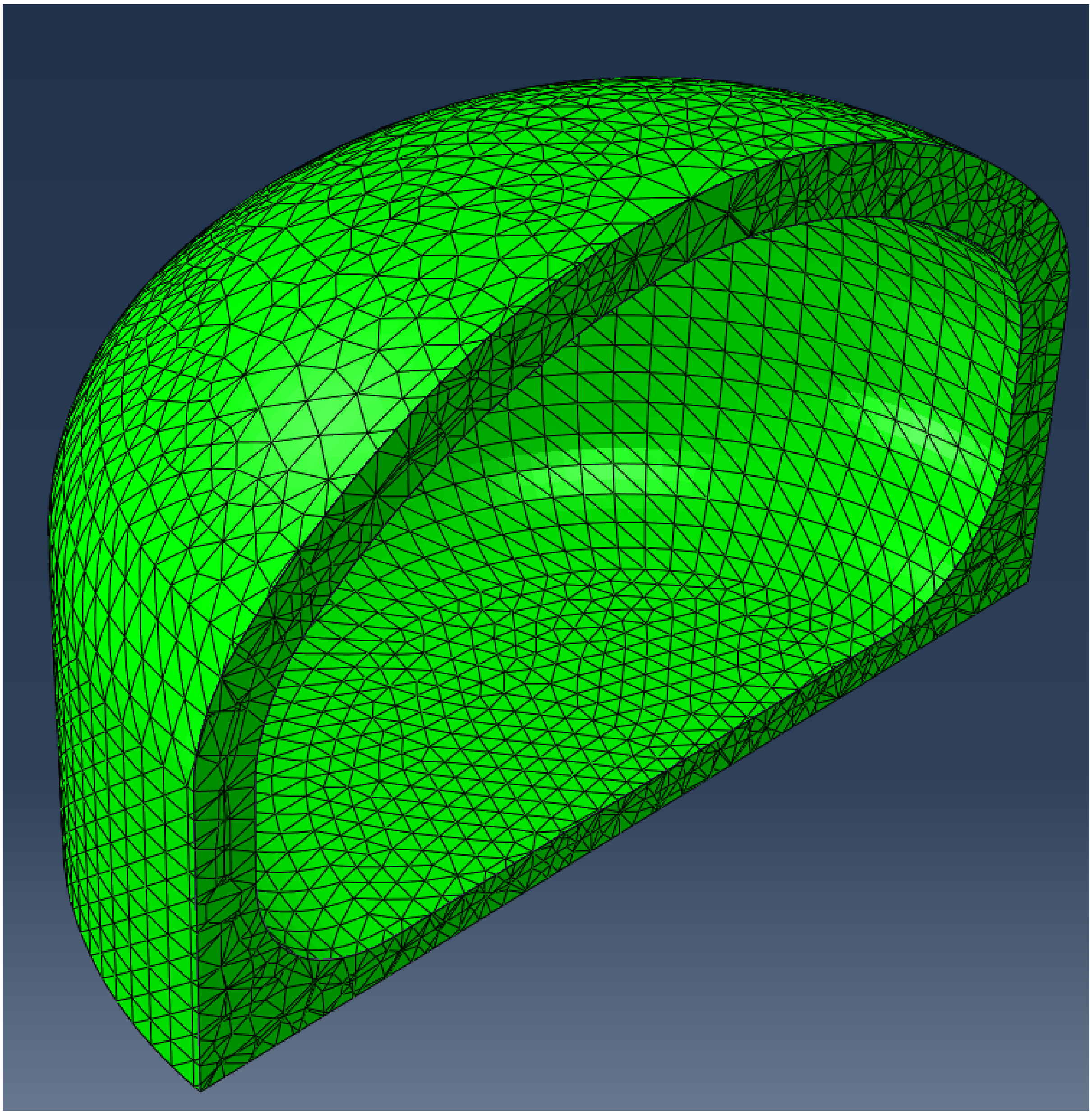


Figure 41: Split version of the pressure vessel in Abaqus

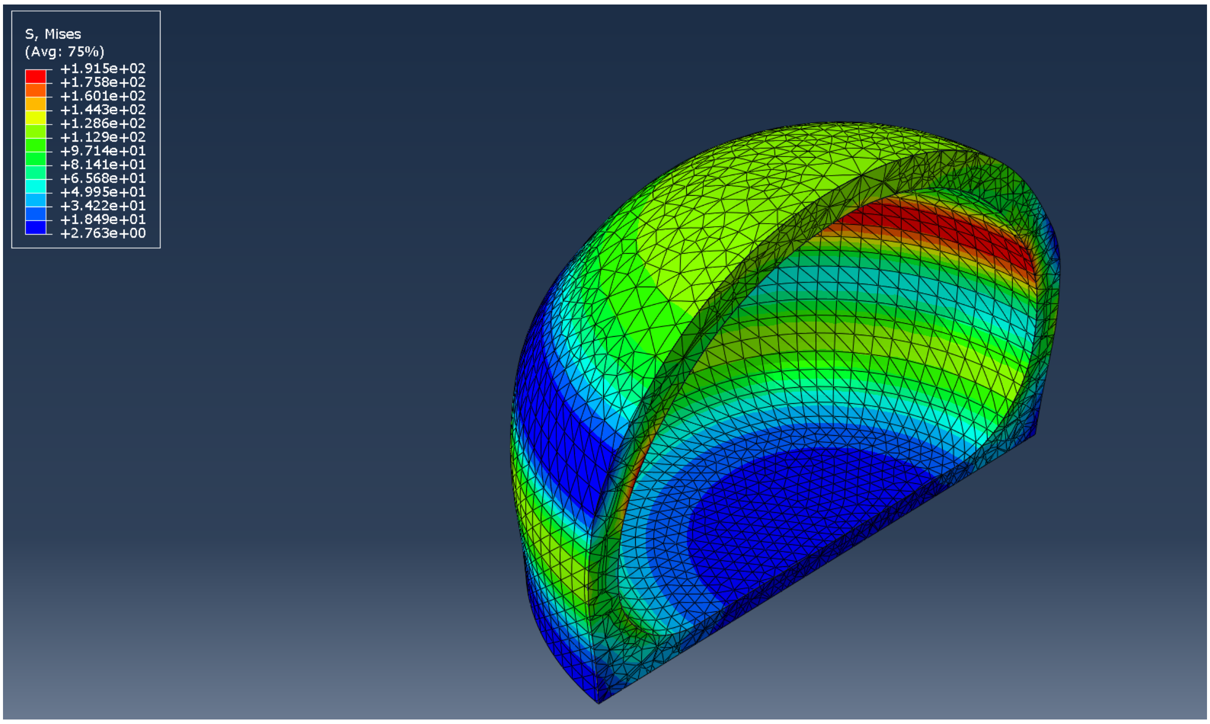


Figure 42: The maximum stress due to the steam pressure

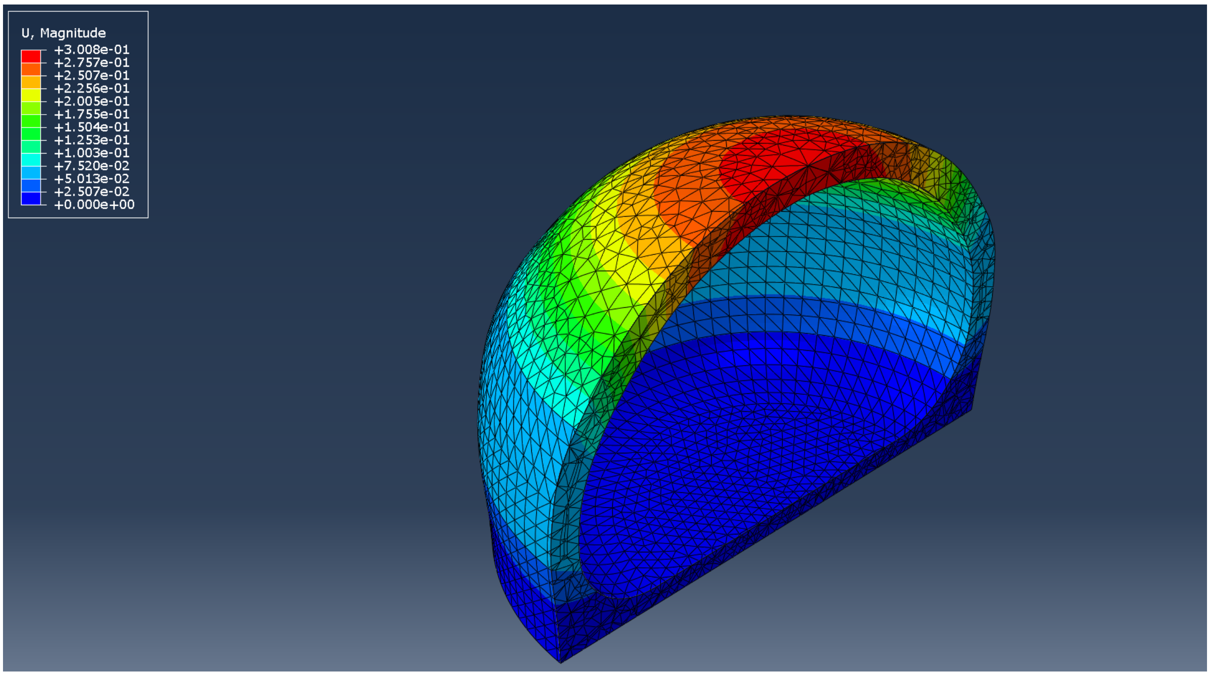


Figure 43: The magnitude of deflection due to the steam pressure.

Internal pressure	10 MPa
Max stress(mises)	191.5 MPa
Magnitude of deflection	0.3 mm

Table 1: Result obtained from abaqus

The chosen material has a yield stress 900 MPa and this type of apparatus has a design factor of three. This means that the maximum stress must be lower than 300 MPa for the vessel not to break. By comparing this to the result in table 1, it is clear that this requirement has been fulfilled since 191.5 MPa < 300 MPa.

Discussion

Comparison of pre existing design

The current market included several solutions of tribometers and several solutions of pressure vessels however there are few solutions on a combined tribometer and pressure vessel. These were used as inspiration such as using magnetic coupling. The function of these were used to transfer torque from a motor outside the vessel to the disk without any physical connection therefore not causing any possibility of leaking. [47]
