DISCRETE ELEMENT METHOD MODELING OF PULP LIFTER PERFORMANCE

Pengbo Chu

Department of Mechanical Engineering
McGill University
Montreal, Canada

August 2011

A thesis submitted to McGill University
in partial fulfillment of the requirements for the degree of
Master of Engineering

A Dedication to My Beloved Father

Congjin Chu, 初从锦

November 9, 1958 – September 11, 2011

Abstract

Pulp lifter assembly is one of the important components at the discharge ends of grate-discharge grinding mills. It discharges grinded materials out through the discharge trunnion like a centrifugal pump running in the reverse direction to that required by a pump. Though it is widely known conventional pulp lifter design associates with drawbacks that cause inefficient discharge operation, little has been done to understand the causes of this particular happening. With the aim to better understand the effects of different pulp lifter designs on the discharge performance and also establish strategies for future design and operation of such equipment, this work is initiated.

Three types of industry scaled pulp lifter designs, including two conventional designs and a new design, were comparably studied using Discrete Element Method (DEM) modeling technique. The discharge performances of these designs were evaluated against three criteria which include discharge rate, power consumption, and flow-back/carry-over. The results have shown that pulp lifter assembly with spiral designed radial arms possesses better discharge performance than that with straight radial arms. The discharge performances of three types of designs are also found to be sensitive to some specific design and operating parameters, such as number of vanes, mill rotational speed, the size of particle, and the coefficients of friction. Based on the results, five guidelines on future design and operation of pulp lifter assembly were established.

L'assemblage du releveur de pates est l'une des composantes importantes à la sortie de grille termine-décharge des broyeurs. Il décharge des matériaux broyés à travers le tourillon de la décharge comme une pompe centrifuge fonctionnant en sens inverse à celui requis par une pompe. Bien qu'il soit largement connu conventionnels associés de pâte de conception lifter avec des inconvénients qui causent opération de décharge inefficaces, peu de travaux ont été fait pour comprendre les causes de cet événement particulier. Dans le but de mieux comprendre les effets des différentes conceptions du releveur pates sur la performance de décharge et également établir des stratégies pour la conception et l'exploitation futures d'un tel équipement, ce travail est lancé.

Trois types de conceptions de releveur de pates d'industrie à l'échelle ont été étudiés, y compris deux conceptions classiques et un nouveau design, à l'aide de technique de modélisation méthode des éléments discrets (MED). Les performances de décharge de ces dessins ont été évalués en fonction de trois critères, qui comprennent le taux de décharge, la consommation d'énergie, et flow-back/carry-over. Les résultats ont montré que l'assemblage de pâte-lève comprenant des bras radiaux conçus en spirale possède une meilleure performance que celle de décharge avec des bras radiaux droits. Les performances de décharge de trois types de conceptions sont également trouvés à être sensibles à certains paramètres spécifiques de conception et d'exploitation, telles que le nombre d'aubes, la vitesse de rotation moulin, la taille des particules, et les coefficients de frottement. Basé sur les résultats, cinq lignes directrices sur la conception et le fonctionnement futurs de l'assemblage pâte-lève ont été établis.

Acknowledgment

I would like to express my sincere gratitude to my supervisors Prof. Peter Radziszewski and Mr. Gabe Larose. I thank for their continuous support, patience and dedicated help during the course of this work.

I am grateful to Natural Science and Engineering Research Council of Canada, Le Fonds québécois de la recherche sur la nature et les technologies, and Norcast Casting Limited for their generous financial support.

Thanks must also go to Norcast members, their kindness and easiness left me good memories of working at Norcast. Special thanks to Nima Gharib for his tireless technical support on EDEM. Thanks must also go for Stephane Beland for his help with French translation.

I thank Xiaoliang Sun for her patience and support during the completion of this work.

Finally and most importantly, I would like to thank my parents, Xuehua Ni and Congjin Chu. Their love and support has been continuously providing me confidence and strength to achieve my goals.

List of Figures

Chapter 1

Introduction

In this chapter, a brief description of mining and mineral processing is presented. With the discussion about the progresses achieved in mining and mineral processing for more efficient operations, the hypothesis of this project is determined. The structure of the thesis is also highlighted.

1.1 MINING AND MINERAL PROCESSING

Mining and mineral processing have been playing an integral role in mankind's history. The methodical extraction of metals and minerals from the earth, and their fashioning into tools, ornaments, building materials and all the panoply of material civilizations, are perhaps the activities which most separate modern *homo* sapiens from his ancestors' brief and brutal existence (Napier-Munn, 1997).

The products of mining industry exist everywhere in our world. From individual's basic necessities - a microscopic point of view, such as the iron and light metals used in our bodies, the buildings in which we live and work, the modern electronics we enjoy, the transportations we use, to a nation's development - a macroscopic level, for instance, highways, power distribution systems, even the terrible engines of modern war, are ultimately dependent on the use of mined, non-renewable materials (Berkel 2007).

The production of minerals from the earth is composed of several distinct steps. As illustrated in Figure 1.1 (Napier-Munn, 1997), mineral processing is a critical step which interlinks the extraction of the ore and the production of metals. Depending on different applications, some minerals can be produced directly from mineral processing and supplied to the potential consumers, such as coal for a thermal power station. The other cases, for instance, the production of precious metal – gold, require one extra step of effort which is commonly referred as metallurgical engineering, usually involves more expensive processes.

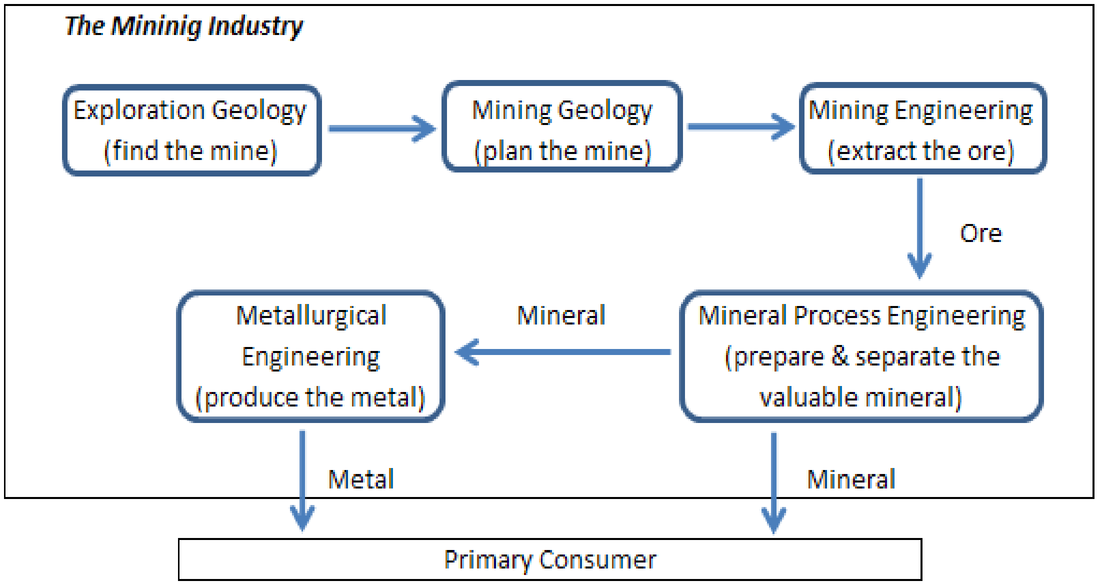


Figure 1.1: The structure of the mining industry

Consisted of numerous complicated processes, mining and mineral processing is indeed an energy intensive industry. According to DOE (2004), the estimated total annual energy required by mining and mineral processing in the USA during 2001, was approximately 1.342×10^3 PJ, whereas the total energy used in the industrial sector in the same year was 34.537×10^3 PJ and the overall national consumption was 101.161×10^3 PJ. These data suggest mining and mineral processing takes over about 3.89% of the energy used by the industrial sector and 1.33% of the total national energy consumption [$1 \text{ PJ} = 1 \times 10^{15}$ J]. Being such a significant energy consumer, its derived environmental impacts are also therefore considerable.

As the global demand for consumer goods continues increasing and the cost for energy becomes pricy, more and more nations have eagerly been looking forward to improving energy efficiency and the efficiency in energy sector (Fang, Wu, and Zeng 2009). To meet the challenges, the technology in mining and mineral processing sector has participated in different ways. Napier_Munn (1997) stated that the most three evolving areas are new processes and technologies, refinements of existing processes and technologies, and increase in scale of operation.

Within the framework of improving efficiency therefore reducing the environmental footprint, this work is initiated. It relates to the comminution process in mineral processing with focus on the discharge end of grate-discharge grinding mills.

