INVESTIGATION OF EFFECT OF OPERATIONAL PARAMETERS ON VERTICAL ROLLER MILLS' PERFORMANCE

İŞLEM DEĞİŞKENLERİNİN DİK DEĞİRMEN PERFORMANSI ÜZERİNE ETKİSİNİN ARAŞTIRILMASI

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Prof. Dr. Fatma SEVİN DÜZ
Director of the Institute of
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to my family,

ETHICS

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- all the information and documents have been obtained in the base of academic rules
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- I did not do any distortion in the data set
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02/07/2015

HULUSİ KONURAY DEMİR

ABSTRACT

INVESTIGATION OF EFFECT OF OPERATIONAL PARAMETERS ON VERTICAL ROLLER MILL PERFORMANCE

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Master of Science, Department of Mining Engineering

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This research study was aimed to investigate the effect of operational parameters on vertical roller mills' performance. Test works were held at a mobile ore grinding plant (OGPmobile) which belongs to Loesche GmbH.

According to aim; effect of dam ring height (design parameter), effect of grinding load, effect of classifier rotor speed, effect of airflow rate and effect of mill differential pressure have been investigated. Test material was epithermal quartz vein type gold ore which has a Bond Work Index 17.8 kWh/t. Within the thesis study, grinding test works were performed to investigate the influences of the design and operating parameters on vertical roller mill grinding performance. In this context, systematic test plans have been generated. According to test plans; dam ring height, grinding pressure, classifier rotor speed, airflow rate, mill differential parameters were tested by considering specific energy consumption and product fineness of the mill. By using measurements, and analysis; relationships between different operational parameters and their effect on vertical roller mill performance has been identified.

In consequence of this study, effects of operational parameters have been investigated on performance of vertical roller mills. The relations and effects are discussed and explained in details.

Keywords: Vertical roller mill, grinding, mobile ore grinding plant

ÖZET

İŞLEM DEĞİŞKENLERİNİN DİK DEĞİRMEN PERFORMANSI ÜZERİNE ETKİSİNİN ARAŞTIRILMASI

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Temmuz 2015, 91 Sayfa

Bu araştırma çalışmasında amaç, işlem değişkenlerinin dik değirmenlerin performansına olan etkisinin araştırılmasıdır. Test çalışmaları Loesche GmbH'ya ait gezici cevher öğütme tesisinde yapılmıştır.

Bu amaç doğrultusunda, bir tasarım değişkeni olan kenar yüksekliğinin etkisi, öğütme yükünün etkisi, sınıflandırıcı dönüş hızının etkisi, hava hızının etkisi ve değirmen içi basınç farkının etkisi detaylı bir şekilde incelenmiştir. Testler sırasında kullanılan besleme malzemesi 17,8 kWh/t Bond iş indeksine sahip epitermal kuvars damar tipi altın cevheridir. Çalışmalar sırasında, işlem değişkenlerinin dik değirmenlerin performansına olan etkisinin araştırılması üzerine birçok test yapılmıştır. Bu bağlamda sistematik deney planları yapılmış ve test planları çerçevesinde; kenar yüksekliği, öğütme yükü, sınıflandırıcı hızı, hava hızı ve değirmen içi basınç farkı değişkenleri; birim enerji tüketimi, ürün tane boyu ve birim aşınma değerleri göz önünde tutularak testler gerçekleştirilmiştir. Testler sırasında yapılan ölçümler, elek analizi verileri kullanılarak; işlem değişkenleri ile dik değirmen performansı arasında ilişkiler kurulmuştur.

Bu çalışmanın sonucu olarak, işlem değişkenlerinin dik değirmenin performansı ve öğütme davranımı hakkında incelemeler ortaya konulmuştur. Değişkenler arası ilişkiler ve değişkenlerin performans üzerine etkileri detaylı bir şekilde incelenmiş ve açıklanmıştır.

Anahtar kelimeler: Dik değirmenler, öğütme, gezici cevher öğütme tesisi

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1. INTRODUCTION

Crushing can be defined as; increasing the surface area of the brittle particles' yield by new crack generation and/or crack propagation under stress. In other words; crushing can be defined as generating smaller particles from a particle. Comminution forms by crushing of more particles simultaneously.

The main aim of the comminution is to liberate particles for downstream processes. Liberation increases the option and efficiency of the downstream mineral processes. On the other hand, comminution is also necessary in order to increase the surface area of the material for downstream chemical and metallurgical processes. Comminution has critical importance for mining, cement, steel, power plants, ceramic, food, chemical industry and etc.

Comminution consists of two stages; crushing and grinding. Grinding is the final stage for comminution and this stage consumes more energy. The energy consumed by grinding process in a mineral processing plant is about 40-60% of the total operational expenditures (OPEX) of the process plant. This value means 0.6% of the world electricity consumption. Despite the consumed high rate of energy, only about 1% of the energy which is given to system is used for crushing. The rest 99% of energy transforms to sound, heat, vibration etc. [1]. In the light of these information, the efficiency of the process plants getting more and more importance. Manufacturers work on decreasing the specific energy consumption of the grinding equipment in order to meet the market requirements. Some manufacturers build complete grinding circuit. They also try to optimize their grinding circuit.

Comminution can be performed by different mechanisms which are classic stress forces. They are impaction, compression, attrition, tensile and shear. Figure 1-1 shows a simple illustration for them.

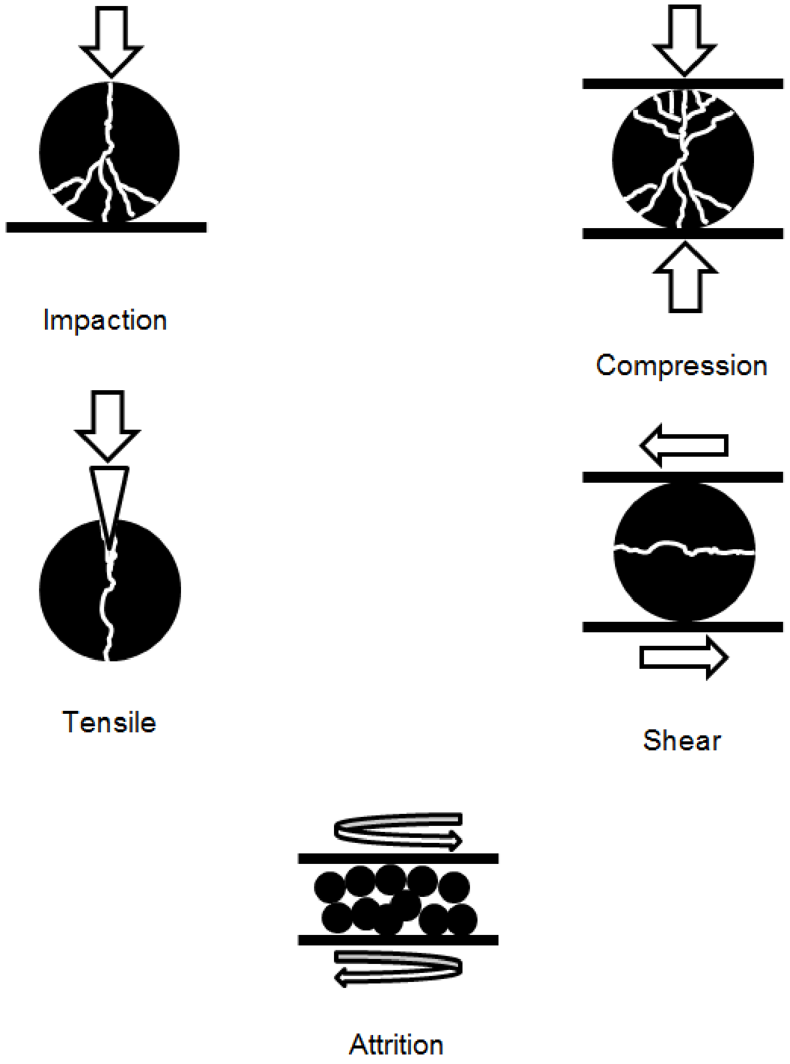

Figure 1-1. Different comminution mechanisms

Grinding can be done by different equipment, such as ball mills, vertical roller mills, high pressure grinding rollers, stirred mills etc. The main mechanism is different for different type of mills/equipment. For ball mills the main mechanism is impact; for vertical roller mills and high pressure grinding rollers the main mechanism is compression; for stirred mills the main mechanism is attrition. Klaus Schönert has claimed that the most efficient way for grinding is compress the particle in between two plates [2]. Vertical roller mills’ grinding mechanism is mainly based on this phenomenon. This is a big advantage of the vertical roller mills.

Vertical roller mills generally have their classification unit integrated. They are compact systems. The system works like black box. Classifier feed and coarse cannot be known. That makes the modelling studies difficult. Several studies have been conducted in order to sort this black box out. WANG J. et al., [3] have tried to conduct mathematical model for vertical roller mills based on experimental data, but these data were not sufficient. KERSTING F.J. [4] has also studied on modelling of vertical roller mills by conducting cub models for grinding, classifying and conveying unit operations. In addition to this, both of the studies assumed that the mill as a black box. AYDOGAN N.A. et al. (2007) [5] developed a unique sampling method inside the mill and managed to make mass balance for mill for each separate flow around the classifier.

The aim of this study is evaluating the effect of operational parameters on vertical roller mills’ performance. This study can be seen as a preliminary step for modelling studies.

2. VERTICAL ROLLER MILLS

By 1900 power stations and civil industry's demand was increasing for high capacity grinding equipment. Tumbling mills were available in order to grind coal, limestone and cement clinker at those days.

In 1906 Curt von Gruber from Berlin and Claudius Peters from Hamburg were visiting USA, perhaps independently, to have a look at grinding mills. At those days small engineering companies/workshops would build grinding mills for local industries. Several of these such as Loesche, Alpine, Polysius and FL Smidth grew into large corporations at the end. Von Gruber brought licences back to their workshops to build mills. The modern vertical roller mills' design started to be shaped since that day.

Vertical roller mills are generally used for the comminution of raw materials for cement industry, for the comminution of clinker and blast furnace slag, for the pulverizing coal for cement kilns, blast furnaces and power stations [6]. Since 1961 there are some applications of the vertical roller mills in mineral processing industry. In 2006 Loesche has commissioned an LM19.2 for comminution of colemanite in Bigadic, Turkey. Loesche has increased their interest in mineral processing industry. In order to get a better position in ore/mineral grinding industry, they are carrying on some projects.

2.1. Working Principle

Comminution has a critical importance for the downstream sorting processes. Increasing metal prices and decreasing reserve figures bring out the necessity of processing of low grade ore bodies. On the other hand grain sizes are getting finer and finer. Liberation is the main aspect on ore process. In order to liberate the ore, grinding must be properly done. The finer the grain size, the finer ground particle size is required.

Vertical roller mills' grinding principle is based on in-bed comminution. In bed comminution particles have many contact point with each other. That means grinding force effects at several points on the particle, during the grinding force is directed through the grinding bed. In this kind of breakage, crack propagation generally directs through the phase/contact borders. This results in a better degree of liberation in comparison with the conventional grinding systems. This can be mentioned as selective ore comminution.

Figure 2-1 shows an illustration of bed breakage.

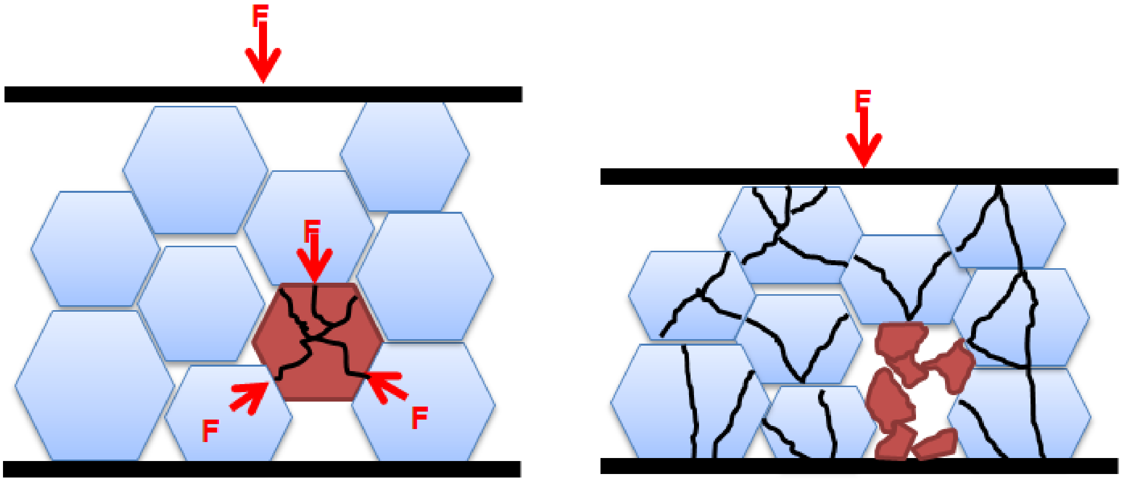

Figure 2-1. Bed breakage [7]

In the vertical roller mills, the material is comminuted between the stationary grinding rollers and the rotating grinding track (Figure 2-2).

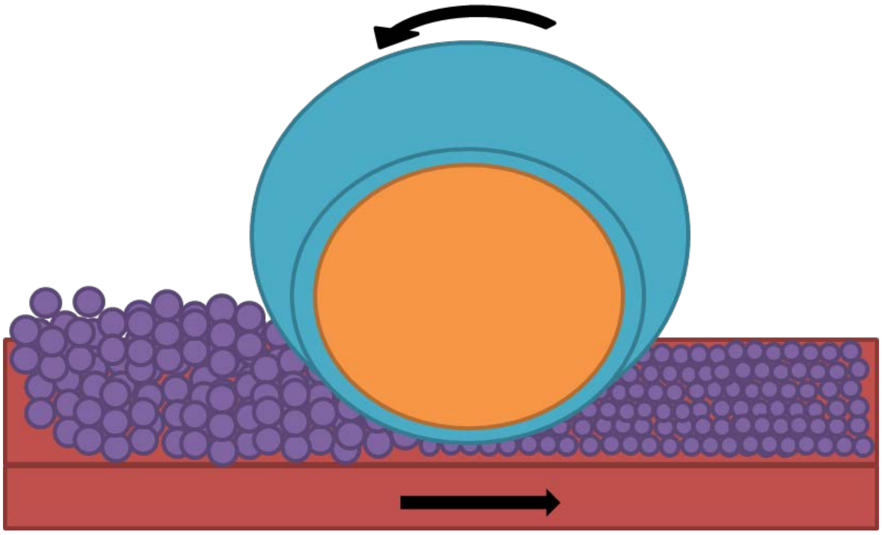

Figure 2-2. Bed comminution between roller and table [7]

For Loesche mills, the feed maximum size is restricted by 5% of average diameter of the grinding roller. The diameter of the rollers is a function of number of rollers and table diameter. The roller diameter can be designed to optimize gripping the feed material.

Based on the geometry of the grinding rollers Loesche vertical roller mills can operate with a compressive comminution system with a shear component. Shear effect can be discarded by modification of the grinding roller geometry that creates a pure compressive comminution system. Since the vertical roller mill employs not only compression grinding but also friction grinding; the material can be ground very efficiently [8]. Figure 2-3 shows the effect of the roller geometrical design on shear forces.

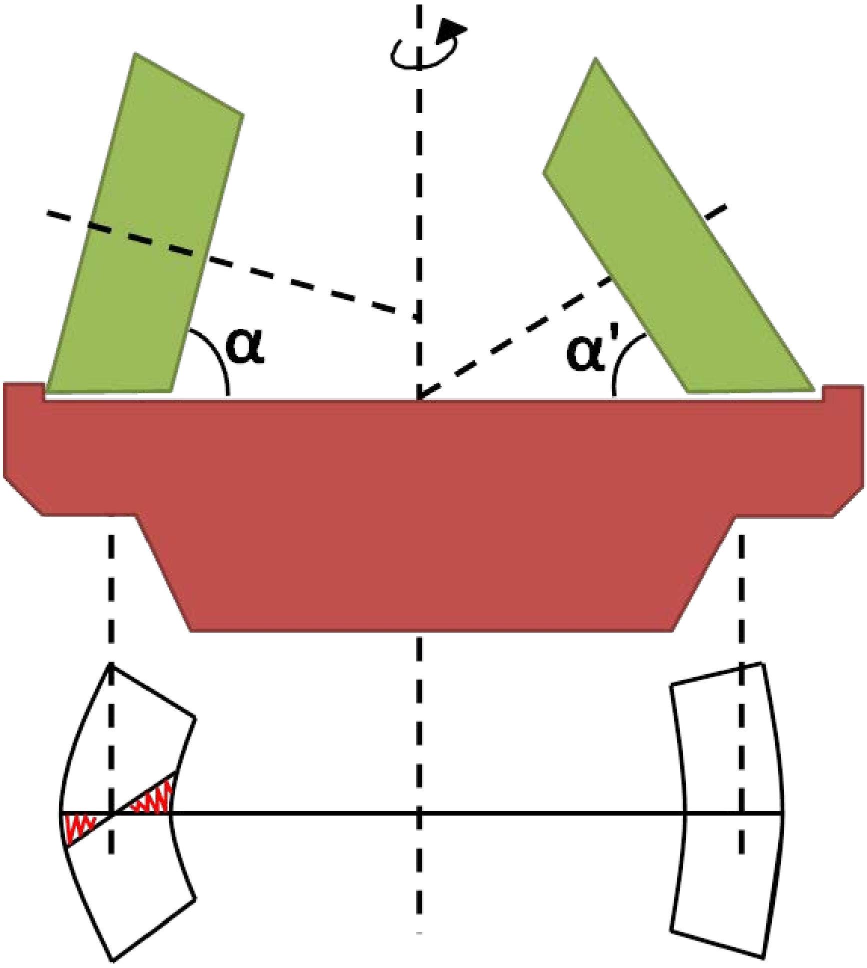

Figure 2-3. Shear and shear free rollers [7]

Shear forces are created by tapered rollers; the rollers axes do not intersect the centre of the grinding table. In order to avoid shear forces, rollers' axis are angled in relation to the horizontal grinding table. For zero shear force, the axes of the rollers must intersect the centre of the grinding table.

There are two different grinding modes for vertical roller mills. They are;

- Airflow (Air Swept) Mode

Milling and classification is done in the same unit. Material is transported by air flow generated by a fan.

- Overflow Mode

Milling is done in the mill body, but the classification is done outside mill body. Material is transported by mechanical equipment.

For these to grinding modes, it is possible to use shear or non-shear (shear free) roller modules.

2.1.1. Roller-Hydraulic Spring Mechanism

The basic layout of the Loesche vertical roller mill is based on the principle of the Loesche modular system which was patented in 1970. Loesche modular system allows same roller types for different diameter of grinding tables. This modular system can be adjusted due to product target, material type, throughput etc. Loesche vertical roller mill has two, three, four and six roller modules (Figure 2-4).

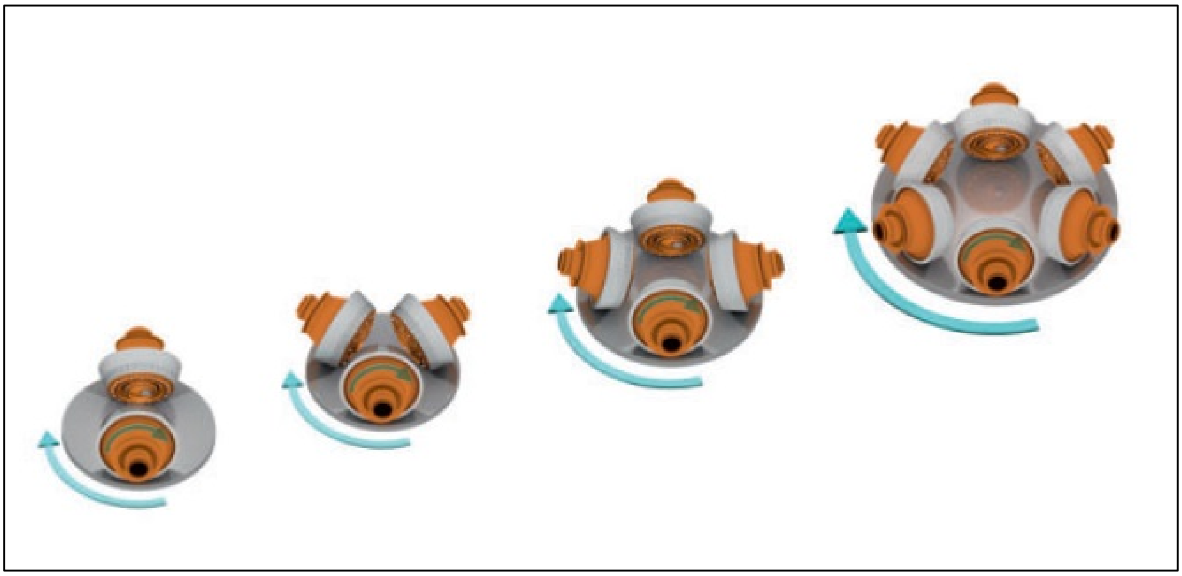

Figure 2-4. 2-3-4-6 rollers vertical roller mill concepts [7]

In Figure 2-5, a general layout of a Loesche vertical roller mill is shown. Each roller module consists of grinding tire (1), roller (2), a rocker arm (3) and pedestal (4). Rocker arm transmits the force to the roller by hydraulic spring loading. Roller-bearing-rocker arm system is supported and guided in a pedestal with integrated hydraulic spring assembly.

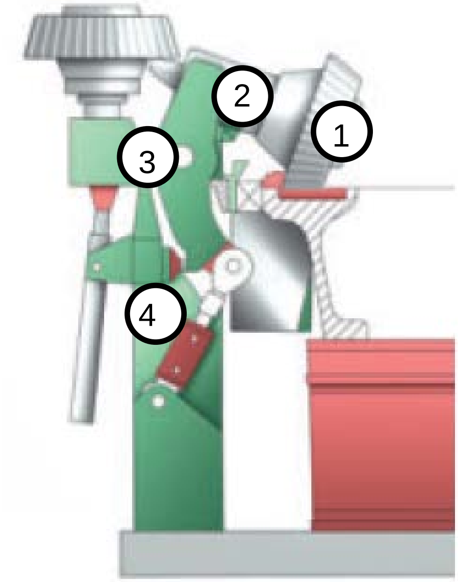

Figure 2-5. Grinding module of vertical roller mill [7]

Patented hydraulic spring loading system has hydraulic pumps, hydraulic cylinders, nitrogen filled bladder accumulator, valves and pipelines. A general sketch of the hydraulic spring system is shown in Figure 2-6.

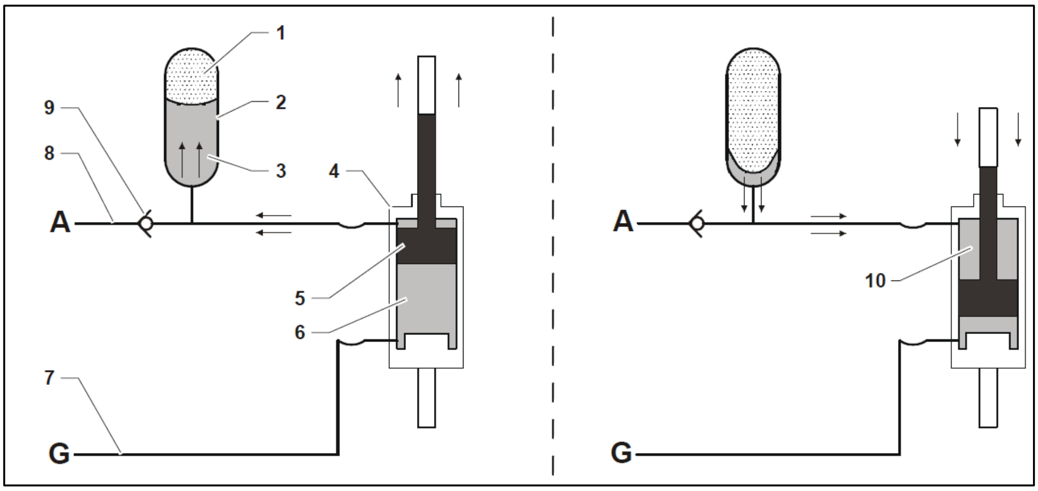

Figure 2-6. N_2 accumulator working principle [9]

1. Nitrogen filled bladder	6. Piston side
2. Hydraulic oil accumulator	7. Back pressure system
3. Hydraulic oil	8. Working pressure system
4. Hydraulic cylinder	9. Check valve
5. Piston	10. Piston rod side

When the system in grinding mode, the working pressure system is activated, then the hydraulic oil pumps through the piston rod side. The bladder accumulator's main duty is placed in order to compensate the effect of sudden pressure increase which might be generated by inhomogeneous grinding bed. Also the bladder accumulator accumulates the piston rod side hydraulic oil when the roller is swung out. Bladder accumulator smoothens the movement of the rollers which results grinding performance at lower vibration levels [3].

