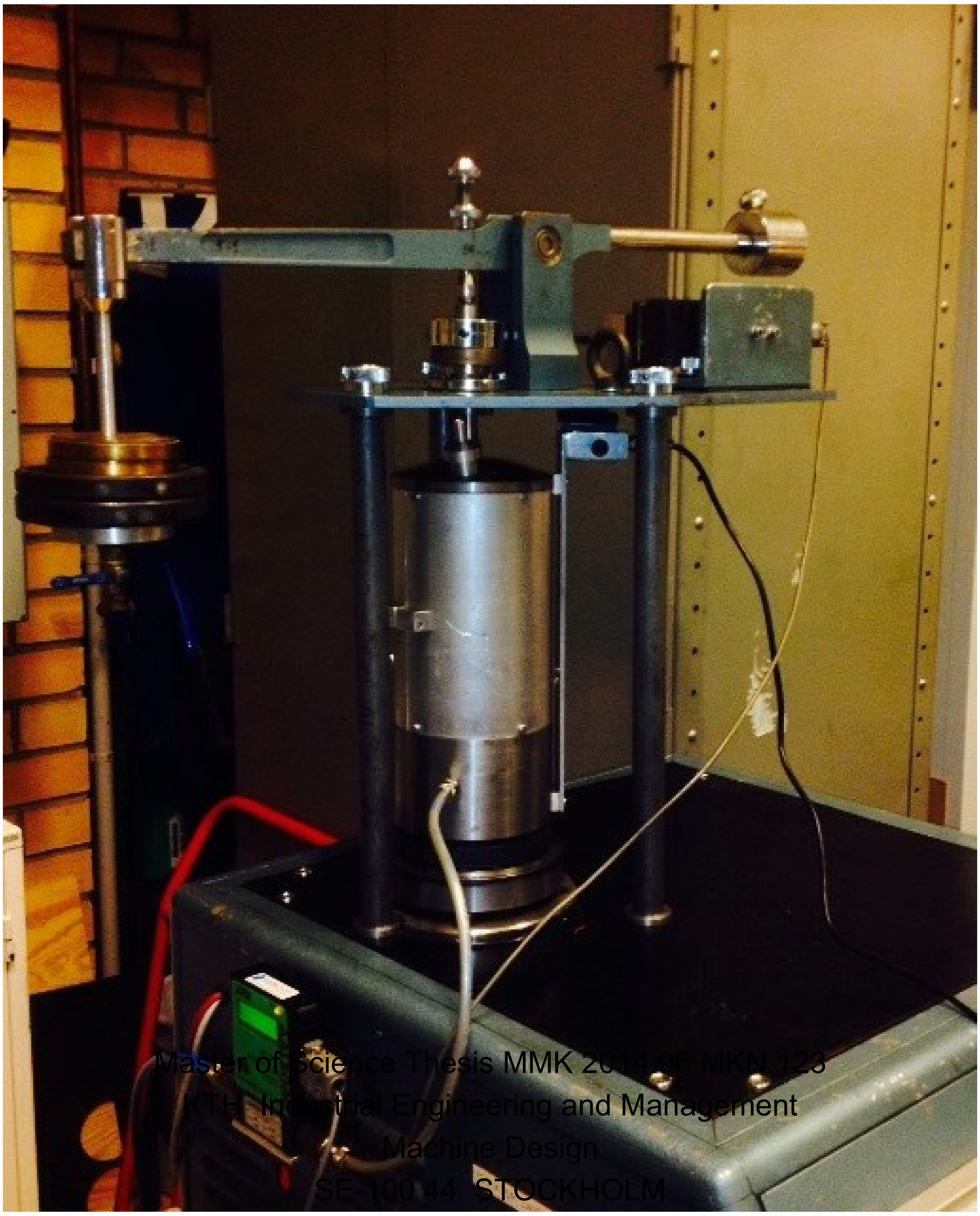
Redesign of a pin-on-disc tribometer focusing on blast furnace off-gas dust

Shimelis Wassie



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KTH Industriell teknik och management	**Examensarbete MMK 2014:96 MKN 123** **Omkonstruktion av en tribometer för att studera bildande av avgasstoft från masugn** Shimelis Wassie

Godkänt	Examinator	Handledare
2014-12-09	Ulf Sellgren	Jens Wahlström

SAMMANFATTNING

Vid järnframställning försöker man minska materialspill i avgasstoft från masugnar. Järnmalm och koksmaterial blåses ut från masugnen i form av avgasstoft. För att minska materialförlusterna i form av dammbildning är det viktigt att förstå mekanismerna bakom dammbildningen och beteendet i masugnen.

En masugn i drift är i allmänhet en kaotisk miljö där det är svårt att genomföra experiment. Av denna anledning är försök i en kontrollerad laboratoriemiljö att föredra.

Möjligheten att bygga en testutrustning i laboratorieskala för att studera bildningen av och beteendet hos avgasstoft har utretts. Studier av masugnsdrift visar att mekanisk dammbildning står för en stor del av avfallet. Denna dammbildning sker i den övre axeln av masugnen där temperaturen är relativt låg. Damm bildas genom mekaniskt slitage av material på grund av en kombination av materialets tyngd och rotation.

Ett stift på tribometerskivan har fått ny utformning för att kunna imitera den mekaniska dammbildningen i en masugn. Delar av tribometern gjordes om och andra nya delar utformades med hjälp av CAD-verktyg och tillverkades och monterades sedan. En elektrisk motor används för att skapa rotation av pelletarna och en trycksatt luft tillförs på ett kontrollerat sätt för att imitera den heta tryckvågen i masugnen. Systemet belastas med en statisk vikt via en hävarm för att imitera tyngden i masugnen. Det fina dammet som blåser ut ur testutrustningen samlas in och analyseras med in inbyggd partikelmätare. Friktionsvärden som uppstår mellan pellets och mellan pellets och vägg loggas med hjälp av ett DAQ-system.

Vid en verifierande provning, som utfördes efter att systemen satts samman, var friktionskraften mellan pellets och vägg 4N. Detta konstaterades med hjälp av en 200N statisk belastning och en motor med en rotationsfrekvens på 5Hz. på grund av felaktig lastcell och en felaktigt monterad slang, kan friktion mellan pellets och partikelstorleksdata från partikelräknare i dagsläget inte presenteras.

Nyckelord: Nötning, pellets, masugn, stoft

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ABSTRACT

In blast furnace ironmaking, efforts are made to decrease material waste due to off-gas dust. Iron ore and coke materials are blown out of the blast furnace in the form of off-gas dust. In order to decrease material losses through off-gas dust formation, it is important to understand off-gas dust formation and behaviour in the blast furnace.

A blast furnace operation generally being a chaotic environment is often difficult to conduct experiments while in operation. For this reason, a laboratory scale imitation of a blast furnace with similar basic properties is usually used to conduct experiments.

The possibility of building a laboratory scale test equipment to study the formation and behaviour of off-gas dust has been studied. A through study of blast furnace operation shows mechanical dust formation accounts for much of the waste due to fines generation. This dust formation occurs in the upper shaft of the blast furnace where the temperature is low. Mechanical dust is formed through mechanical wear of material due to burden decent and rotation.

A pin on disc tribometer has been re-designed to be able to imitate blast furnace mechanical dust formation. Parts of the tribometer were remodelled or redesigned and other new parts were designed using CAD software and then manufactured and assembled to give a laboratory test equipment. An electric motor is used to generate the rotation of the pellets and a pressured air is supplied in a controlled manner to imitate the hot blast in the blast furnace. The system is loaded using dead weight via a lever arm to imitate the burden weight in the blast furnace. The fine dust that blows out of the equipment is designed to be collected and measured by a particle sizer device that is incorporated in the equipment. The friction values that arise from pellet/pellet and pellet/wall friction are recorded and logged using a DAQ system.

At a partial demonstration made after the systems are assembled, the friction value between pellets and wall was found to be 4N. This was found using a 200N load and a motor rotational frequency of 5Hz. Although the equipment is fully functional, pellet/pellet friction value and particle size data from particle counter could not be found presented due to faulty load cell and tube fitting respectively.

Keywords: Wear, pellet, blast furnace, off-gas dust

FOREWORD

Acknowledgement, assistance, cooperation and inspiration important for the presented project are listed here.

I would like to thank my supervisors Ulf Olofsson and Jens Wahlström at Machine design department, KTH for giving me the chance to work on this project and helping me out with all the questions I had regarding this project.

I also want to thank Andrey Karasev and Muhammad Nabeel at Material Department, KTH for their assistance in clarifying the very concept in the project and their continued support in materials and suggestions.

Shimelis Wassie

Stockholm, November 30 2014

Notations

Symbol	***Description***
f_g	Gravitational force
m	Mass
a	Acceleration
Q	Flow rate
ρ	Density
ω	Angular speed
μ	Friction coefficient
ω_o	Eigen frequency
k	Elasticity constant
N	Newton
A	Area

Abbreviations

CAD	Computer Aided Design
PC	pulverized coal
FEM	Finite Element Method
DFX	Design for Excellence
BF	Blast Furnace
EBF	Experimental Blast Furnace
DAQ	Data acquisition
LED	light emitting diode
AC	Alternating current
DC	Direct current

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1. INTRODUCTION

This chapter describes the background, the purpose, the limitations and the method(s) used in the project are presented.

In this thesis work a pin-on-disc tribometer is redesigned to be able to study blast furnace off-gas dust particles. This project is done in collaboration with Department of Material Science, KTH. It includes the task of redesigning some part of the tribometer so as to simulate blast furnace operation. The equipment is designed mainly to test iron ore pellets; but it can also be used to test other materials under similar conditions

1.1 Background

In iron and steel production process large amounts of waste by-products are involved, for example dusts and sledges. The study of these by-products become more and more important as legal requirements demand a through utilization ,existing landfill capacities as well as the scarcity of primary resources and in the long term the rising prices of metals makes such utilization economically attractive[1**].**

In the blast furnace process, material losses are caused by particles that are blown out of the furnace by the off-gas dust. One of the ways off-gas dust is formed is through coke degradation. Coke degradation in a blast furnace stock line and upper shaft is generated by shattering and abrasion. Fines generation from the bosh level downwards is generated by sheer stress due to the increased load to the coke bed. The coke weakens by solution loss reaction (Boudouard reaction), direct reduction of wustite and other compounds. Further down in the blast furnace, the coke weakens by the carburization of Iron. In the raceway, coke fines are produced by mechanical impact of rotating coke, thermal stress, and combustion and solution loss reactions [2**].**

In order to understand off-gas dust formation and material content, it is important to understand the correlations between furnace conditions and off-gas dust formation.

1.2 Purpose & aim

The aim of this thesis work is to redesign a pin-on-disc tribometer to be able to study blast furnace off-gas dust formation in a controlled environment. The equipment is to be designed in a way that simulates actual blast furnace conditions.

There is an interest to study off-gas dust generation and behaviour in a blast furnace to decrease material losses. This study in turn will help in raising the understanding of pellet behaviours and improve development of pellets. The development of this equipment will provide an excellent opportunity to study pellet behaviour and off-gas dust formation in a blast furnace through wear of pellets due to burden material movement. It could also be used to study other materials subjected to similar conditions.

1.3 Problem definition

Product development and Cost minimization are main concern in an iron and steel industry. Much effort is spent on developing new pellets with better properties, contributing to decreased hot metal cost. New pellets are traditionally developed in a laboratory and tested in a production blast furnace. Such trials are risky and evaluation is difficult [3]. To overcome this problem development of a laboratory equipment that simulates the condition of pellets in a blast furnace becomes at most important.

1.3.1 System requirements

The equipment is to be built equipped with systems that simulate certain aspects of a blast furnace. Starting with the design of a cylindrical sample holder for the pellets, the sample holder should be designed to mimic the contact situation between pellets in a blast furnace. Visibility of the sample holder to observe pellet rotation and wear is a requirement. A system to create movement of pellets as in a blast furnace should also be designed.

Material burden on pellets in a blast furnace causes pellet shearing and degradation forming dust particles. To create the same condition in the experimental pellets, a loading mechanism is designed. The loading should be mechanical and controlled.

The dust created in the process is blown out of the sample holder by a jet of ambient temperature pressurised clean air. To make sure of the off-gas dust measured originated from wear of pellets a cleanliness technique should be introduced.

The measured and controlled parameters in this system are; friction force, rotational speed and air flow. A data acquisition system should also be incorporated to log these parameters.

1.4 Delimitations

In this project, the following delimitations have been defined.

- Dust collection system design will not be considered in this project
- Only cold air supply will be investigated
- The maximum budget should not surpass Kr. 50,000
- Only average measured parameter results are main concern
- The design is based on a pin-on-disc tribometer.

1.5 Method

The method used in this project is derived from Design for Excellence. In DFX a collection of specific guidelines that addresses different issues that may occur in a product life cycle are used. The primary task in this method is to understand the user wants and specify the requirements. After evaluating related projects and frame of reference on the subject matter, ideas on solutions will be generated. The generated ideas will be discussed with the customer and gauged against the requirements, which will then be reduced to principal solutions.

Based on the principal solutions, a CAD-model is developed for the chosen concept. After the model is evaluated and confirmed good by all parties involved, manufacturing drawings will be developed and parts will be manufactured. Finally, components are assembled to give a functional prototype.

After the completion of the equipment, a pre-test will be conducted to test the functionality of the equipment and validity of test results of some important parameters.

This chapter presents the theoretical reference frame that is necessary for the performed research, design or product development.

In order to understand the very concept of the problem and help in brainstorming it was vital to study related subjects. A good starting idea was gathered on each sub-system subject matter. To best imitate blast furnace operation a number of related papers and measurement techniques has been studied.

2.1 Blast furnace process

A cross section of a blast furnace is shown in Figure 1. The raw material (iron-bearing material, slag formers and coke) is charged at the top and molten hot metal and slag is tapped at the bottom. The coke is charged in alternating layers with iron-bearing material (ore, sinter or pellets). Slag formers are charged together with the ferrous material. Slag formers are mainly limestone and BOF slag. The reducing gases and the heat needed for the process are generated by the combustion of coke and often other material injected through the tuyeres, usually pulverized coal (PC). Preheated air, which can be enriched with oxygen, is blown through water-cooled tuyeres, see Figure 1, and carbon (C) in coke and PC is combusted in the raceway. The combustion gives temperature of 1800–2300°C, depending on the blast temperature and moisture, oxygen content and type of injected reduction agent. The hot reducing gases ascend counter current to the descending raw materials; imparting heat and providing for the reduction of the raw materials and finally exiting at the furnace top [4].

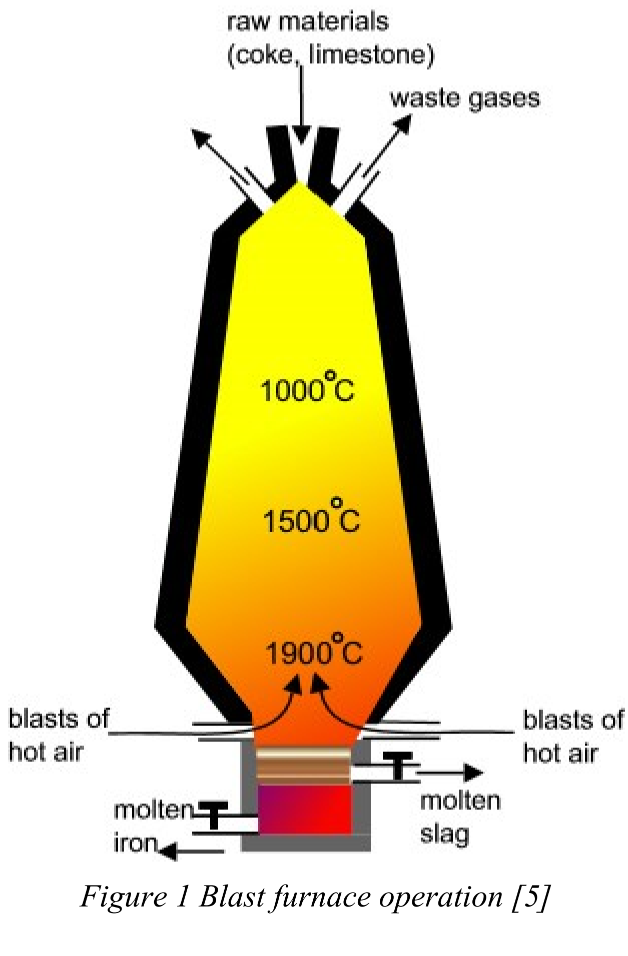

Figure 1 Blast furnace operation [5]

2.2 Iron ore pellets

The making of steel from iron ore or taconite requires a long process of mining, crushing, separating, concentrating, mixing, pelletizing and shipping. The mining process is both labours intensive and expensive. It involves heavy industrial mining equipment, diamond-bit rotary drills, hydraulic shovels, heavy trucks, conveyors and so on.