1.2 GRATE-DISCHARGE GRINDING MILLS

Grate-discharge grinding mills are operated in the last stage of comminution. It reduces the particle sizes by a combination of impact and abrasion, either in dry or in suspension in water (Wills 2006). Figure 1.2 and Figure 1.3 shows the completed configuration and the simplified schematic of a grate-discharge grinding mill, respectively. During operation, the charge material - rocks is fed from the feed end into the grinding chamber. The mill shells which compose the grinding chamber rotate to transfer motions to the charge and the grinding media which could be steel rods, balls or rock itself. After size reduction, the fined products pass through grate aperture and fall into pulp lifters, and eventually they are transported out of the mill through discharge trunnion.

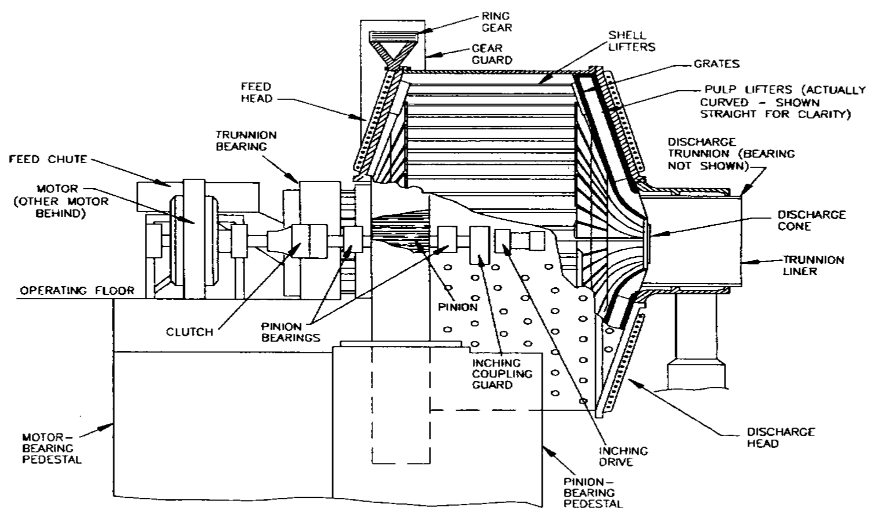


Figure 1.2: Schematic Diagram of a Grate-Discharge Grinding Mill
(Courtesy of Norcast Wear Solutions)

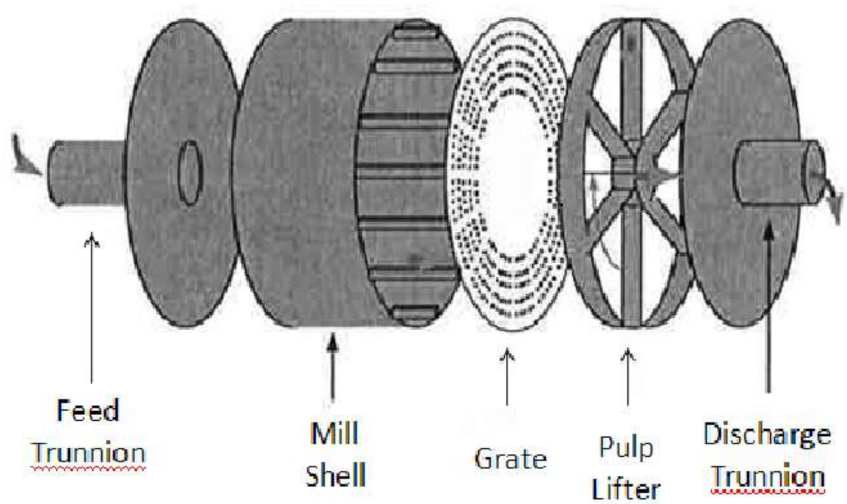


Figure 1.3: Simplified View of a Grate-Discharge Grinding Mill
(Latchireddi and Morrell, 2003)

While considered as energy intensive equipment with low operating efficiency, the popularity of grate-discharge grinding mills still continues. The demand for techniques to improve the performance of these machines is extended under a wide range of conditions. For instance, Morrell, Finch, Kojovic, and Delboni Jr. (1996) analyzed the performance of large mills in terms of breakage rate distributions. Cleary (1998) studied the charge behavior, torque and power draw for a 5 m diameter ball mill. Kotake, Kuboki, Kiya, and Kanda (2010) compared the influence of dry and wet grinding conditions on fineness and shape of particle size distribution of product in a ball mill. In addition to the studies of operating conditions, researches are also quite active from the mills design perspective. Powell (1991) investigated the effect of liner design on the motion of the outer grinding elements. Djordjevic, Shi, and Morrison (2004) used 3D DEM modeling technique to determine the effects of liner designs in autogenous mills.

The design of discharge ends is also of interest. Moys (1986) developed a model to predict the effect of the grate design on the hold-up slurry in a grate-discharge grinding mill. A laboratory based study performed by Morrell and Stephenson (1996) enabled equations which relate the hold-up of slurry in grate-discharge grinding mills with the flow capacity of the grate. Latchireddi and Morrell (1997) presented experimental results obtained from a lab scale model indicating that the discharge capacity of the pulp lifter assembly was always less than that of a grate-only configuration. After another few years of studies, Latchireddi and Morrell (2003) concluded that the conventional pulp lifter designs cause considerable restriction to slurry flow resulting in reduce flow capacity. To overcome the drawbacks of conventional design, Latchireddi and Morrell delivered an efficient pulp lifter design – Twin Chamber Pulp Lifter (TCPL). Their studies have shown the TCPL has significantly overcome the disadvantages of traditional pulp lifters, and it allows the mill to operate close to their design flow capacity.

1.3 OBJECTIVES AND STRUCTURE OF THESIS

1.3.1 Objectives of Thesis

In contrast to the constant studies being conducted on all other aspects to improve the mill performance, literature review has found little from the discharge end perspective. Even though researchers like Morrell, Lachireddi, Stephenson, Moys devoted much of their time on this subject, their findings are observations and conclusions restricted to lab scale mills. There still lacks of understandings and guidelines on how to optimize the design of discharge ends in general, and this is the motivation of this study. Of the two main components of the discharge ends – grate aperture and pulp lifter, this work focuses on the latter. It is the hope that through the comprehensive study of operating conditions and design parameters at pulp lifter region will provide insights for more efficient operation and better design of such important devices in the future.

The completion of this study is accomplished by the following specific objectives:

i. Define performance criteria for pulp lifters

ii. Complete general studies of different pulp lifer configurations based on the criteria established

iii. Conduct studies for different types of pulp lifter with selected operating conditions and design parameters.

iv. Evaluate the results of different configurations exposed to different conditions.

v. Summarize research outcomes to establish strategies for better operations and future design optimization of pulp lifters

1.3.2 Structures of Thesis

This thesis includes five chapters. Chapter One provides a general description of research progresses made on grate-discharge grinding mills and introduces the objectives. Chapter Two is divided into two parts: literature review on the research work focuses on pulp lifter and the establishment of performance criteria. The Third Chapter describes the methodology which includes the description of modeling software – EDEM, the types of pulp lifter configurations, and simulation parameter settings. Chapter Four will be presentation and discussion of results. Chapter Five summarizes outcomes of this study, and establishes general guidelines for future design and operation of pulp lifters. Finally, it presents recommendations for future work.

Chapter 2

Pulp Lifter Performance Criteria

Pulp lifters are one of the important types of components at the discharge end of grate-discharge grinding mills. They act as a pump to lift the slurry up from the pool to overflow through the discharge trunnion (Powell and Valery, 2006). The performance of the pulp lifters in conjunction with grate design determines the ultimate flow capacity of the grate-discharge grinding mills (Latchireddi and Morrell, 2003). This chapter discusses the different types of pulp lifter configurations, and also determines the criteria to be used to evaluate the performance of pulp lifters.