In existing designs, pneumatic actuators are mostly used to apply the load. By using a pneumatic actuator the volume could be decreased compared to using a lever arm since the weight is applied from above, it requires no lever. The accuracy of the pneumatic actuator could however be affected by the high temperature and high pressure steam and result in inaccurate measurement.
A lever arm tribometer is a commonly used tribometer whose loading application is in the form of dead weights. This is a loading application which does not get highly affected by steam. This is placed in a cylindrical pressure vessel and inspired by a pre-existing design where a tribometer is lowered down in a vessel.[29][30][31]

Critical machine elements

Strain gauge
A strain gauge is utilized and placed on the lever arm to obtain the friction force since it can be encapsulated and not be affected by the steam. The including temperature must however be compensated for by using equation 24 described in the machine element section. Another benefit is the easy conversion from strain to friction force. A linear variable differential transformer(LVDT) was considered an alternative since it measures linear displacement which can be converted to friction force. however this could get affected by the environment and result in inaccurate measurement. [51]

Magnetic coupling
The motor is placed beneath the vessel to function properly. To transfer torque from the motor to the disk, a rotary seal was considered. A seal of this magnitude was however challenging to find because of the high pressure and temperature. This could result in leakage thus having hazardous effects. To prevent leakage a magnetic coupling is preferred since it can transfer torque from one shaft to another without any physical connection using a magnetic field which is highly suitable for this kind of apparatus. [47]

Dead weights
To regulate and measure the applied load dead weights will be used. This will consist of stainless steel which is the chosen material which is most suitable to handle this type of environment. Therefore it is the solution which is the least affected by the steam. A

pneumatic actuator and a piezoelectric actuator were considered to be used since it would not require any lever and lead to a decreased volume of the vessel. This is however a solution which could lead to inaccurate measurements because of the affection from the environment. Dead weights are easily regulated and easily measured and since they are placed right above the pin the magnitude of the load can directly be converted into the normal force.