A cut of hydraulic oil accumulator is given in Figure 2-7.

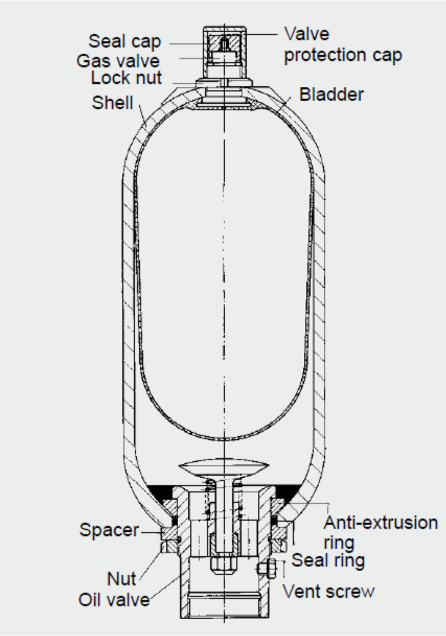

Figure 2-7. Section of an N_2 accumulator [9]

Nitrogen pressure in the bladder is set with respect to working pressure. There is a general set limit;

$$1.25 \times P_b < P_w < 4 \times P_b \qquad (2.1)$$

P_b : Nitrogen pressure in bladder

P_w : Hydraulic oil working pressure

2.1.2. Master and Support Roller Mechanism

Master and support roller mechanism was designed to reach higher Blaine values for cement. Increasing grinding pressure is necessary in order to grind a finer end product. An illustration of master-support roller mechanism is given in Figure 2-8.

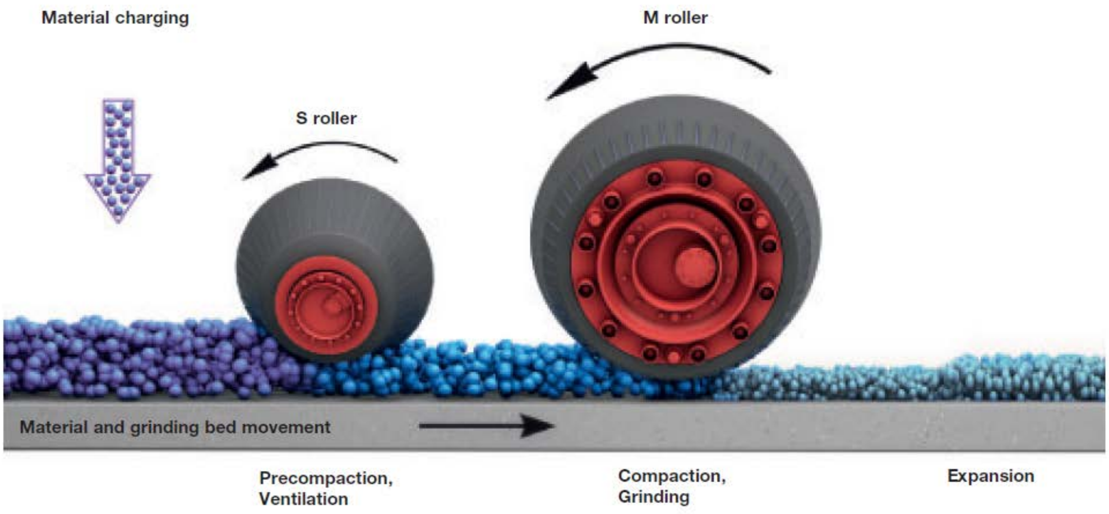

Figure 2-8. Master and support roller concept [7]

This technology allows for much finer product by increasing the grinding bed stability. The concept is based on two different types of rollers. The smaller rollers (support rollers) are being used for grinding bed preparation and the large rollers (master rollers) are being used for grinding. The support rollers prepare the grinding bed, thus master rollers can apply higher hydraulic pressure without. Vibration is eliminated by this mechanism [10].

2.1.3. Shear Forces

According to process requirements and ore characteristics, shear free rollers might be beneficial. Shear force application increases the fines amount in the product. Also, wear on the shear rollers is more than wear on shear free roller. Shear forces' magnitude can be arranged by geometric design study. The angle and the shear force relation is illustrated in Figure 2-9.

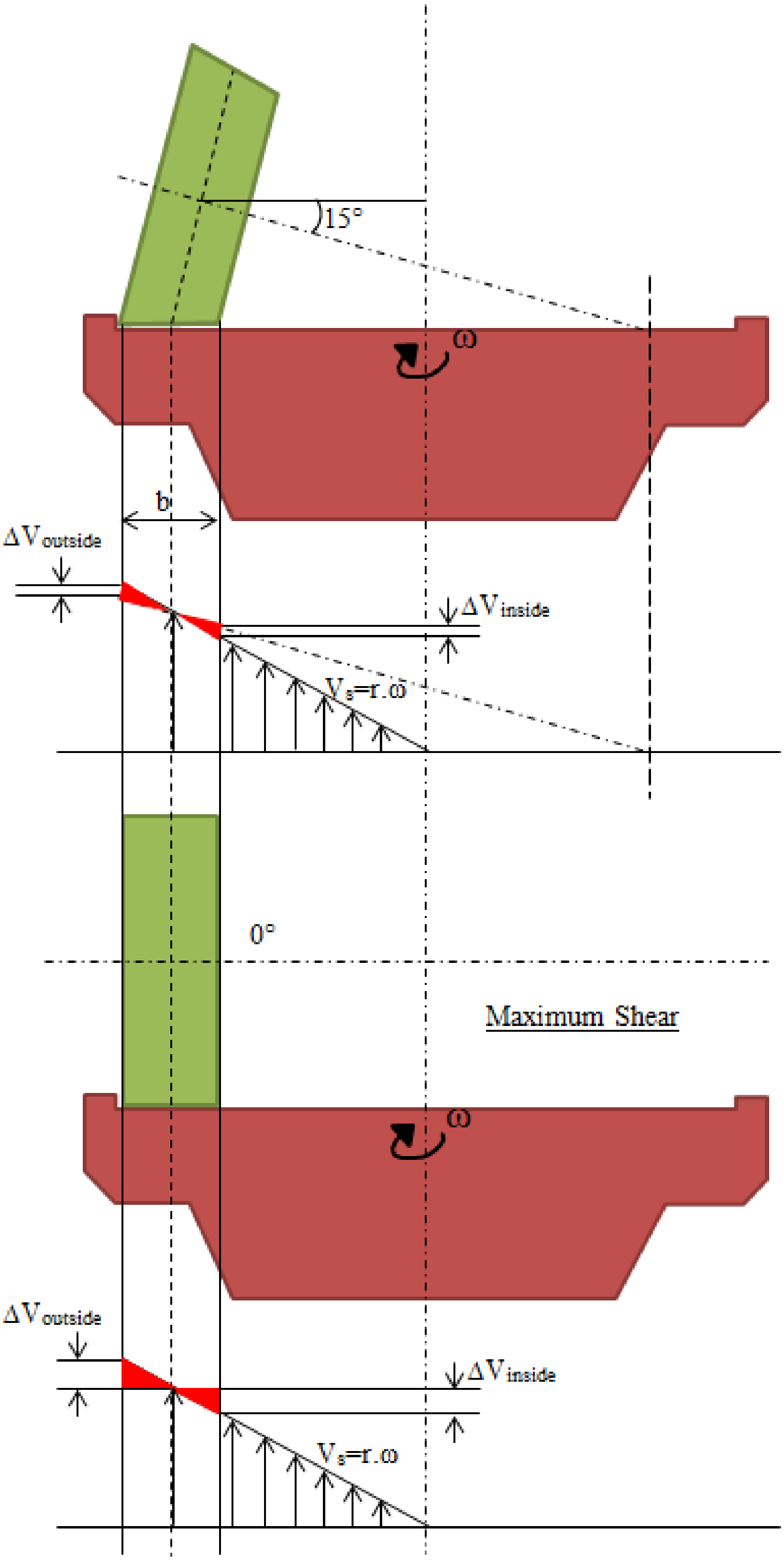

Figure 2-9. Effect of roller angle on shear force (A.Bätz special conversation)

The area which is highlighted by red is an indication of shear force magnitude. On the middle line (----) of the grinding roller the linear speed equals the linear velocity of the grinding roller at the mean radius. The difference of the linear velocity at the inside and outside is related with shear force magnitude. Also roller width affects the velocity difference. Bigger the width means bigger velocity difference. When the roller centreline (-····-) intersects with the centre of table, there is no linear velocity difference between inside and outside of the grinding roller.

2.1.4. Classification

Classification with higher circulating loads eliminates the overgrinding. Classification is an important aspect to optimize grinding operation. The traditional vertical roller mills have their classification unit integrated to mill body. These classifiers are still under development.

As a developing technology, some vertical roller mill applications can have external material circulation and external classification (Chapter 2.2).

A drawing of the last generation classifier of Loesche mill (LSKS)[1] is given in Figure 2-10.

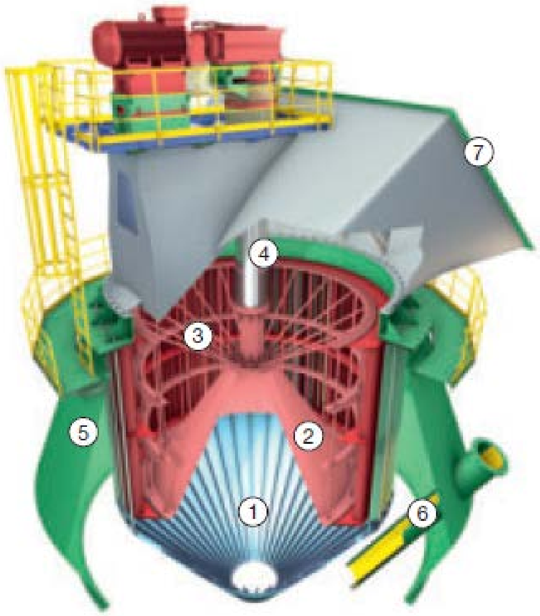

Figure 2-10. Cross section of an LSKS [7]

1. Grit cone
2. Guided vane assembly
3. Rotor with blades
4. Rotor shaft
5. Housing
6. Material feed chute
7. Product discharge

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[1] LSKS represents for Loesche Stabkorb Sichter (=Loesche Bar Cage Classifier).

The gas/particle flow rising from the mill is directed via a static guide vane assembly (2) to the classifying chamber. The gas/solid-matter mixture flows into the space between the guide vane assemblies (2) and the concentric-running rotor with blades (3). The centrifugal force generated in the process rejects oversized particles. The coarse particle is directed to grinding table through grit cone (1). The fine particles which are met with the specifications go to bag house through product discharge (7) [7].

Static guide vanes angle determines the range of fineness and steepness of the product particle size distribution [11].

In overflow mode classification takes place externally. Before grinding pre-classification can be considered in order to take out the material which is fine enough for product preliminarily. It is possible to provide several classifying stages to recover different fractions of products.

2.2. Grinding Modes

According to material characteristics and product specifications, two different mode options are available. These are airflow and over flow modes. In the airflow mode the circulating load is mainly kept inside the mill. In contrast, in overflow mode all of the material is externally circulated.

2.2.1. Airflow Mode

Airflow mode is the mode which has the grinding, drying, classification combination in one mill body. A dynamic classifier is integrated on the top of the mill. Air stream (generally hot air) is fed from the air inlets located bottom side under the louver ring. This air stream also has a static classification effect at louver ring. The schematic view of unit operations in the vertical roller mill is shown in Figure 2-11.

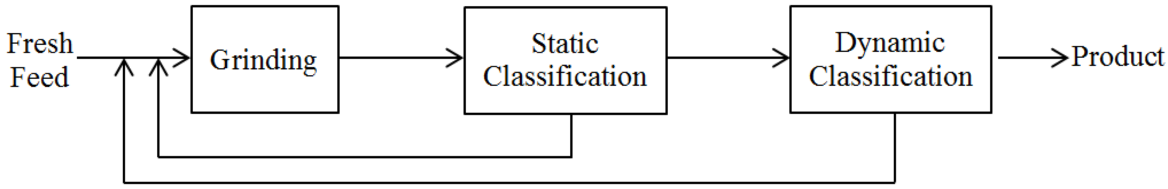

Figure 2-11. Unit operations and simplified internal flowsheet of air swept mode

A perspective cut of an airflow Loesche vertical roller mill is shown in Figure 2-12.

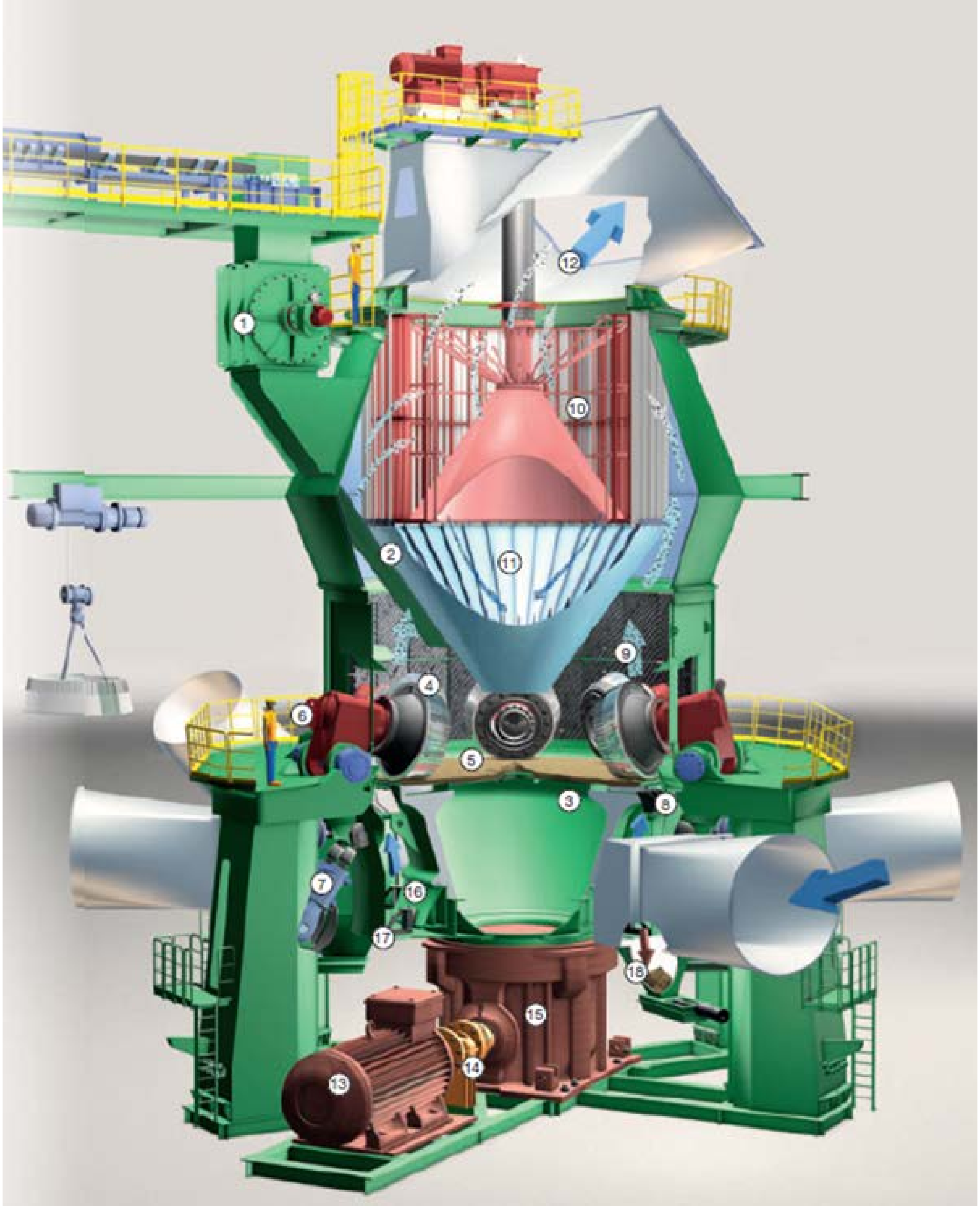

Figure 2-12. Perspective cut of a Loesche vertical roller mill (air swept mode) [7]

Fresh feed material is fed by a conveyor belt. On the belt fresh feed and very coarse mill reject material is combined and is fed to an air isolated rotary valve or gate feeder (1). The feed material goes through feed chute (2) and falls onto the centre of the grinding table. Free ferrous foreign objects which can damage grinding units of the mill are removed by a magnetic separator over the feeding belt before reaching the air isolated feeding mechanism. The material to be ground moves on the grinding table towards the edge. The movement is generated by centrifugal forces. This centrifugal force is created by table rotation. The material by this way passes under the hydro-pneumatically spring loaded grinding rollers (4). The material which has been caught by the rollers is ground in the material bed (5) in the gap between grinding rollers and grinding track. The grinding rollers (4) are displaced upwards as they roll over the grinding bed (5). As a result of displacement upwards of the roller, the rocker arm (6) is moved; spring rod and pistons of the hydraulic cylinder (7) are also moved. The piston displaces the hydraulic oil from the cylinder into the nitrogen filled bladder accumulator unit. Those nitrogen filled bladder accumulators act as gas springs. Gas springs can be set to be harder or softer depending on the fracture behaviour of the material to be ground.

The ground material in the grinding bed is subjected to centrifugal force and goes outwards over the edge of the grinding table (3). There is a louver ring (8) which is placed around the table (3). The air stream (generally hot), is fed under the louver ring generally by two opposite sides. That air stream (9) directed upwards catches the ground material and transfers to the dynamic classifier (10).

A small amount of material cannot be conveyed by airflow due to their higher weights and falls through the louver ring (8) into the ring channel (16) as reject material. This reject material is collected by scrapers (17) in the ring channel and taken out via reject chute (18). Then the reject material is conveyed to feeding belt generally by belt conveyor-bucket elevator conveying system.

Depending on settings of the classifier (10) it rejects the coarse materials. Coarse material falls into a grit cone (11) and through the cone onto the grinding table (3) in order to be reground.

The material which is ground enough passes from the classifier and is taken out from vertical roller mill by air stream.

The grinding table is driven by an electric motor (13) via elastic coupling (14) and the mill gearbox with vertical output (15).

Before the mill motor is started, the grinding rollers (4) are lifted hydraulically from the grinding track. The mill can start then be started at lower torque not only empty but also partially filled. This also prevents grinding parts metal-metal contact and reduces the wear which is formed during the mill is empty.

In airflow mode, internal material circulating load can be higher than 1000%. Airflow is produced by fan. In order to transfer materials from grinding zone up to the classifier zone, fan consumes power. Loesche vertical roller mills have reject material about 10% of the fresh feed. To keep this amount low, the design principle of the fan is bigger than the other type of vertical roller mills. Some of the other vertical roller mill manufacturers keep the airflow rate lower through the mill body in order to reduce energy consumption of fan. That causes higher amount of mill reject. On the other hand mechanical transportation of the material is much more energy efficient than the air conveying.

In airflow mode, higher internal circulation decreases the overgrinding. In addition to this, higher airflow rate increases the classification and drying efficiency in the mill.

2.2.2. Over Flow Mode

According to ore characteristics or coarser particle size requirements, it might be beneficial to change the classification operation. In order to achieve this, splitting grinding and classification unit operations is necessary.

In contrast to airflow mode, classification operation in the overflow mode takes place not in the mill body. The classification is not done in the mill body but in an external classifier. The classifier or classifiers (depending on the circuit design) are placed outside the mill body generally (if air classification) over the mill. The material is not transported by airflow. It is transporting by corresponding external mechanical conveying line from mill discharge to external classifier(s). An illustrative drawing of the mill body is given in Figure 2-13.

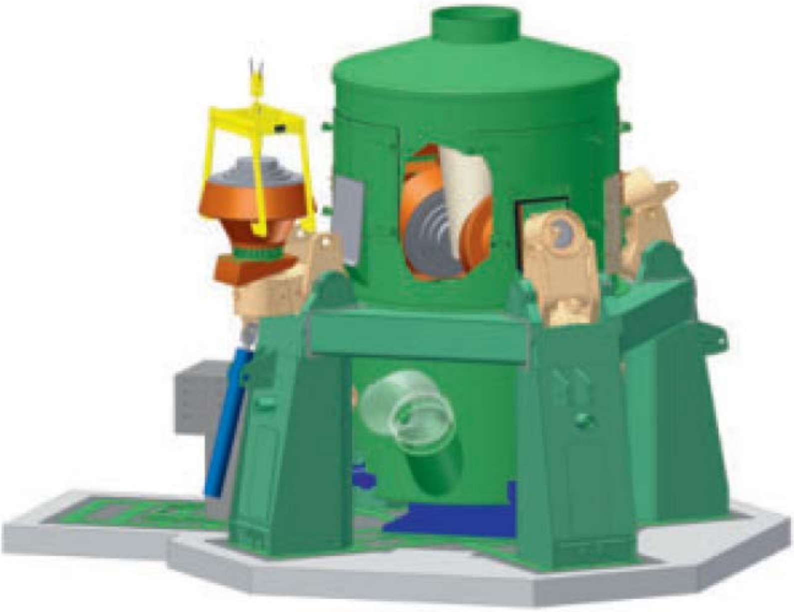

Figure 2-13. Loesche vertical roller mill (overflow) [7]

The material ground by the grinding rollers is conveyed by centrifugal force. Then material falls down to ring channel, is collected and taken out through the discharge chute. There is no louver ring in overflow mode.

In Figure 2-14, an illustrative overflow circuit is given. The fresh feed is fed by a belt conveyor (1); on this belt conveyor metal detector separates the metal foreign pieces by a diverter gate. The feed material is combined and fed to static classifier (LUS) (5) through reject belt (2), bucket elevator (3) and feed chute of static classifier (4), respectively. In the static classifier material is subjected to a rough separation operation, this classification is directly made by static plates and airflow which is generated by a fan (11). Relatively fines are subjected to dynamic classifier (8) and coarse particles falls down to mill (7). In the dynamic classifier the second step of the classification took place. The final fines are collected by filter (9) and coarse particles are goes to mill (7). The product is taken out the filter (9) is transferred to a product silo. Then the downstream processes can be fed regularly and homogenously. If necessary a hot gas generator (6) can be operated in order to dry the material.

This system also gives chances to fines already stay in the feed can be taken out as product.