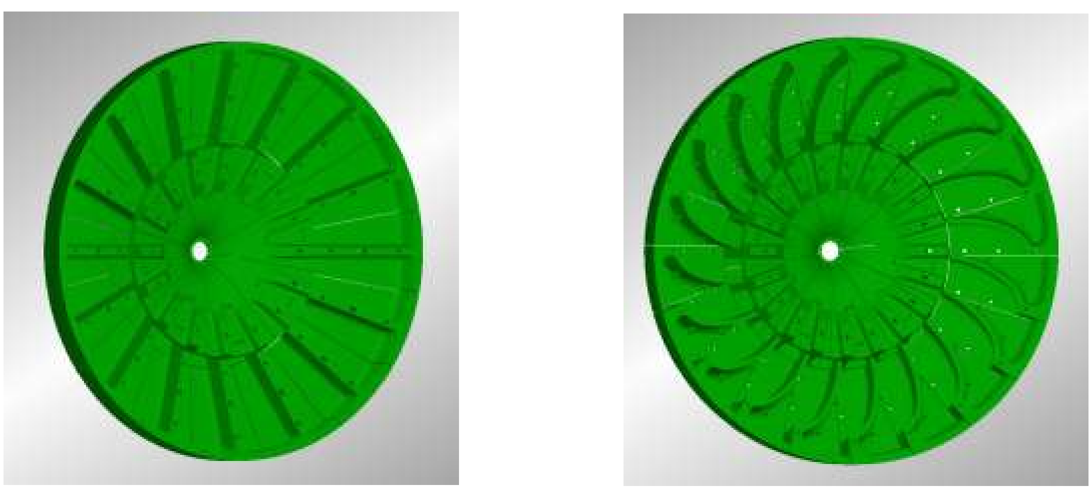
2.1 PULP LIFTER CONFIGURATIONS

As previously shown in Figure 1.3, pulp lifters are radial vanes located between the grates and the end of grate-discharge grinding mills. Depending on the types of mills, vanes walls can be straight, or curved. They extend out from the discharge cone to the periphery of the mill. The most conventional pulp lifters are straight radial arms, such as shown in Figure 2.1 (a). A more efficient design of the pulp lifter, as illustrated in Figure 2.1 (b), is curved.

Even though effort has been done to improve the design of the pulp lifters, the inefficiencies associated are still inevitable. The early record of the inefficiency of the pulp lifters was made by Mokken, Blendulf, and Young in 1975 during their study of the influence of the arrangement of pulp lifters on a mill performance. It was also observed by Latchireddi and Morrell in 2003. Their studies had demonstrated that for the same slurry hold-up in a mill, the maximum discharge rate of the mill with only grate at its discharge end was much more than that of the mill with standard radial pulp lifters.

The highlighted inefficiencies of the pulp lifter system consequently raise a series of questions, such as why one has to appreciate the issues associated with pulp lifter systems and how these happen. Powell and Valery (2006) gave a vivid example. The pulp lifters are effectively a centrifugal pump running in the reverse direction to that required by a pump. A pump drawing liquid in at the centre and flings it to the periphery, whereas the pulp lifters move slurry from the periphery to the centre.

Since the grate-discharge grinding mills are complicated systems integrated with numerous types of components, determining the cause of the inefficiencies associated with the pulp lifters is not easy. Bond and Kjos (1985) pointed out that the problems associated with pulp lifter assembly was critical and needed to be solved. In 1994, Stromayr observed inconsistencies between the actual and theoretical flow rate of pan lifters in his test using a lab-scale mill. Even though drawbacks of the pulp lifter assembly are crucial, literature review has found little concentrated on this particular aspect. The only recent investigation was made by Latchirreddi and Morrell (2003). During their studies of a 0.5 m long grate-discharge grinding mill with 1 m in diameter, they have made several findings. With a specific given conditions, the discharge rate increases as the size of the pulp lifter increases. The influence of the mill speed is differentiated with the types of the pulp lifter configurations. The improvement in the discharge rate resulted by the charge volume is confined within a specific range. The investigator also compared the variation between different pulp lifter configurations. They have found that irrespective to the test conditions, the discharge rate of the curved pulp lifters is always higher than that of the straight pulp lifters.



(a) Straight Pulp Lifter (b) Curved Pulp Lifter

Figure 2.1: Conventional Pulp Lifter Configurations
(Courtesy of Norcast Wear Solutions)

2.1.1 Geometry of Radial Arms

The terminologies of 'straight' and 'curved' for the pulp lifer designs are primarily designated for the geometry of the radial arms. As shown in Figure 2.1 and Figure 2.2, the pulp lifters are series of straight or curved arms that extend from the centre of the mill which is typically referred as discharge trunnion, to the periphery of the mill. They behave like a reversed centrifugal pump which collects materials from its periphery and transport them out via its centre. Figure 2.2 shows a schematic of the process.

The influence of the radial arm designs on the performance of pulp lifters arises from a few aspects. For the straight type, the length of arm is one of the key factors. This is because the length of the arms determines the distance for which the materials travel from the periphery of the mill to the discharge trunnion. It also regulates the opening the discharge trunnion for a given mill diameter since the arms are based on the outer side of the mill and can only be extended inwards to the centre. The curved design affects the pulp lifter performance in a similar manner except the existence of curvatures will speed up the acceleration of the materials toward the discharge trunnion hence achieve a faster discharge rate. Another critical factor is the height of the arm walls. It is obvious that the increased height will result in a large surface area and therefore introduce an enhanced transportation capacity. But there are immediate tradeoffs, such as the potential increase in the worn areas which will result in costly assembly replacement.

Even though curved pulp lifters possess a better performance, the straight type is the most commonly used in industry. This is probably due to the fact that lots of the mills in operations are bidirectional, and the curved pulp lifers can only be functioning in one direction. Other lacks of attention may also include the cost and the complexity involved during replacement of existing mills.

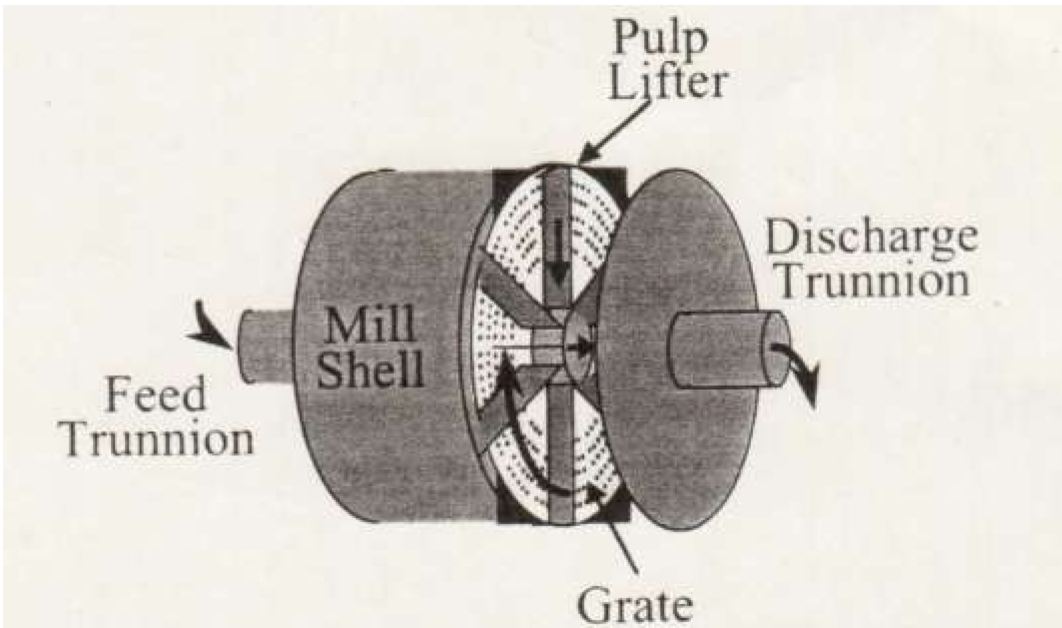


Figure 2.2: Schematic of Grate and Pulp Lifters in SAG Mill
(Latchireddi and Rajamani, 2005)

2.1.2 Number of Vanes

Vane, also known as radial arm, is the primary component of the pulp lifter. The number of vanes determines the volume of segment formed by the adjacent vanes. Each formed segment is similar to a conical structure with its base at the periphery of the mill and its peak at the discharge trunnion. It acts a chute of the water wheel that scoops the materials from the pool at bottom of the mill, and then rotates to certain height, finally discharges the contents. The capacity of segment is a threshold to the performance of pulp lifters system since it determines how much material can be loaded and unloaded. With no formal guidelines on how to select the number of vanes, industry usually makes their decisions by conventional method. The number of vanes would be match closely to the diameter of the mill. For instance, the number of vanes for an 18 ft mill in diameter could be from 16 to 20.

Since the segments are formed by the arrangements of radial arms, the number of segments is thereby roughly equivalent to the number of vanes. Incorporated with the geometry of the vanes, these two are important factors that influence the performance of pulp lifter systems. They will be addressed in this study.