Iron is usually found in the form of magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite, limonite or siderite. For industrial use the mined ore is usually prepared and sold as pellets. Palletisation of iron ore produces spheres of typically 8-18 mm diameter. [6] The processes include agglomeration and thermal treatment to convert iron ore in to pellets which has improved physical properties for use in industrial blast furnaces. Additional materials are added to the iron ore to meet the requirements of the final pellets. Typically limestone and olivine is added and Bentonite is used as binder.

The process of pelletizing combines mixing of the raw material, forming the pellet and a thermal treatment baking the soft raw pellet to hard spheres. The raw material is rolled into a ball, then fired in a kiln to sinter the particles into a hard sphere. [7]

Figure 1 Iron ore pellets [8]

2.3 Physical modelling of a blast furnace

A number of experiments has been performed in the past on blast furnace operations. A physical modelling of a blast furnace in a laboratory in smaller scale is usually a preferred method in dealing with experiments about blast furnace operations. It is impossible to conduct some experiments with an actual blast furnace because the environment involves very high temperature and tends to be very chaotic.

An experiment conducted by University of New South Wales, Sydney gives an insight on how a physical model of a blast furnace is designed. In the experiment a 2D and 3D model of a blast furnace were modelled. The effect of operational parameters on the material and gas flow were examined , including gas and solid flow rates, material properties such as particle roughness and shape, and abnormal conditions such as asymmetric charging and scabs.

The experimental set up is described briefly as follows. A thin layer of different coloured pellets are laid at various heights with in the vessel. A solid extraction system is activated from the bottom that drains out pellets in a defined manner. A gas flow system is activated through tuyeres around the vessel. Although the gas used in this experiment is cold in contrast to an actual blast furnace. After the gas flow reaches a steady state condition, the size and shape of the different zones were recorded by using tracer particles that were mixed in the bulk pellets. [9]

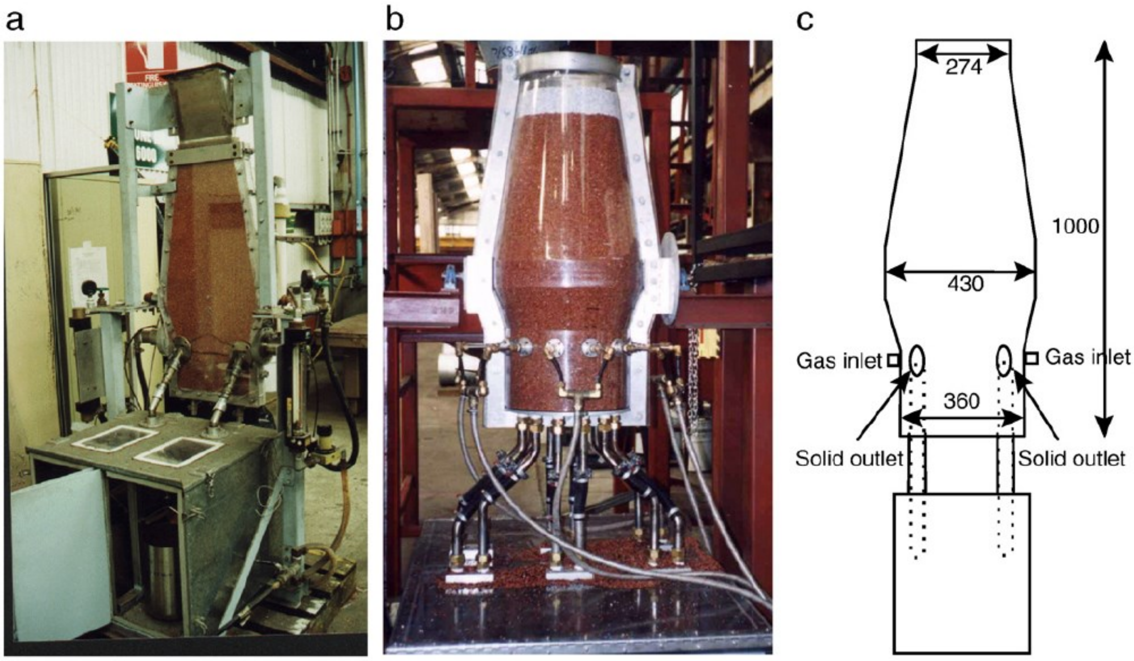

Figure 2 Experimental set up (a), 2D slot model; (b), full 3D model; and (c), schematic and dimension of the 2D slot model (mm).[9]

This experiment gives an insight to how a cold laboratory scale imitation of an actual blast furnace should be modelled. Although in this case material decent and extraction is not considered, pellet movement, interaction and air flow systems used in this project owes much of the concept from this modelling experiment.

2.4 LKAB Experimental blast furnace

LKAB´s experimental blast furnace is the world´s only experimental blast furnace and a vital link between the laboratory and the production blast furnace. Despite its size it provides a test environment with the same conditions as a full-scale production blast furnace [10].

The furnace is built by Luossavaara-Kiirunavaara AB (LKAB), which is world leading producer of processed iron ore products for steelmaking. It was built to overcome the gap between laboratory behaviour of pellets and that of industrial application as it has been LKAB's experience that laboratory testing is not sufficient for the development of new pellet types. The experimental blast furnace is an important tool, not only for developing pellets, but also for applied research and development of the blast furnace process. It allows the unique possibility of gaining rapid, relevant test results without the risk of lost production.

The Experimental BF (EBF) is equipped with all systems typical for a full-scale blast furnace operation (Figure 2). Starting with material handling system, the material is screened with respect to size and then transported to bins and from there weighed on precision scales before charged to the furnace via a single skip and a bell-less type top. A hot blast of air, which is produced in propane-fired pebble bed type hot stoves, is supplied through the tuyeres.

The top gas is cleaned by a dust catcher for the cursed grain size and the finer part of the dust is cached by a venturi scrubber in combination with a wet ESP. A pneumatic drilling hammer and a hydraulic mud gun are used for tapping the furnace.

The EBF is equipped with two gas analysers, one for the top gas and one for the shaft gas probes. The pressure drop over the furnace is monitored by pressure gages in five levels at two positions per level. The vertical temperature profile can be monitored by a device that allows a thermocouple to be inserted anywhere over the radius of the furnace top. The thermocouple will follow the burden down to a temperature where it burns off. The furnace is equipped with two shaft probes and one that penetrates the cohesive zone (Figure 2). The inclined probe for the cohesive zone sample solids and the other two samples both solids and gas/temperature [11].

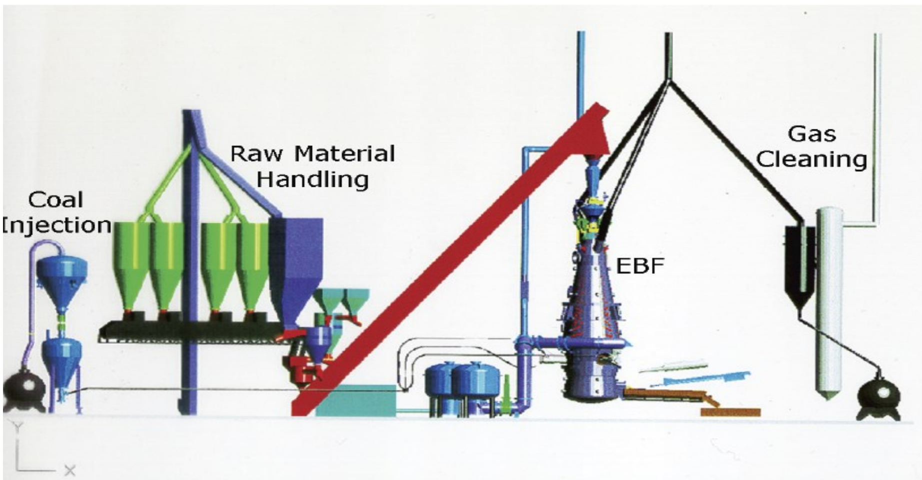

Figure 3 LKAB Experimental blast furnace [10]

2.5 Load cells

Load cells are transducers that convert force to electrical signal. There are different kinds of load cells; hydraulic load cells, pneumatic load cells and strain gauge load cells. The most commonly used load cells are strain gauge load cells.

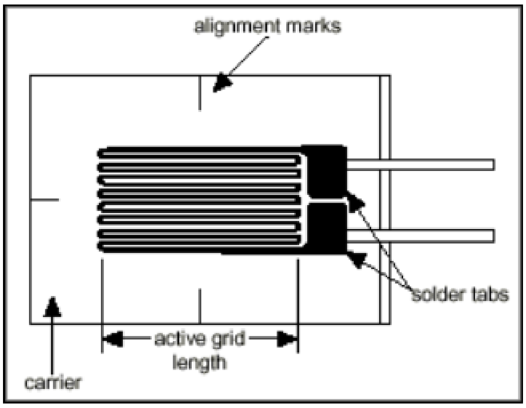

Figure 4 Bonded metallic strain gauge [12]

Strain gauge load cells usually consists of four strain gauges in a Wheatstone bridge configuration, see figure below. The strain gauges measures deformation or strain due to applied force as change in electrical resistance.

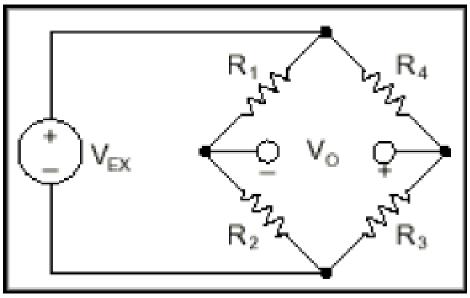

Figure 5 Strain gauges in a Wheatstone bridge configuration [13]

For industrial applications strain gauges are normally integrated in a precisely machined metal cage which is load cells. Practical load cells are made with yoke assemblies designed so that mounted strain gauges cannot be exposed to stresses other than those caused by the compressional force applied to the cell. [14]

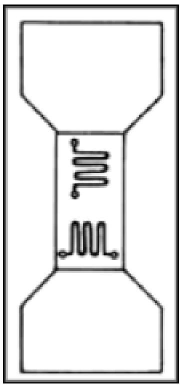

Figure 6 Strain gauges integrated in a load cell [14]

2.6 Data acquisition

Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer. A DAQ system consists of sensors, DAQ measurement hardware, and a computer with programmable software. A complete DAQ system contains the following elements. [15]

Sensors - are devices that measure physical variables for example a force applied on an object. They converts a physical variables to an electrical signal.

- Signal conditioning – converts the electrical output from the sensors in to signals readable by an analogue input board (A/D) in a computer.
- Analogue input (A/D) board – converts these signals into a digital format readable by a computer.
- A software – a computer with an appropriate application software processes, analyses, controls and log data. Such software also provides a graphical display of results.

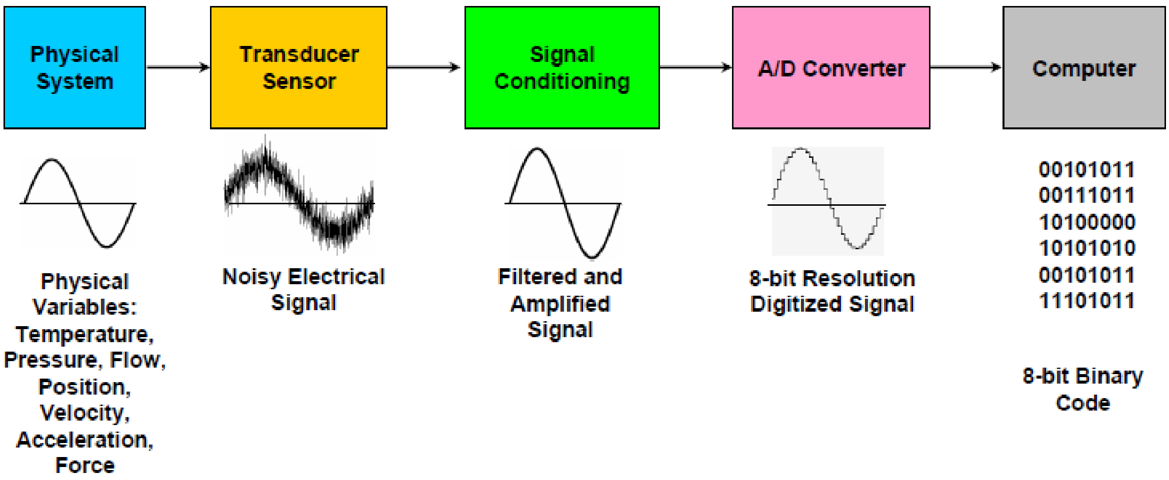

Figure 7 Basic data acquisition system [16]

3. THE DESIGN PROCESS

In this chapter the working process is described. Requirements are specified, and base processes are explained.

The design processes starts with specifying system requirements. A through study of the blast furnace operation leads to simplified imitation of the basic operations. The pin-on-disc tribometer is studied to adapt or re-design the system with the new required system.

3.1 Requirements specification

With the measurements, variables and parameters of interest established, initial wants for the accuracy of these were established in discussion with Material science department, KTH. During the project these wants has been transformed into requirements, which take into account economic constraints, technical difficulties and time management. The most important specifications are shown in **Error! Reference source not found.**

Table 1. Requirements specification

Requirement	**Target**	**Description**	**How to validate**
Spinner rotational speed	0 – 1000rpm		Motor specifications
Test loading	0 – 500N	Loading the pellets will be subjected to	Calibration
Eigen frequency	Should not be within spinner shaft frequencies		Numerical calculation
Air flow	0 – 10 l/min		Air flow meter
Air pressure	Ambient – 5 bar		Pressure gauge
Pellet friction sampling rate	500 Hz	30 samples per revolution	Data acquisition module specifications
usability	Easy to set up and operate	Parts should be designed to ease operation	Design simulations
Interaction	Visual signal during run and completion	Using computer	
Automation	Fully automated during run	Operator doesn't need to be present during test	user knowledge
Safety	Emergency stop button	Positioned distant from the equipment	
Upgradability	Subsystems should be designed for upgradability	Subsystems designed for cost should be possible to implement a more durable and robust system in the future	
Components	Standard parts used when possible		
End of life	10 years	Continuous use	FEM-analysis of most stressed part
Movability	Should be easy to relocate the machine	Using pellet-jack	

3.2 Analysis of pin-on-disc Tribometer

The tribometer in which the new design is based on is a pin-on-disc tribometer. It uses a dead weight loading system through a lever system. It has a motor with a frequency converter to vary the spinning speed. A load cell is mounted connected to the top of the loading system.

Most of the parts and measurement systems can be borrowed for the new design. Although, Part of the loading system has to be changed since loading with a pin is not feasible to apply load on a bulk material. Also the whole loading system and upper fixtures should be raised to allow a cylindrical testing area to be placed. The electrical motor. The load cell, part of the loading mechanism and the table can be used as they are in the new design.

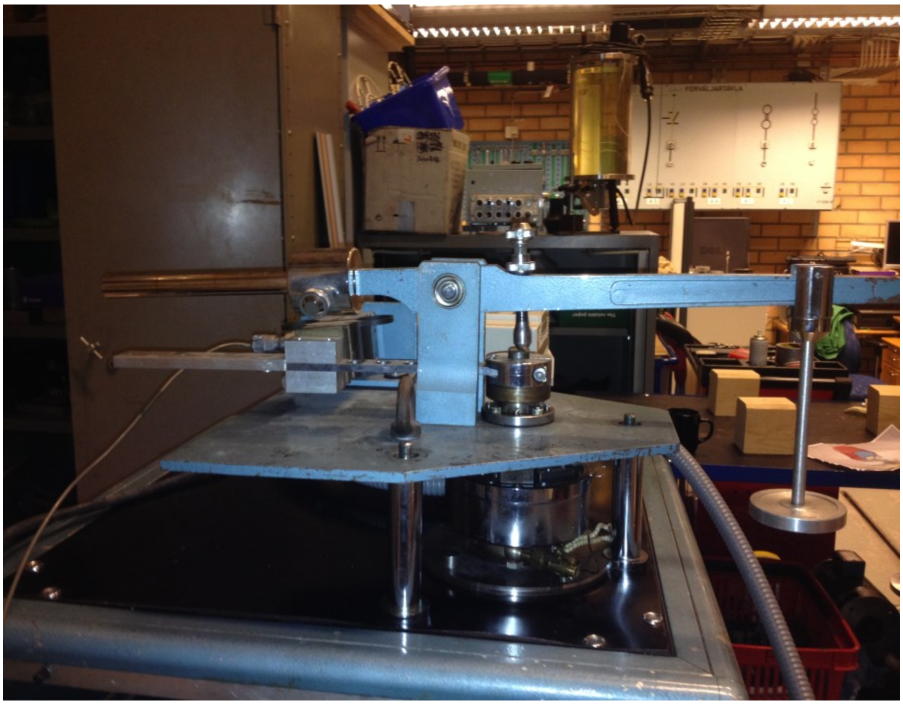

Figure 9 Pin-on-disc tribometer

3.3 Pellets in a blast furnace

During the concept generation process the actual blast furnace processes was analysed thoroughly. From the analysis many ideas were proposed and ideas that best imitates the actual process under the circumstances were further developed. Due to a lesser degree of dependence between sub-systems, the main system was broken down in to sub-systems. Each sub-system were then analysed for the best solution to meet their specific requirements.