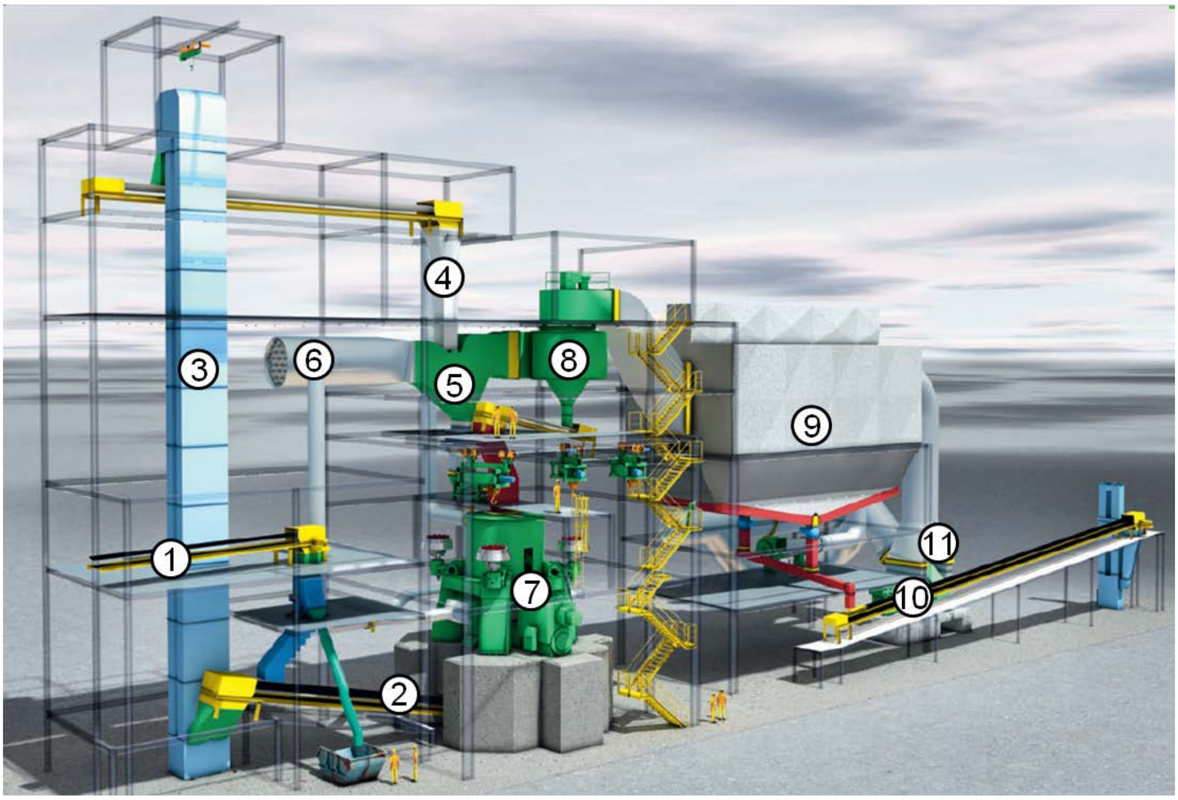

Figure 2-14. Over flow mode plant illustration [7]

Some overflow vertical roller mills were being used as pre-grinder on cement grinding circuits [12].

2.2.3. Pre-Grinding Mode

Vertical roller mills have been used as pre-grinders in order to increase capacity of the existing mill production. Pre-grinding vertical roller mills are nearly the same as over flow mode mills. Only the grinding portion of the mill is used as pre-grinding operation. There is no airflow or separator inside the mill. The purpose is to supply only coarse grinding. Some of the crushed material can be re-circulated both to balance the mill operation and crush any material that was by-passed. The use of vertical roller mills as pre-grinders can reduce the overall circuit energy consumption about 10% [13].

2.3. History and Development of Vertical Roller Mills

The origin of the roller grinding mills can be found in ancient age. The grinding tools were stones. A single or several grinding rollers combination was rolled on a circular grinding path. Grains and olives were the first ground materials. And probably these ancient roller mills have been used for grinding of minerals. Figure 2-15 shows an ancient single-roller mill was still in operation in Iraq in 1978. The grinding force is based on its own weight of grinding roller [10].

Figure 2-15. An ancient vertical roller mill [14]

In FIGURE, the basic design of a vertical roller mill has already shown. However during the 20th century the forms of roller grinding mills very varied. Certainly, they were first named by their inventors. Since August 1983 DIN 24 100, Part 2 “Mechanical Comminution: Machine Terminology” has given a standardized name “Roller Grinding Mill”. The definition:

> *“Machine in which the grinding surface is annular. Grinding bodies (rollers or balls) roll on it. The grinding bodies are pressed down on the grinding surface either by their own weight or by centrifugal force, by springs, or by hydraulic or pneumatic systems. Both the grinding surface and the grinding bodies may be driven”*

2.3.1. Mill Development

The industrial development started at the beginning of the 20th century in United States of America. In 1906 Curt von Gruber who had started the Loesche Mills’ development, had licences to build the Maxecon spring loaded roller mill (Figure 2-16) [15].

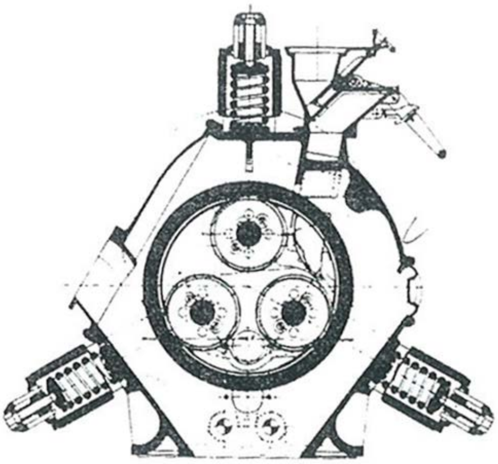

Figure 2-16. Maxecon mill [16]

The rollers are pressed outside of the ring against the inner surface by springs. One of the rollers is driven by a pulley. The grinding ring is also moved by friction. The achievable production rate is about 2-5t/h.

In the middle of first quarter of the 20th century, one of the biggest energy company BEWAG[2] were interested in installing bigger mills with higher capacity. Ernst Curt Loesche who was the director of Curt von Gruber Maschinenbauanstalt has acquired the licence for Raymond centrifugal ring roller mill (Figure 2-17). Each mill could grind 10-12 t/h raw coal for the power plant at the beginning. Then he has developed this meal and increased the capacity up to 50t/h.

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[2] BEWAG: Berliner Elektrizitätswerke (=Berlin Electricity Supplier Co.)

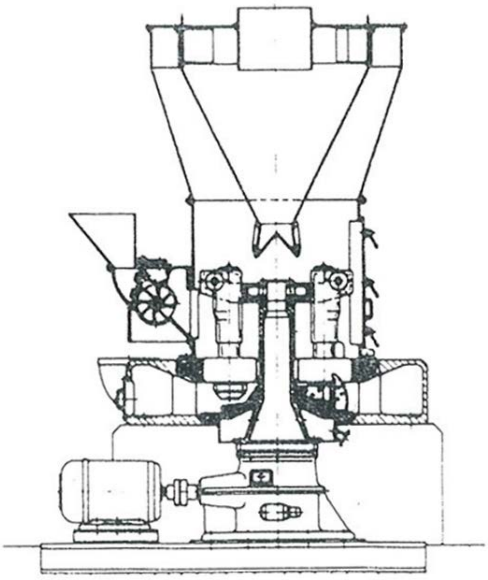

Figure 2-17. Raymond mill [16]

The centrifugal ring roller mills are classified as natural force mills [14]. The design was based on the fact of grinding forces were produced by centrifugal forces which has a direct effect on the rollers. The rollers were hanged like pendulum to a certain rotating support which is rotated by motor. This rotation causes centrifugal force on the roller which pushes the rollers against to inside of the ring.

The advantages of Maxecon spring loaded mill and the advantages of Raymond centrifugal ring roller mill were combined and the current vertical roller mills' mechanism developed. The experiences gained by these two types of mills give a unique opportunity to Loesche GmbH.

Ernst Curt Loesche has invented the Maximal mill (Figure 2-18) in 1925 after consideration of the knowledge and experience of the Maxecon and Raymond's mills. He has decided that the grinding surface should rotate. By the way, the raw material can be fed and carried under the rollers by centrifugal forces. Incidentally, this mill was the first mill which had a bowl type grinding surface.

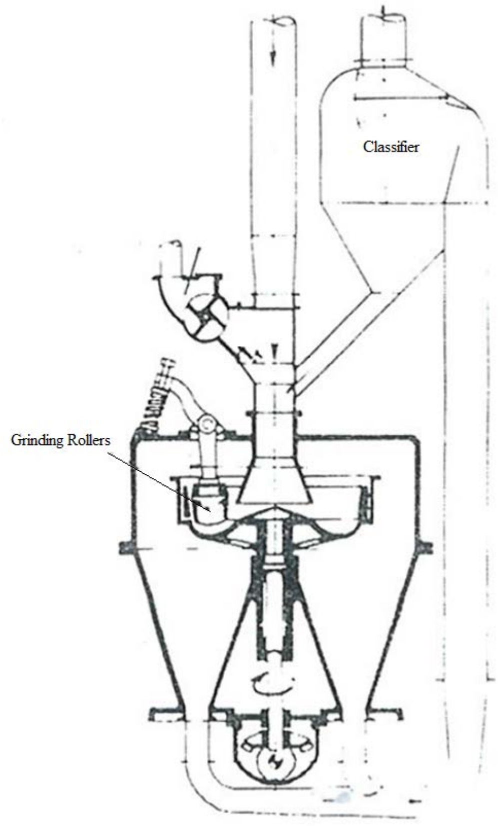

Figure 2-18. Maximal mill [16]

After Maximal they have designed and manufactured another mill (Figure 2-19) in 1927.

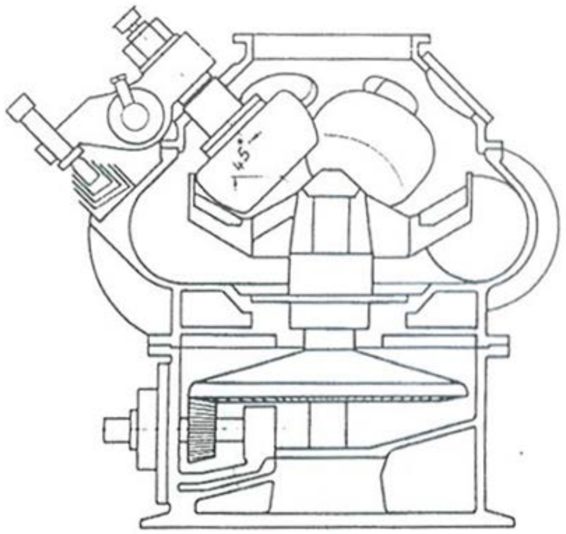

Figure 2-19. Mill 1927 [16]

Only 1 year later, the first Loesche Mill has been manufactured (Figure 2-20).

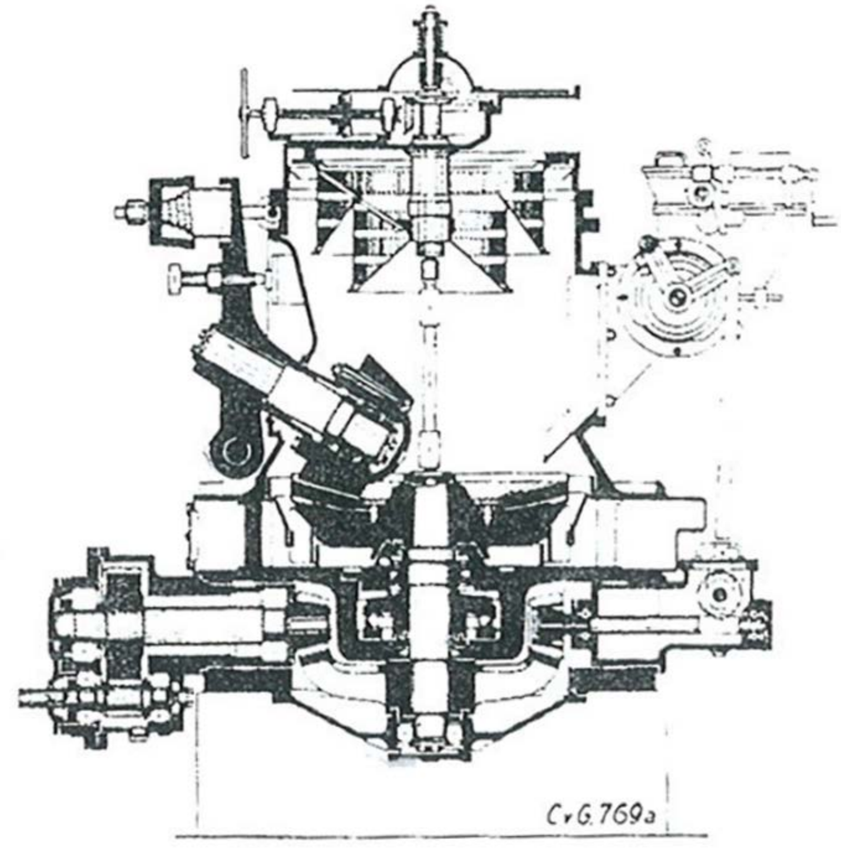

Figure 2-20. The first Loesche mill [16]

The grinding surface is flatter than the Roller Mill 1927. The main idea was increasing the roller diameter and use of the weight of the roller as an auxiliary grinding force.

Especially in the second half of the 20th century the big machine companies such as Gebr. Pfeiffer AG, Polysius and FL Smidth have decided to manufacture vertical roller mills.

Gebr. Pfeiffer AG has employed Siegfried Schauer who was a previous employee of Curt von Gruber, has combined the Loesche mill and MB mill together. The Pfeiffer MPS mill has three rollers. All three rollers are connected to a thrust frame by individual pivot connections. This redesigning of MB mill is known as Pfeiffer MPS mill since sixties. Figure 2-21 shows an illustration of MPS mill.

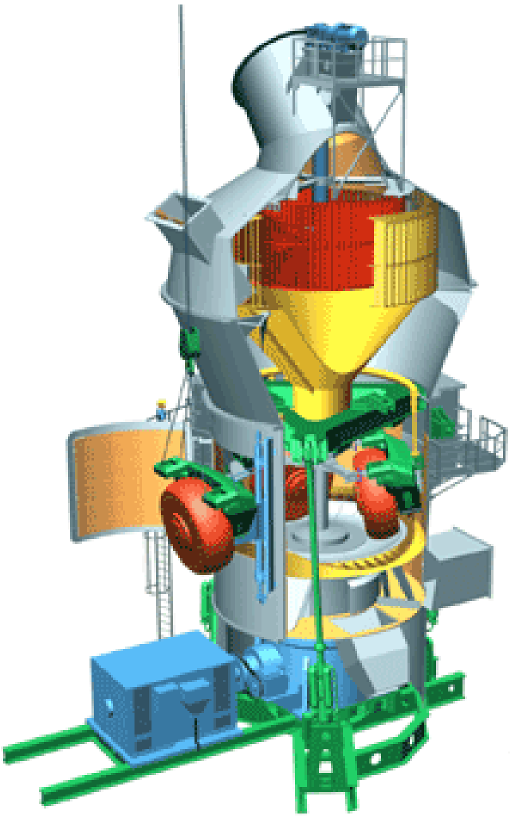

Figure 2-21. Pfeiffer MPS mill [17]

At the beginning of sixties Krupp acquired some licences for different type of vertical roller mills for the cement industry. The main concept is nearly the same with other vertical roller mills. Polysius[3] vertical roller mills have double roller concept and channel type grinding path. Figure 2-22 shows an illustration of Polysius vertical roller mill.

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[3] Polysius (Previously): Now held by Thyssen Krupp Industrial Solutions

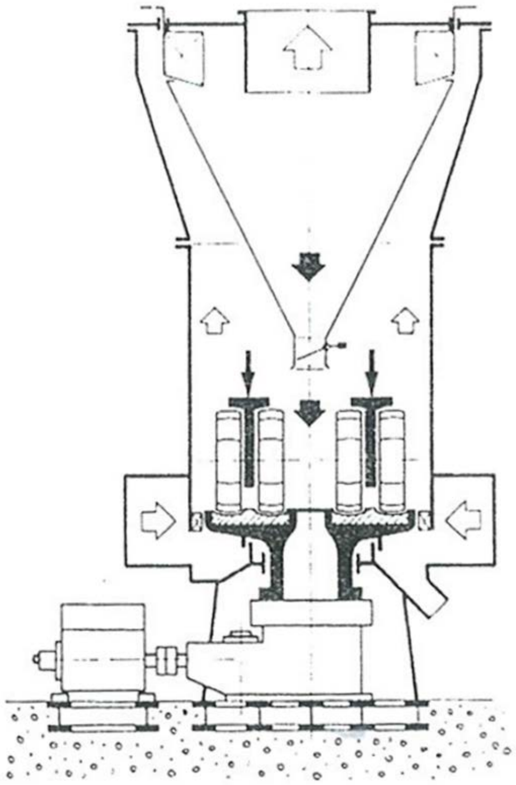

Figure 2-22. Polysius vertical roller mill [16]

For some years the Danish cement machine manufacturer FL Smidth used to manufacture MPS coal mills during their licence which has been rented from Pfeiffer for a limited time period by FL Smidth.

After the expiry of the MPS licence, FL Smidth has designed and manufactured their vertical roller mill. FL Smidth vertical roller mill is known as Atox mill (Figure 2-23).

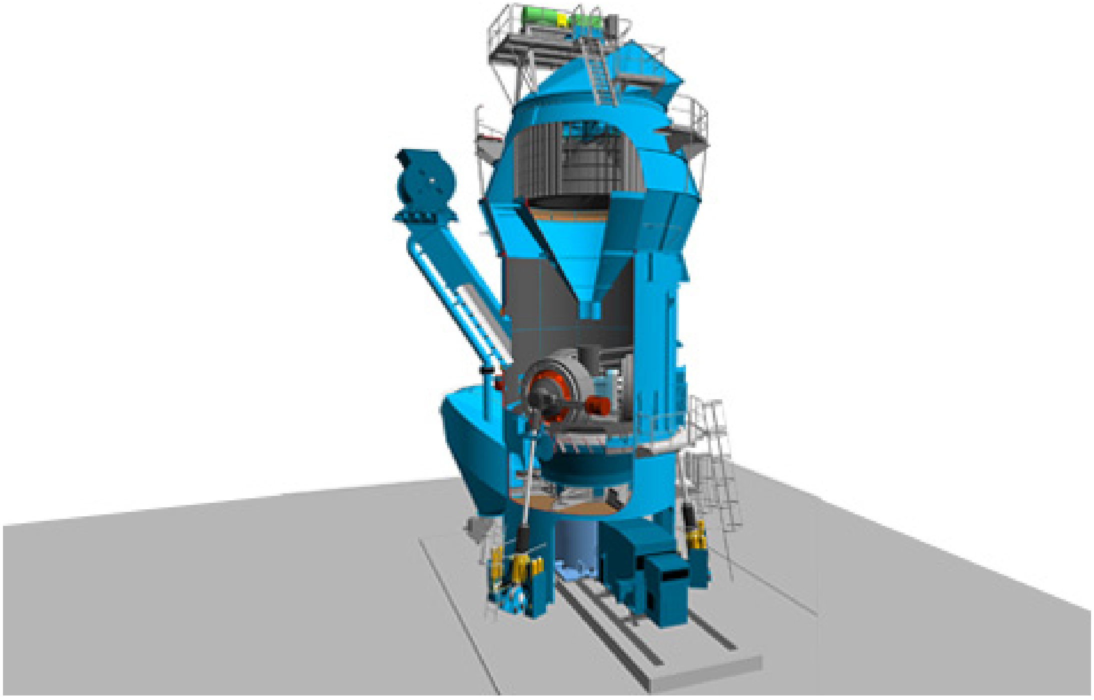

Figure 2-23. FL Smidth ATOX mill [18]

The three roller concept which is the main design phenomena of the MPS is kept for Atox mill. The centres of the rollers are connected in the middle of the mill. The roller shape is a perfect cylinder.

These are the well-known continuous vertical roller mills. There are also different types of Polish, China and Japan origin vertical roller mills.

2.3.2. Grinding Element Shapes Development

Grinding elements shapes have been developed since 1906. The geometrical design of the grinding elements affects directly the mill performance. Kinematic requirements are the main aspect on designing grinding elements.

One of the oldest one for the first mechanized vertical roller mills is Raymond mill. It is a ring roller type mill. The pivot point is higher than the rollers. In Raymond type of mills not the grinding table, only grinding rollers rotate. Raymond mill has perpendicular roller axle and grinding surface. Figure 2-24 shows a basic sketch of Raymond mills' roller ring layout.

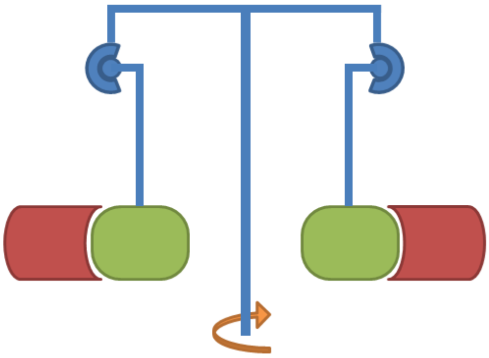

Figure 2-24. Raymond mill's roller ring layout [16]

In order to control the material flow and use the dead weight of the roller, the grinding surface (table) gets flatter. This type of concept is called as EVT[4] type. EVT type has elevated pivot point and conical grinding surface. Figure 2-25 shows a basic sketch of EVT type mill.

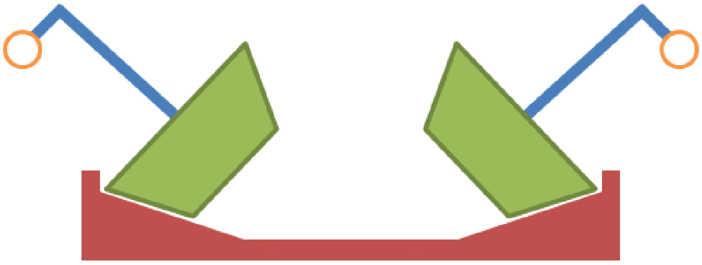

Figure 2-25. EVT type roller-table layout [16]

Loesche type rollers have been using since 1928. Rollers have a conical shape (Figure 2-26). As a consequent of this geometrical design Loesche mill can handle with feed material which has a top size of 5% of the roller mean diameter. In addition to this, more space is available for more rollers.

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[4] EVT was a German company which manufactures coal grinding mills

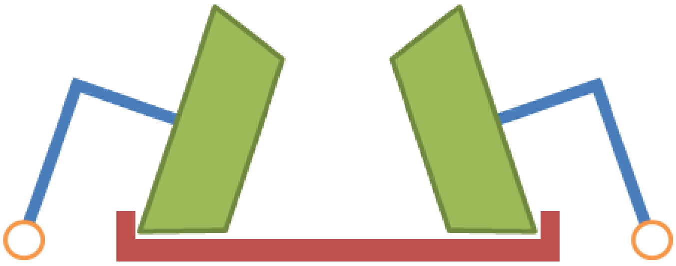

Figure 2-26. Loesche type roller table layout [16]

As mentioned before shear forces can be controlled by changing the geometry (=angle) of the roller.

MPS roller type was first used in the middle of sixties. There are overhead joints between rollers' arm and thrust frame. For the grinding surface; tracking groove guide system is reduces the wear and shear forces. Also the grinding rollers are hemispherical. Figure 2-27 shows a basic sketch of MPS mill.

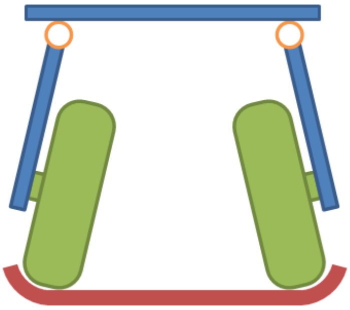

Figure 2-27. MPS type roller table layout [16]

There are many type of grinding elements being used in vertical roller mills. The mentioned types are the most popular and critical types.

The spherical shape of the roller tyre enables it to be reused by turning it over. Some vertical roller mills have groove for preventing vibration to its surfaces subject to pressure. The gap between the table and roller is kept to nip materials easily and securely [19].

2.4. Advantages and Disadvantages of Vertical Roller Mills

Vertical roller mills have been generally used to grind coal, cement raw meal, clinker, blast furnace slag. By the light of mechanical developments and finer product requirements of ore industry, vertical roller mills are getting more and more important position in the industry. In ore industry, the main consideration points are energy consumption, availability, process recovery and operability of the equipment.

Vertical roller mill is used for dry grinding. It can handle with up to 25% moisture by a hot gas generator. The product is dry and it is quite easy to regulate the solid content of the downstream process. Generally the downstream process's (such as leach, flotation, etc.) solid content has a big influence on overall recovery. Hence it is a dry grinding operation there is no need to add extra water to the system. This system also saves water.

Galvanic interaction of steel grinding media has an adverse effect on downstream process recovery. In bed comminution galvanic interaction is also reduced. The comminution in vertical roller mill is mostly autogenously [20].