2.1.3 Mill Diameter

Grate-discharge grinding mills have been used in the mineral processing industry for more than 100 years. With the design changing little, yet the size of individual pieces of equipment increases significantly. Today 38 ft and 40 ft SAG mills with a motor powers of more than 20 MW and ball mills with a diameter of 24 ft and a corresponding motor power of more than 11 MW are in operation and operators are now looking for even larger equipment to be installed (Riezinger, Knecht, Patzelt, and Errath, 2001). Figure 2.3 shows a 40 ft SAG mill in operation.

In addition to the increased energy consumptions, the increase in mill diameter also brings up several other issues. For instance, the necessity of a larger facility to manufacture the equipment, the applicability of larger transportation tools to relocate the mill, the requirements of more powerful motor systems to drive the mill operation, the complexities involved during regular maintenance, and the various cost associated. As an integrated component of the grate-discharge grinding mills, pulp lifters system also faces same issues. The increase in mill diameter causes changes to pulp lifters from several aspects. For example, it brings variation to the number of vanes and consequently affects the capacity of each vane, and therefore causes changes in discharge performance. In this work the effect of large mill diameter on mill performance will be investigated in conjunction with several other factors.

Figure 2.3: A 40 ft SAG Mill in Operation
(Courtesy of Norcast Wear Solutions)

2.2 PERFORMANCE CRITERIA

There are a number of criteria to evaluate the performance of grate-discharge grinding mills. Depending on specific interest, researchers have different focuses. For instance, Chenjie and colleagues conducted experiments to study the cost effectiveness index of the types grinding media and the milling performance for a ball mill. Cleary (2001) investigated the power consumption in a ball mill exposed with different operation conditions, liner geometries and charge compositions. An inferential model for semi-autogenous grinding (SAG) mill built by Apelt and co-researchers measured the SAG mill discharge and feed streams and mill rock and ball charge levels. In 2007, Makokha and Moys presented their work to investigate the effect of liner/lifter profile on the discharge capacity of dry ball mill products.

With concentration on the pulp lifters assembly, the performance criteria in this work will be based on three important areas, the discharge rate, the power consumptions, and the flow-back/carry-over. It is of great interest to evaluate the performance of different types of pulp lifters against these factors, and it is the hope that useful information can be extracted for future improvement of this equipment.

2.2.1 Discharge Rate

Discharge end has many constrictions that are widely used in mineral processing systems (Ozer, Egrun and Benzer 2006). Measurement of the mill discharge rate is required to satisfy the basic grinding circuit control requirement of determination of the circulating load (Lynch, 1997). For overflow grinding mills, the product is transported out of the mill driven by the flow gradient due to the fact that the diameter of the discharge end is larger than that of the feed end. However, the grate-discharge grinding mills are different. The process starts with the materials being fed from the feed end, followed by size reduction through the grinding chamber, and then the materials reach the grate where the first stage of discharge occurs. If discharge end consists of grate system only, the maximum discharge capacity (rate) for this given mill can be obtained by the grate design in terms of open area and position of holes (Latchireddi and Morrell, 2003). However, for a system consists of grate and pulp lifters, Latchireddi and Morrell found that the existence of pulp lifters causes considerable restrictions to flow resulting in reduced discharge capacity.

The cause of limitations of pulp lifter on the discharge rate is in conjunctions with other factors. Abouzeid and Fuerstenau (1980) investigated the flow rate in a constricted ended lab scale mill for various feed rates, rotational speeds, particle size range of the feed material. Moys (1986) studied the problems used a 54 x 83 cm pilot ball mill in which the discharge arrangement were varied. Afacan and Masliyah (1990) examined the flow of granular solids in another lab scale mill with different design combinations at four different feed rate and various rotational speeds. Researchers, such as Morrell and Stephenson (1996) conducted pioneering studies during which they proposed two equations relating the hold-up in the grinding media and pool zone with flow rate, grate design and mill diameter for a mill at laboratory scale.

All of these studies are valuable and important to provide guidelines for investigating the effects of different mechanisms on discharge rate. However, these studies were conducted in lab scale mills. In this work, industrial scale models are adopted. The discharge rate of different pulp lifter assemblies will be thoroughly evaluated against factors that are of most concerned, including the number of vanes, the mill rotational speed, particle size, and coefficient of friction.

2.2.2 Power Consumption

Power consumption of mills has always been drawing researchers' attention. Test work and development of mathematical models to predict energy requirements for grinding mills has been in progress for well over 100 years (Levannaho et al. 2001). Investigations have been conducted from different aspects to understand the mechanism of mill's power draw. Cleary (2001) conducted a comprehensive study to analyze power consumption in a ball mill sensitive to mill operating conditions, liner geometry and charge composition. One of important observations from his research was that when the mill is operated at a speed which is higher that the mill's critical speed, the power consumption decreases. Whereas for a speed that is lower than the critical speed, the power consumption increases. The author concluded the speed for which the peak power consumption occurs is a result of combination of effects of the shear strength of the charge material and the fill level.

Even though there are adequate investigations being conducted to improve the energy efficiency of grate-discharge grinding mills, most of them are related to the grinding process. Pulp lifters as an important component of the mill system draws a certain amount of power and this power draft is clearly linked with mill throughput (Latchireddi and Rajamani, 2005). However, little attention has been paid to this consideration. Since the operation of grate-discharge grinding is an integrated process with many different factors involved, it is logical to understand the influences of each of the variables in order to understand the mill capacity much more clearly. With this in mind, this work will precisely study the power consumptions at pulp lifters region. It is expected that through the comparison studies of different designs exposed by different operating conditions, certain useful information can be found.

2.2.3 Flow-Back and Carry-Over Phenomena

Flow-back and carry-over are important phenomena existed at the discharge region of grate-discharge grinding mills. The geometry of the conventional pulp lifters (straight and curved) is such that the slurry, once passed through the grate into pulp lifter will always be in contact with the grate until it is completely discharged, which makes the 'flow-back' inevitable (Latchireddi, 2002). Carry-over occurs at higher mill speeds at which the materials collected by vanes are not completely discharged out through the discharge trunnion for one discharge cycle. Rather, it eventually flows through the gate back into the mill by the time it starts a new cycle (Latchireddi, 2002). An illustration of the slurry flow in grate-discharge grinding mills has summarized by Latchireddi and Morrell (1997), and is shown in Figure 2.4.

Flow-back and carry-over are drawbacks during mill operations. To prevent or minimize their impacts, researchers have made considerable efforts. Among those, the most pioneered are Latchireddi and Morrell (2006) who developed a new pulp lifter design which is Twin Chamber Pulp Lifter – TCPL, shown in Figure 2.5. They conducted extensive tests and showed that the TCPL completely blocked the flow-back process, and thus allowing the mill to operate close to their design flow capacity. The innovative design is also found to be independent of variations in charge volume, whereas it significantly affects the performance of conventional pulp lifters, such as shown in Figure 2.6.

Three pulp lifters designs, straight, curved, and a new design inspired by TCPL are investigated for the study of flow-back/carry-over. The objective is to identify the response of these phenomena on the types of pulp lifters design and also obtain better understandings on how to control these drawbacks.