Pellets pass through a number of transportation systems from where they are manufactured to the blast furnace. This may include; conveyor belts, silo filling, silo discharging, railway and shipping. During these handling systems; the pellets are exposed to different form of stresses and abrasion resulting in degradation of strength and disintegration.
Once they are discharged in a blast furnace the pellets can have two types of motion: translational and rotational. The translational motion or burden decent is due to melting and combustion followed by tapping of iron; while the rotational motion is due to the blowing of hot blast of air and fuel from the tuyeres which are positioned at an angle around the blast furnace.[17]

In an industrial blast furnace four flowing zones can be identified: lumpy zone, cohesive zone, dipping zone, stagnant or dead man zone [18]. The following figure summarizes the mechanism of flow and the factors affecting the flow.

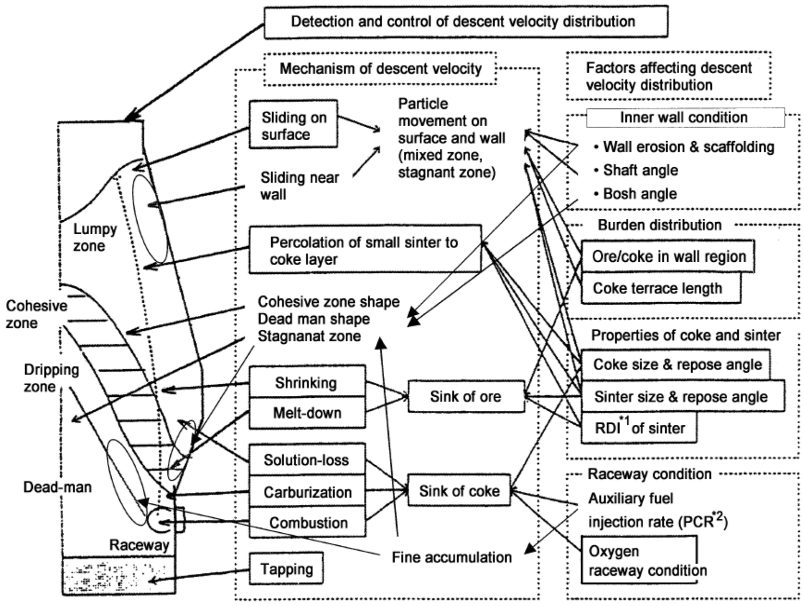

Figure 10 Mechanism of descent velocity radial distribution and factors affecting its distribution [19]

4. CONCEPT GENERATION, DESIGN AND EVALUATION

In this chapter the different concepts generated their considerations, and evaluations are presented.

During the concept generation phase many alternative ideas were investigated for each subsystem, with each idea having their own pros and cons. These ideas were further developed and gauged against the requirements.

4.1 Loading

Different methods of applying loading were investigated. The loading in general can be applied directly or via a lever arm.

4.1.1 Dead weight

Dead weight loading is the cheapest and simplest to implement. A dead weight can be applied to the pellets via a lever arm. The main problem with this solution is resonance due to natural frequency of the weight. With applying varying loads various natural frequencies could arise as it can be given in the equation below (1). This varying natural frequency could result in damage in the equipment.

$$\omega_0 = \sqrt{\frac{k}{m}} \qquad (1)$$

4.1.2 Spring loading

The main problem of resonance discussed in the dead weight loading system could be reduced by using a spring and dampener. Spring loading can be implemented either together with a dead weight loading or directly by compressing the spring. The natural frequency of a spring is higher due to lower weight and system loading. Resonance from this frequency can be reduced to a much acceptable level by using a dampener. However, using a direct spring loading could be a danger to operator if the spring break and fly away due to high tensions.

4.1.3 Hydraulics

A hydraulic cylinder could be used directly over the pellets or via a lever arm to apply the loading. A manual actuator or an electric pump could be used to supply the loading. It consists of a cylinder, hoses, pump, and a manometer to regulate the loading. This solution had a minimum resonance and another advantage is it could be possible to control and vary the loading over a computer. A hydraulic loading is simple in concept but it is to too expensive to implement.

4.2 Air supply

The air supply system will deliver pressurised air to the pellets. The air flow should be measured and controlled in a way that is sufficient to blow friction dust particles out to the particle counter device.

The main components of the air supply system are air fan, air filter, pressure regulator, air flow meter, tubes and connection tube fittings. From these, the air fan and air filter are part of external system that will not be designed in this project.

4.2.1 Air flow meter

An air flow meter that that could be adjusted to a pre-defined value is essential for experiments. To gain knowledge on air flow mechanism and measurement a company Aalborg Instruments & Controls Inc. was consulted. They recommended a thermal mass flow meter with digital output. This device can be configured to meet the requirements set for equipment.

The selected air mass flow meter is, XFM17A-VAL6-A2, digital thermal mass flow meter with a readout display and 8mm compression fittings with a maximum flow rate of $10\frac{l}{\min}$.

Figure 11 XFM17A-VAL6-A2, digital thermal mass flow [20]

4.2.2 Pressure regulator

The air flow system should also incorporate a pressure regulator. Due to the need to vary the pressure of supplied air from the external air supply system, a pressure regulator should be implemented to gauge the supplied pressure to a required value.

A digital regulator that can be controlled with software or a regulator with a manual dial can be used. Using a digital regulator can be useful to control the flow pressure through time over a computer. This could be important in an experiment set-up where a variable pressure is during a single run. Although in our case since there is no need to vary the supplied air pressure during a run, a manually controlled pressure regulator is selected. This solution is cheaper and easy to implement.

Figure 12 Air pressure regulator [21]

4.3 Friction measurement system

As the main functional requirement from the equipment is to measure friction between pellets and pellet/cylinder wall friction, different methods were discussed and evaluated. Out of this evaluation, two alternative solutions were considered further. One way is to use load cells and the other is using torque meter.

4.3.1 Torque meter

A torque meter coupled in line with the motor shaft and the spinner can measure the resistant torque that arises due to friction among the pellets.

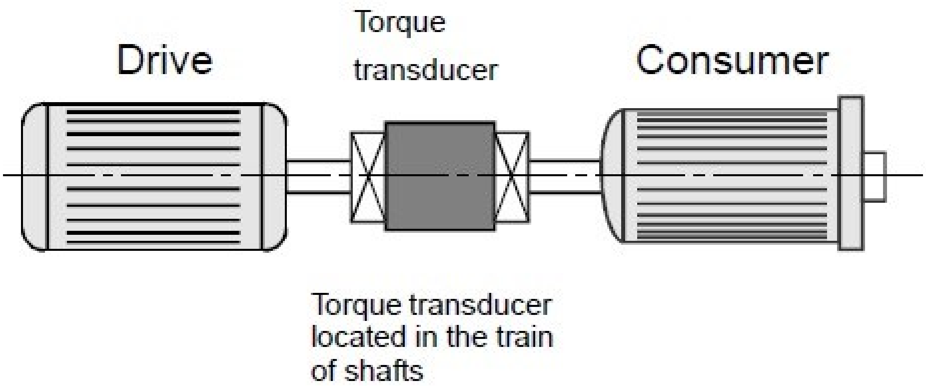

Figure 13 torque meter basic principles [22]

A digital torque meter with a DC or AC electrical signal can provide online measurement of torque level and rotational speed. Using a torque transducer would simplify the friction measurement system in a way that it does not require additional parts to be designed. It goes directly between the motor shaft and the spinner shaft. For this to be possible the motor fixture should be longer to make space for the torque transducer. The main deterrent from using this solution is the price. Torque sensors are generally expensive; Honeywell 1104 Rotating Shaft Torque Sensor Complete Package from national instruments costs around 48,000 Swedish kronor.

Figure 15 Honeywell 1104 Rotating Shaft Torque Sensor [23]

4.3.2 Load cell

The preferred solution to measure frictional torque in the pellets is using load cells. Load cells are cheap compared to torque transducers. Although they require additional parts to be designed for fixtures and connection mechanisms, the principle and application is very simple.
To measure frictional torque between pellets a load cell can be connected with the loading mechanism. Due to friction in the bulk pellets the loading shaft will be subjected to rotational torque. By holding the loading shaft against rotation by fixing it with the load cell the rotational torque will be transmitted to the load cell. This mechanism is simple to apply and since there already exists a load cell with fixtures in the old tribometer a little modification can be made to make this system applicable.

4.4 Usability and safety considerations

The core concept in considering usability is to simplify operation and number of steps and taking ergonomics in design considerations. And the concept behind safety considerations is injuries to operators or damage to property due to faulty or hazardous operations. The following points were made in these considerations.

- Systems should be designed to allow easy set-up of equipment to prepare for run
- Parts which are to be removable for operation set-up or maintenance should be easily accessible
- Easy and clear way of assembly and disassembly
- Complete cover of rotating pellets from the surrounding
- Easy stopping system of motor through frequency control and motor converter in case of faulty operation

5. SUB-SYSTEM DESIGN

The integrated system of the tribometer is composed of mainly three subsystems: which were mainly designed independently due to their lesser interdependency.
These are:

1. Rotational motion system: This includes design of housings, spinner and selection of motor and bearings.
2. Loading system: which includes design of support structures for loading and selection of load cells for friction measurement
3. Air flow system: which includes selection of a flow meter and tubing connections

The CAD model of the integrated system is as shown below;

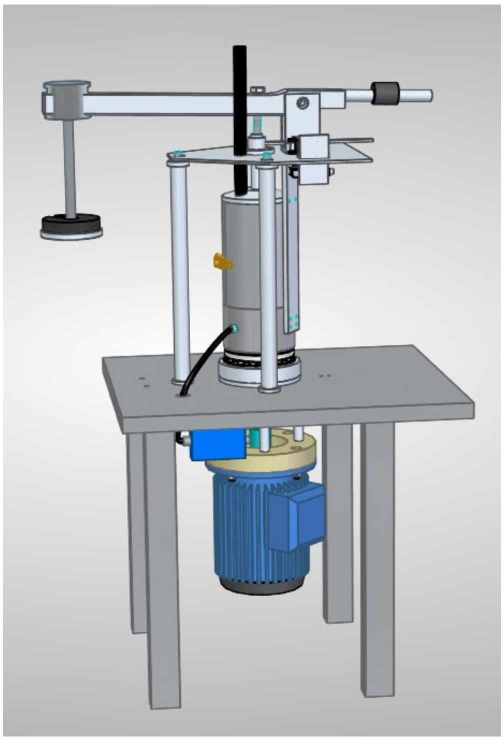

Figure 16 CAD model of the tribometer

5.1 Pellet burden movement

As explained earlier pellets in an actual blast furnace have rotational and translational movement. But this laboratory equipment will be limited to imitating only the rotational movement. This is due to the main purpose of the equipment which focuses on mechanical dust formation. Mechanical dust formation mainly arises from the rotational motion of the pellets which creates collision between pellets rather than the vertical decent of burden material [24].

The formation of dust in a blast furnace varies along the length of the blast furnace due to temperature differences in different zones. At the lower part of the blast furnace the dust formation is mainly due to chemical reaction. Which tends to produce finer dust particles that rises out of the BF through the permeability of the burden or withdrawn from the BF along with the sledge.

In the upper part of the blast furnace (upper shaft) the dust formation is mainly due to mechanical reaction. This is due to the low temperature and limited chemical reaction in this part of the BF. This laboratory equipment being a cold imitation of a blast furnace is designed to simulate the behaviour of pellets movement and dust formation in the upper shaft.

The rotational movement of the pellets is brought by a motor fixed underneath the table. The motor shaft is coupled with a spinner shaft with a rubber coupling. The spinner has a flat head where the pellets sit and rotate with the motor. The parts designed to bring about the pellets movement are listed below:

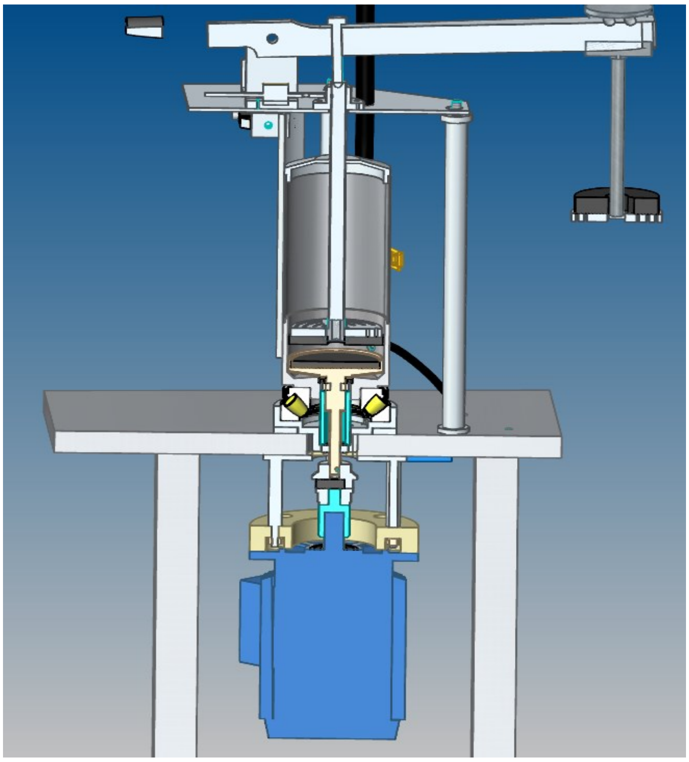

Figure 17 Section view of the test rig

5.2 Bearing housing

The need for measuring the wall friction makes a significant change to the redesigned old tribometer. This requires the whole loading mechanism to be raised to make space for the bearing and bearing housing. The spinner needs to have a longer shaft to be coupled with the motor shaft.

To measure the wall friction the cylinder body should be able to rotate in response to the interaction of the pellets with the cylinder wall. This leads to the use of a bearing between the cylinder body and the table fixture.

The loading pressing down on the pellets is in axis with the spinner rotation and the cylinder body. For this reason the bearing selected should be able to accommodate axial loading. A tapered cylindrical thrust bearing from SKF was selected for this purpose.

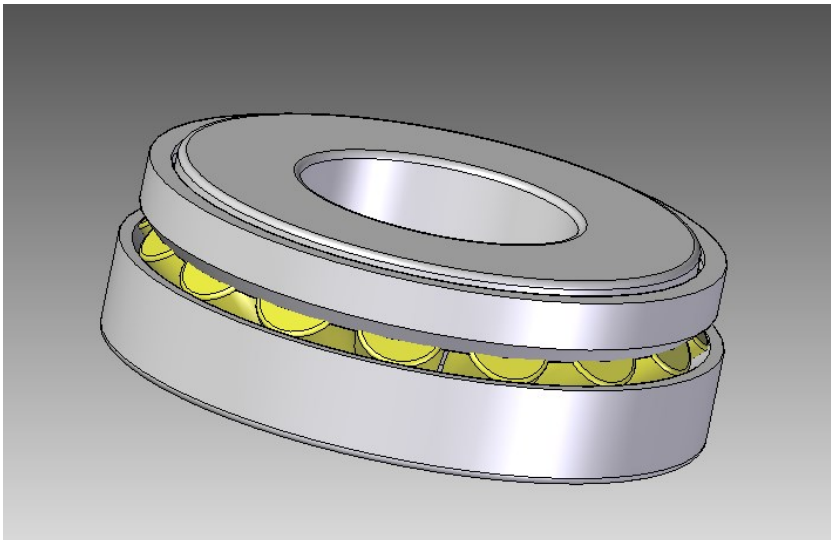

Figure 18 Tappered roller thrust bearing from SKF

The housings for the thrust bearing were designed with the old tribometer in mind since the same table stand is going to be used. Due to the addition of a thrust bearing it was not possible to use the old cylinder fixture. The old cylinder fixture is a one part that is fixed to the table with bolts. It is a stationary part mainly used as a support to the spinner and cover to the tested material.

Rotation of the housing is crucial in measuring the wall friction. For this necessary function it was decided to design the housing in two parts; upper housing and lower housing. While the lower housing is made stationary by fixing it to the table, the upper housing is left to be free to rotate by placing it on a thrust bearing.