For vertical roller mills, feed top size is a big advantage. The rollers can nip coarser particles. For rod milling the feed size is about 20-30mm (depends on mill design). But for Loesche vertical roller mills top size is only limited by 5% of roller diameter. Vertical roller mills can nip particles up to 80-120mm. That means tertiary crushing can be eliminated. On the other way, the crushing capacity will be increased and wear on crushing & screening equipment will be decreased.

Coarse particles which are in the feed of the vertical roller mill have a positive effect on stabilized grinding bed. Both fine and coarse materials enable the stabilized bed [20].

The hydro-pneumatic system allows adjustment for grinding pressure in order to cope with fluctuations of ore characteristics e.g. particle size distribution, hardness, moisture content etc. [6].

The ground product can be stored in silos which provide an opportunity to use the ground material in the silos as buffer material in case of raw material supply line problems. Downstream process can continue [6].

The compact design of airflow vertical roller mills need smaller footprint (the classifier is integrated directly on mill body). Higher circulating loads and ultra-efficient air classifiers give opportunity in order to have steeper particle size distributions while preventing over grinding. Steep particle size distribution has a positive effect on most of the downstream process of ore industry.

Since the material is being transported through the mill by airflow which is generated by a fan; the fan energy consumption might be high. In order to reduce the fan power mechanical material transportation can be applied as in overflow mode. The material is transported by bucket elevators or belt conveyors to classifier levels. This application reduces the fan energy consumption.

If necessary, the product can be produced with wide particle size distribution. Some operational settings and sometimes small mechanical modifications can easily be effective on particle size distribution.

Since mostly autogenous grinding takes place, the wear rates are less than conventional grinding circuits. It also reduces the downtime. Less wear rates, means more availability. For 4 and 6 roller systems opposite rollers can be swung out and the grinding rollers can be changed while the mill is still running (50-60% capacity)

On vertical roller mills, it is easy to control the fineness by operational parameters. The response time is very short and system stabilization is quite simple. The pressure difference through the mill gives identification about how full the mill is. The operability is also simple, when the pressure difference is being kept constant the throughput can be set by automatically.

Taberlet, N. et all. [21] have made some research studies on dynamics of granular surfaces under rolling wheels at University of Cambridge. They have found that granular surfaces tend to develop lateral ripples under the action of surface forces produced by rolling wheels [21]. That causes vibration on vertical roller mills' grinding table. To prevent this, Loesche's patented master-support roller design can be applied. Support rollers regulate the grinding bed by pre-compression and prevent the ripple formation.

For conventional grinding systems, most of the energy transforms to heat, vibration, sound, wear on grinding media and etc. Since the vertical roller mills have mostly autogenous grinding, the heat, sound and wear levels can be kept lower. The mill motor energy consumption is quite efficient in compression with conventional grinding systems.

The research work of Anglo American Research Laboratory in Johannesburg, South Africa, showed that the grade-recovery can be significantly improved when the material ground by vertical roller mill [6].

3. EXPERIMENTAL STUDIES

The research studies were held at a mobile ore grinding plant which belongs to Loesche GmbH. Test work was aimed to investigate the effect of operational parameters on vertical roller mills' performance. On the light of this aim; effect of dam ring height (design parameter), effect of grinding load, effect of classifier rotor speed, effect of airflow rate and effect of mill differential pressure have been investigated. In addition to these, wear measurements were also taken into consideration.

Test work was conducted for different operational parameters. In addition to this, effect of dam ring height was also taken into consideration.

3.1. Mobile Ore Grinding Plant

Loesche GmbH's Ore Process Technology and Research & Development departments have designed and manufactured a mobile ore grinding plant (OGPmobile). A general view of the OGPmobile is shown in Figure 3-1.

Figure 3-1. OGPmobile

This plant consists of three 40 ft. high cube sea containers. A vertical roller mill (LM4,5.4[5]) with integrated dynamic classifier (LSKS[6] 6) and for overflow mode; static (LUS[7]) and dynamic classifiers (external LSKS 6) and conveying equipment and a small laboratory were located in two containers. The other container has central control room (CCR), process control system and workshop. An illustrative 3D sketch is shown in Figure 3-2.

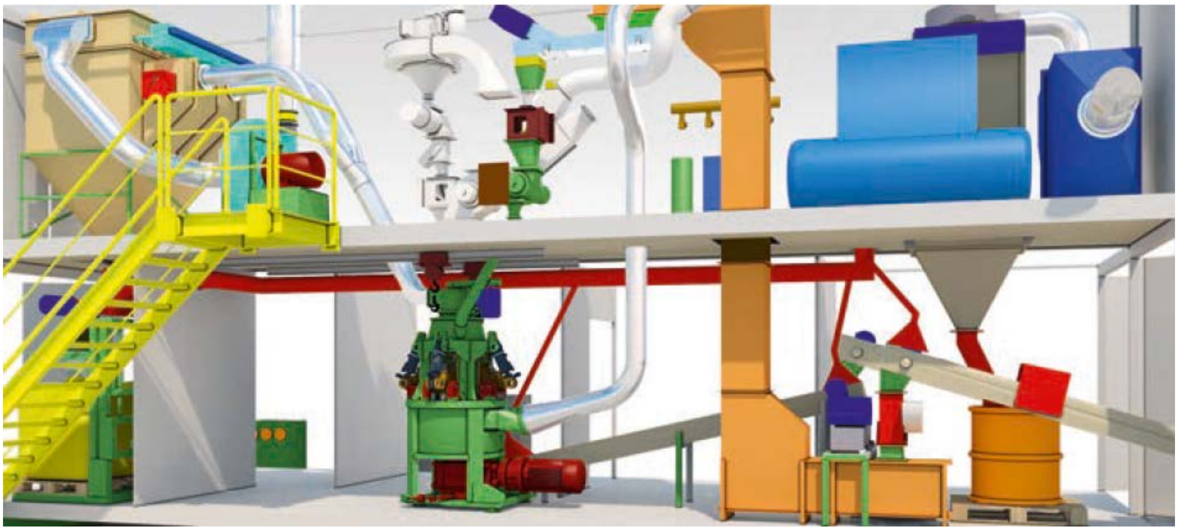

Figure 3-2. A cross-section of OGPmobile [22]

Photos of LM4,5.4 vertical roller mill in OGPmobile is given in Figure 3-3

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[5] LM represents for Loesche Mill; 4,5 represents for table diameter of 4,5 decimeter; .4 represents for 4 rollers.

[6] LSKS represents for Loesche Stabkorb Sichter (=Loesche Bar Cage Classifier).

[7] LUS represents for Loesche U Sichter (=Loesche U Classifier); U represents for the shape of the static flaps inside the static classifier.

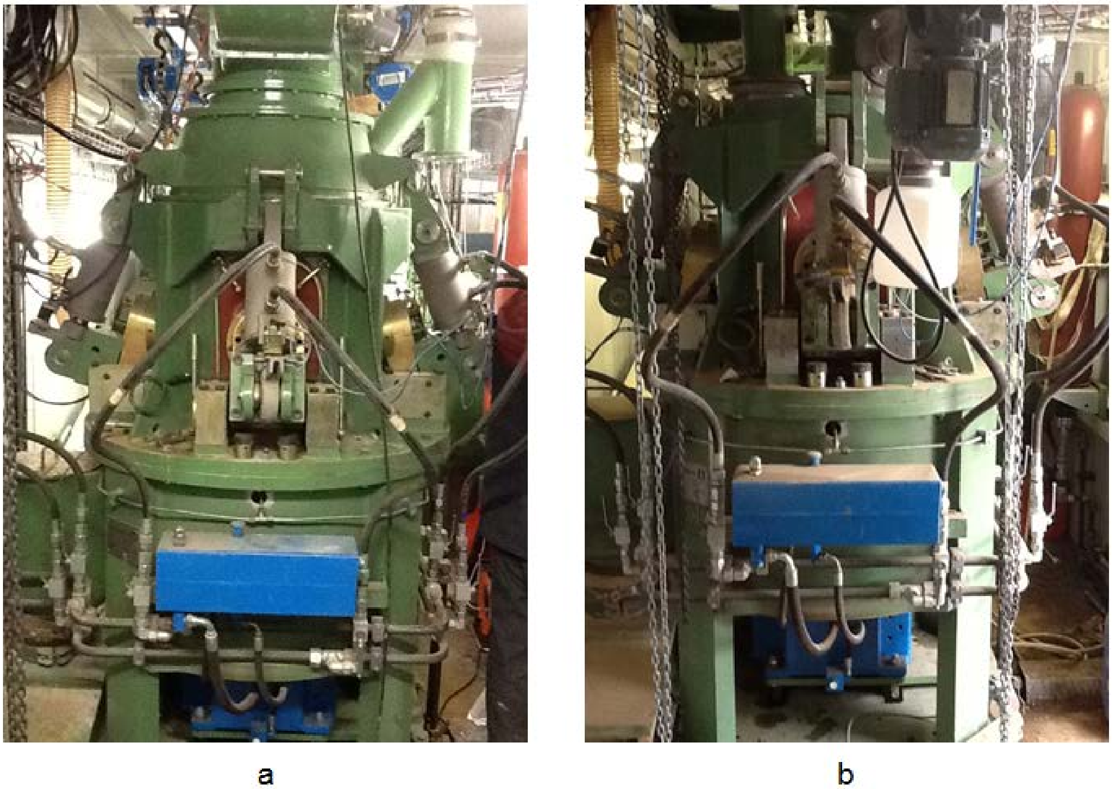
a
b

Figure 3-3. LM 4,5.4 in OGPmobile a)air swept; b)overflow

This containerized mobile plat is designed for carrying on research and development studies on vertical roller mills in ore industry directly on site. Vertical roller mills are quite fresh in ore industry only a couple of application is working for now.

Technical specifications of the OGPmobile are given in Table 3.1.

Table 3.1. Technical specifications of OGPmobile

Specification	***Unit***	***Description***
Installed Power	*kW*	*420 (300 is only for heaters)*
Nominal Capacity	*kg/h*	*940*[8]
Maximum Capacity	*kg/h*	*3000*
Nominal Volumetric Airflow Rate	m^3/h	*2500*
Maximum Volumetric Airflow Rate	m^3/h	*5000*
Dust Emission	mg/m^3	*<20*
Grinding Modes	-	*Air swept & Overflow*
Rocker Arm & Roller Design	-	*Shear & Shear Free*

3.1.1. Operational Parameters

Grinding pressure, classifier rotor speed, airflow rate, mill differential pressure and grinding table speed are main operational parameters.

Industrial vertical roller mills are mechanically limited by 1100kN load. But OGPmobile is designed for 5000kN grinding load. Further research studies are being carried on in order to apply more grinding force in industrial vertical roller mills. Grinding pressure is an operational parameter which defines the comminution energy. Grinding load and no load (without material) main mill motor mechanical power draw relation is given in Figure 3-4.

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[8] Depending on material properties and product requirements.

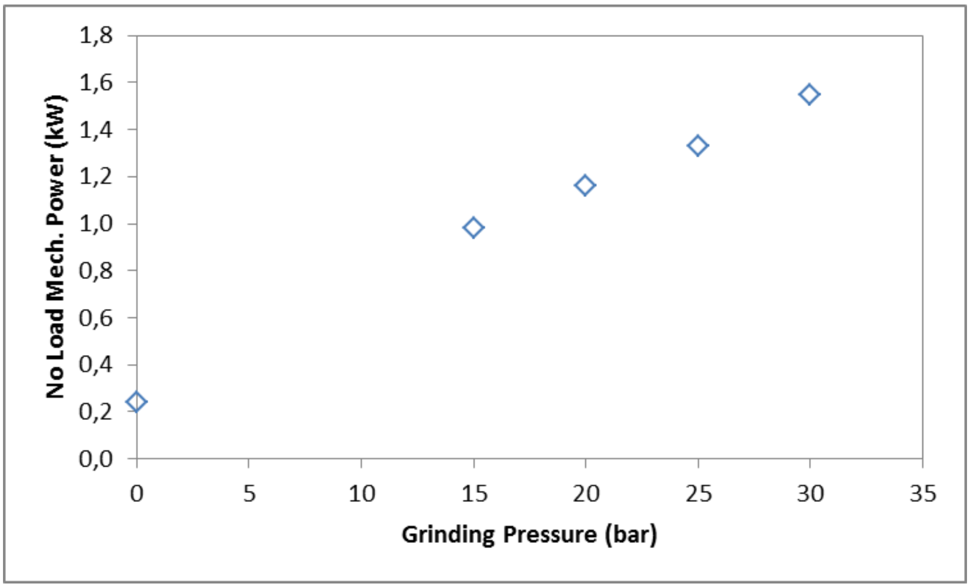


Figure 3-4. Mill main motor power draw for 84rpm.

Also the effect of grinding table speed on mechanical power draw of the mill main motor is given in Figure 3-5.

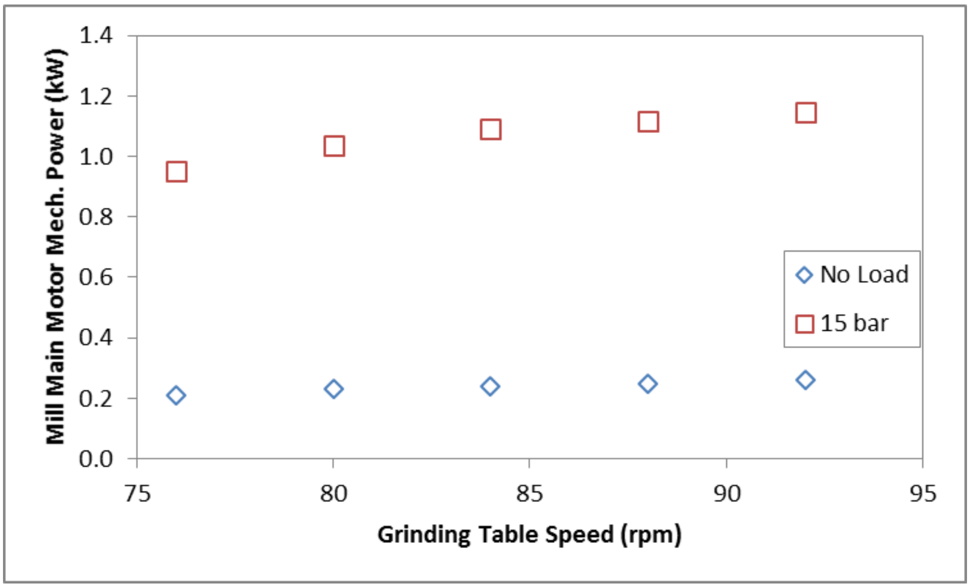


Figure 3-5. Mill main motor power draw - table speed relation

Airflow rate is the volumetric amount of air which passes through the mill. It must be capable to transport the ground material to classifier. Loesche vertical roller mills are designed for reject amount of 10% of fresh feed (which cannot be transported to classifier). Airflow rate and classifier rotor speed are the main parameters in order to regulate the fineness.

Mill differential pressure can be defined as pressure drop through the mill. This parameter is related with airflow rate, classifier rotor speed, dam ring height, temperature, barometric pressure, material amount inside the mill. Classifier rotor speed and dam ring height have the minimum effect on differential pressure. If no load (without material) differential pressure is kept constant, differential pressure is an indicator of the material load inside the mill.

Effect of classifier rotor speed on no load mill differential pressure for different airflows is shown in Figure 3-6. Dam ring height is 21mm and the mill outlet temperature is 90°C.

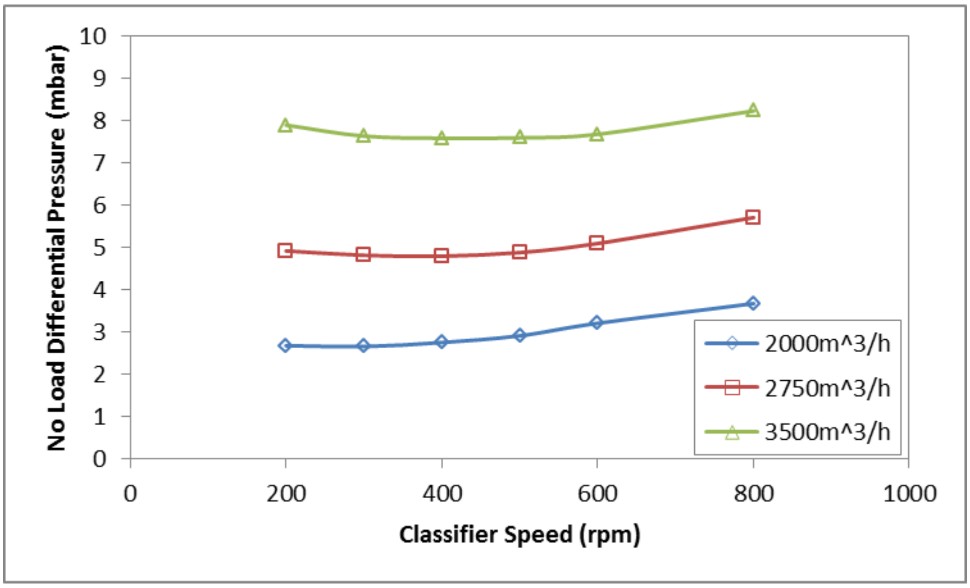


Figure 3-6. No load mill differential pressure for different airflow rates

Effect of dam ring height on no load mill differential pressure for different dam ring heights is shown in Figure 3-7. Airflow rate is 2750m^3/h and the mill outlet temperature is 90°C.

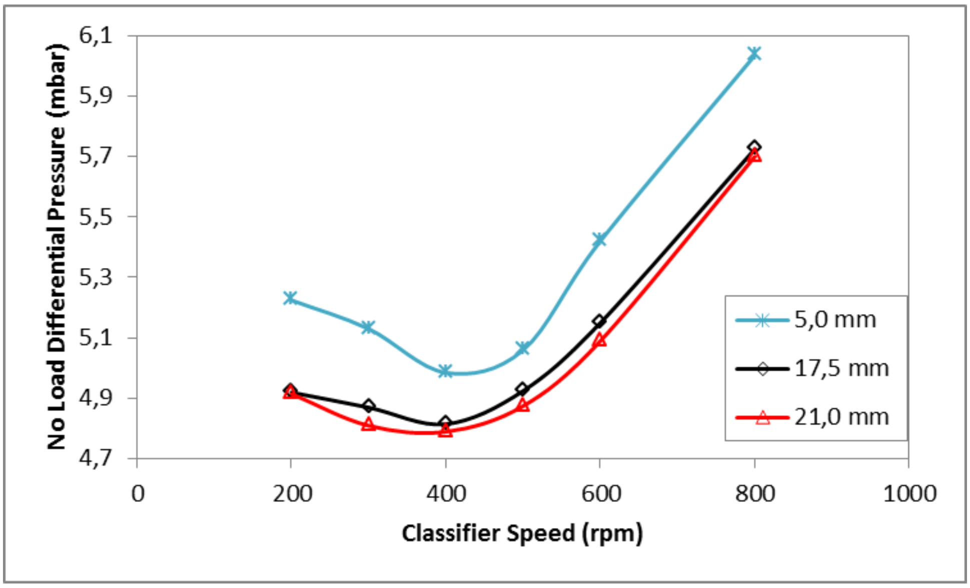


Figure 3-7. No load mill differential pressure for different dam ring heights

Effect of mill outlet temperature on no load mill differential pressure for different dam ring heights is shown in Figure 3-8. Airflow rate is 3500m^3/h, with 5mm dam ring and 300rpm classifier rotor speed.

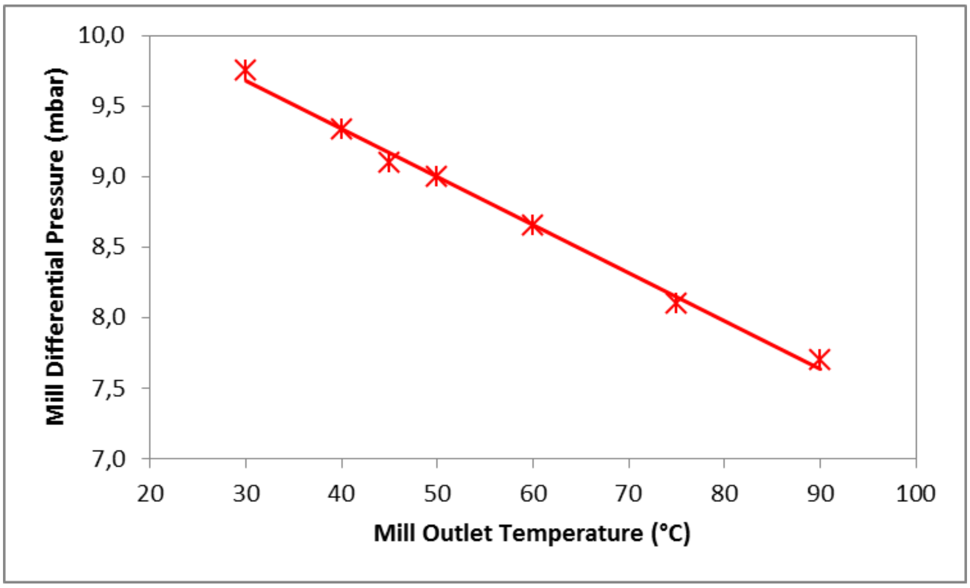


Figure 3-8. No load mill differential pressure for different mill outlet temperatures

For industrial applications, grinding table speed is generally kept constant. Previous in house research works shows that grinding table speed parameter has the minimum effect on vertical roller mills’ performance.

3.1.2. Design Parameters

Dam ring height, louver ring angle and roller type (shear/non-shear) are main design parameters which are relatively easy to set. In this study, only the effect of dam ring height is investigated.

Dam ring can be defined as a wall at the edge of the grinding table. This wall tries to keep the material on the grinding table. Theoretically, higher dam ring keeps more material on the table which has a positive effect on bed stabilization as well. Actually it also increases the over grinding if the target product size is coarser. In addition to these, the higher dam ring higher amount of material in grinding zone; that means the retention time is also increases by increasing dam ring height. Photos of dam ring are given in Figure 3-9 (a: 5mm dam ring; b: 13mm dam ring).

Figure 3-9. LM 4,5.4 inside

Louver ring consists of several static guide flaps which guide the airflow around the table and on the wall of mill body. Lower louver ring angle is increases the length of airflow path inside the mill. Flatter louver ring increases the time of air transportation inside the mill which increases the drying efficiency. On the other hand, steeper louver ring is essential for coarser products as the ground material should be transported directly to classifier.

OGPmobile has two different rocker arm designs. One of them is with shear forces, the other one is without shear forces (Section: 2.1.3 Shear Forces). Shear rollers' dimensions are 210mm x 64mm (Figure 3-10 a); 15°. Shear free rollers' dimensions are 190mm x 58mm; 27° (Figure 3-10 b).


a

b

Figure 3-10. Shear (a) and shear-free (b) rollers for LM 4,5.4

3.1.3. Instrumentation and Control System

In this section, control system and main instrumentation of the OGPmobile is explained briefly. The system is fully automatic and each data related with the grinding plant can be observed instantaneous in the CCR. A photo of CCR is given in Figure 3-11.

Figure 3-11. OGPmobile control room

By using automation software, each operational parameter and output values collected from the OGPmobile can be stored in database. A screenshot of the software is given in Figure 3-12.