DC motor
The choice of motor was between an AC motor and a DC motor. An AC motor is less expensive and requires less maintenance however a DC motor has a higher control and pressicon when regulating the speed and it provides a constant torque over a wide range of speed. Since it is important to keep track of the magnitude of the parameters to get accurate results, the DC motor proves to be more beneficial to this area of use.[49]

Interview

The content of the interview was used when deciding the most suitable type of machine elements. To get accurate results the parameters must be controlled so that the test could be compared. Therefore a component to measure and regulate parameters such as load, velocity, temperature and pressure were required.
The test rig will not include a function to simulate the wear since it could be executed afterwards and would be a challenge to find a well functioned solution for because of the high pressure environment.
With regard to the environment the angle of the pin will be able to be regulated which utilizes the entire half sphere of the pin which causes less waste.
The vessel is in the shape of a cylinder with rounded corners. This results in a greater distribution of steam and better flow.
The vessel involves a function to introduce the steam in the form of a pipe and a ball valve and a function to release the excessive pressure in the form of a safety valve.

Choice of material

With the assistance of Granta EduPack a suitable material for the chamber and the components were selected. It is uncertain if these results reflect reality and how correct the EduPack data turns out to be. According to edupack, the selected material is a stainless steel with a yield strength of approximately 900 MPa which is required to handle high temperature and high pressure steam according to the equation in the theory section under “pressure vessel”. X20CrMoV12-1 is suitable stainless steel for this type of application since it has a high corrosion resistance, high strength under high-temperature strength and a suitable yield strength.
This is based on properties such as corrosion, cost, environment friendly, thermal expansion, creep strength and fatigue strength.
An alternative material is a nickel based superalloy like Inconel 718. This material has excellent properties considering corrosion resistance, creep strength and ability to handle high

temperatures and pressures. A nickel based superalloy is however more expensive compared to a stainless steel.
However for the magnetic coupling to work, the material is required to be para- or diamagnetic. This leads to the material Ti-6Al-4V being the most favorable. The is a Grade 5 titanium which has a yield strength of 900 MPa. It has properties including high strength, high corrosion resistance, low thermal expansion and paramagnetism.

FEM-analysis

A simulation of the pressure vessel was executed with the assistance of Abaqus. The ingoing steam acted as internal pressure with a magnitude of 10 MPa. This simulation presented a clear picture where the vessel were affected the most. This resulted in a minor change of geometry by rounding the edge additionally to achieve a kinder flow of pressure. The diameter and thickness of the wall were increased. Eventually the most optimal regarding maximum stress and the ingoing components were accomplished. This design fits all components and machine elements and simultaneously fulfills the requirement of maximum stress. The maximum stress does not exceed the yield stress of the material with a design factor of three.

Conclusion

- A cylindrical vessel with rounded corners is the most favorable geometry. The reason is to achieve the best distribution of steam and still placing the tribometer on a flat surface to achieve a fully horizontal disk which is required to get accurate results. The flat surface additionally suits the usage of the magnetic coupling which would be able operate otherwise.

- A strain gauge is most favorable to simulate the friction force since it can handle the environment by using an encapsulation and the strain can be easily converted to a friction force.

- Magnetic coupling is most suitable in this case. It prevents the possibility of leaks, it causes less friction and it is an alternative to a rotary seal which was challenging to find with properties to match the environment.

- Dead weights is the most favorable solution to regulate and measure the applied since it gets the least affected by the environment compared to the alternative solutions. It is additionally easily converted to the normal force.