The lower housing is used to fix the bearing with the table. It is designed to have an interference fitting with the bearing and fixed with the table with four M6 bolts. Since there is no lateral load acting up on the wall of the housing it is decided to be made from aluminium with a wall thickness of 6 mm.

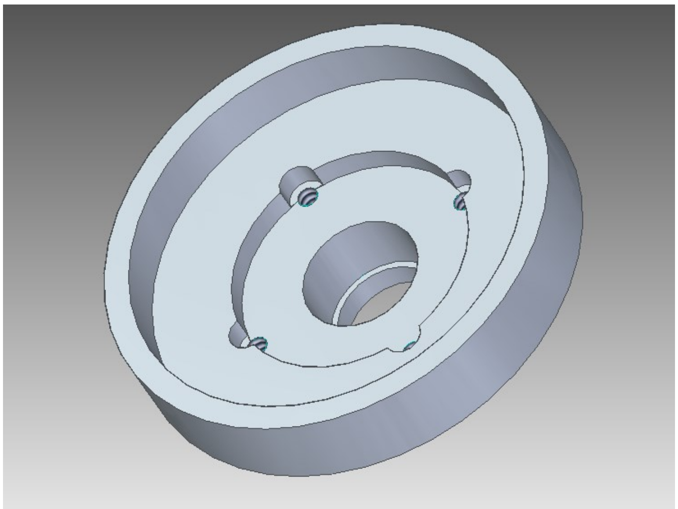

Figure 19 Bottom housing

A support bearing is used for the spinner rotation. This bearing is constrained axially by an end stop washer that is screwed to the bottom of the housing with four M5 bolts.

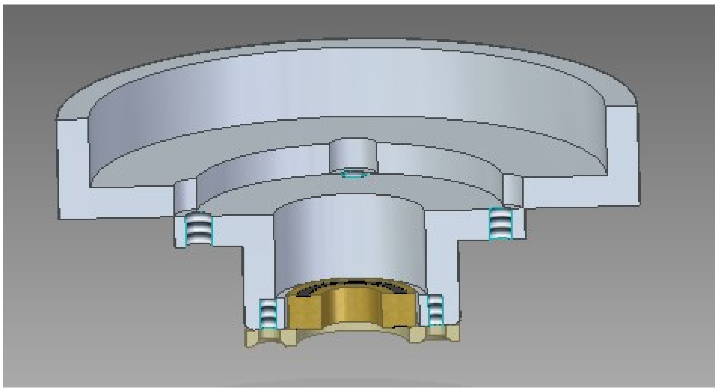

Figure 20 Section view of bottom housing with washer and bearing

The upper housing is designed as part of the containing cylinder. It is fixed with the bearing with an interference fitting and also serves as a container for the tested pellet material. Stress analysis was performed and steel with a wall thickness of 6mm was capable to take up the lateral load of the pellets contained.

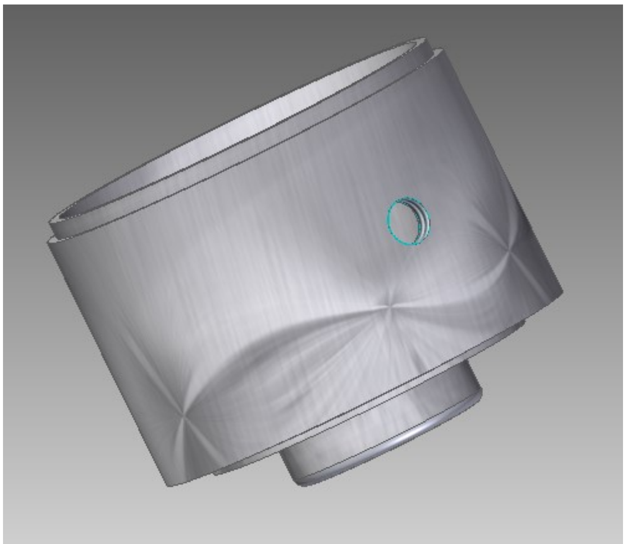

Figure 21 Upper housing with air inlet hole

It was crucial to decide the height of the housing cylinder since it is not necessary to have this thickness of wall all the way up to the cover. The steel material it is made of and the thickness makes it unnecessarily heavy and difficult to assemble. By discussing the matter with material science department it was decided that it is enough to test four layers of pellets at the same time. One pellet being 9-12 mm in diameter four pellets will have a maximum height of 48 mm. including the measurement between the bottoms of the housing to the top of the spinner plate which is 30 mm, it was decided to have a housing cylinder height of 82 mm.

The rest of the cylinder wall where there is no loading of pellets is decided to be made of sheet metal of thickness 3 mm. The top edge of the housing cylinder has a groove of 3 mm wide and 5 mm deep to serve as a fixture for the sheet metal.

5.3 Loading system

In the old tribometer the loading system is applied using a dead weight load through a lever arm. After analysing the problem different ways of applying loading were considered for the new design. The alternatives discussed was spring loading and hydraulic. Applying the load by compressing a spring or using a hydraulic cylinder reduces vibration compared to direct loading with a dead weight. While both methods are simple to apply it was decided to keep the already existing dead weight loading system with a few modifications for cost reasons.

5.3.1 Dead weight loading through a lever arm

This system has a problem of resonance due to the natural frequency of the weight. Due to the need to limit the number of parts to be re-designed this mechanism was decided to be kept as it is although there are other mechanisms with better resonance dampening capabilities; for example, spring loading and hydraulic.

The loading mechanism works in a way that the applied dead weight load is transferred to the loading rod through a lever arm. The lever arm which has a ratio of 1:3 has an adjustable counter weight at the other end for the equilibrium of the system and a threaded pin at the pivot point. The pin is threaded so that it allows height adjustment of the loading rod in coherence with the number of pellet layers being tested. The load transferred through the loading rod pushes down on the pellets through a loading plate.

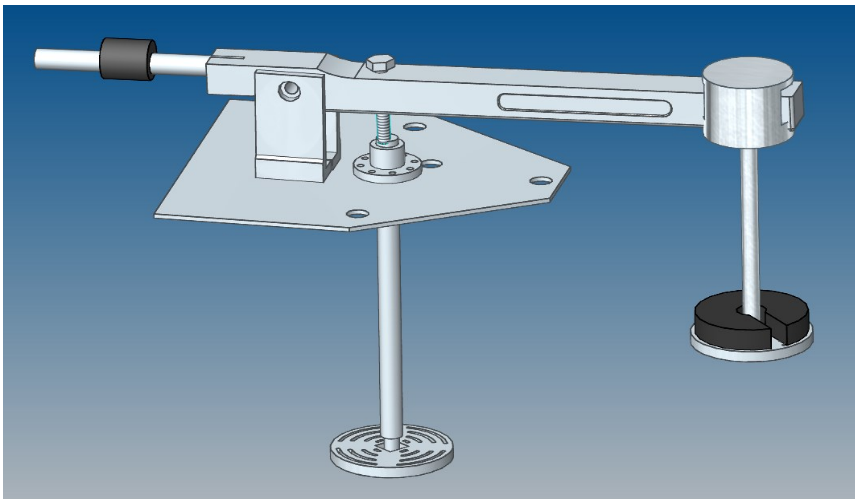

Figure 22 Dead weight loading system

5.3.2 Loading rod and plate

In order to apply the load on a bunch of pellets contained in the cylinder a few modification of the existing system was necessary. For this purpose a steel rod with a retraining end and a plate were designed. A 20mm in diameter steel rod threaded at the end is welded with the retaining end. The retaining end has a square profile followed by a threaded top end. The square profile is needed to transfer torque from the loading plate to the loading rod.

To be able to assemble the loading plate and the retaining end, a locational clearance fit between the cut-out square profile of the loading plate and the square profile on the retaining end is placed. The plate is placed in position on the retaining end on the bottom side with the integrated circular end and on the top side with an M10 nut that goes down the rod and tightened on the threaded end of the retaining top end.

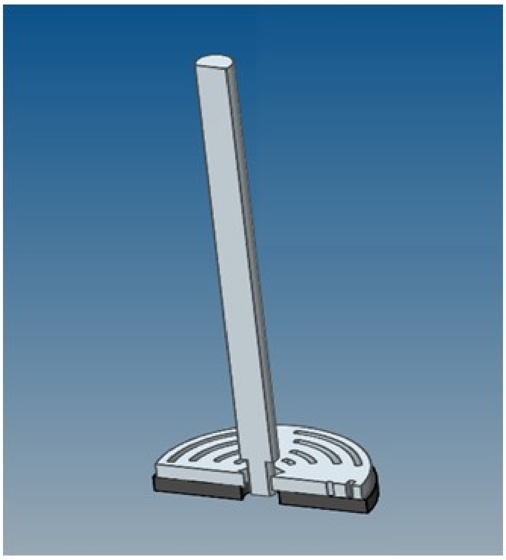
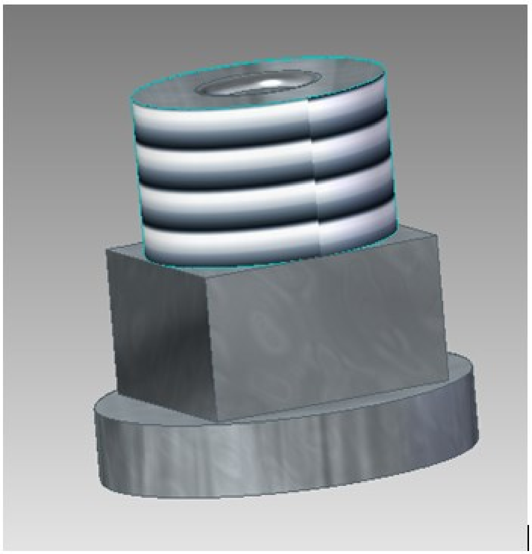

Figure 23 Loading rod positioned with load plate (left), retaining end (right)

A plate of 108 mm in diameter with a rectangular cut out in the middle is used to apply the load on the pellets. The plate has a pattern of 4 mm wide cut-out profiles designed to allow dust particles through. A natural rubber with matching profiles is screwed with 4 M5 bolts underneath the plate. The rubber holes for the bolts have a countersink of 8 mm in diameter and 4mm deep to avoid contact between the pellets and bolt heads.


Figure 24 Loading plate and rubber profile

5.4 Air flow

The air flow system consists of a blower, compressor, flow meter, tube connections, and dust catcher (particle counter). Only the flow meter and connection tubes are considered in this design since it was decided to use the existing facilities for air blower compressor and dust catcher.

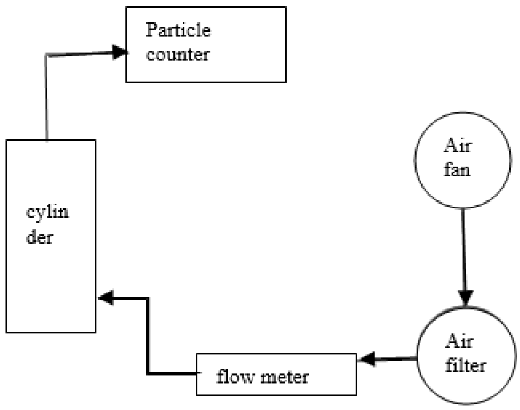

Figure 25 Air flow system

It is crucial to regulate and measure the flow of air that goes in to the system as it is one of the factors that determines the amount and size of the dust particle to be counted in the experiment. Here the important factor in selecting a flow meter is maximum flow rate.

The maximum flow rate for the mass flow meter was selected to be 10 L/min. To check the flow rate is sufficient to blow and carry the particles forces acting on the particle were calculated.

There are different kinds of forces acting up on the dust particle in the experiment. The main forces are; pressure gradient force, gravity, buoyancy and forces associated with collision of dust particles. Due to the extremely small size of the dust particles forces correlated with interaction of particles and buoyancy was ignored in the calculation.

In a flow of fluid a difference in pressure across a surface implies a difference in force, which can result in acceleration according to newton second law of motion. This force that arises from pressure difference is referred to as pressure gradient force [25]. In order for a particle to be set in motion the pressure gradient force must be greater than the gravitational pull on the particles.

Gravitational force (f_g)

$$f_g = m_p g = \rho_p v_p g = \frac{\pi}{6} d_p{}^2 \rho_p g \qquad (2)$$

The mass of pellet dust particle m_p can be calculated by using the bulk density of iron ore pellets ($\rho_p = 2260 \frac{kg}{m^3}$) and the maximum flue dust particle size of ($d_p = 1000 \mu m$) with gravitational acceleration $9.8 \frac{m}{s^2}$ gives us the gravitational pull to be $f_g = 11.59 X 10^{-9} N$.

Pressure gradient force (f_p)

Pressure gradient force is given by the formula

$$f_p = \rho_a V_p \frac{\delta v_p}{\delta t} = \frac{\pi}{6} d_p{}^3 \rho_a \frac{\delta V_p}{\delta t} \tag{3}$$

Where;

ρ_a = density of air at atm

V_p = volume of particle

$\frac{\delta v_p}{\delta t}$ = dust particle acceleration

$\frac{\delta v_p}{\delta t}$ The flow acceleration can be calculated from the flow force using the selected rate of flow (Q) of 10$\frac{l}{\min}$ which is equivalent to $1.67X10^{-4} m^3/\sec$.

Where; $f_f = \dot{m} v_f$ $\dot{m}$ = mass flow, v_f = flow velocity (4)

Flow velocity can be found from the flow rate and inlet area (A) where the diameter of the inlet tube to the system is 8mm.

$$Q = v_f A \Rightarrow v_f = \frac{Q}{A} = \frac{1.67X10^4 \frac{m^3}{s}}{\frac{\pi}{4} 0.008^2} = 10.42 \frac{m}{s} \tag{5}$$

$$\dot{m} = \rho_g Q = \left(1.2922 \frac{kg}{m^3}\right) 1.67X10^4 \frac{m^3}{s}$$

$$= 2.162X10^{-4} \frac{kg}{s}$$

$$f_f = \left(2.162X10^{-4} \frac{kg}{s}\right) 10.42 \frac{m}{s}$$

$$= 2.25X10^{-3} N$$

From $f = ma$ the acceleration of the particle becomes; (6)

$$a = \frac{f_f}{m_p} = \frac{2.25X10^{-3} N}{\frac{\pi}{6} 2260 \frac{kg}{m^3} (1000\mu m)^3} = 2.25X10^6 \frac{m}{s}$$

The pressure gradient force using equation (3) becomes;

$$f_p = \frac{\pi}{6} (1000\mu m)^3 1.2922 \frac{kg}{m^3} \left(2.25X10^6 \frac{m}{s}\right)$$

$$= 1.522X10^{-3} N$$

Since the pressure gradient force is much larger than the gravitational force on the particles the flow rate is sufficient enough to lift even the largest dust particles if set at maximum flow.

5.4.1 Mass flow meter

The selected air mass flow meter is, XFM17A-VAL6-A2, digital thermal mass flow meter with a readout display and 8mm compression fittings with a maximum flow rate of $10\frac{l}{\min}$. XFM flow meters support various functions including: programmable flow totalizer, high and low flow alarm, automatic zero adjustment, 2 relay outputs, and jumper selectable 0-5 Vdc or 4-20 mA analog outputs, status LED diagnostic. A local 2 x 16 characters LCD display with adjustable back light provides Flow, Total and diagnostic reading simultaneously.

Figure 26 XFM digital mass flow meter [20]

5.4.2 Principle of Operation

The stream of gas entering the Mass Flow transducer is split by shunting a small portion of the flow through a capillary stainless steel sensor tube. The remainder of the gas flows through the primary flow conduit. The geometry of the primary conduit and the sensor tube are designed to ensure laminar flow in each branch. According to principles of fluid dynamics, the flow rates of a gas in the two laminar flow conduits are proportional to one another. Therefore, the flow rates measured in the sensor tube are directly proportional to the total flow through the transducer. In order to sense the flow in the sensor tube, heat flux is introduced at two sections of the sensor tube by means of precision-wound heater sensor coils. Heat is transferred through the thin wall of the sensor tube to the gas flowing inside. As gas flow takes place, heat is carried by the gas stream from the upstream coil to the downstream coil windings.

The resultant temperature dependent resistance differential is detected by the electronic control circuit. The measured temperature gradient at the sensor windings is linearly proportional to the instantaneous rate of flow taking place. An output signal is generated that is a function of the amount of heat carried by the gases to indicate mass molecular based flow rates. [26]

5.5 Cleanliness of off-gas dust sampling

Cleanliness of the supplied air is at most important in terms of genuine test results. Since the purpose of the test equipment is to study dust particle behaviour contaminated air supply with alien dust particles will give false information on the required measured parameters.