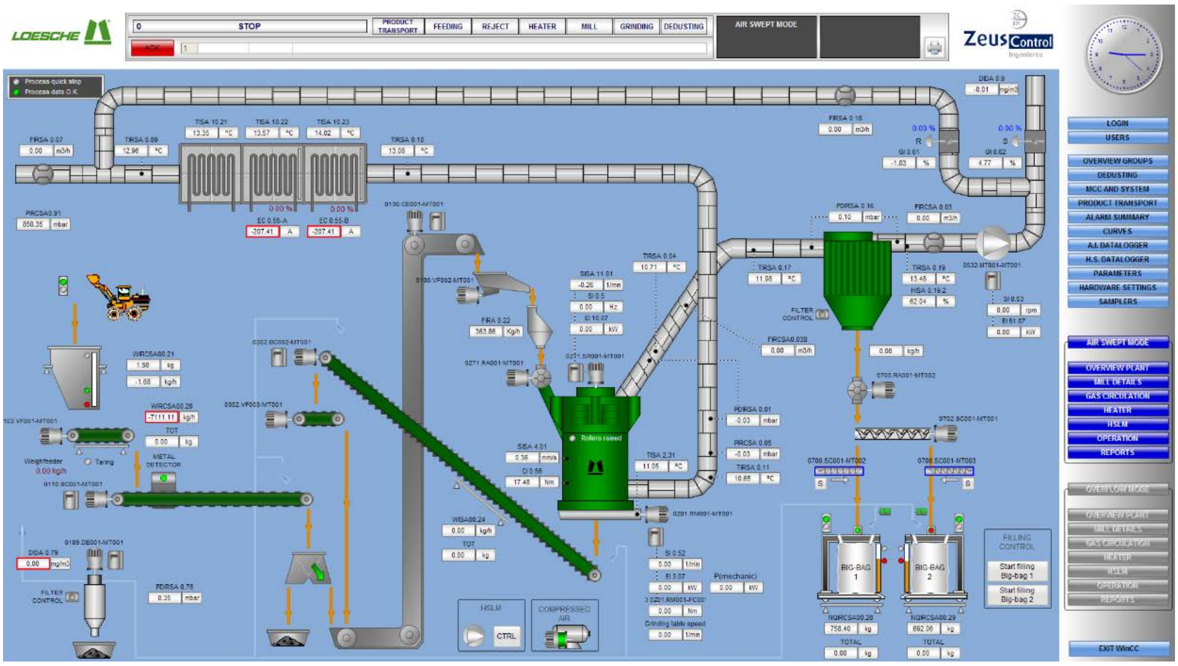


Figure 3-12. A screenshot of automation system

There are two different concepts for measuring the power draw of the main mill motor. One of them is conventional power draw which includes electrical losses etc. The other one is mechanical power draw which is a calculated value. A load cell is attached (Figure 3-13) at the end of a bar which is fixed on the motor standing.

Figure 3-13. Load cell to calculate torque

The length of the bar is known and load cell measures the mass which is created by motor torsion. Then the torque on the table can be calculated easily.

$$F = m \times a \quad (3.1)$$

F : Load applied by motor

m : Mass reading on load cell

a : Acceleration (gravity)

$$\tau = r \times F \quad (3.2)$$

τ : Torque

r : Distance between centre of shaft and centre of load cell

$$P = \tau \times 2\pi \times \omega \quad (3.3)$$

P : Power

ω : Angular velocity

To compare results and scale-up studies mechanical power is used. Because the main mill motor is over designed as well as fan motor. That is why fan power is not considered in this study.

Feed and reject mass flow rates are measured by belt scales which manufactured by Spanish ATD Systemas™. The mill total feed is measured by an impact mass flow meter which is called Rembe© is produced by Rembe™. Product mass flow is measured by 4 load cells under big bag platform. The software calculates the mass difference with respect to time.

Differential pressures are measured by DP sensors which is called PTSXR. And the airflow rates are measured by Wilson-Staugitter type flow meters which have DP sensors (PTSXR) and transmitter. An illustrative sketch is shown in Figure 3-14.

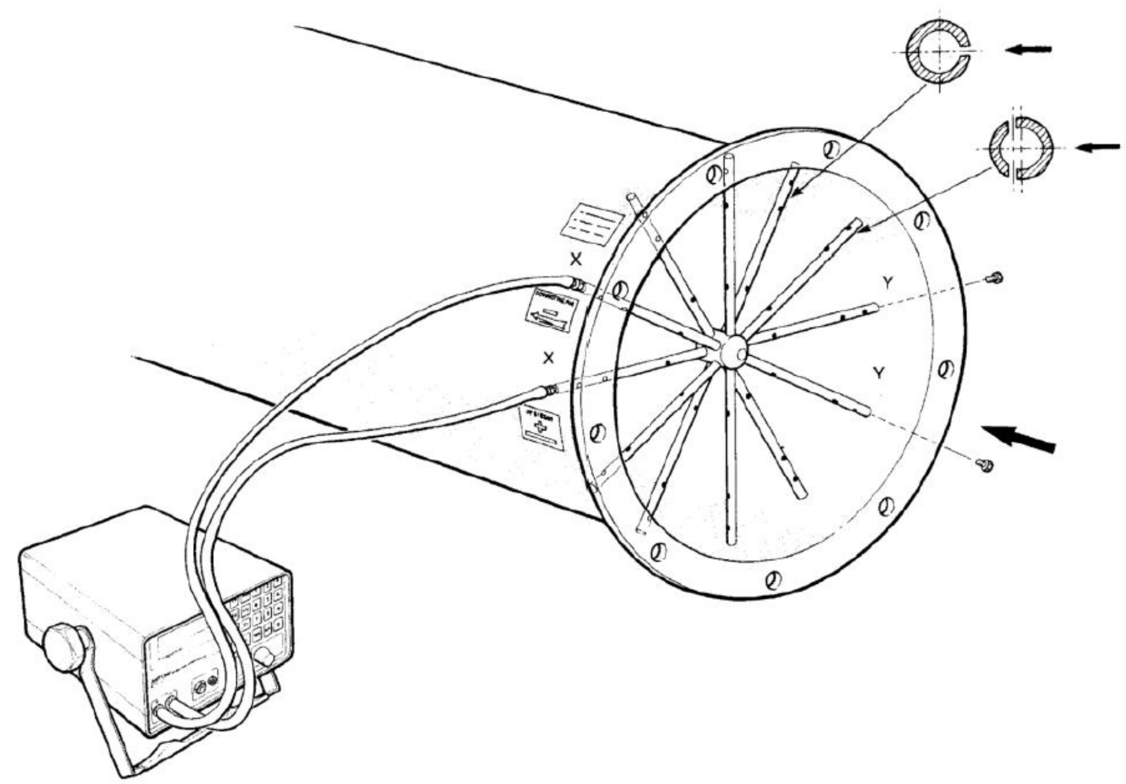


Figure 3-14. Wilson-Staugitter type flow meter [23]

Air flow is the main transfer energy for material transportation.

The air swept mode has an internal control loop with feedback signal. The loop is integrated between feeder and mill differential pressure measurement. Feeder is set by PLC (Programmable Logic Control) circuit in order to keep the mill differential pressure (ΔP Mill) at a certain point which is defined before testing. A diagram of the control loop is given in Figure 3-15.

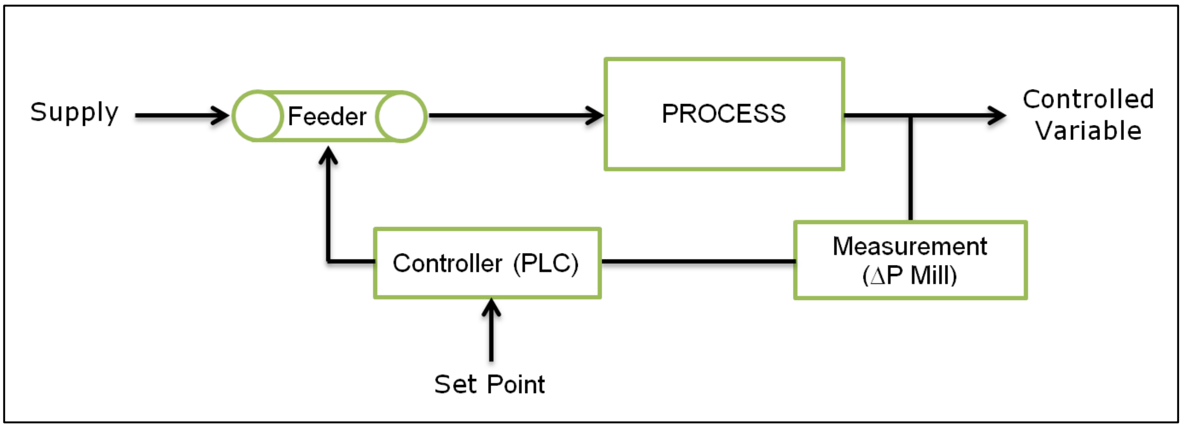


Figure 3-15. Control loop flow chart

3.2. Test Procedure

Test procedure can be defined as, first the mobile ore grinding plant is started without material, the system is heated up to 90°C in order to get rid of moisture, and then the feed material is fed to the system up to a certain differential pressure during test work all the main data trends are observed. After the whole plant gets stabilized, the system is kept running for 15 minutes more. Then the final check of the data trends is made. If the system is still stable, the reporting option of the software is used. The duration of the reporting can be arranged due to conditions. Generally the reporting is set for 5-7 minutes. Each data is taken every second and is taken into calculation of average and standard deviation.

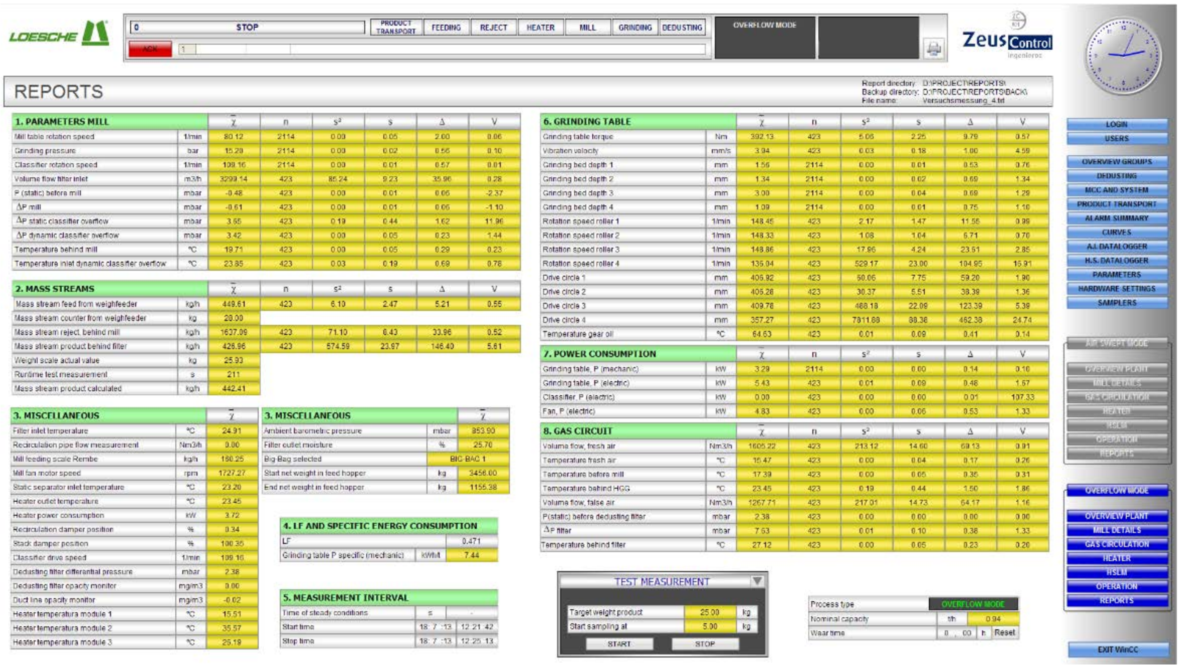
On this report page;

- Mill Parameters
    - Table speed
    - Grinding pressure
    - Classifier rotor speed
    - Volumetric air flow rate
    - Static pressure before mill
    - Differential pressure (ΔP) of the mill
    - Temperature behind mill
    - Load factor
    - Grinding table P specific (mechanic)

- Energy consumption
    - Grinding table P (mechanic)
    - Grinding table P (electric)
    - Classifier P (electric)
    - Fan P (electric)
- Mass Flows
    - Mass flow feed from belt scale
    - Counter of belt scale
    - Mass flow of reject
    - Mass flow product
- Grinding Table
    - Torque
    - Vibration
    - Grinding bed of all rollers
    - Rotation speed of all rollers
    - Drive circle of all rollers
    - Gearbox oil temperature
- Gas Circuit
    - Volumetric flow rate of fresh air
    - Temperature of fresh air
    - Temperature before mill
    - Temperature after heaters
    - Volumetric flowrate of false air
    - P (static) before dedusting filter
    - Differential pressure of filter
    - Temperature behind filter
- Miscellaneous
    - Filter inlet temperature
    - Recirculation line air flowrate
    - Mill feeding scale (rembe)
    - Mill fan motor speed
    - Heater energy consumption
    - Recirculation damper position
    - Stack damper position

- o Classifier drive spped
- o Dedusting differential pressure
- o Duct line dust measurement

A screen shot of reporting section is given in Figure 3-16.



Report directory: D:\PROJECT\REPORTS\
Backup directory: D:\PROJECT\REPORTS\BACK\
File name: Versuchsmessung_4.txt

1. PARAMETERS MILL		$\bar{\chi}$	n	s^2	s	Δ	V
Mill table rotation speed	1/min	80.12	2114	0.00	0.05	2.00	0.06
Grinding pressure	bar	15.20	2114	0.00	0.02	0.56	0.10
Classifier rotation speed	1/min	109.16	2114	0.00	0.01	0.57	0.01
Volume flow filter inlet	m3/h	3299.14	423	85.24	9.23	35.96	0.28
P (static) before mill	mbar	-0.48	423	0.00	0.01	0.06	-2.37
ΔP mill	mbar	-0.61	423	0.00	0.01	0.06	-1.10
ΔP static classifier overflow	mbar	3.65	423	0.19	0.44	1.62	11.96
ΔP dynamic classifier overflow	mbar	3.42	423	0.00	0.05	0.23	1.44
Temperature behind mill	°C	19.71	423	0.00	0.05	0.29	0.23
Temperature inlet dynamic classifier overflow	°C	23.85	423	0.03	0.19	0.69	0.78

2. MASS STREAMS		$\bar{\chi}$	n	s^2	s	Δ	V
Mass stream feed from weighfeeder	kg/h	449.61	423	6.10	2.47	5.21	0.55
Mass stream counter from weighfeeder	kg	20.00					
Mass stream reject, behind mill	kg/h	1637.09	423	71.10	8.43	33.96	0.52
Mass stream product behind filter	kg/h	426.96	423	574.59	23.97	146.40	5.61
Weight scale actual value	kg	25.93					
Runtime test measurement	s	211					
Mass stream product calculated	kg/h	442.41					

3. MISCELLANEOUS		$\bar{\chi}$
Filter inlet temperature	°C	24.91
Recirculation pipe flow measurement	Nm3/h	0.00
Mill feeding scale Rembe	kg/h	180.25
Mill fan motor speed	rpm	1727.27
Static separator inlet temperature	°C	23.20
Heater outlet temperature	°C	23.45
Heater power consumption	kW	3.72
Recirculation damper position	%	0.34
Stack damper position	%	100.35
Classifier drive speed	1/min	109.16
Dedusting filter differential pressure	mbar	2.38
Dedusting filter opacity monitor	mg/m3	0.00
Duct line opacity monitor	mg/m3	-0.02
Heater temperature module 1	°C	15.51
Heater temperature module 2	°C	35.57
Heater temperature module 3	°C	25.19

3. MISCELLANEOUS		$\bar{\chi}$
Ambient barometric pressure	mbar	853.90
Filter outlet moisture	%	25.70
Big-Bag selected		BIG-BAG 1
Start net weight in feed hopper	kg	3456.00
End net weight in feed hopper	kg	1155.38

4. LF AND SPECIFIC ENERGY CONSUMPTION		
LF		0.471
Grinding table P specific (mechanic)	kWh/t	7.44

5. MEASUREMENT INTERVAL		
Time of steady conditions	s	-
Start time	18 : 7 : 13	12 : 21 : 42
Stop time	18 : 7 : 13	12 : 25 : 13

6. GRINDING TABLE		$\bar{\chi}$	n	s^2	s	Δ	V
Grinding table torque	Nm	392.13	423	5.06	2.25	9.79	0.57
Vibration velocity	mm/s	3.94	423	0.03	0.18	1.00	4.59
Grinding bed depth 1	mm	1.56	2114	0.00	0.01	0.53	0.76
Grinding bed depth 2	mm	1.34	2114	0.00	0.02	0.69	1.34
Grinding bed depth 3	mm	3.00	2114	0.00	0.04	0.69	1.29
Grinding bed depth 4	mm	1.09	2114	0.00	0.01	0.75	1.10
Rotation speed roller 1	1/min	148.45	423	2.17	1.47	11.55	0.99
Rotation speed roller 2	1/min	148.33	423	1.08	1.04	6.71	0.70
Rotation speed roller 3	1/min	148.86	423	17.96	4.24	23.51	2.85
Rotation speed roller 4	1/min	135.04	423	529.17	23.00	104.95	15.91
Drive circle 1	mm	405.92	423	60.06	7.75	59.20	1.90
Drive circle 2	mm	405.28	423	30.37	5.51	38.39	1.36
Drive circle 3	mm	409.76	423	488.18	22.09	123.39	5.39
Drive circle 4	mm	357.27	423	7811.68	88.38	462.38	24.74
Temperature gear oil	°C	64.63	423	0.01	0.09	0.41	0.14

7. POWER CONSUMPTION		$\bar{\chi}$	n	s^2	s	Δ	V
Grinding table, P (mechanic)	kW	3.29	2114	0.00	0.00	0.14	0.10
Grinding table, P (electric)	kW	5.43	423	0.01	0.09	0.48	1.57
Classifier, P (electric)	kW	0.00	423	0.00	0.00	0.01	107.33
Fan, P (electric)	kW	4.83	423	0.00	0.06	0.53	1.33

8. GAS CIRCUIT		$\bar{\chi}$	n	s^2	s	Δ	V
Volume flow, fresh air	Nm3/h	1605.22	423	213.12	14.60	69.13	0.91
Temperature fresh air	°C	15.47	423	0.00	0.04	0.17	0.26
Temperature before mill	°C	17.39	423	0.00	0.05	0.35	0.31
Temperature behind HGG	°C	23.45	423	0.19	0.44	1.50	1.86
Volume flow, false air	Nm3/h	1267.71	423	217.01	14.73	64.17	1.16
P(static) before dedusting filter	mbar	2.38	423	0.00	0.00	0.00	0.00
ΔP filter	mbar	7.63	423	0.01	0.10	0.38	1.33
Temperature behind filter	°C	27.12	423	0.00	0.05	0.23	0.20

TEST MEASUREMENT

Target weight product	25.00	kg
Start sampling at	5.00	kg

Process type	OVERFLOW MODE			
Nominal capacity	t/h	0.94		
Wear time	0 , 00	h	Reset	

Figure 3-16. Report section screenshot

A stable condition trends screenshot is given in Figure 3-17.

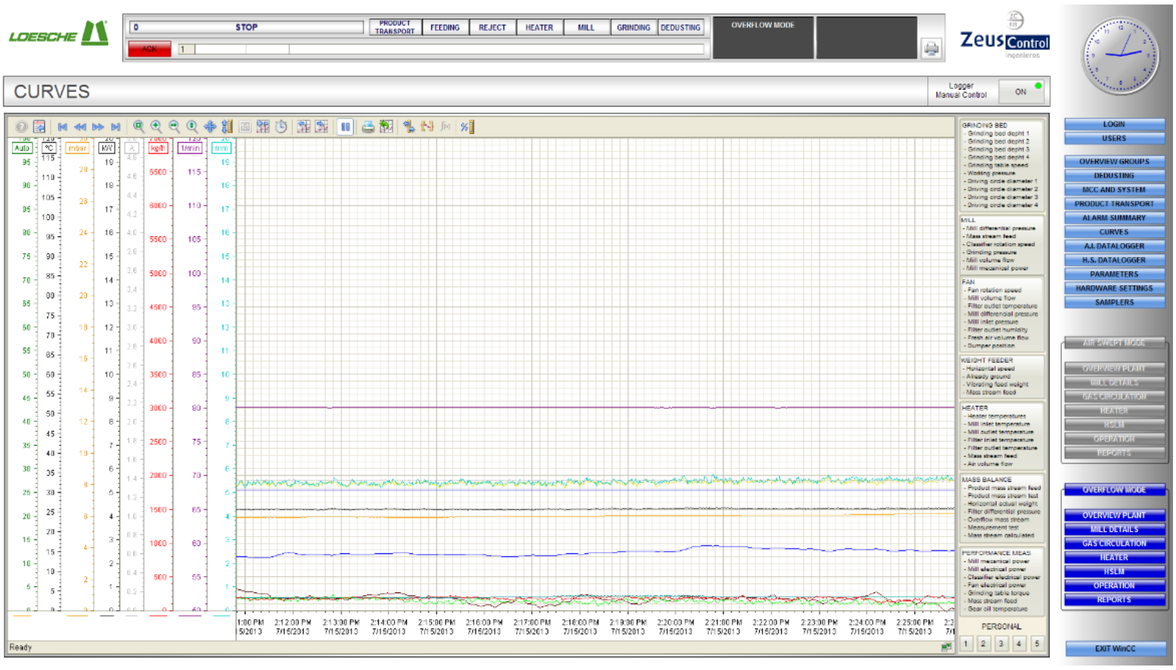


Figure 3-17. Trend curves

3.3. Material Characterization

During grinding tests, feed and product, reject samples are taken and processed in the laboratory. Feed and reject samples were taken by using belt-cut method. This samples are also taken for mass flow calculation. Product sample were taken by auto screw sampler. All the product samples were analyzed in terms of particle size distribution by air jet sieving machine.

3.3.1. Feed Material

Test material was epithermal quartz vein gold ore which has a Bond Work Index of 17.8kWh/t. Particle size distribution of the feed material is given in Figure 3-18.

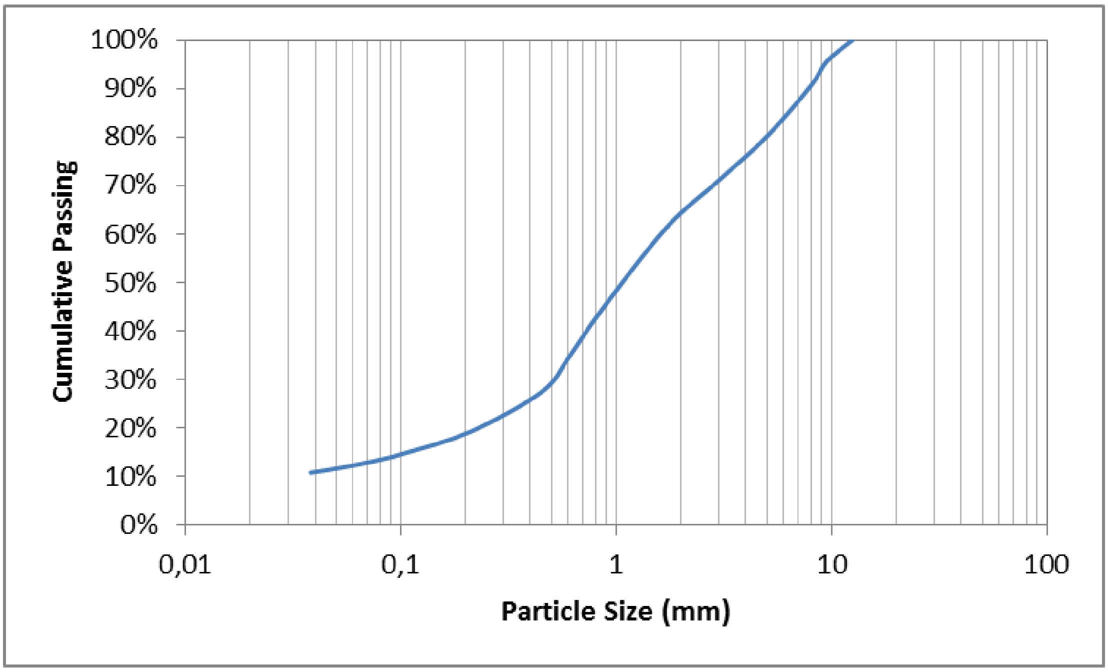


Figure 3-18. Feed particle size distribution

The feed material is quite abrasive. The ore’s chemical composition is 98% SiO_2. Existing conventional rod mill-ball mill circuit consumes 3500-4000g/t grinding media [24].

3.3.2. Product Samples

Product samples were collected by a screw sampler which is directly on product line. Screw sampler is shown in Figure 3-19.

Figure 3-19. Screw sampler on product line

All the product samples have been screened by using air jet stream sieving machine and screens (Figure 3-20) on site.