- A DC motor is the choice of motor since it has high accuracy and control and provides torque over a wide range of speed.

- The most suitable material with regard to the environmental properties is a titanium with a high yield strength, for example Ti-6Al-4V . It has excellent properties considering corrosion resistance, strength, thermal expansion and paramagnetism.

Future work

- Find suitable screws which can handle the environmental properties without leading to failure.

- Include a device which registers and displays the number of revelations of the disk.

- Perform a more thorough material selection to obtain the most optimal material in regard to the parameters.

- To find a fitting closure function which is in the shape of a half sphere and does not cause any leaks.

- Find a solution to insert and remove the specimen in an optimal way.

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Appendix A - Risk analysis

Risk	Propability	Consequence	Value of risk	Actions	Propability	Consequence	Value of risk
Construction error	4	5	20	Be meticulous	2	3	6
Economic limitiations	3	3	9	Communication with invencon	2	2	4
Calculation error	3	4	12	Be meticulous	2	3	6
Lack of time	3	3	9	Scheduling	2	3	6
Lack of competence	4	3	12	Take help from competent people	2	2	4
Miscommunication	3	3	9	Weekly meetings	2	2	4
Late changes of requirements	2	4	8	Good foresight	1	2	2
Lack of resources	2	4	8	Be innovative	2	2	4
Scheduling error	3	3	9	Good foresight	1	2	2

Appendix B - Requirement specification

Nr.	Criteria	Description
1.	Simulation	The test rig will be able to simulate friction
2.	Regulation	The test rig will have function to regulate parameters such as pressure, load, velocity, temperature and pin angle
3.	Measuring	The test rig will have function to meassure parameters such as pressure, load, velocity, temperature and number of revolutions
4.	Preserving	The test rig will include a pressure vessel that can preserve the steam
5.	Introducing	The test rig will include a function to introduce the steam
6.	Drive	The test rig will include a function drive the disc
7.	Standards	This project will follow following standards: ASTM G99, ASTM G133, ASTM F732, DIN 50324, DIN ISO 7148-1, DIN ISO 7148-2, AFS 2016:1, ASTM G132, ASTM D2266
8.	Safety	The test rig must not be a hazard for the user
9.	Maintenace	The test rig must be designed with the possibility to be maintenaced
10.	Sustainability	The test rig will be designed through a sustainable perspective

Appendix C - Functional specification

Verb	Substantive	Type	Limitations
Simulate	Friction	Main function	
Drive	Disc	Part function	
Regulate	Load	Part function	
Regulate	Velocity	Part function	
Measure	Load	Part function	
Measure	Velocity	Part function	
Measure	Revolutions	Wish	
Regulate	Pin angle	Wish	At most 45°
Preserve	Steam	Main function	
Regulate	Temperature	Part function	not higher than 450 °C
Regulate	Pressure	Part function	not higher than 100 bar
Measure	Temperature	Part function	
Measure	Pressure	Part function	
Introducing	Steam	Part function	
Shut	Down	Wish	At pressure higher than 100 bar
Regulate	Excessive pressure	Wish	

Appendix D - Concept generation

Criteria	Solution A	Solution B	Solution C
Simulate normal force	Strain gauge	Dead weights	LVDT
Simulate friction force	Strain gauge	LVDT	
Drive the disc	AC motor	DC motor	
Transfer torque from spindle to disk	Rotary seal	Magnetic couplings	
Preserve steam	Vessel containing all components	Seperate tribometer and vessel	Vessel with seals containing component on the outside
Apply load	Dead weights	Pneumatic actuator	Piezoelectric Actuator
Type of tribometer	Lever arm tribometer	Pin attached to upper part of tribometer	

Appendix E - Concept evaluation

	Concept 1	Concept 2	Concept 3	Concept 4
Practicability	3	4	2	2
Usability	2	4	2	3
Requirements fulfillment	2	3	3	3
Safety	1	4	2	4
Maintenance	3	4	4	4
Weight	5	2	4	3
Sustainability	2	4	3	3
Total score	18	25	20	22