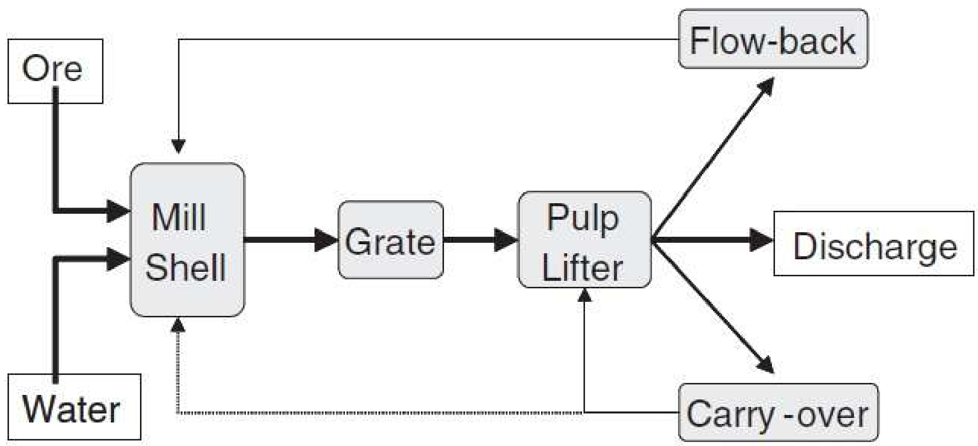


Figure 2.4: Flow in a Grate-Discharge Grinding Mill

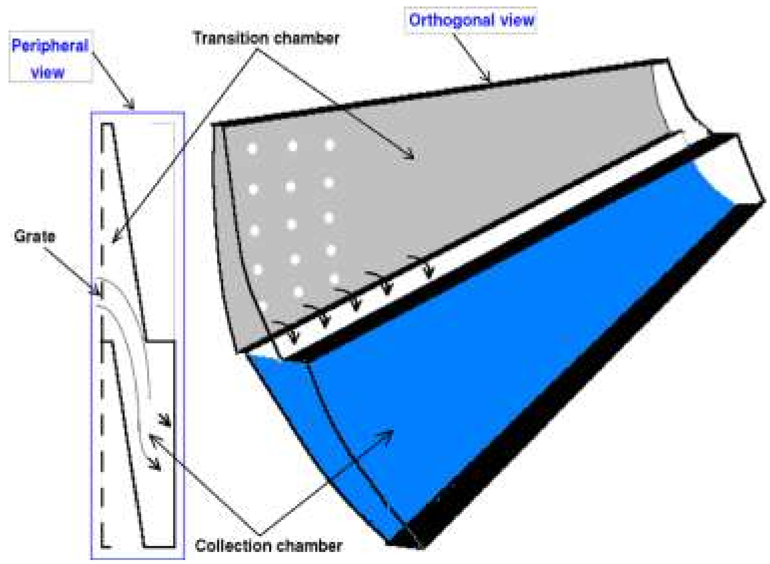


Figure 2.5: The Schematic of TCPL Arrangement

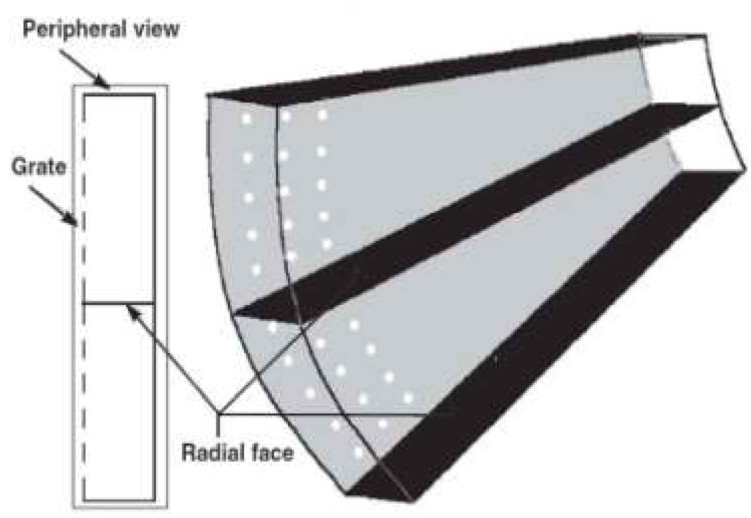


Figure 2.6: The Schematic of a Straight Pulp Lifter

2.3 SUMMARY

Among various design parameters that cause changes in discharge performance of pulp lifter assembly, this work will focus on the three, the geometry of the radial arms, the number of vanes, and the mill diameter. Combined with variations of these design parameters made on three types of pulp lifter assemblies, changes in operating factors, such as mill rotational speed, particle size, and coefficient of friction, will be simultaneously integrated throughout this study. It is of great interest to investigate the effects of these factors on the discharge performances of pulp lifter assemblies evaluated against discharge rate, power consumption, and flow-back/carry-over.

Chapter 3

Methodology

The Discrete Element Method (DEM) is nowadays acknowledged to be an effective procedure for analysis of granular and rock materials under static and dynamic loads (Onate and Rojek, 2004). The first part of this chapter introduces the background of DEM. Then it describes straight, curved and a newly designed pulp lifters adopted in this study. The last section is to present the simulation parameter settings.

3.1 THE DISCRETE ELEMENT METHOD

Discrete Element Method is a numerical method which is use to compute dynamics of many particles. It is quite computationally demanding, which reflects on the fact that it either restricts the number of particles that it can simulate or limits the length of a certain simulation. Some DEM methods adopt the use of parallel processing to increase the number of particles or decrease the length of a specific simulation, such as its application for molecular dynamics. There are also other approaches. For example, researchers sometimes treat many particles independently and therefore treat material as a continuum. Study related to DEM usually involves combination of other numerical method, such as finite element method, computational fluid dynamics.

Thank to the rapid development in computer technology and computing algorithms, it is now possible to apply DEM technique to studies that are related to larger number of particles. Nowadays, DEM has become a popular and effective method to address engineering problems related to granular materials, especially in mining and mineral processing industry.

Among the applications of DEM in mining and mineral processing industry, the most pioneered work was carried out by Cleary and colleagues (1998, 2001, 2003, 2006, 2009, and 2011). The researchers have modeled ball mills and SAG mills with several crucial interests, such as predication of charge motion, power consumption, segregation, liner geometry, transportation of slurry, and ore breakage. The important findings they made have been broadly accepted by the industry, and some of which has been adopted as operating guidelines. These progresses reflect the applicability of DEM has been widely recognized and it is a reliable method for analyzing engineering problems in mining and mineral processing.

EDEM is a software application developed by a UK company named DEM Solutions. It is the world's only computer-aided-engineering software platform powered by Discrete Element Method. It has the capability to generate simulations and analysis to solve complicated problems in design, prototyping and optimization of bulk material handling and process equipment (DEM Solutions).

EDEM consists of three components – Creator, Simulator and Analyst, as shown in Figures 3.1, 3.2, and 3.3, respectively. Four assignments need to be completed in Creator, and they are specification of parameters, definition of particles, initialization of models, and regulation of particle generation. Simulator is essentially the discrete element solver, where user inputs information, such as Rayleigh time step, the desired simulation time and number of processors to be used. When simulation is completed, user has several analysis options in Analyst to study their results. EDEM is also capable to generate high quality videos and pictures for simulations.

It should be emphasized that the use of EDEM software greatly depends on the available computing power. The computers used for this study are two workstations of which both have four central processing units. Their other hardware also satisfies the requirement of the application of EDEM on this study.

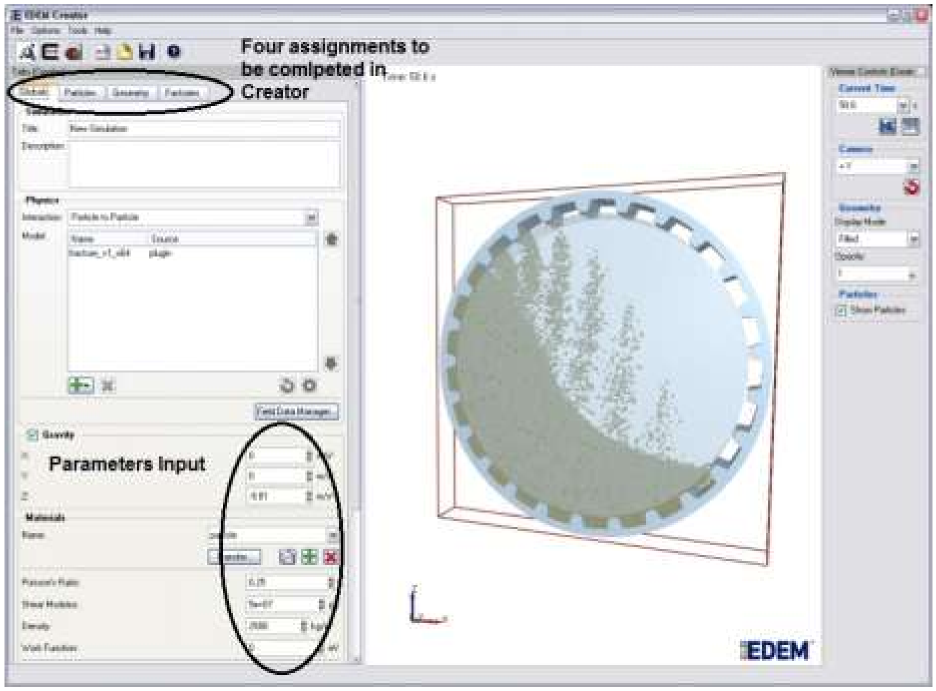


Figure 3.1: EDEM Creator (EDEM Manual)