Figure 3-20. Air jet sieving machine and screens

The shape of the size distribution directly affects the downstream processes or material properties, i.e., floatation recovery. Thus it is an important parameter that should be evaluated. In determining the slope of the size distribution curve, n parameter in RRBS[9] equation [18], was calculated to find out whether the operating conditions had some effects on the slope of the size distribution curve. This parameter was estimated by applying non-linear regression technique where the equation was fitted with the minimum change in size distribution.

Slope of the particle size distribution curve (n), is an expression of the fine to coarse particles ratio. If fines are relatively higher than coarse particles; than slope (n) is high. That is also an expression of over-grinding (more fines have created).

3.3.3. Calculation of Linear Velocity at the Point of Louver Ring

Air flow is necessary in order to transfer the material directly to dynamic classifier. Louver ring is the air channels around the grinding table. Cross-section area of the louver ring section of LM4.5 is 0.0327m^2. Table 3.2 shows a simple conversion table for volumetric air flow rate (m^3/h) to linear velocity (m/s) of the air flow at the point of louver ring.

Table 3.2. Conversion chart to linear velocity of air flow

m^3/h	m/s
1500	12,75
1800	15,30
2000	17,00
2200	18,70
2400	20,40
2600	22,10
2800	23,81
3000	25,51
3300	28,06
3500	29,76
4000	34,01
4500	38,26
5000	42,51

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[9] RRSB : Rosin, Rammler, Sperling, Bennet equation. $Q_3(x) = 1 - exp\left[(\frac{x}{x_{63,3}})^n\right]$

4. RESULTS AND DISCUSSION

Within the thesis study, several test works were performed to investigate the influences of the design and operating parameters on vertical roller mill grinding performance. In this context, dam ring height, grinding pressure, classifier rotor speed, airflow rate, mill differential parameters were tested by considering specific energy consumption and product fineness of the mill.

All product samples have been sieved by air-jet sieve and analyzed. Product particle size distribution curves are given in

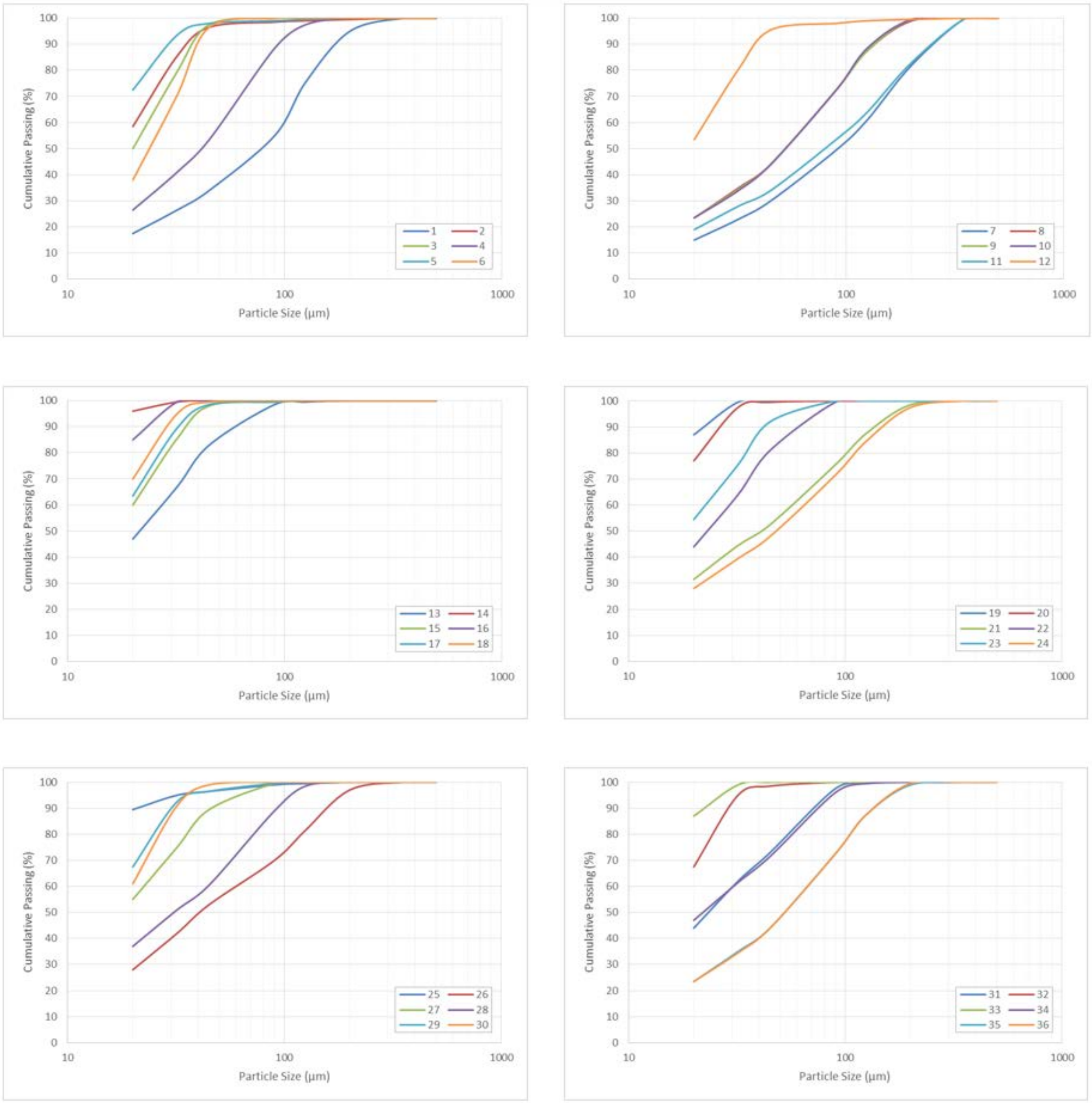


Figure 4-1. Particle size distribution curves of product samples

4.1. Effect of Dam Ring Height

In order to determine the effect of dam ring height on vertical roller mill performance; 5 different dam ring heights (5mm-8,5mm-13mm-17,5mm-21mm) were tested at specified operating conditions given in Table 4.1.

Table 4.1. Specified operating conditions for dam ring height effect

Parameter	***Unit***	***Description***
Grinding Pressure	bar	15
LSKS Speed	rpm	500
Airflow Rate	m^3/h	3300
∆P Mill	mbar	14
Grinding Table Speed	rpm	84

Theoretically, the higher the dam ring height the finer the product. This is because of the increased retention time of the material on the grinding table that results in grinding the product down to finer size range. In addition to that, the portion of the material bypassing from the grinding table is prevented.

The effect of dam ring height on throughput and reject mass flow rate is given in Figure 4-2.

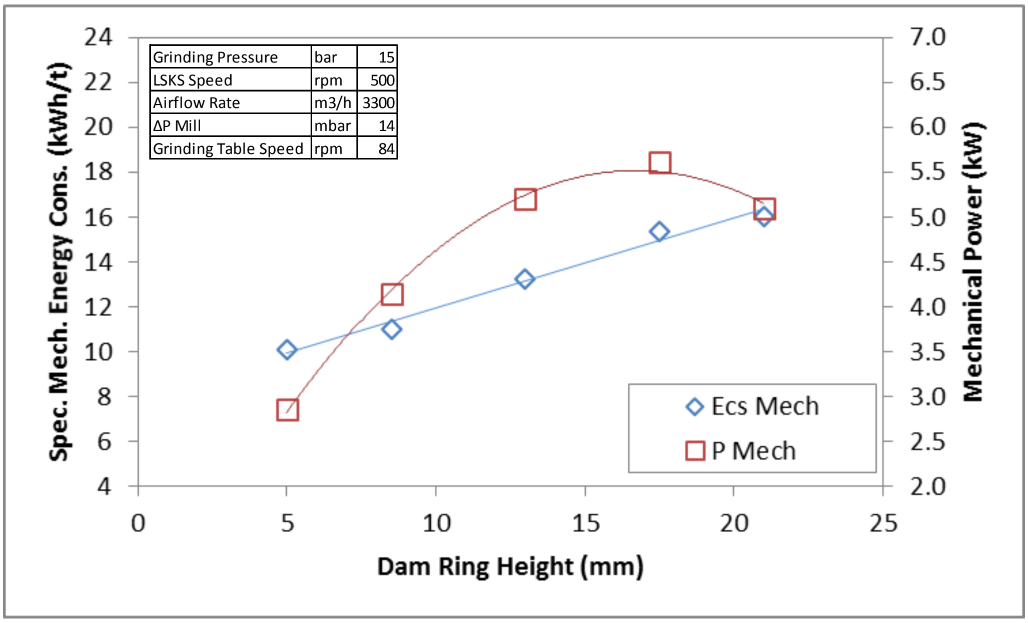


Figure 4-2. Effect of dam ring height on mass flow

As can be seen from the Figure 4-2, increasing dam ring height increases the throughput of the mill up to a certain point (350kg/h) then it starts to decrease. That means the optimum dam ring height for the material having $P_{80}\approx 60\mu m$ product is 15mm. It is thought that higher dam rings have more material on the table and over grind the material in the mill. Consequently, amount of the reject material decreases by increasing dam ring height.

Increasing dam ring height, increases the volume of grinding zone on the table. This volume defines the residence time of grinding zone.

The effect of dam ring height on specific mechanical energy consumption and power draw of the mill main motor is given in Figure 4-3.

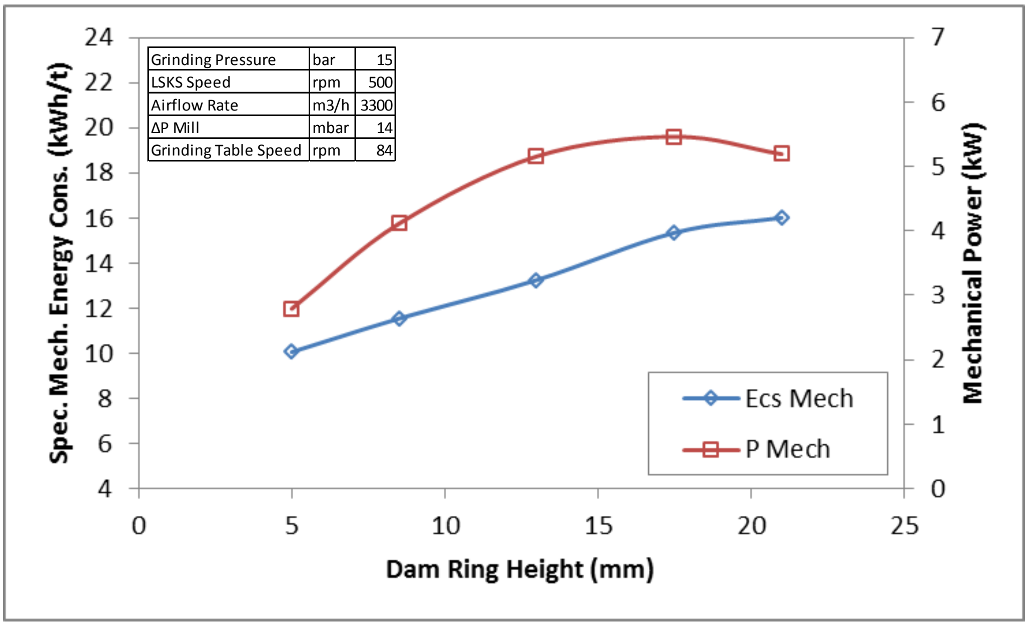


Figure 4-3. Effect of dam ring height on specific energy consumption and power drawn

Higher dam ring height allows to process more material on the table that creates more resistance. This resistance increases the torque which is required to keep rotating the table at certain speed.

More material on the grinding table demands higher energy utilization in order to achieve same product fineness. As can be seen from FIGURE, there is a linear correlation between dam ring and specific mechanical energy consumption. From throughput perspective, higher dam ring height increases the production rate that decreases the specific mechanical energy consumption.

The effect of dam ring height on product fineness (P_{80}) and steepness of the product particle size distribution (n) is given in Figure 4-4.

From RRSB equation, the higher values of n parameter implies steeper size distribution product.

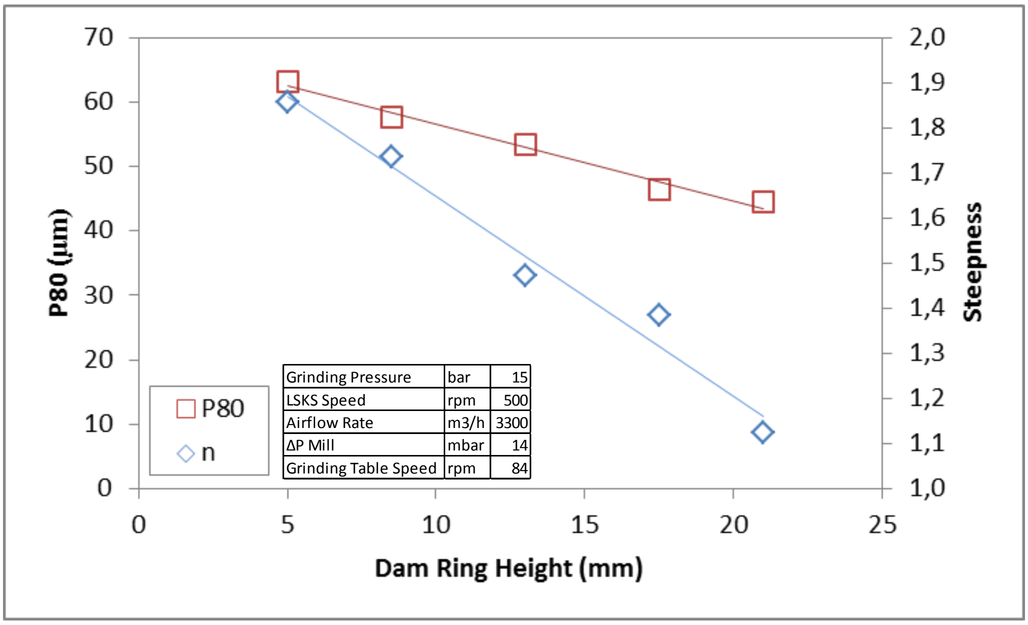


Figure 4-4. Effect of dam ring height on P_{80} and steepness

Increasing dam ring height increases the retention time of the material on the grinding table which creates more fines. Finer material is fed to the classifier, and consequently the product gets finer.

More fines mean flatter particle size distribution. It is also clear that for higher dam rings, the product particle size distribution gets flatter.

The effect of dam ring height on grinding bed height is given in Figure 4-5.

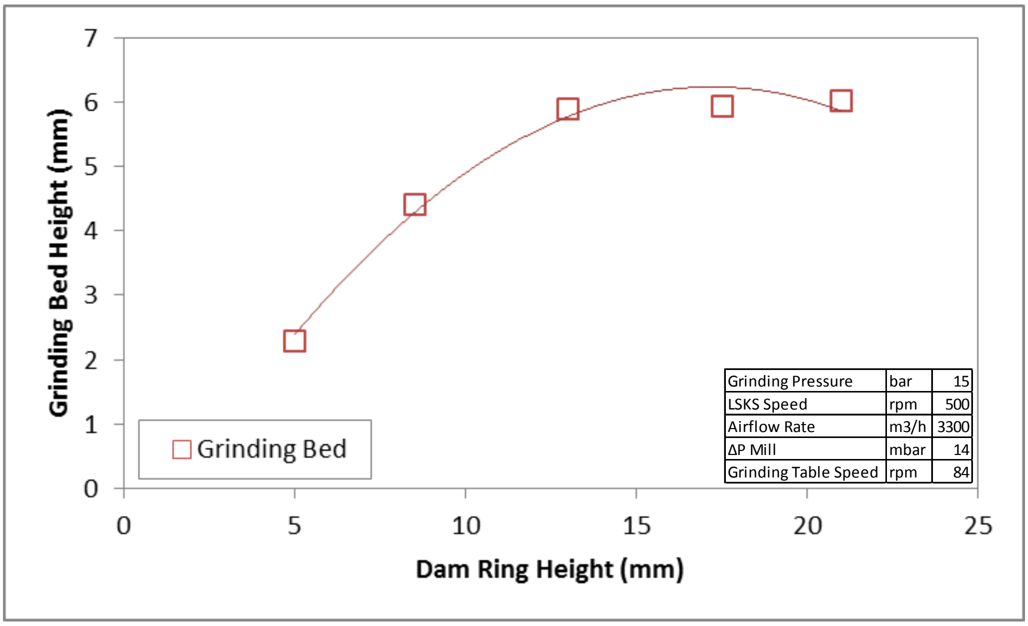


Figure 4-5. Effect of dam ring height on grinding bed height

Higher amount of material is processed on the grinding table with higher dam ring height thus more stable grinding bed is obtained. As shown in Figure 4-5, grinding bed height cannot be increased after a certain dam ring height. Material on the table increases up to a certain point and approaches to asymptote. The amount of material in the mill is adjusted by ΔP mill and for these operational parameters (mentioned above in TABLE); the grinding bed height is maximum 6mm.

4.2. Effect of Grinding Pressure

In order to determine the effect of grinding pressure on performance of vertical roller mill; grinding tests at 4 different pressure levels (15bar-20bar-22bar-25bar) were conducted. The operating parameters adjusted during the grinding tests are given in Table 4.2.

Table 4.2. Specified operating conditions for grinding pressure effect

Parameter	***Unit***	***Description***
Dam Ring Height	mm	13
LSKS Speed	rpm	500
Airflow Rate	m^3/h	3300
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

Throughout the studies it was observed that grinding pressure had an improved effect on grinding performance for most of the ore types. Theoretically, as the product gets finer grinding pressure should be increased as well. That means higher comminution energy is applied to material on the table. Higher comminution energy produces more fines and might over grind. Therefore, the discharged material from the table has finer size distribution.

The effect of grinding pressure on throughput and reject mass flow rate is given in Figure 4-6.

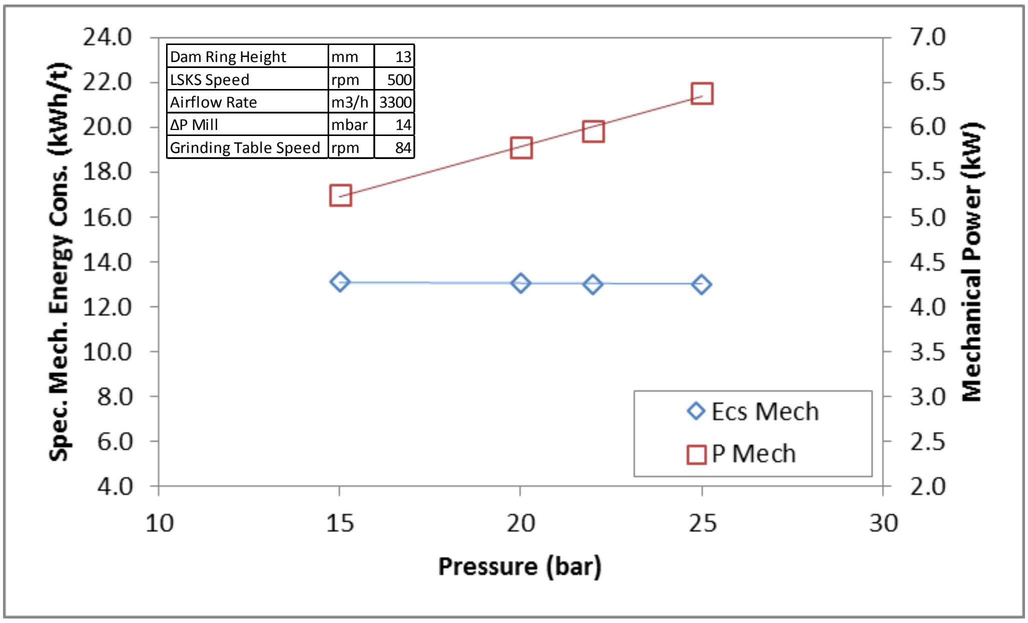
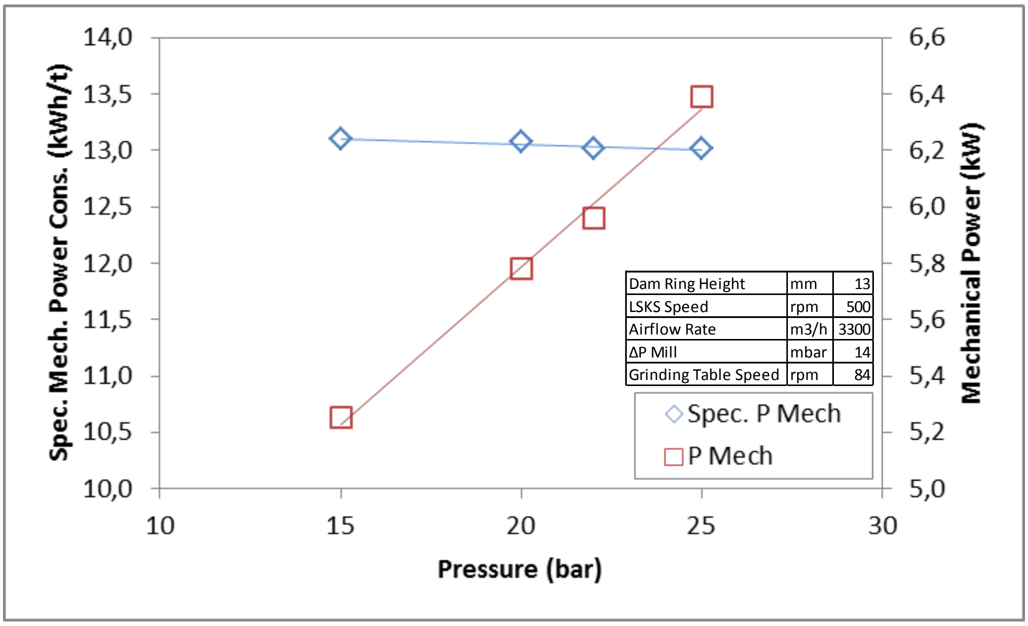


Figure 4-6. Effect of grinding pressure on mass flows

Increasing grinding pressure increases the throughput directly. Higher grinding pressures produce more fines and it increases the overall plant throughput.

The ground material that leaves the table has less coarse material. Thus, the material can be transported to classifier more efficiently. The material amount which cannot be transported is less. That is why the reject mass flow is decreasing by increasing grinding pressures.

The effect of grinding pressure on specific mechanical energy consumption and power draw of the mill main motor is given in Figure 4-7.



Dam Ring Height	mm	13
LSKS Speed	rpm	500
Airflow Rate	m3/h	3300
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

Figure 4-7. Effect of grinding pressure on specific energy consumption and power drawn

Higher grinding pressure on the table results in having more resistance. This resistance increases the torque that is required to keep rotating the table at a certain speed. As a conclusion, the power draw of the mill main motor is increasing linear by increasing grinding pressure.

The effect of grinding pressure on specific mechanical energy consumption is nearly constant. In order to discuss this effect the throughput values must be taken into consideration.

The effect of grinding pressure on product fineness (P_{80}) and grinding bed height is given in Figure 4-8.

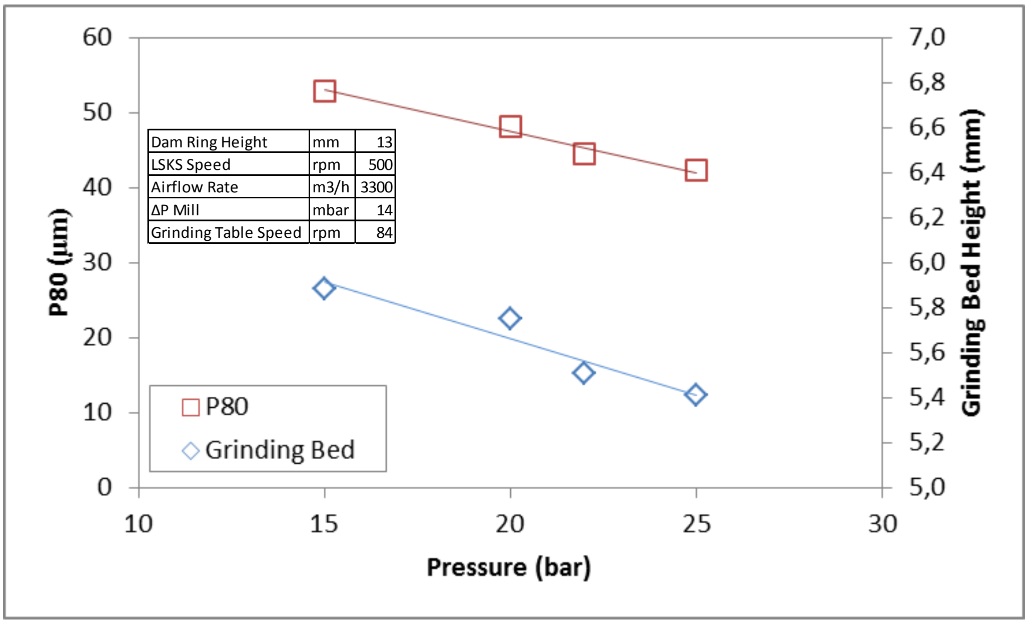


Figure 4-8. Effect of grinding pressure on P_{80} and grinding bed height

Increasing grinding pressure increases the comminution energy applied to the material on the grinding table that leads to the production of finer material. The classifier feed is finer; even the airflow rate and classifier rotor speed are kept constant, the product is finer.