Although cleanliness of air supply system is not part of the design task, it is worth mentioning a system designed by Olofsson and Olander [27], which is going to be used in the experiment. A variable speed fan sucks the air from the room in to a filter where the air is purified. Then the air passes through a flow measurement device before it is fed to the test equipment through an 8 mm flexible tube.

The clean air passes through the rotating pellets carrying pellet dust particles to the top of the cylinder where there is an escape tube that leads to the particle counter. In this way both the cleanliness and the rate of flow can be adjusted to the required amount.

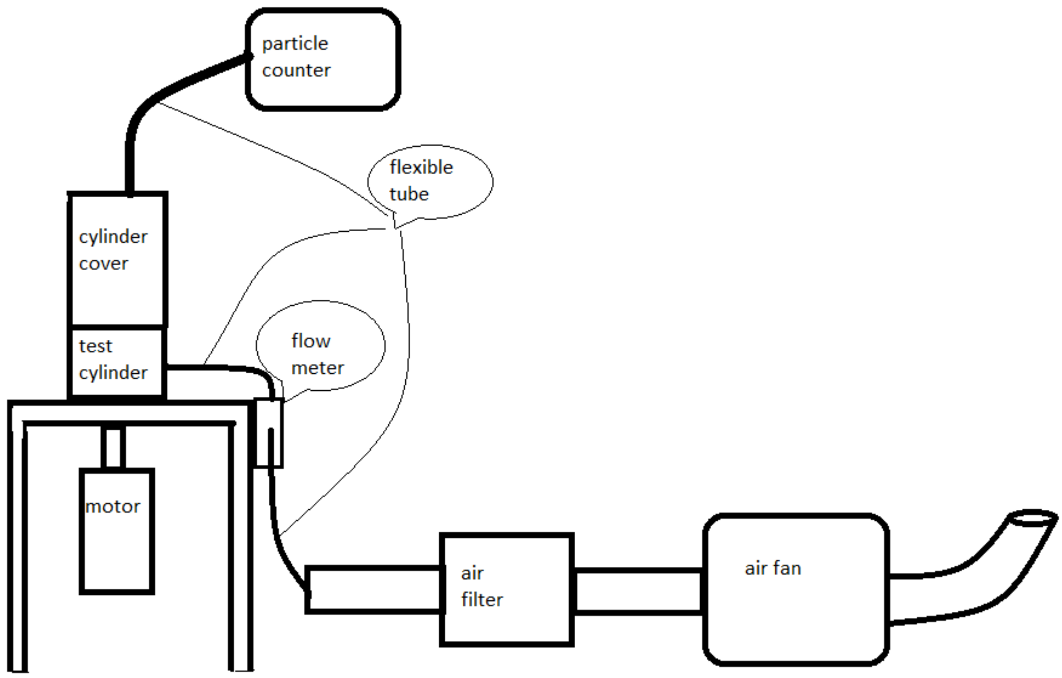

Figure 27 Pressurised air flow mechanism

5.6 Accessibility and usability

Accessibility of the equipment is defined in terms of the ease to which the operator can easily load pellets before operation and unload pellets and large dust particles that cannot be taken away by the air flow after a test period. For this purpose a variety of design alternatives has been considered.

Due to the requirement that the testing cylinder chamber should be of a defined length for uniform dust sampling, it makes it impossible to accesses the pellets from the top of the cylinder.

If the cylinder is to be made of a single part, it would have given more space for holding pellets and it would have been possible to test several layers of pellets at once. But this requires the operator to dismantle the above parts of the equipment, the loading system, just to get access to the test pellets. This is considered to be problematic and not safe for the operator.

A different concept where the holding cylinder can be made of two short cylinders was proposed. The lower cylinder where the actual testing is performed and the above cylinder where its main purpose is as a dust cover and access door to the lower cylinder is designed. This design does not require dismantling of the equipment during each run.

The upper cylinder is made up of 3 mm aluminium plate since it will not experience any force acted up on it. It is split in to two half cylinders where one part is fixed to the lower cylinder and the top dust cover by screws, while the other half cylinder is made free to open and close fixed with a hinge to the other fixed half cylinder. After the pellets are loaded this cylinder cover can be closed and locked with a pin.

Once the cylinder is open we will still have the loading plate blocking us from accessing the pellets. This problem can be solved by using a plate that moves up and down on the loading pole. After loading is complete the plate will be lowered on top of the pellets and locked by an M15 nut with the pole.

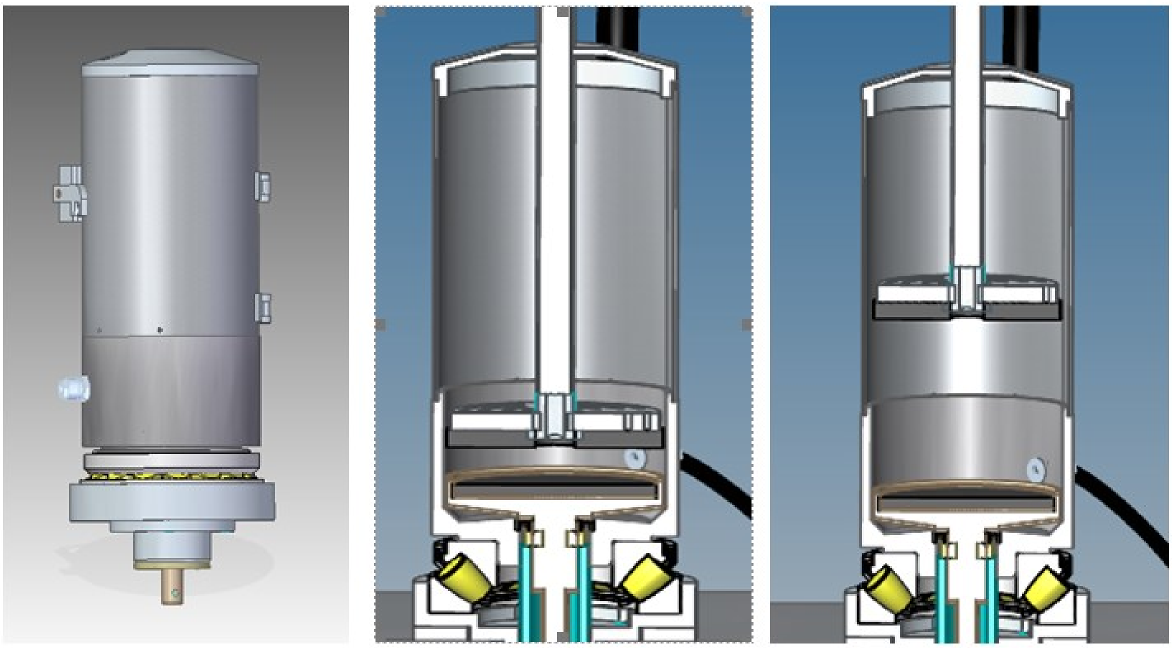

Figure 28 Accessing mechanism

5.7 Friction measurement

Since the coefficient of friction of a material combination depends on contact conditions, well characterized measuring method is required for measuring the friction. To get realistic friction values a number of contact conditions should be controlled i.e. contact pressure, speed and, temperature.

As mentioned earlier there is a need to measure the friction between pellets and the friction between pellets and the cylinder wall. This function is performed by using a load cell attached to the equipment with connection frames. Care must be taken in measuring friction in this way because unwanted friction values may interfere with the intended friction torque that is going to be measured.

The mechanism for friction measurement is used in this project is described as follows. The rotational torque that is applied from the motor through the spinner rotates the pellets sitting on the spinner top surface. While the pellets are rotating along with the spinner they will exert a frictional force on the wall of the cylinder and the upper loading plate. The upper part of the equipment that includes the cylinder, the loading plate and the connection between the cylinder and the load cell is put on a cylindrical tapered thrust bearing to allow it to be free to rotate. This makes the cylinder and the loading plate rotate along with the pellets. But to measure the friction between the pellets and the wall of the cylinder the rotation of the cylinder is constrained by bolting the cylinder in place with a load cell. The reaction force that is exerted by the load cell to hold back the rotation of the cylinder is equal to the friction force that pellets create in contact with the cylinder wall. This reaction force gives measured by the load cell gives us the wall friction value.

The friction experienced amongst the pellets while rotating is transferred through the leaver arm that push against the upper compression load cell load which measures friction between pellets.

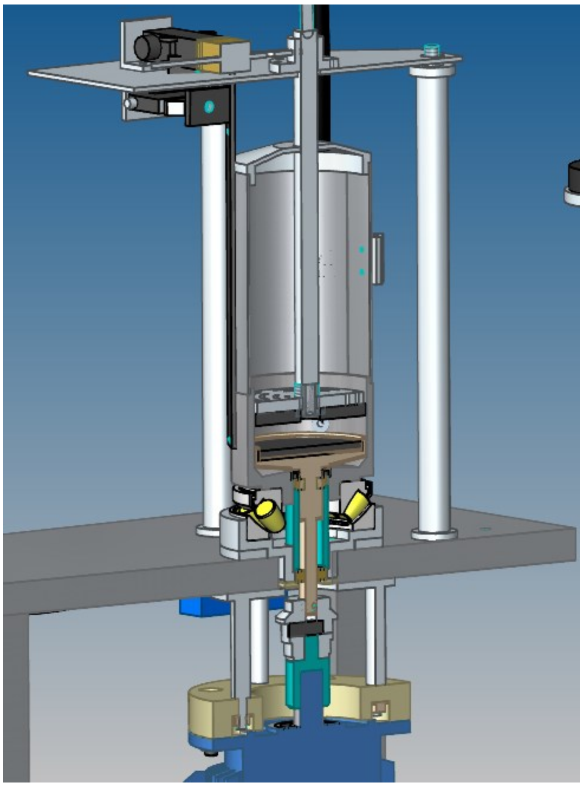

Figure 29 Friction measurement mechanism

5.7.1 Friction between pellets

In order to measure the friction between pellets the frictional torque that arises from the interaction between pellets should be isolated out for measurement. In this case other frictional torque values that may interfere with this measurement are; the friction torque that arises from the contact between pellets and the loading plate, the friction torque that arises from the contact between pellets and the spinner surface and the frictional torque that arises from other elements like bearings and tubing connections. In the latter case a flexible plastic tubing of 8mm in diameter were used that will have little interference in the friction measurement and the friction that arises from the needle bearing from the spinner support and the tapered cylindrical thrust bearing are significantly small to affect the intended measured friction value.

The major focus in dealing with friction measurement interference was the friction that arises from the contact between the pellets and the loading plate/ spinner surfaces. The contact behaviour between these elements should be designed in a way that no relative motion between these elements arises. Since the loading plate and the spinner are made up of metal direct contact between the pellets with these surfaces creates friction and dust particles. This will create a problem both friction measurement values and unwanted dust particles because the interest in dust particles is in those that arise from pellet with pellet friction.

For these reasons it was decided to separate the contact surface with softer material. A natural rubber with modules of elasticity of 0.007-0.004 GPa is selected to be used. This mechanism serves two functions; first, it prevents slipping of pellets that would have happened in metal to pellet contact. Second, since the friction between pellet and a rubber material is very high pellets tend to stick with the rubber that it eliminates any dust formation in these contact areas.

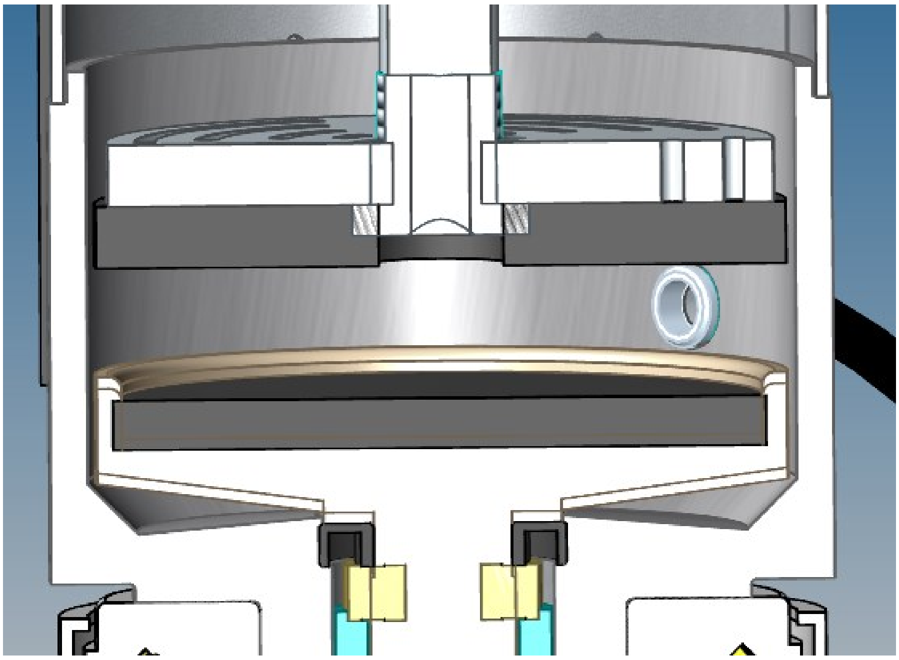

Figure 30 Rubber plate on spinner and loading plate

This seems to be a good mechanism since the operation is a cold processes and the rubber material is not subjected to heat.

5.8 Standard components and materials

As the CAD-model reached its final design, it was time to order all the necessary standard components in order to build the full-scale functional equipment. The following section lists required components and material described in short.

5.8.1 Material and standard components

The bullet points below describe the needed materials and from where the parts were ordered and bought.

- The steel block for the cylinder and the aluminium block for the bearing housing and top cover were available at KTH.
- Steel rod for the loading pole, steel frames for the load cell connection, and aluminium plate for the upper cylinder were available at KTH.
- Natural rubber with required stiffness were available at KTH
- A cylindrical tapered thrust bearing from SKF were provided by Uf Olofsson, KTH
- Pneumatic plastic tubing with 8 mm diameter and ¼ inch compression fittings were ordered from *AIRTEC* Pneumatic *Sweden* AB
- Thermal mass flow meter and its accessories were ordered from Aalborg Instruments & Controls
- RLT tension load cell with a range of 25kg were ordered from RDP Electronics Ltd
- 4-Ch Universal Measurement compact DAQ chassis with USB and accessories were ordered from National Instruments Corporation.

5.8.2 Instruments for demonstration

After the equipment is manufactured and assembled a demonstration were performed. For the demonstration the following devices and equipment were used.

- Particle seizer from KTH laboratory
- A complete air supply system with an air fan, air cleaner and the necessary connections from KTH laboratory

5.9 Data acquisition

A typical data acquisition system consists of individual sensors with necessary signal, data handling and transmission, conditioning, and data processing software. In this project load cells and thermal mass flow meter are used as sensors and frequency converter are used to control the motor for rotational speed and air fan. Lab-View software is used in this project for data acquisition, data processing and display.

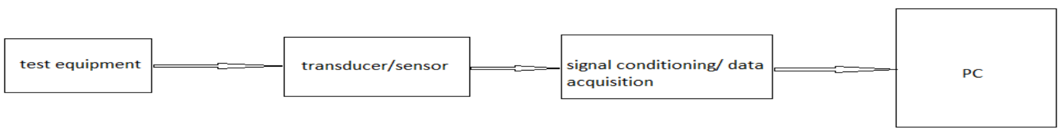

Figure 31 Bloc diagram of DAQ system

Measured and controlled parameters in this project are;

- Pellet friction - measured
- Pellet/wall friction - measured
- Air flow – measured & controlled
- Rotational speed – controlled

5.9.1 Pellet friction measurement system

As it is discusses above the mechanism for measuring friction between pellets is done via the loading system. The friction experienced between the pellets in the rotation of the spinner will create a torque on the loading plate. This torque can be measured with a load cell that is connected to the loading system via a link.

The load cell used for this purpose is a tension load cell by Sangamo Weston Controls LTD, which was initially part of the old tribometer. The link carrying the torque from the pellets presses down on this load cell creating analogue electric signals. These signals can be interpreted to a physical output for example in newton by using Lab-View. Although, due to lack of specific information about this particular load cell the calibration and acquiring of data could not be achieved in this project.