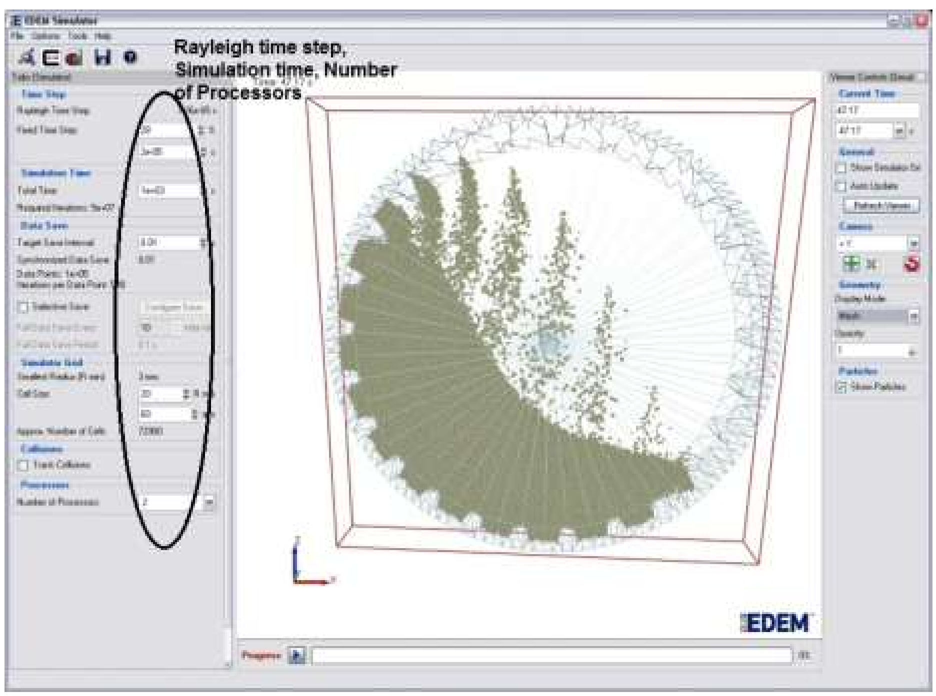


Figure 3.2: EDEM Simulator (EDEM Manual)

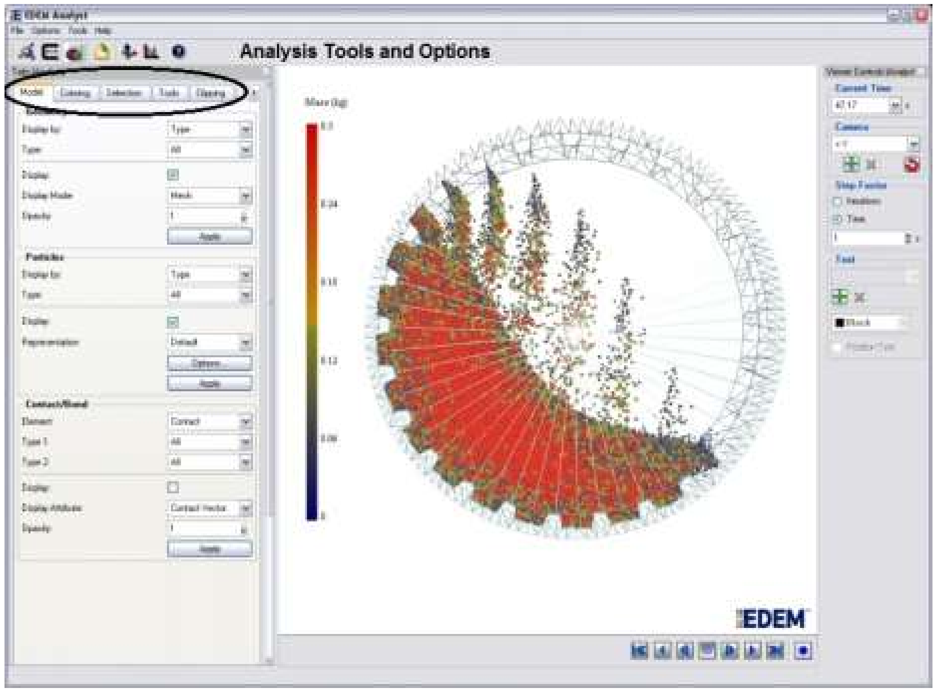


Figure 3.3: EDEM Analyst (EDEM Manual)

3.2 DESCRIPTIONS OF MODELS

Depending on the geometry of the discharge end, there are two kinds of mills – flat and conical-ended, as shown in Figure 3.4. The three types of pulp lifter assemblies (Designed by Norcast Wear Solutions) studied in this work are incorporated with conical-ended mills. Because the focus of this work is pulp lifter, there is only one type of grate design throughout this study. This guarantees the minimized distractions from factors other than pulp lifters and also ensures the consistency of the results.

The first model shown in Figure 3.5 is a pulp lifer assembly which has straight radial arms. The diameter of this discharge end is 18 ft, and the number of vanes is 20. It should be noted that the radial arms are not fully extended to each of the radial lengths. The arrangement is such that every second arms are shorter than their neighbor. The benefit of this layout is to prevent flow constriction at the centre of the discharge that is caused by the convergence of the thick pulp lifter bars (Powell and Valery, 2006). Figure 3.6 shows a curved design with same diameter and number of vanes.

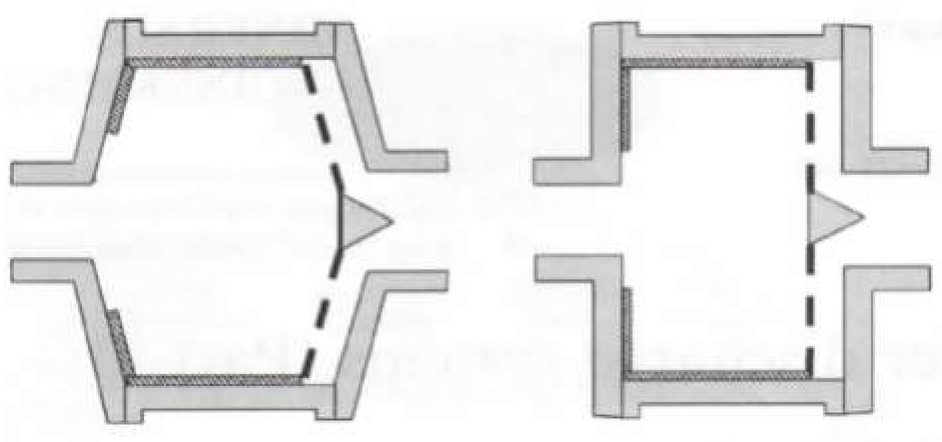


Figure 3.4: Schematic of conical-ended and flat-ended mills
(Latchireddi and Morrell, 2003)

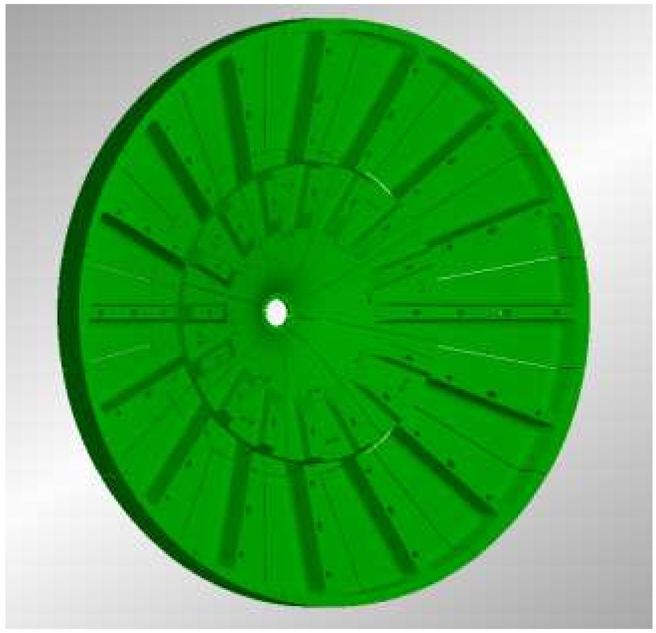


Figure 3.5: Straight Pulp Lifters

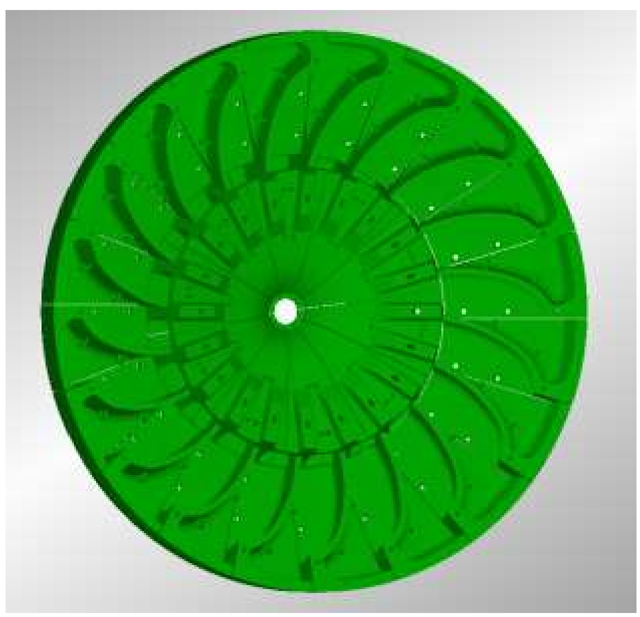


Figure 3.6: Curved Pulp Lifters

A new pulp lifter design (referred as the New Design) inspired by the Twin Chamber Pulp Lifter (TCPL) by Latchireddi and Morrell (2006) was the third type of assembly studied in this work. Designed by the sponsoring company of this project, it is believed the new design possesses features similar to TCPL which is capable to block the flow-back and increase discharge capacity. As shown in Figure 3.7, the 18 ft diameter new design looks like the curved pulp lifter. However, the difference is that the box-designed vanes in the new design are not exposed directly to the grate, which eliminates the ability of materials to flow backward into the mill through grate.