Increasing grinding pressure means higher load on the grinding bed which squeezes the grinding bed more. It is obvious that higher grinding pressure creates a shallow grinding bed.

4.3. Effect of Classifier Rotor Speed

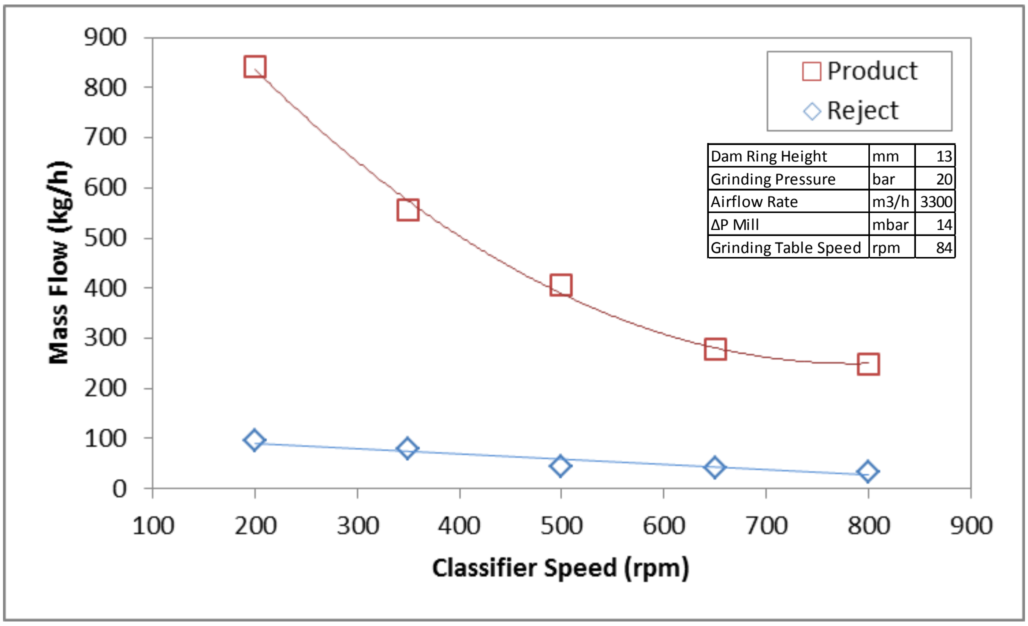
In order to determine the effect of classifier rotor speed on performance of vertical roller mill; 5 different classifier rotor speeds were adjusted (200rpm-350 rpm -500 rpm -650 rpm -800 rpm) at operating conditions given in Table 4.3.

Table 4.3. Specified operating conditions for classifier rotor speed effect

Parameter	***Unit***	***Description***
Dam Ring Height	mm	13
Grinding Pressure	bar	20
Airflow Rate	m^3/h	3300
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

Theoretically, increasing classifier rotor speed decreases the cut size of separation process and ultimately finer product is obtained. In this study it was concluded that classifier rotor speed and circulating load are directly proportional to each other.

The effect of classifier rotor speed on throughput and reject mass flow rate is given in Figure 4-9.



Dam Ring Height	mm	13
Grinding Pressure	bar	20
Airflow Rate	m3/h	3300
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

Figure 4-9. Effect of classifier rotor speed on mass flows

Higher classifier rotor speed increases the internal circulating load which gives chance to particles which don't meet the product specification. Higher classifier rotor speed reduces the throughput dramatically as seen in Figure 4-9.

For constant ∆P mill, the internal material circulation will be finer for higher classifier rotor speed. That has a slight effect on reject mass flow. The reject mass flow is slightly decreasing by increasing classifier rotor speed.

The effect of classifier rotor speed on specific mechanical energy consumption and power draw of the mill main motor is given in Figure 4-10.

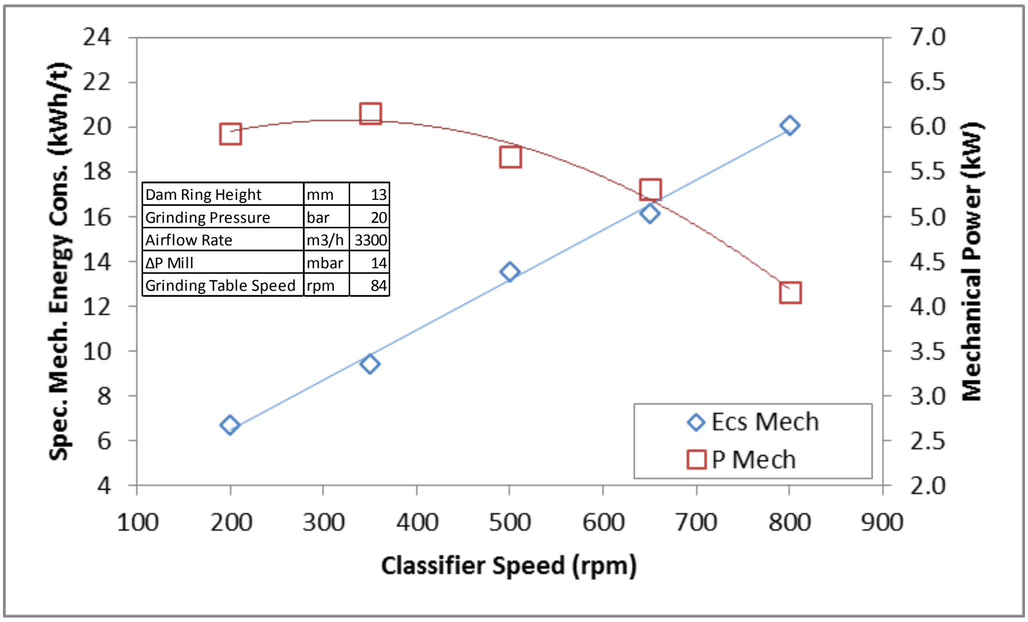


Figure 4-10. Effect of classifier rotor speed on specific energy consumption and power drawn

Higher classifier rotor speed increases the internal circulation and this circulating stream is generally finer. These fine particles keep the ΔP mill higher even the amount of material on grinding zone is less. Less material on grinding zone creates less resistance which directly affects the grinding table torque. In addition to this, the material on the grinding table has less coarse material that also reduces the resistance.

Higher classifier rotor speed reduces the throughput as mentioned above. Even the power draw is less; the specific mechanical energy consumption is getting higher by increasing classifier rotor speed.

The effect of classifier rotor speed on product fineness (P_{80}) and steepness of the product particle size distribution (n) is given in Figure 4-11.

Steeper particle size distributions have higher “n” values.

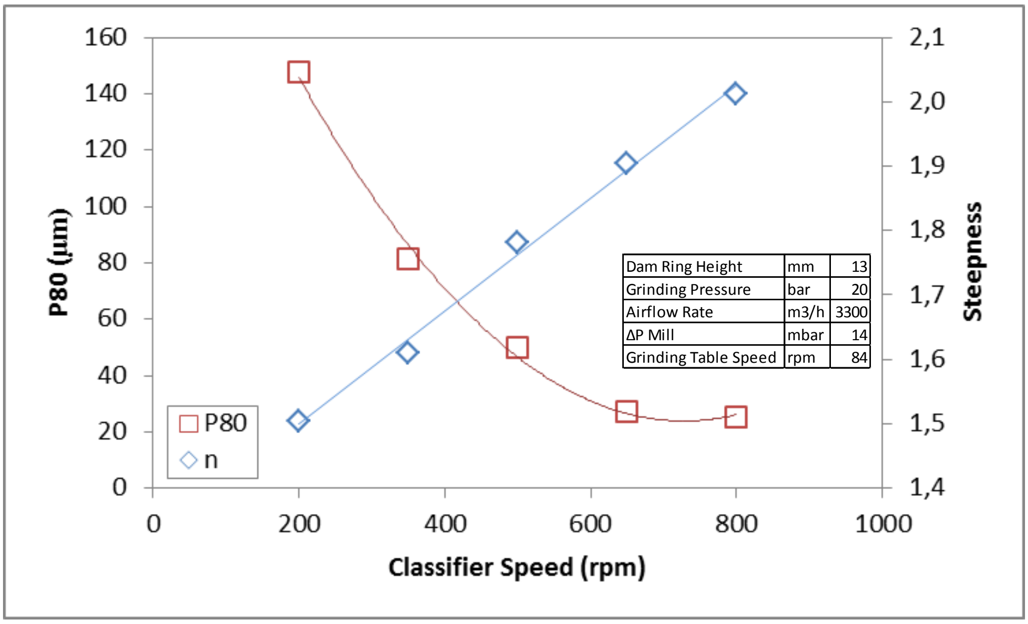


Figure 4-11. Effect of classifier rotor speed on P_{80} and steepness

Increasing classifier rotor speed decreases the passing chance of the particle which is dragged by airflow through the classifier. Only fine particles (=light particles) can pass through the classifier at higher classifier rotor speed. Thus the P_{80} values of the product are getting smaller by increasing classifier rotor speed.

In practice finer products have steeper particle size distribution. The reason for this is higher circulating load in the vertical roller mill. Higher circulating loads gives opportunity to particle to be classified if the particle meets the product requirement.

The effect of classifier rotor speed on grinding bed height is given in Figure 4-12.

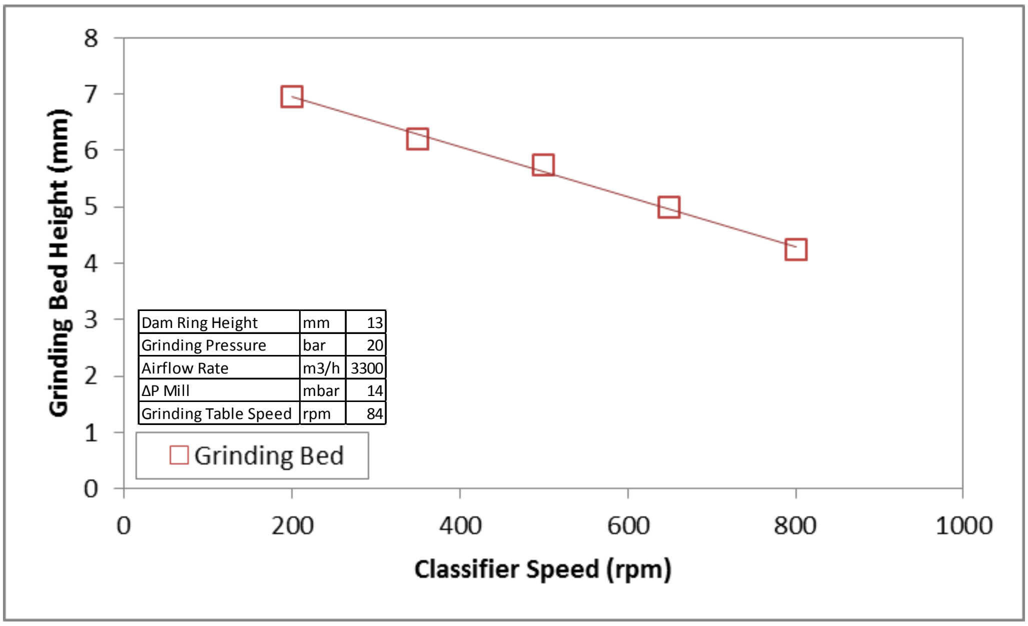


Figure 4-12. Effect of classifier rotor speed on grinding bed height

Higher classifier rotor speed increases the internal circulation and this circulating stream is generally finer. These fine particles keep the ΔP mill higher even the amount of material on grinding zone is less. The grinding zone is the grinding bed. Less material on the grinding zone means shallow grinding bed.

4.4. Effect of Airflow Rate

In order to determine the effect of volumetric airflow rate on vertical roller mill's performance; 3 different volumetric airflow rates (2800m^3/h-3300m^3/h -3800m^3/h) were tested, ceteris paribus. The other operational parameters are given in Table 4.4.

Table 4.4. Specified operating conditions for airflow rate effect

Parameter	***Unit***	***Description***
Dam Ring Height	mm	13
Grinding Pressure	bar	20
Classifier Speed	rpm	450
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

Theoretically, higher airflow rate increases the drag force which is applied on the particles in the mill. Higher airflow rate increases the speed of the particles in the mill. Higher airflow rate decreases the internal circulating load.

The effect of airflow rate on throughput and reject mass flow rate is given in Figure 4-13.

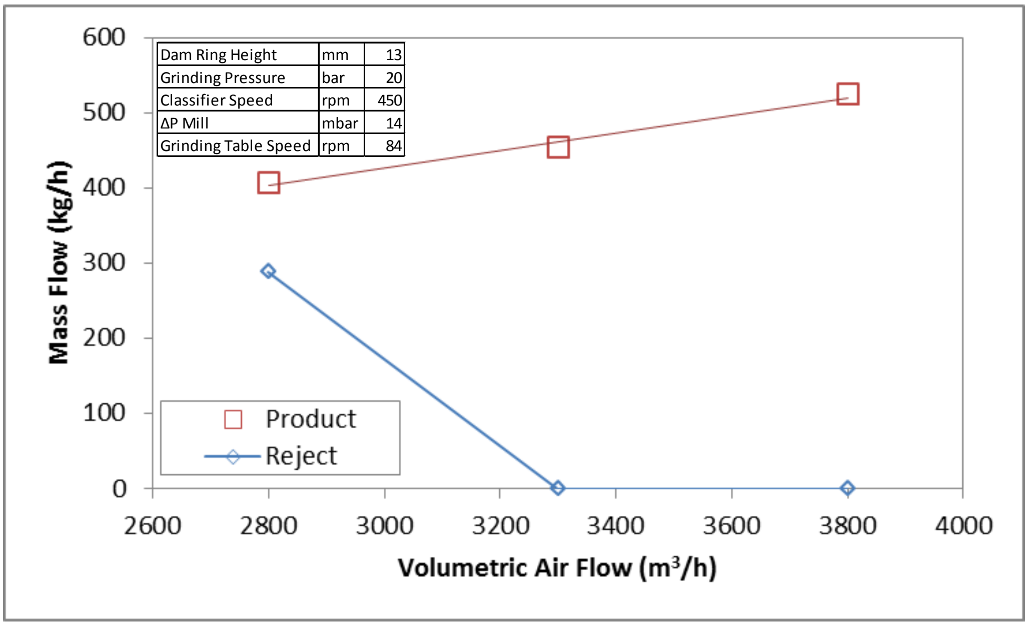
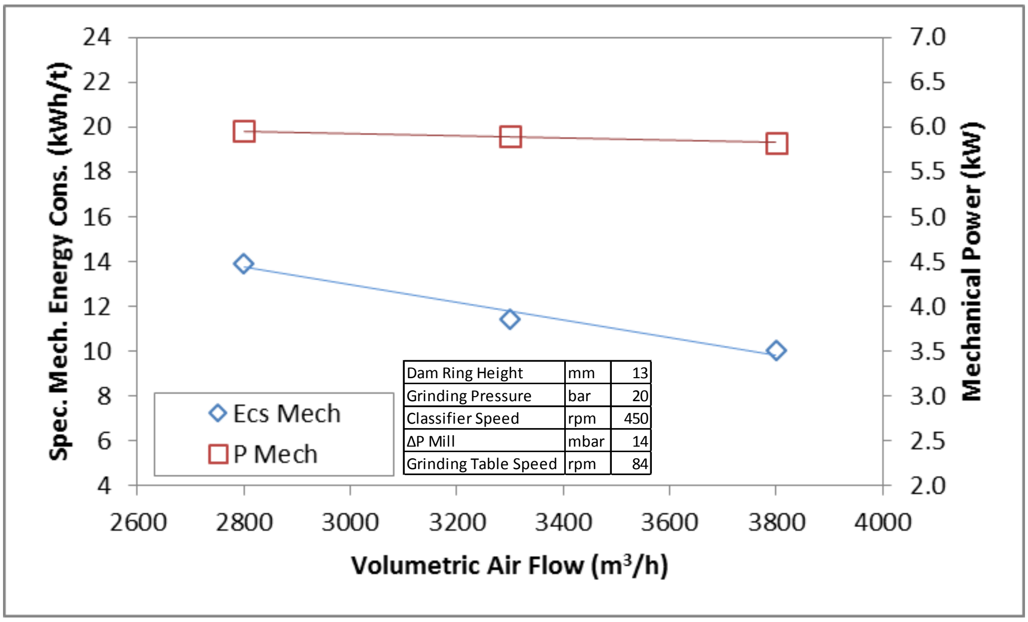


Figure 4-13. Effect of volumetric airflow rate on mass flows

Higher airflow rate increases the speed of the particles in the mill which gives chance to particles to pass through the classifier even they are coarser for defined classifier speed. Higher airflow rate increases the throughput because more particles can pass through the classifier as their velocity is higher under the effect of higher drag force created by higher airflow rate.

Higher airflow rate creates higher drag force which is applied on particle inside the mill. Higher drag force can carry more and coarser particles inside the mill. This effect reduces the amount of reject material.

The effect of airflow rate on specific mechanical energy consumption and power draw of the mill main motor is given in Figure 4-14.



Dam Ring Height	mm	13
Grinding Pressure	bar	20
Classifier Speed	rpm	450
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

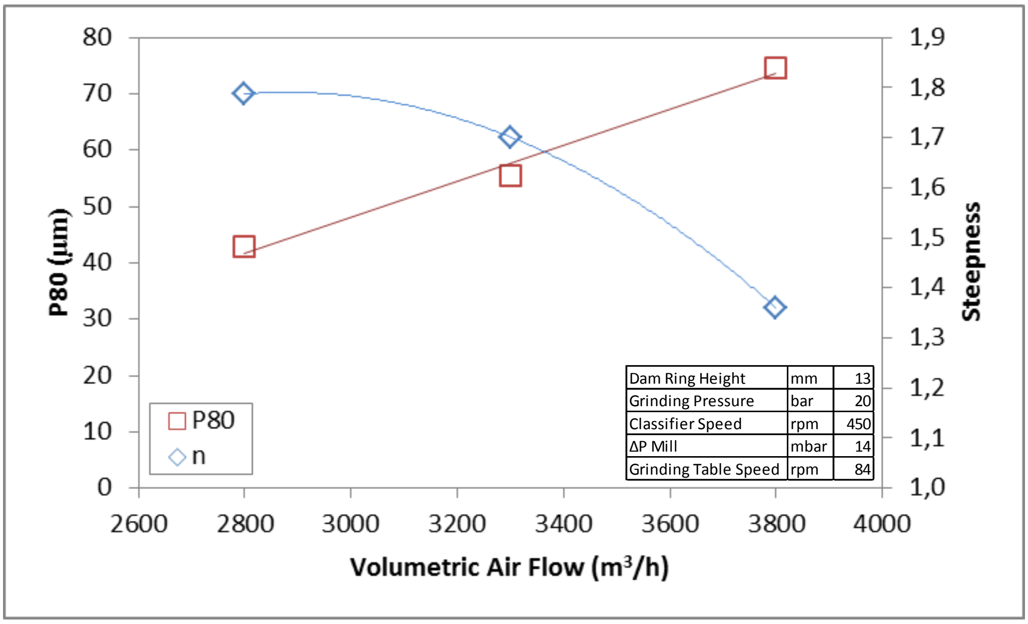
Figure 4-14. Effect of volumetric airflow rate on specific energy consumption and power drawn

Higher airflow rate directly affects the ΔP mill. For higher airflow rates under certain ΔP mill condition, there is less material in the mill. Less material creates less resistance on torque of the grinding table. Thus the power draw of the mill main motor is decreasing by increasing airflow rate.

Higher airflow rate increases the throughput as mentioned above. The specific mechanical energy consumption reduces by increasing airflow rate. The effect of airflow rate on specific mechanical energy consumption is greater. Because the powers draw decreases while the throughput increases by increasing airflow rate.

The effect of airflow rate on product fineness (P_{80}) and steepness of the product particle size distribution (n) is given in Figure 4-15.

Steeper particle size distributions have higher “n” values.



Dam Ring Height	mm	13
Grinding Pressure	bar	20
Classifier Speed	rpm	450
ΔP Mill	mbar	14
Grinding Table Speed	rpm	84

Figure 4-15. Effect of volumetric airflow rate on P_{80} and steepness

Increasing airflow rate increases the passing chance of the particle which is dragged by airflow through the classifier. Also coarse particles have higher velocity values for higher airflow rates. Coarser particles can pass through the classifier. Thus the P_{80} values of the product are getting greater by increasing airflow rate.

Higher airflow rates transport more particles to classifier which directly affects the classifying performance. For higher airflow rates, the particle size distributions are getting flatter.

The effect of airflow rate on grinding bed height is given in Figure 4-16.

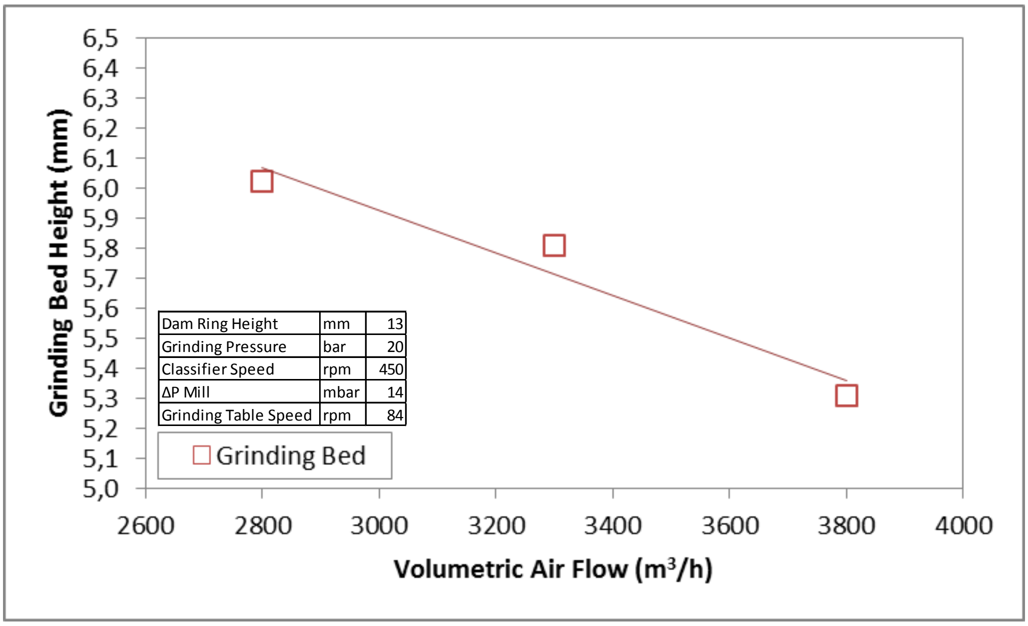


Figure 4-16. Effect of volumetric airflow rate on grinding bed height

Higher airflow rate directly affects the ΔP mill. For higher airflow rates under certain ΔP mill condition, there is less material in the mill as well as on the grinding table. Less material on the grinding table creates shallow grinding bed.

4.5. Effect of Mill Differential Pressure

In order to determine the effect of mill differential pressure on vertical roller mill's performance; 3 different mill differential pressure settings (12mbar-15mbar-18mbar) were tested, ceteris paribus. The other operational parameters are given in Table 4.5.