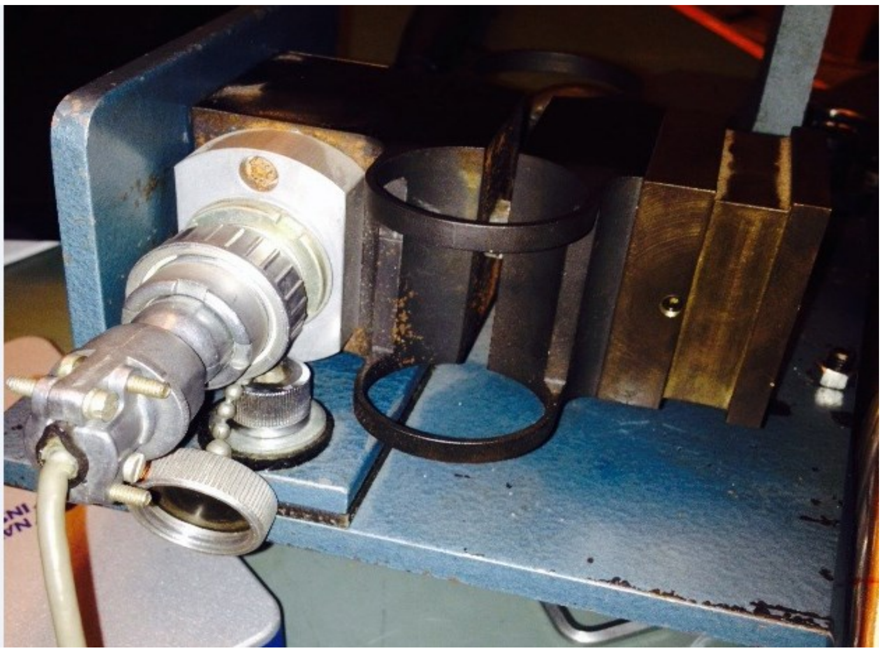

Figure 32 Picture showing the old load cell mounted on the machine

5.9.2 Pellet/wall friction

The friction between the rotating pellets and the wall of the cylinder is measured by a strain gauge tension load cell model RLT0020 from RDP Electrosense.

Selecting a right load cell to measure the friction force requires analysing the parameters and operating conditions. In general the following characteristic of a load cell should be analysed.

- Load capacity should be over the maximum operation load
- Size (depends on the size of the arm)

- Resolution
- sensitivity
- Easy surface mount

To select the appropriate load cell capacity the approximate friction force that could occur between the pellets and the wall is calculated.

The centripetal force of the moving pellets assuming a spinner speed of 1000 rpm or $104.67 rad/s$ can be calculated as follows;

$$F = \frac{mv^2}{r} = mr\omega^2 \quad , \qquad (7)$$

Where,

m = mass of pellets
v = rotational speed
r = rotational radius
ω = angular speed

To get the approximate mass of the bulk pellets knowing the density of pellets to be $\rho = 2200 kg/m^3$ and radius of the containing cylinder 14mm, gives us volume of the containing cylinder to be $0.3m^3$ and the mass contained to be $m = 0.67kg$.

From this the centripetal force of the pellet exerted on the wall can be found by substituting these values.

$$F = (0.67kg)(14x10^{-3}m)(104.67rad/s)$$
$$F = 10N$$

Taking the friction coefficient value of $\mu = 0.54$ for steel on steel contact as an approximation to our particular case which is steel/iron ore contact, the friction force value can be found to be;

$$F_f = \mu F = 5.4N \qquad (8)$$

Since the friction force value too low a load cell with the lowest capacity range of 20kg can be used. The specifications for the selected load cell RDP Electrosense is listed below.

- Capacity/range = 20kg
- Rated output = 2mv/v
- Full scale output = 3000mv
- Output for 0.54kg = 16.2 mv
- Resolution = 0.1gram

Figure 33 Model RLT0020 load cell [28]

In the results chapter the results that are obtained with the methods described in the method chapter are compiled, and analysed and compared with the existing knowledge and theory presented in the frame of reference chapter.

6.1 Manufacturing and Assembly

All the manufacturing was performed at KTH machine design department workshop. Technical detail drawings were prepared after the completion of the CAD model and approved for manufacturing by the department. The following sections describe the manufacturing process for each part of the complete assembly.

Before the actual manufacturing of the equipment, the design had to be verified. After presenting the final design to both the supervisors, Ulf Olofsson and Jens Wahlstöm, it was decided to start manufacturing the prototype. The final CAD-models and assembled physical equipment can be seen in the figures below

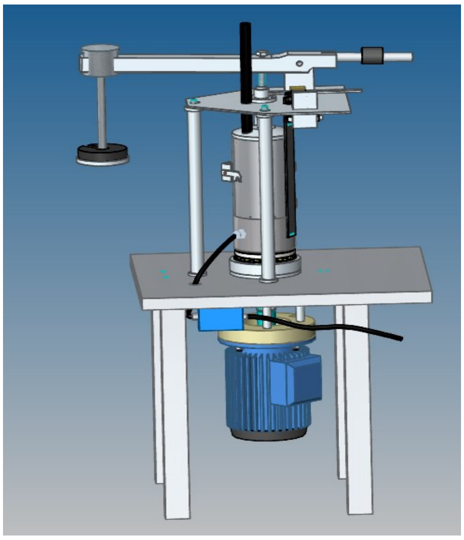

Figure 34 The final CAD model

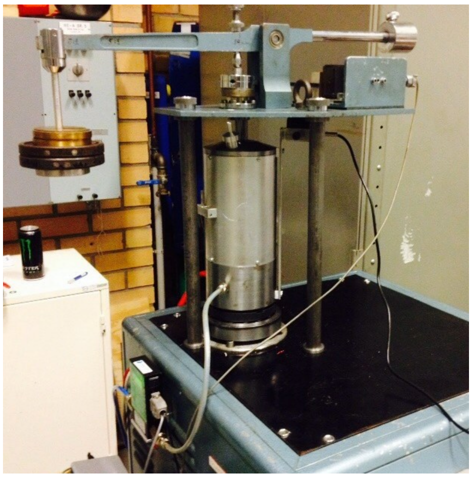

Figure 35 The final assembled equipment

6.2 Spinner

The spinner was designed in two parts for material conservation and ease of machining. The amount of torque the spinner could handle is low enough to have a weld between the upper plate part and the lower shaft. A hole of 24.5 mm was bored on the bottom of the plate for the shaft to be inserted. A counter sink diameter of 26.44 mm with an angel of 82 ^{o} around the hole serves as a welding groove for more strength.

The spinner is turned on a lathe machine out of a 112 mm diameter still block and the shaft from 25 mm diameter steel rod. The shaft has 25 mm in diameter at the upper part where the needle bearing sits and 14mm in diameter at the lower part where it is fixed with the motor shat via a rubber coupling.

Figure 36 Spinner

6.3 Bottom bearing housing

The bottom bearing housing was decided to be made of aluminium. It is manufactured out of a 146 mm diameter aluminium block. It has a bore hole of 34 mm in diameter in the middle for the spinner shaft alignment using two cylindrical roller bearings. A retaining ring for the bearings is attached to the housing by 5 mm screws. It is fixed in place with the table using M8 bolts and has an interference fitting with the thrust bearing on top of it.

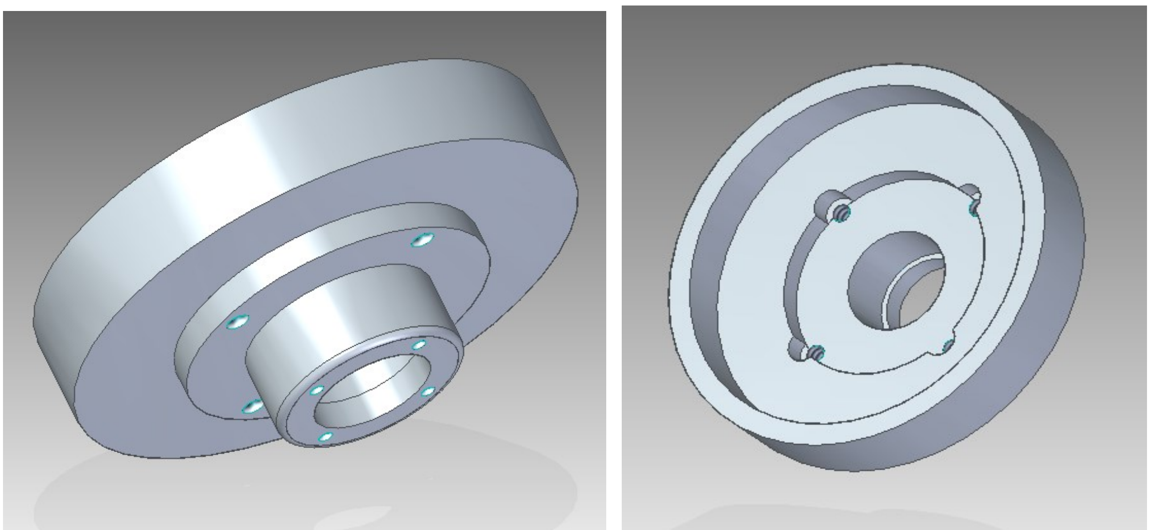

Figure 37 Bottom bearing housing

6.4 Upper cylinder/ upper housing

The upper cylinder where the pellets are placed also serves as the upper housing for the thrust bearing. It was decided to be made of steel due to the pellet interaction with the cylinder wall. The pellet materials being hard it will wear out the wall and small metal wear particles will interfere with our measurements.

It has an interference fitting with the thrust bearing and is attached with the 3mm sheet metal dust cover with 4mm screws. It has an M16 threaded hole on the side for air inlet where a ¼ inch compression fitting is assembled.

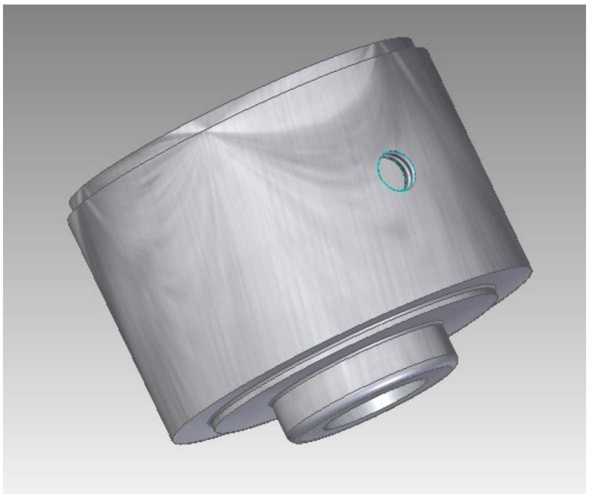

Figure 38 Upper bearing housing/pellet containing cylinder

6.5 Sheet metal dust cover

The sheet metal dust cover is the part where pellet dust particles will be guided up to the outlet and protect contamination with external dust particles. It is also the part where access to the pellet testing area is provided. In order to allow access to the pellet testing area it is designed to be made in two half cylinders where one of them is screwed to the upper cylinder and the top dust cover. The non-attached half cylinder is allowed to open and close by attaching it to the fixed part with hinges. A closing mechanism with a pin allows closing of the two halves during operation.

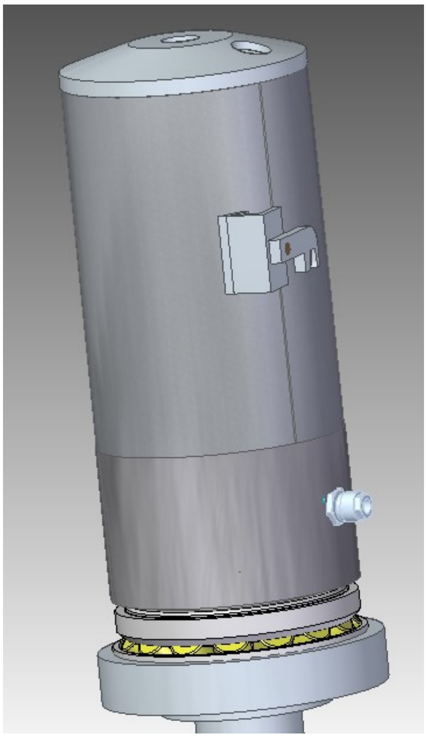 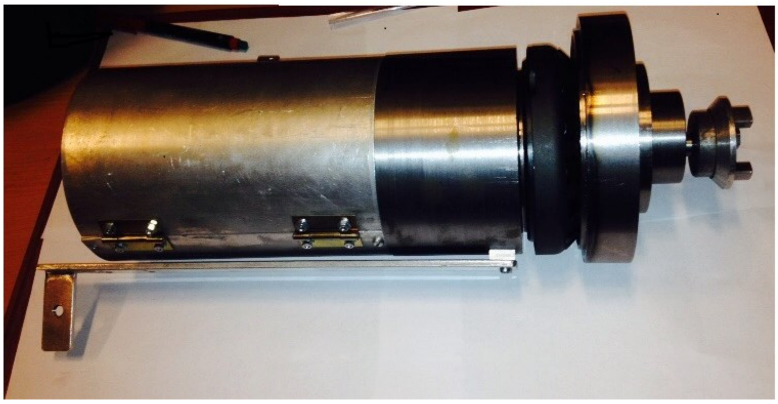

Figure 39 Sheet metal cylinder assembly with closing mechanism

6.6 Top dust cover and load cell fixture frames

The top dust cover was made of 126mm aluminium block. There was a need for uniform dust particle sampling that requires the part to have a conical shape. It has an air outlet hole of 20 mm in diameter which later needed to be adjusted to 8mm using a new part to match the particle seizer tubing.

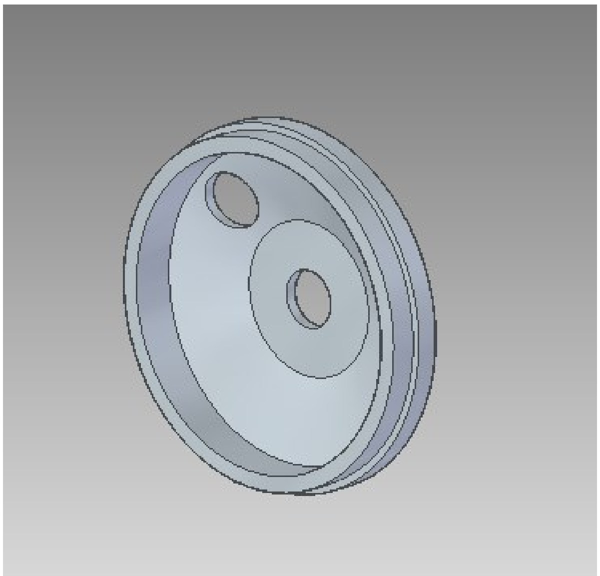 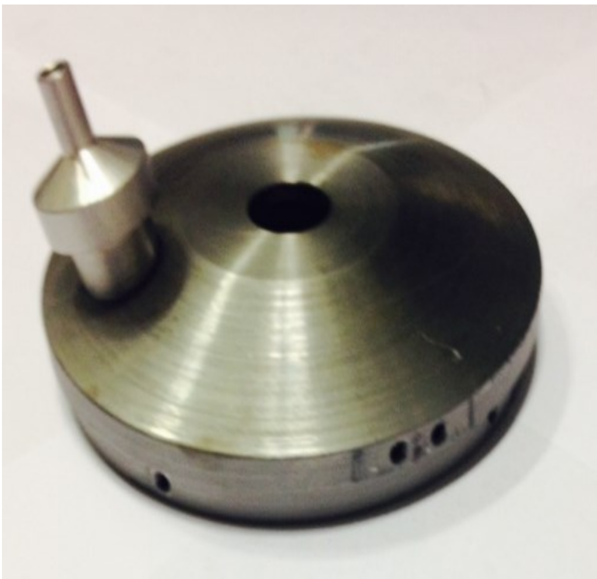

Figure 40 Top dust cover

6.7 Loading mechanism parts

Parts to be designed for the loading mechanism includes load plate and load pole. These parts two basic functions; to transfer load to the pellets and to transfer torque from the pellets to the pellet friction load cell.

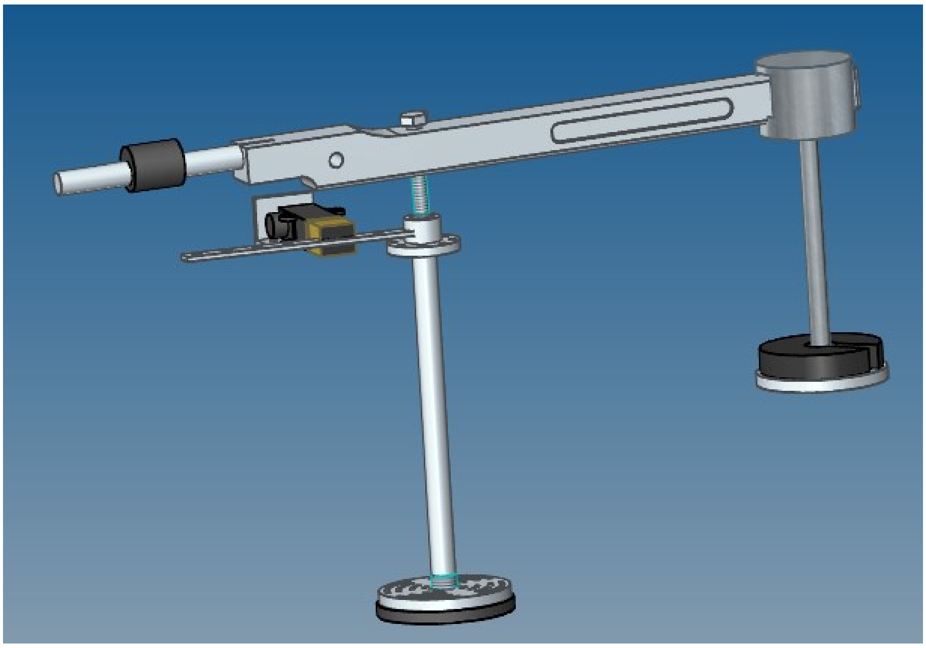

Figure 41 Load plate and load pole assembly

The load plate with the pattern of holes was manufactured by water-jet cutting. After the CAD design was complete the file is converted to DXF format and cut out of aluminium material. It is attached with the threaded end of the load pole by an M15 nut.