Figure 3.7: Newly Designed Pulp Lifters

All the models investigated in this work were based on the three described but with modifications according to specific research interest. The following chapter presents the details of these modifications and the results with which were obtained.

3.3 SIMULATION PARAMETER SETTINGS

The entire work of this study was based on the assumption that mill was operated in **DRY** conditions. Each of the discharge simulations was carried out for one complete revolution – one discharge cycle.

EDEM offers several types of physics interaction models to describe how element behave when they get in contact with each other. Among Hertz-Mindlin no slip condition, Hertz-Mindlin with heat conduction, and Hertz-Mindlin with bonding, this work adopted the first.

The environment of the simulations was assumed on earth, where the gravitational field is 9.81 m/s^2. The materials for pulp lifters and particles were two types and their properties are listed in Table 3.1, respectively. The interactions between pulp lifters and particles are sophisticated because there are many variables participated, such as the coefficient of friction, the elasticity of the materials, and the coefficient of restitution. This work focused on the variation of coefficient of friction. Results of simulations with different coefficients of friction are presented in the following chapter.

The size of particle is another important subject. To reduce the computational complexity, the particles were assumed as sphere balls. Even though particles are guaranteed to have the same or smaller sizes than those of the grate holes, it is important to identify whether the variation of this parameter will cause inefficient discharge at the pulp lifter region, which may further affect the overall grinding operation. Three diameters – 10mm, 15mm, and 18 mm were chosen with respect to the size of the designated grate design.

Another relevant factor is the number of particles. It should be mentioned that the charge volume mentioned in this research is about the amount of materials that have passed the grate and fallen into the pulp lifter chamber. A maximum mass-based charge volume was provided by the sponsoring company according to their mill operation. With this charge kept constant, numbers of particles with different diameters were consequently determined. The number of the particles is also dependable on the number of vanes because which determines the segment capacity. The details about the number of the particles for 18 ft pulp lifters are summarized in Table 3.2. It should be reminded that for the same mill diameter, the numbers of vanes for straight, curved and a new design pulp lifters are kept the same. To provide an intuition on the simulation length, the amount of time required for a simulation that involved with 1000 particles of 15 mm for five seconds is typically around 15 hours.

	Density (Kg/m^3)	Shear Modulus (Pa)	Poisson's Ratio
Pulp Lifters	7850	7.93×10^{10}	0.27
Particles	2700	2.00×10^{10}	0.30

Table 3.1: Properties of Materials for Pulp Lifters and Particles.

18 ft Pulp Lifters			
Diameter of Particles	Number of Particles per Segment		
	16 Vanes	20 Vanes	22 Vanes
10 mm	8100	6750	6075
15 mm	2400	2000	1800
18 mm	1389	1157	1042

Table 3.2: Number of Particles for 18 ft Pulp Lifters

The engine that drives the flow inside a mill operation is the pressure gradient across the feed end and the discharge end. Figure 3.8 shows an operation in a typical grate-discharge grinding mill. It is expected and also observed that the grinding materials level is higher at the inlet due to continuous feeding, and lower at the discharge end because of the constant discharging. If one observes the mill in the opposite direction of material flow, such as Figure 3.9, it can be seen that materials are mostly accumulated at one side of the mill. Inside the grinding chamber where it closes to grate, the materials are lifted up as mill rotates. When they reach to certain height, commonly referred as shoulder position, they leave contact with the mill body to fall onto a lower location called toe position, and then rotate with the mill body again. It is during this process that the grinded materials pass through the grate to fall into the pulp lifter chamber. The specific drive of this transportation is due to the hydrodynamic pressure across the grate where one side of it has material piled up at a higher level, whereas the other side is lower. However, this hydrodynamic pressure vanishes as mill rotates. It is evidence that at the bottom six o'clock of the mill, the effect of this pressure is the maximum because material piled up height difference across the grate is the largest. But when mill rotates to somewhere between nine and ten o'clock positions, the effect of this drive becomes less significant, essentially because there is little material available at this height inside the grinding chamber to pass through the grate. Since the focus of this study does not involve the effect of this pressure, the particles are pre-located at somewhere between nine and ten o'clock position at the beginning of discharge. Figure 3.10 demonstrates an example of the initial position of particles when a typical simulation is about to start.

The rotational speeds of the discharge simulations were based on the mill diameters. Given the following equation provided by Norcast, the critical speed of a specific mill can be calculated. Depending on certain circumstances, mills usually do not operate at their critical speeds. In this study, the researcher has investigated the effect of 50%, 70% and 100% of critical rotational speeds on the discharge performance of three types of pulp lifters. It should be noted that the unit of critical speed obtained from the given equation is revolution per minute. However, it is converted into radian per second when it is specified in EDEM for consistency of other SI units.

$$N_c = \frac{76.6}{\sqrt{D}}$$

Where N_c, revolution per minute, is the critical speed; D, feet, represents the diameter of the mill.

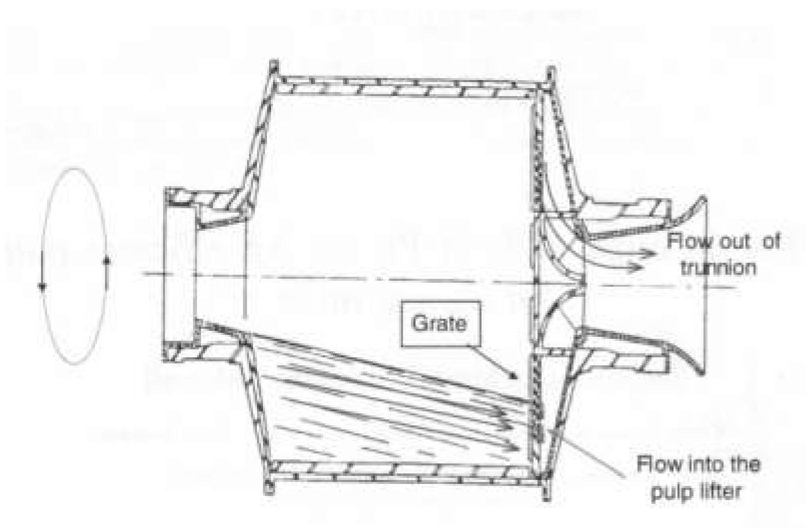


Figure 3.8: Schematic of a Typical Grate-Discharge Grinding Mill in Operation (Latchireddi and Morrell, 2006)

Figure 3.9: Materials Fill-Up Level of Grate-Discharge Grinding Mill
(Cleary 1998)

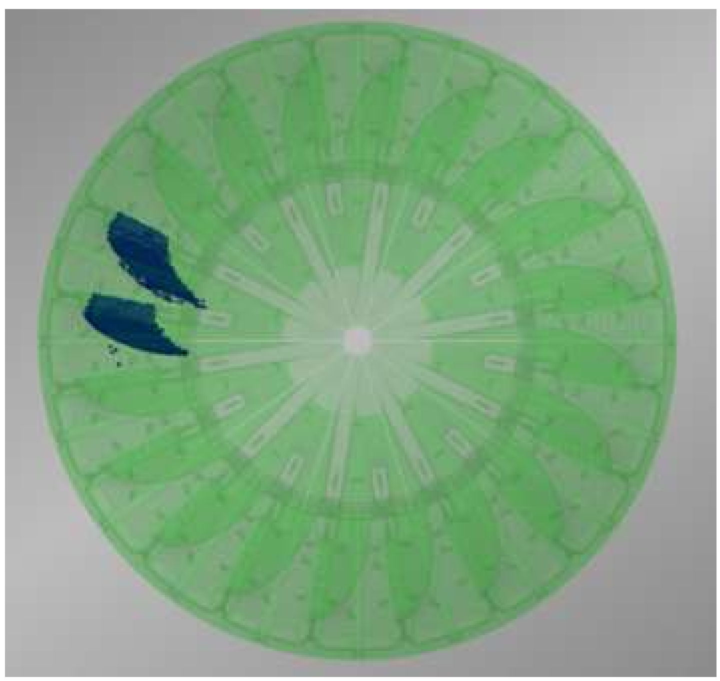


Figure 3.10: An Example Showing the Initial Position of Particles
at the Beginning of a Simulation

3.4 SUMMARY

This chapter provides a background for the EDEM software application used in this work. Three types of pulp lifter design, a straight, a curved and a new design inspired by TCPL, were shown and described. Finally, the simulations parameters, such as the particle contact model, the material selections, the particle sizes, the numbers of particles, were presented.