Table 4.5. Specified operating conditions for mill differential pressure effect

Parameter	***Unit***	***Description***
Dam Ring Height	mm	13
Grinding Pressure	bar	20
Classifier Speed	rpm	450
Airflow Rate	m^3/h	3300
Grinding Table Speed	rpm	84

Theoretically, mill differential pressure is an indication the fullness of the mill. That means higher mill differential pressure reports higher amount of material inside the mill.

The effect of mill differential pressure on throughput and reject mass flow rate is given in Figure 4-17.

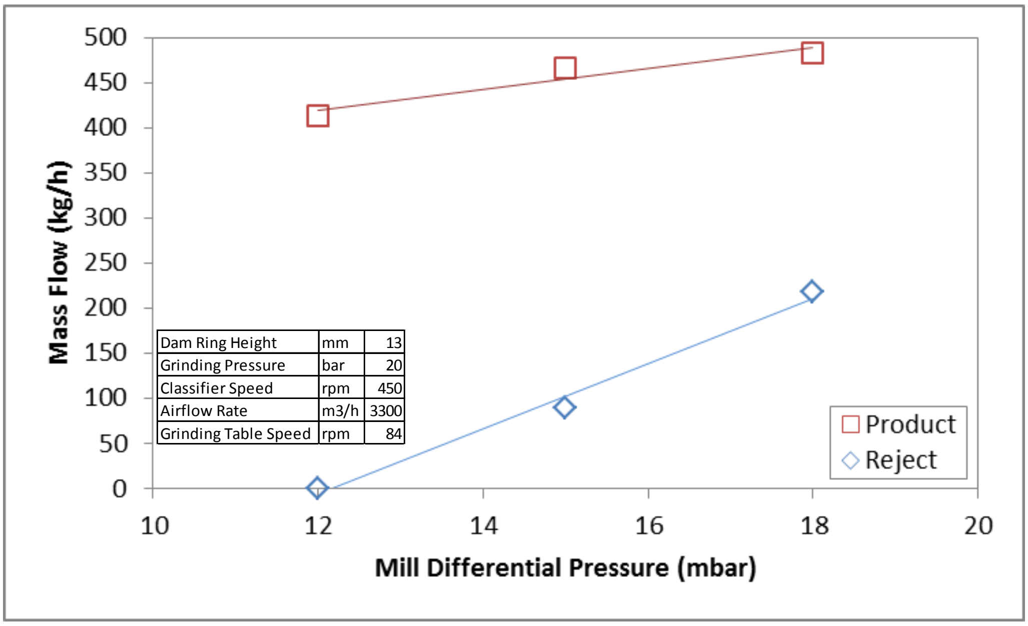


Figure 4-17. Effect of mill differential pressure on mass flows

Higher mill differential pressure represents higher amount of material inside the mill. If there is more material in the mill the fine production rate will be higher which increases the throughput slightly.

If there is more particles in the mill the drag force which is created by airflow is not sufficient to carry all particles. Thus the amount of reject material increases by increasing mill differential pressure.

The effect of mill differential pressure on specific mechanical energy consumption and power draw of the mill main motor is given in Figure 4-18.

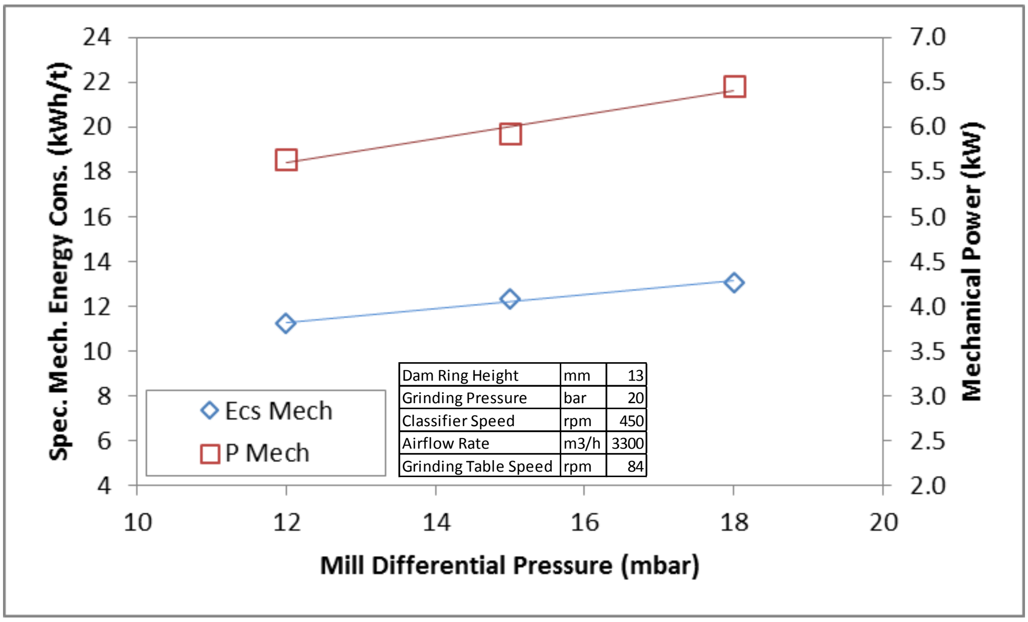


Figure 4-18. Effect of mill differential pressure on specific energy consumption and power drawn

Higher mill differential pressure represents higher amount of material inside the mill as mentioned above. Much material in the mill means much material on the grinding table which creates higher torque on the grinding table. Thus the power draw of the mill main motor increases by increasing mill differential pressure.

Higher mill differential pressure slightly increases the throughput as mentioned above. The specific mechanical energy consumption reduces by increasing airflow rate. The effect of mill differential pressure on specific mechanical energy consumption is less. Because the power draw and the throughput are both increasing by increasing mill differential pressure.

The effect of mill differential pressure on product fineness (P_{80}) and steepness of the product particle size distribution (n) is given in Figure 4-19.

Steeper particle size distributions have higher “n” values.

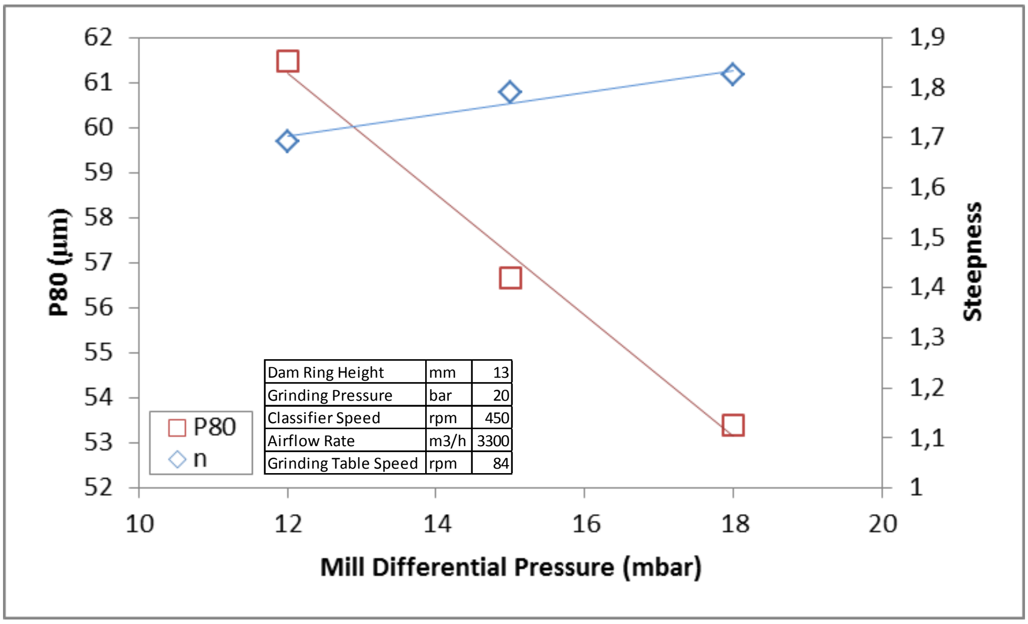


Figure 4-19. Effect of mill differential pressure on P_{80} and steepness

Higher mill differential pressure represents higher amount of material inside the mill as mentioned above. Reject material has a big effect on mill differential pressure. The energy generated by fan for material transportation consumes mainly by medium and coarse particles. The classifier feed is slightly finer. Thus the product is getting finer by increasing mill differential pressure.

In practice, finer products have steeper particle size distributions. That is why the steepness of the particle size distribution is getting slightly steeper by increasing mill differential pressure.

The effect of mill differential pressure on grinding bed height is given in Figure 4-20.

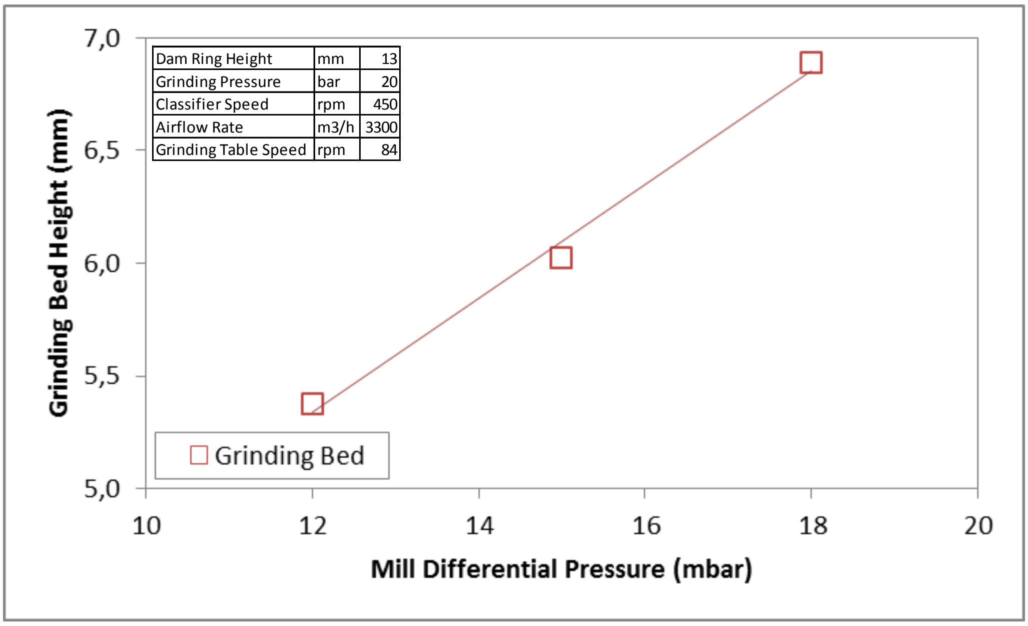


Figure 4-20. Effect of mill differential pressure on grinding bed

Higher mill differential pressure represents higher amount of material inside the mill as mentioned above. Much material in the mill means, much material on the grinding table which creates a higher grinding bed.

4.6. Wear Results

Vertical roller mills' grinding principle is based on in-bed comminution. The grinding elements never touch each other. Table 4.6 shows the wear results for different grinding pressures.

Table 4.6. Total wear rates of Loesche Mill

Grinding Pressure (bar)	*Total Wear Rate (g/t)*
15	341,93
20	504,00
25	597,50

Higher grinding pressures have higher rate of total wear. Higher grinding pressure creates more energy and shallow grinding bed which results higher total wear rate.

For the existing plant for the same fineness the specific wear of the only grinding media of rod and ball mills is about 3500-4000g/t [24].

As it is obvious vertical roller mill has significantly less specific wear rate than conventional grinding circuits. In order to prevent metal contamination for downstream processes, it is a benefit for vertical roller mill.

5. CONCLUSIONS

- The effects of operational parameters have been compared in terms of energy consumption, product fineness, throughput, product particle size distribution and wear.
- Also the effect of dam ring height has been compared in terms of energy consumption, product fineness, throughput, product particle size distribution.
- Dam ring height directly increases the amount of material on the table which is directly proportional to retention time of grinding zone. But for energy efficiency, there is an optimum point which depends on material characteristics and product requirements.
- Higher dam ring prevents by passing on the grinding table. For higher dam rings, the reject mass flow decreases.
- Higher grinding pressures increase the comminution energy which is applied to grinding bed. This effect creates more fines. Even the mill main motor power draw is increasing; the specific energy consumption of the mill is decreasing. Because the throughput increases significantly.
- Higher classifier rotor speeds report finer product. If the rotor speed increases, rotor can catch slower particles which dragged by airflow through classifier. Also higher classifier rotor results an increase on internal circulation ratio.
- Finer products have steeper particle size distributions.
- Vertical roller mills’ products are steeper than conventional grinding equipment’s products. Higher inner circulation ratio prevents over grinding. Particles is ground then classified in one compact unit. The super-efficient dynamic classifiers can make classification efficiently.
- Higher airflow rate inside the mill crates much drag force on the particles. Coarser particles can report to product by higher airflow rate.
- Higher airflow rate increases the mill differential pressure. For constant ΔP mill value, the mill material load is less.
- Mill differential pressure is a good indicator of mill material load. Higher ΔP mill values make a slight increase on throughput.
- Vertical roller mills grind the material in a grinding bed which reduces the specific wear on grinding elements.

- For the test material gold ore, vertical roller mill has less specific wear rates in comparison with existing conventional rod-ball mill circuit.
- A very fresh grinding technology of vertical roller mills has been tested for very abrasive and hard gold ore. The pilot scale testing showed that vertical roller mills will be applied in ore industry in the future.

For further studies;

- Overflow and shear-free modes can be used for further testing for different product requirements. Theoretically, shear-free rollers create fewer fines. Thus the product has steeper particle size distribution. Overflow mode can be beneficial especially in the coarse product size range (+200µm).
- Different types of ores can be tested in order to identify the effect of ore type.
- An ore characterization method can be built up in order to investigate the ore behavior in vertical roller mills.
- Vertical roller mill (air swept) is like a black box which has comminution and classification spontaneously. There is no mathematical model for vertical roller mills. Further studies can come up with a mathematical model for vertical roller mills.

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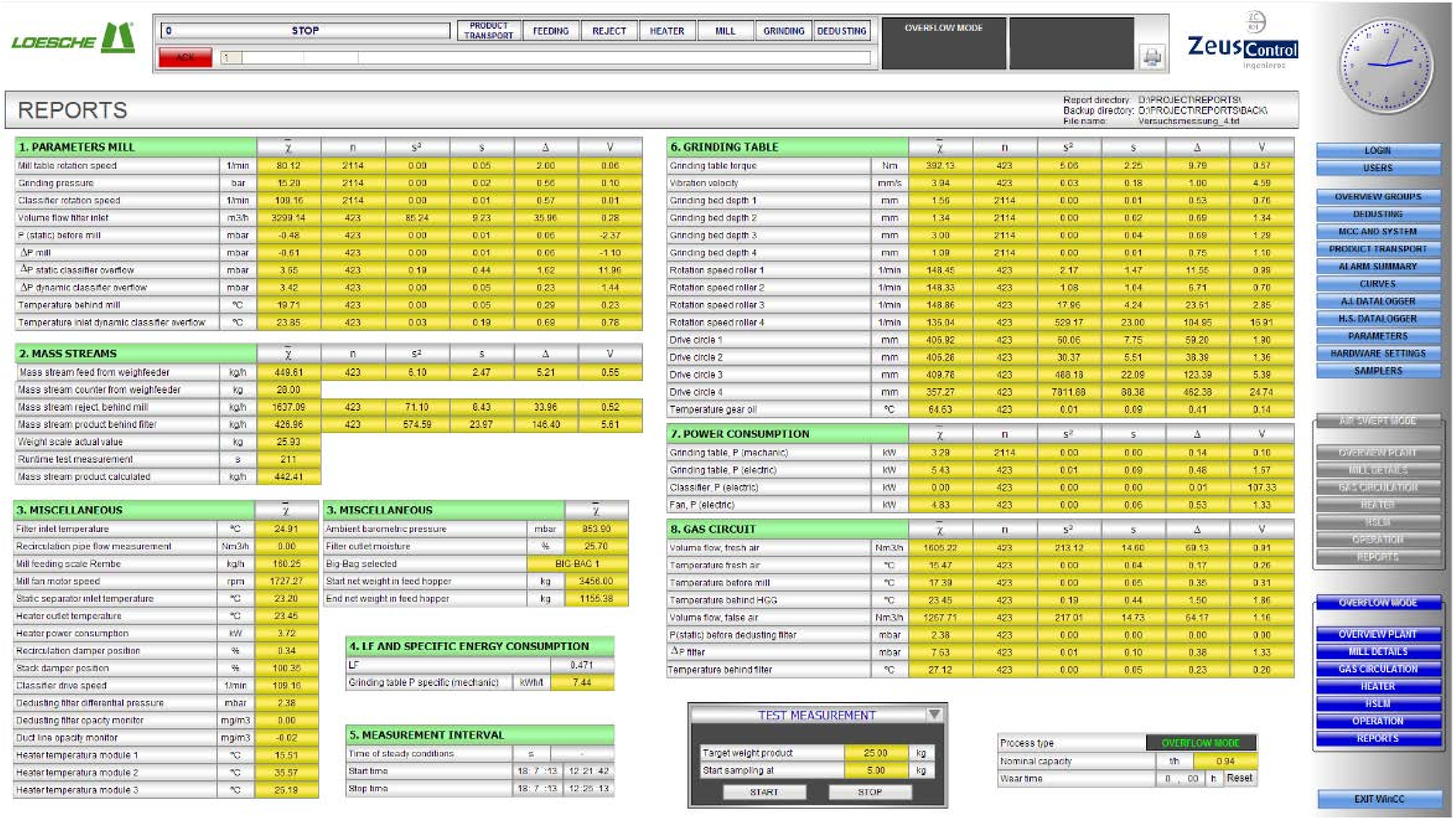
APPENDIX



REPORTS

Report directory: D:\PROJECT\REPORTS\
Backup directory: D:\PROJECT\REPORTS\BACK\
File name: Versuchsmessung_4.txt

1. PARAMETERS MILL		$\bar{\chi}$	n	s^2	s	Δ	V
Mill table rotation speed	1/min	80.12	2114	0.00	0.05	2.00	0.06
Grinding pressure	bar	15.20	2114	0.00	0.02	0.56	0.10
Classifier rotation speed	1/min	109.16	2114	0.00	0.01	0.57	0.01
Volume flow filter inlet	m3/h	3299.14	423	85.24	9.23	35.96	0.28
P (static) before mill	mbar	-0.48	423	0.00	0.01	0.06	-2.37
ΔP mill	mbar	-0.61	423	0.00	0.01	0.06	-1.10
ΔP static classifier overflow	mbar	3.65	423	0.19	0.44	1.62	11.96
ΔP dynamic classifier overflow	mbar	3.42	423	0.00	0.05	0.23	1.44
Temperature behind mill	°C	19.71	423	0.00	0.05	0.29	0.23
Temperature inlet dynamic classifier overflow	°C	23.85	423	0.03	0.19	0.69	0.78

2. MASS STREAMS		$\bar{\chi}$	n	s^2	s	Δ	V
Mass stream feed from weighfeeder	kg/h	449.61	423	6.10	2.47	5.21	0.55
Mass stream counter from weighfeeder	kg	28.00					
Mass stream reject behind mill	kg/h	1637.09	423	71.10	8.43	33.96	0.52
Mass stream product behind filter	kg/h	426.96	423	574.59	23.97	146.40	5.61
Weight scale actual value	kg	25.93					
Runtime test measurement	s	211					
Mass stream product calculated	kg/h	442.41					

3. MISCELLANEOUS		$\bar{\chi}$
Filter inlet temperature	°C	24.91
Recirculation pipe flow measurement	Nm3/h	0.00
Mill feeding scale Rembe	kg/h	180.25
Mill fan motor speed	rpm	1727.27
Static separator inlet temperature	°C	23.20
Heater outlet temperature	°C	23.45
Heater power consumption	kW	3.72
Recirculation damper position	%	0.34
Stack damper position	%	100.35
Classifier drive speed	1/min	109.16
Dedusting filter differential pressure	mbar	2.38
Dedusting filter opacity monitor	mg/m3	0.00
Duct line opacity monitor	mg/m3	-0.02
Heater temperatura module 1	°C	15.51
Heater temperatura module 2	°C	35.57
Heater temperatura module 3	°C	25.19

3. MISCELLANEOUS		$\bar{\chi}$
Ambient barometric pressure	mbar	853.90
Filter outlet moisture	%	25.70
Big-Bag selected		BIG-BAG 1
Start net weight in feed hopper	kg	3456.00
End net weight in feed hopper	kg	1155.38

4. LF AND SPECIFIC ENERGY CONSUMPTION		
LF		0.471
Grinding table P specific (mechanic)	kWh/t	7.44

5. MEASUREMENT INTERVAL		
Time of steady conditions	s	-
Start time	18: 7 :13	12:21:42
Stop time	18: 7 :13	12:25:13

6. GRINDING TABLE		$\bar{\chi}$	n	s^2	s	Δ	V
Grinding table torque	Nm	392.13	423	5.06	2.25	9.79	0.57
Vibration velocity	mm/s	3.94	423	0.03	0.18	1.00	4.59
Grinding bed depth 1	mm	1.56	2114	0.00	0.01	0.53	0.76
Grinding bed depth 2	mm	1.34	2114	0.00	0.02	0.69	1.34
Grinding bed depth 3	mm	3.00	2114	0.00	0.04	0.69	1.29
Grinding bed depth 4	mm	1.09	2114	0.00	0.01	0.75	1.10
Rotation speed roller 1	1/min	148.45	423	2.17	1.47	11.55	0.99
Rotation speed roller 2	1/min	148.33	423	1.08	1.04	6.71	0.70
Rotation speed roller 3	1/min	148.86	423	17.96	4.24	23.51	2.85
Rotation speed roller 4	1/min	135.04	423	529.17	23.00	104.95	15.91
Drive circle 1	mm	405.92	423	60.06	7.75	59.20	1.90
Drive circle 2	mm	405.28	423	30.37	5.51	38.39	1.36
Drive circle 3	mm	409.78	423	488.18	22.09	123.39	5.39
Drive circle 4	mm	357.27	423	7811.69	88.38	462.38	24.74
Temperature gear oil	°C	64.63	423	0.01	0.09	0.41	0.14

7. POWER CONSUMPTION		$\bar{\chi}$	n	s^2	s	Δ	V
Grinding table, P (mechanic)	kW	3.28	2114	0.00	0.00	0.14	0.10
Grinding table, P (electric)	kW	5.43	423	0.01	0.09	0.48	1.57
Classifier, P (electric)	kW	0.00	423	0.00	0.00	0.01	107.33
Fan, P (electric)	kW	4.83	423	0.00	0.06	0.53	1.33

8. GAS CIRCUIT		$\bar{\chi}$	n	s^2	s	Δ	V
Volume flow, fresh air	Nm3/h	1605.22	423	213.12	14.60	69.13	0.91
Temperature fresh air	°C	15.47	423	0.00	0.04	0.17	0.26
Temperature before mill	°C	17.39	423	0.00	0.05	0.35	0.31
Temperature behind HGG	°C	23.45	423	0.19	0.44	1.50	1.86
Volume flow, false air	Nm3/h	1267.71	423	217.01	14.73	64.17	1.16
P(static) before dedusting filter	mbar	2.38	423	0.00	0.00	0.00	0.00
ΔP filter	mbar	7.63	423	0.01	0.10	0.38	1.33
Temperature behind filter	°C	27.12	423	0.00	0.05	0.23	0.20

TEST MEASUREMENT

Target weight product	25.00	kg
Start sampling at	5.00	kg

START STOP

Process type	OVERFLOW MODE		
Nominal capacity	t/h	0.94	
Wear time	0 , 00	h	Reset

CURRICULUM VITAE

Credentials

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Education

High School : 2001-2004 Fatih Anatolian High School Eskisehir

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Foreign Languages

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German	Good

Work Experience

2010 – 2012 : R&D Engineer, HCG Madencilik Ltd.

2012 – 2014 : Development Engineer, Loesche GmbH

2014 – Present : Technical Manager, TAHE International Metal Madencilik A.S.

Areas of Experiences

Research and Development on Mineral Process Plants, Gold Cyanidation, Comminution, Gravity Concentration of Gold.

Projects and Budgets

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Publications

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Oral and Poster Presentations

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