Figure 42 Load plate (left) assembled (right)

6.8 Load cell fixture

A steel frame of 310x30mm with 10mm in thickness is welded at the top with 30x30 mm steel for the wall friction load cell connection. This frame is screwed to the cylinder assembly with four M6 screws two at each end. It is attached with the load cell with M8 bolts to constrain the cylinder assembly rotation by transferring the torque to the load cell.

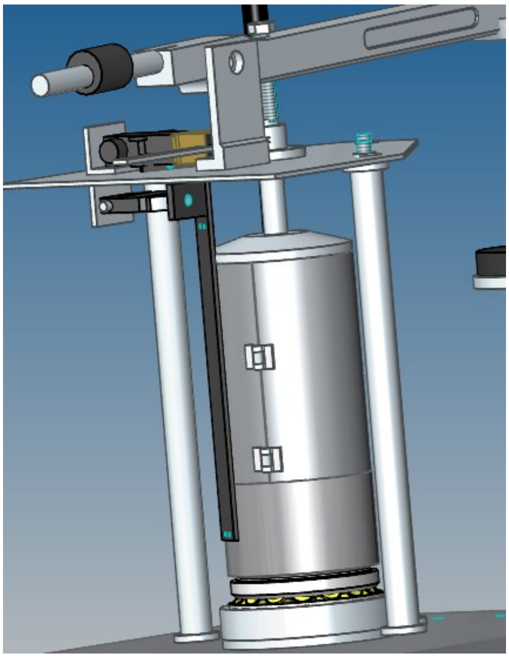

Figure 43 Load cell fixture assembly with cylinder

6.10 Demonstration & Experiment

An experiment for demonstration of the test equipment was performed to validate the functionality of the already completed systems of the equipment. The experiment was conducted using Grimm particle counter instrument with polytetrafluoroethylene (PTFE) filters to collect the off-gas dust particles. The test parameters are as listed below.

- Test period, ΔT = 4:29 min
- Load = 2 Kg
- Rotation speed = 5Hz (300 rpm)
- Initial weight of pellet W_o = 400.666 g
- Air flow rate = 8 L/min
- Air pressure 0.5 Bar

The experimental set-up is conducted carefully to obtain as accurate results as possible. First, pellets with an average size of 9mm in diameter were weighted with a scale which has a three digit precision. This is crucial because the amount of wear particle could be significantly small. The pellets were then put in the pellet holder cylinder and air was blown them to illuminate any dust particle that may be present prior to the experiment. Then the parameters for the rotational speed, load and air flow were set to the required values. After running the experiment for 4:29 minutes according to the experimental plan, results were logged by the data acquisition system and illustrated through LabView. The results for the experiment and comparison is as shown in the table below.

Table 2 Experimental result

Pellet group	Pellet group
Intial weight (Wo, g)	400.667
Final Weight (Wf, g)	389.0524
Weight change (ΔW)	11.6146
% ΔW	2.898816224
Wear rate (%wt/min)	0.599796446

The friction force value for pellet friction measurement could not be logged due to faulty load cell. The load cell used to measure pellet friction comes with the old tribometer. It was found out to be a challenging task to calibrate this load cell due to missing information of the load cell specifications and calibration data. Since it was impossible to do this without some vital missing information this load cell could not be calibrated. So, the value for pellet friction force could not be presented.

The other main measurement result is the pellet/cylinder wall friction force value. The load cell for this functionality was successfully calibrated and force data was recorded in LabView virtual instrument in the form of a wave-form graph shown in the figure below.

For the pre-test a nominal applied load of 19.6 N and rotational speed of 5 hertz that will give us 300 RPM was used. In less than a minute a stable operation condition was maintained and a stable friction value of 4.69 N was recorded.

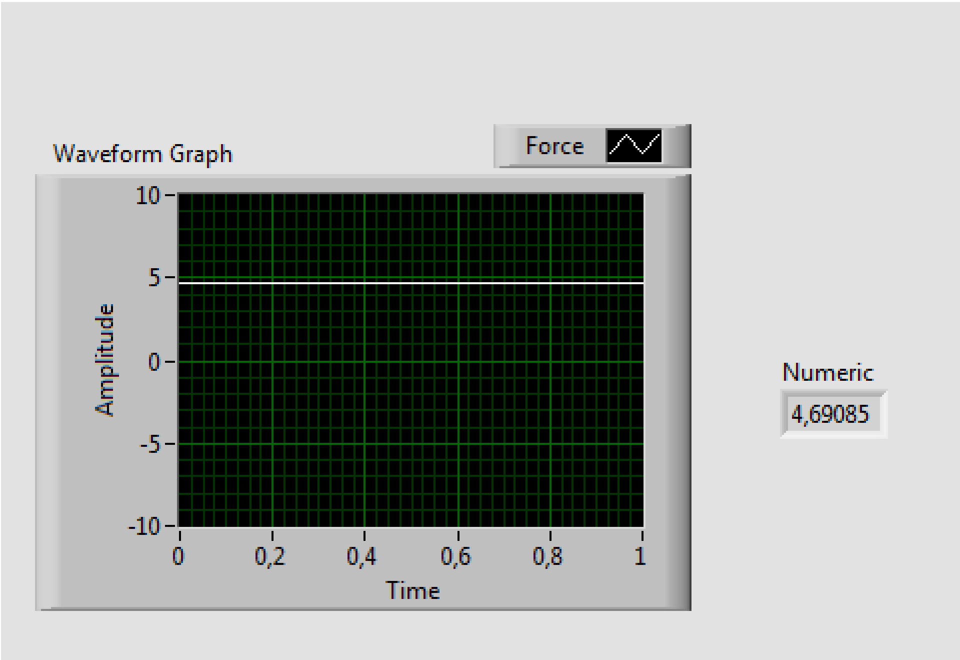

Figure 44 Pellet/wall friction force value in Newton

7. DISCUSSION AND CONCLUSIONS

In this chapter the overall project is discussed.

7.1 Discussion

The project is based on the old pin-on-disc tribometer. Redesigning the tribometer to an equipment for testing a blast furnace equipment was a challenge. This is due to the difference in the mechanism where pin-on-disc friction and bulk pellet friction is measured. This needed changes in most of the parts from the tribometer than it was initially anticipated. The analysis during the pre-study took a longer period of time than estimated in the time plan. This is due to a number of factors. First, my knowledge of blast furnace operation was limited. Second, it was a challenging task to imitate blast furnace operation in a laboratory scale equipment. Blast furnace operates in a very chaotic environment. The movement of pellets in the furnace is due to a hot blast of air through tuyeres plugged all around the shaft. This hot blast of air moves the pellets in a random manner unlike the spinning motor in this equipment. Third, the pellets movement is not only rotational but also translational. The extraction of molten metal from the furnace creates burden descent. This phenomenon could not be simulated in this laboratory equipment because it requires large amount of pellets to carry out the testing operation. Last, figuring out how to redesign the tribometer keeping the number of parts to be changed less, was challenging. It also constrained the flexibility in the newly designed parts. It would have been easier to design the equipment from scratch.

All the CAD models designed were set to fit on the basic parts from the old tribometer. Hand measurements were used to measure all fitting parts; holes, distances of elements, and patterns. But a small human error in measuring those elements created a huge problem later in assembling the mating parts in the old tribometer. This forced some parts to be redesigned and others to be modified to fit the equipment. Due to this the assembly of parts took a considerable amount of time before it gets right at last.

Although it was not possible present the friction value for pellet on pellet interaction, all other required results were obtained. Only by replacing the pellet friction load cell with a functional one the equipment can give all the intended results it was designed to deliver.

The original time plan was ambitious in its time allocation. The amount of task to realize the concept to a physical equipment was underestimated. Although this is one of the reason the project took a longer period of time than the time plan, other unexpected problems also arise as discussed in the assembly and data accusation. Overall, it was managed to demonstrate a functional prototype except the result of internal pellet friction values due to difficulty in calibrating the old load cell where the calibration certificate could not be found. If this old load cell is replaced with a new one all the required results from the equipment could be acquired and the equipment becomes complete.

7.2 Conclusion

After analysing the whole process and results the following conclusions can be drawn.

- A blast furnace environment in the upper shaft where the temperature is colder can be imitated to a satisfactory degree in a cold laboratory scale equipment
- Friction behaviour of pellets in relation to rotational movement, burden weight, and pressurised air flow can be understood in a safer and simpler way using small scale laboratory equipment than in actual blast furnace
- Other granular materials friction behaviour can be studied using the same equipment
- The frictional torque between pellets and the container wall increases with increasing rotational speed
- Using much lower proportional parameter values for burden weight and rotational speed to find friction values, can be interpolated to approximate the actual frictional values in a blast furnace

8. RECOMMENDATIONS AND FUTURE WORK

In this chapter, recommendations on more detailed solutions and/or future work in this field are presented.

Although the goal was to deliver a fully functioning test rig by the end of the project period, a few tasks were left as future work due to extended time taken in assembly and limited knowledge in data acquisition system.

A recommendation for better functionality of the equipment could be to redesign the pellets loading/unloading accessing mechanism. As in this design it is a little bit difficult to do this operation due to compact design and tight spacing of elements. The loading stand could be shifted a bit apart to give more spacing. The pellet container cylinder could also have an inside shell that can be dragged out and filled with pellets. This shell should be locked with the spinner to transfer the torque and should be easily removable after testing to unload the pellets.

A spring loading mechanism can be used to apply the load since they have vibration damping capability. During the demonstration a vibration was noticed with the dead weight loading system. This vibration could be a problem if the testing parameters are set high.

Work that has to be done on the equipment to realise the currently defined functionality is to complete the data acquisition system. To complete the data acquisition all that is required is either to properly calibrate the old load cell or replace it with a new load cell. Using a new load cell may require to design a new part for fixing the load cell if it has a different size or mounting mechanism.

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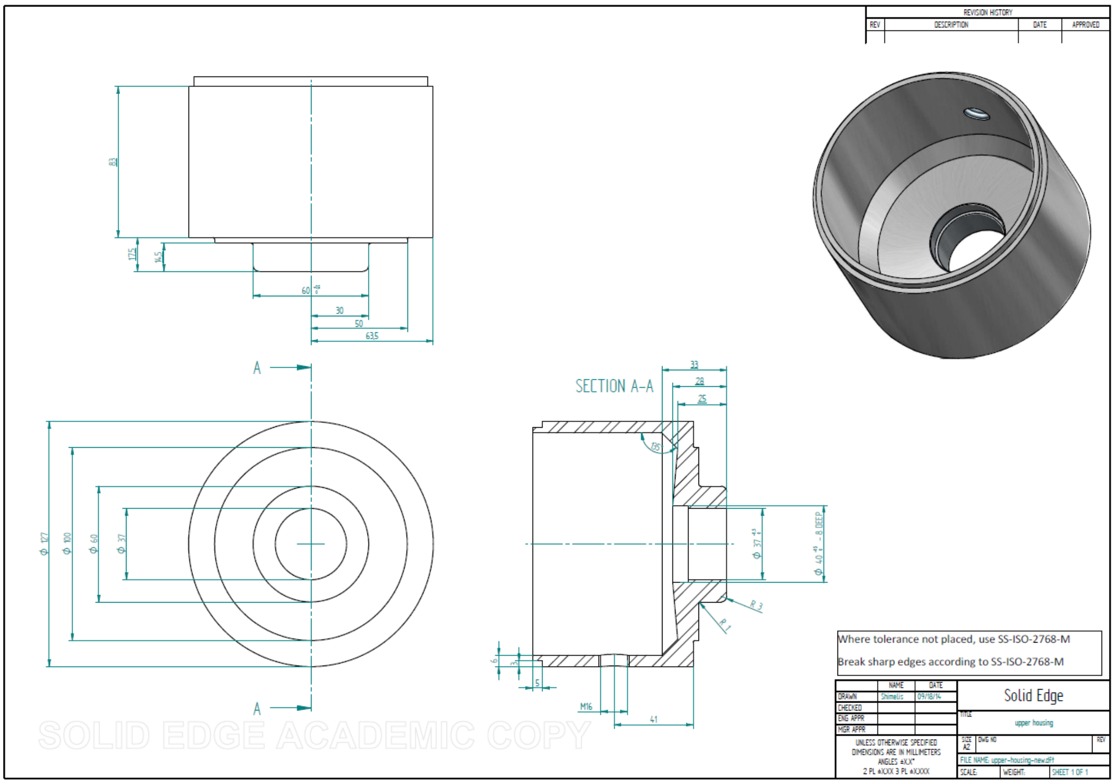
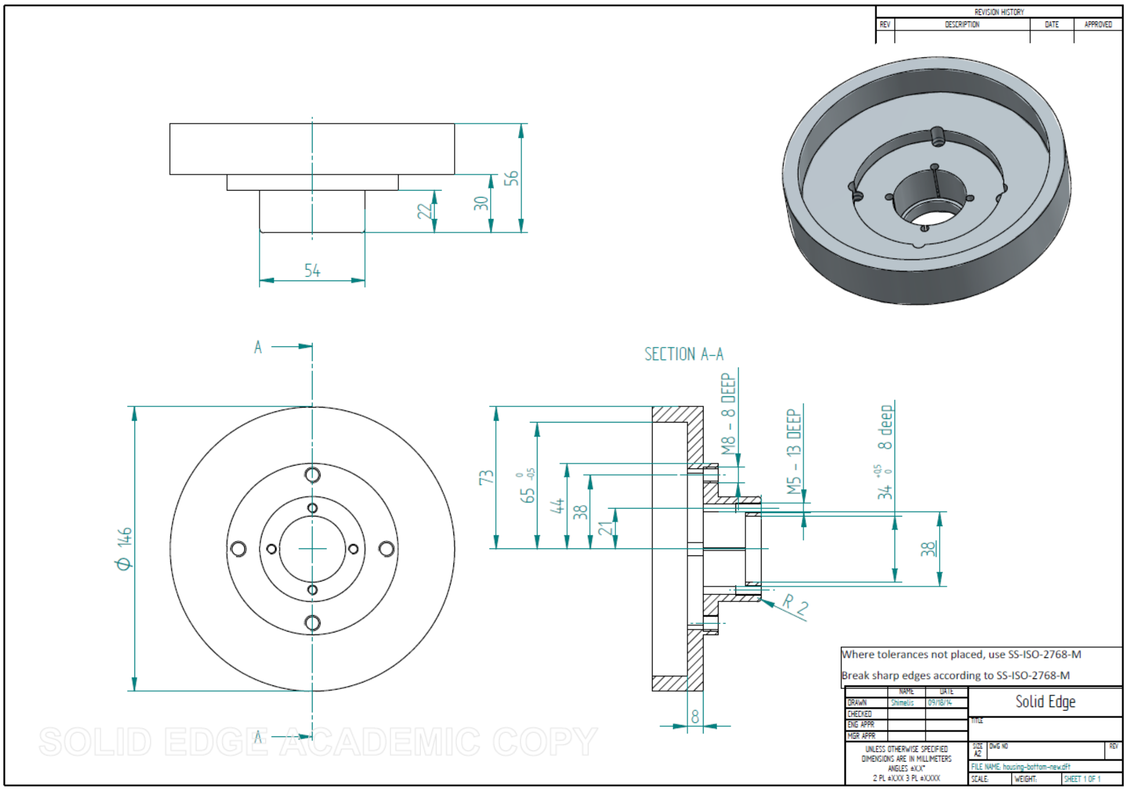
The complete Solid-Edge CAD model (attached) -can be accessed in “Cygnus CAD” folder)

Excel file (attached) - containing time plan and budget

Drawings:

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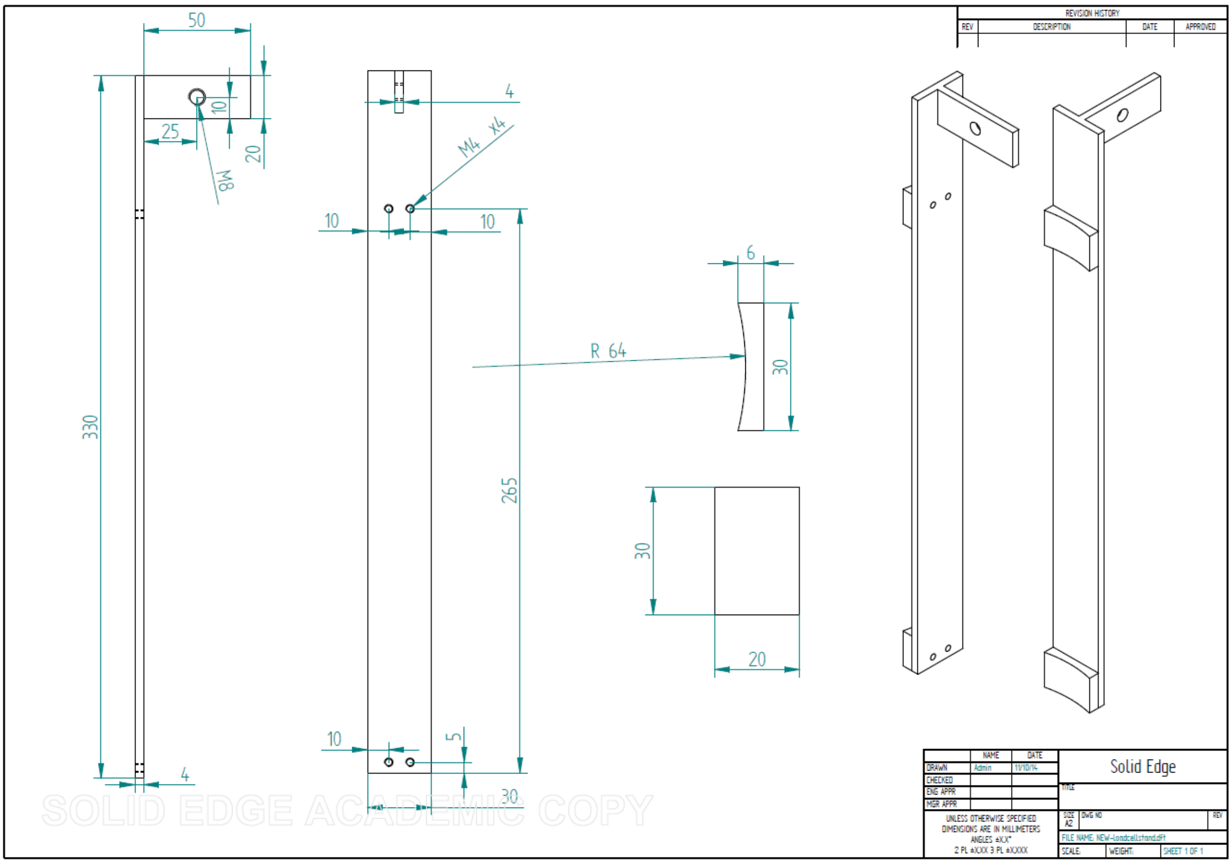

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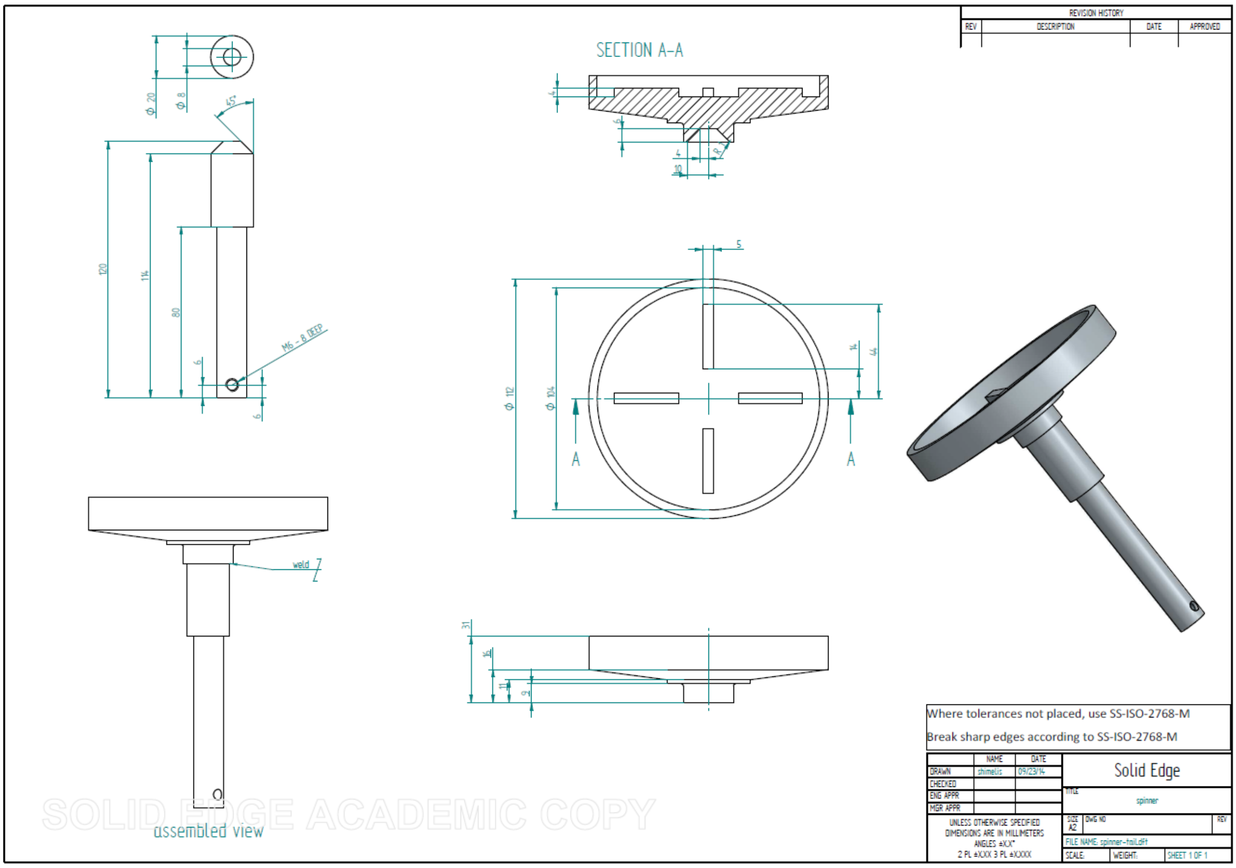

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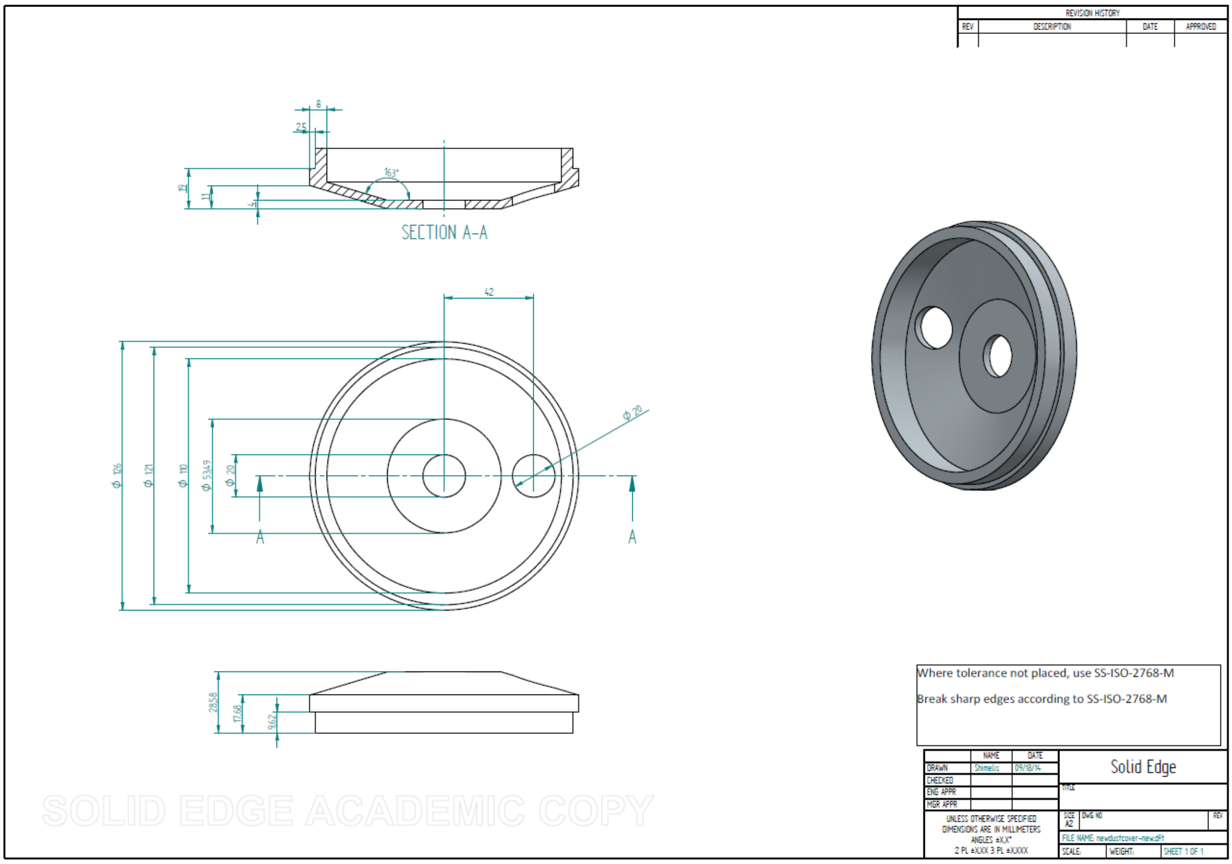
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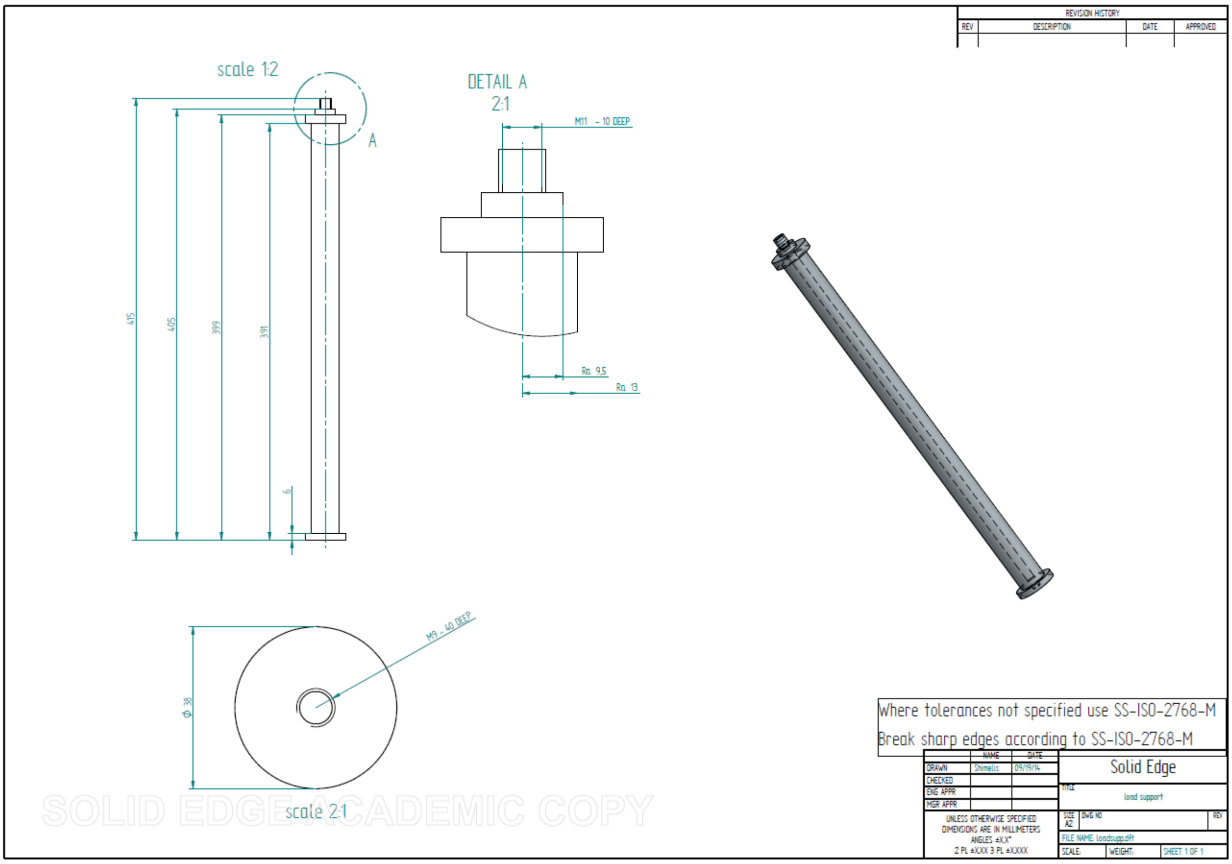
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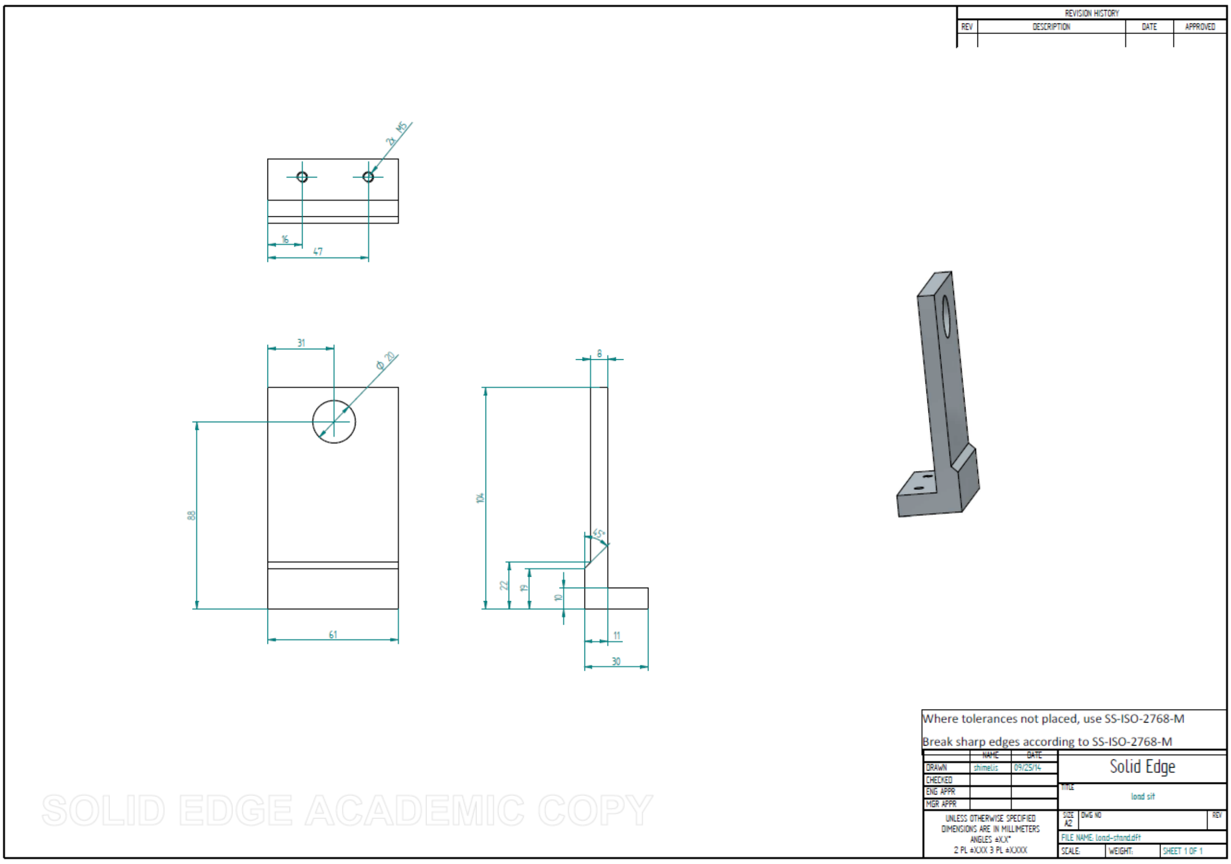
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