Chapter 4

Results and Discussions

Simulation results are obtained according to the three performance criteria listed in Chapter 2 – discharge rate, power consumption and flow-back/carry-over. Discussions of these results are also presented.

It should be noted that during the course of this study, all simulation parameters other than the specific investigated are kept constant so that the effect of each of interested variables can be evaluated independently. This study is anticipated to demonstrate the functional dependencies of the performances of pulp lifters on different design parameters and operating conditions. Because it is difficult to obtain detailed data for comparison and the DEM model is simplified, the dependencies are currently still qualitative. The results in this work are based on relative changes of pulp lifter performances with changes in design and operating parameters and not on absolutely accuracy of pulp lifter performance.

4.1 REPRODUCIBILITY

As discussed in previous chapter, EDEM offers different contact models to simulate particles behaviors. With Hertz –Mindlin no slip condition applicable to this work, preliminary simulations were carried out to examine the reproducibility of EDEM. Figure 4.1 shows discharge activities obtained from repeated simulations for an 18 ft new designed pulp lifter systems. The curve represents the number of particles discharged through the trunnion with time.

During simulations, all simulation parameters were kept constant except the initial positions of particles. Under random generation mode, particles are continuously being generated in designated virtual particle factories. It may be often the case that the volume of the required number of particles is beyond that of the virtual particle factory. When this happens, the particles located at the front are pushed off by the particles behind them to quickly exit the virtual particle factory. Since the particles are generated randomly at the beginning, their positions and velocities at the moment to exit the virtual particle factory for three repeated simulations are consequently different. After falling into the vane of pulp lifters, the particles are regulated by the pulp lifters until they are discharged.

Different from traditional method of using standard deviation to study the reproducibility, this study adopted the analysis of the effect of particle initial velocities positions on the simulations. Since the discharge activity is functionally dependent on the design parameters of pulp lifters and operating conditions, it should not vary with the change of particle initial positions and velocities during repeated simulations. The results show a good agreement with the expectations. Three repeated simulations have indicated that this specific pulp lifter assembly is able to discharge about 70% of the initially charged particles. Even though there are tiny fluctuations towards the end, they are reasonable which may be explained by the fact the particles have more random freedom towards the end of one discharge cycle due to less restrictions from pulp lifters.

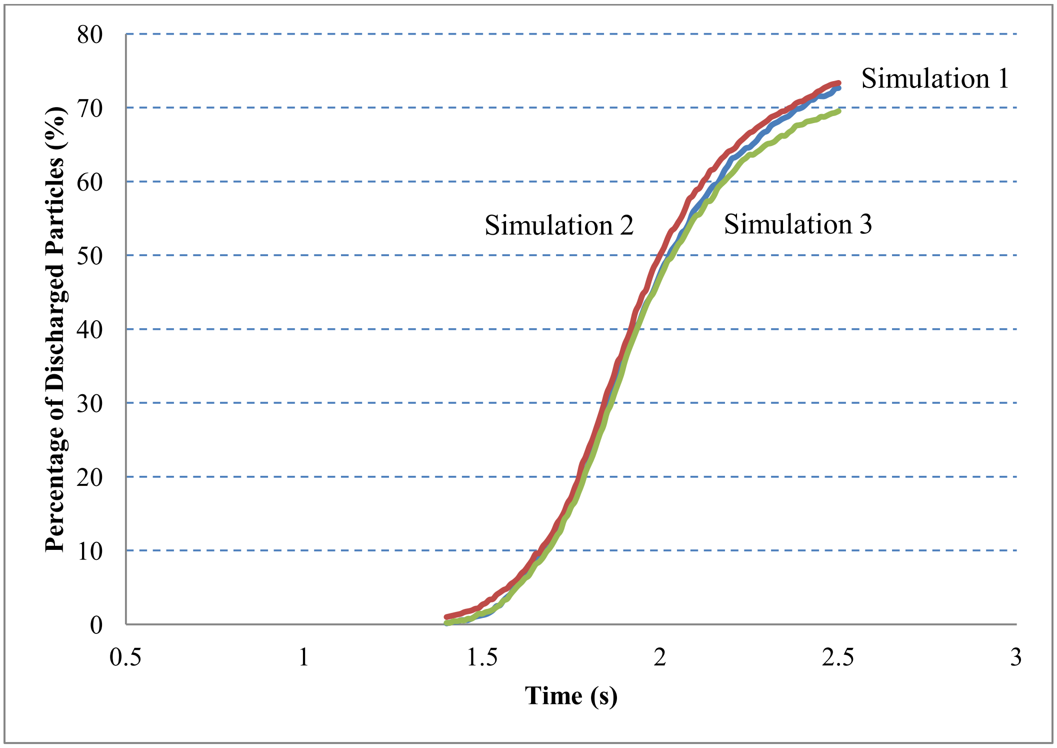


Figure 4.1: Preliminary Simulations for an 18ft new designed Pulp Lifter System

4.2 DISCHARGE RATE

EDEM is capable of tracking several physical quantities during simulation, such as the number of particles in a specific domain, the kinetic energy, the potential energy, and the torque of a specific geometry. However, it does not directly provide record for the discharge rate that is of interest to this study. To calculate this quantity, one can get a hint from Figure 4.1, which shows a typical graph for the number of discharged particles elapsed by time.

Known as the common discharge rate, tons/hour, is based on the mass of the discharged particles over a certain period of time, the discharge rate can be obtained from the graph by calculating the slope of the linear portion. Since all results in this work are based on relative changes of one parameter to another, the discharge rate obtained is also on a relative basis, mass/mass/time.

4.2.1 The Effect of Radial Arms' Geometry

The discharge rates with variation in radial arms' geometry were obtained through simulations with changes in mill rotational speed, coefficient of friction, and particle size. As discussed previously, the three types of pulp lifers include straight, curved and a new design inspired by TCPL. The other influential parameters, number of vanes, diameter of the assembly, and charge volume were kept constant during simulations.

4.2.1.1 Variation in Mill Rotational Speed

Figure 4.2 shows the relative discharge rates for three types of pulp lifter assemblies at 50%, 75%, and 100% of critical speed for an 18ft mill. It is observed that the new design has the best discharge performance when mill rotates at 75% of its critical speed. It was able to discharge about 45% of the charged materials for one discharge cycle, compared to 38% for curved and 32% for straight, respectively. When mill was operated at 100% of its critical speed, the relative discharge rates for all three designs decreased. The performances of the new design, curved, and straight fell to about 22%, 20%, and 0%, respectively. However, discharge performance behaved differently when rotational speed was lower. At 50% of critical speed, the best discharge performance was achieved by straight pulp lifters for about 40%, whereas the new design only accomplished for about 31%. The performance of curved design has been consistently located in between the new design and straight where it was about 35%.

It is concluded that there exists an optimal mill rotational speed in order to achieve the maximum discharge rate for a specific pulp lifer design. If curve-fit the data using a second degree polynomial, one can observe that the maximum discharge rate occurs at around 70% of critical speed for the new design, 60% for the curved, and about 50% for the straight. One reason to explain the new design and the curved possess better discharge performance at 75% of critical speed is that their spiral designed radial arms assist particles to accelerate during discharge. The spiral arms provide particles more space to move in the direction of gravity hence creates additional vertical velocity components to weaken the effects of centripetal forces and eventually results large discharge velocities. As for the straight pulp lifters, the particles only slide on the surfaces of the radial arms or on top of other particles. This layup is less efficient since there are barely reductions on centripetal forces which drag down the discharge velocity. Another reason to explain the advantages of spiral designed radial arms is that the spiral geometry acts a scoop that is able to collect more particles than the straight design does. The weight of additional collected particles creates extra pressure to accelerate the particles underneath to exit faster. Figure 4.3 shows an illustration of the explanations. It should be noted that the above is only true when mill rotational speed is higher, and it is reversed for lower mill rotational speeds.

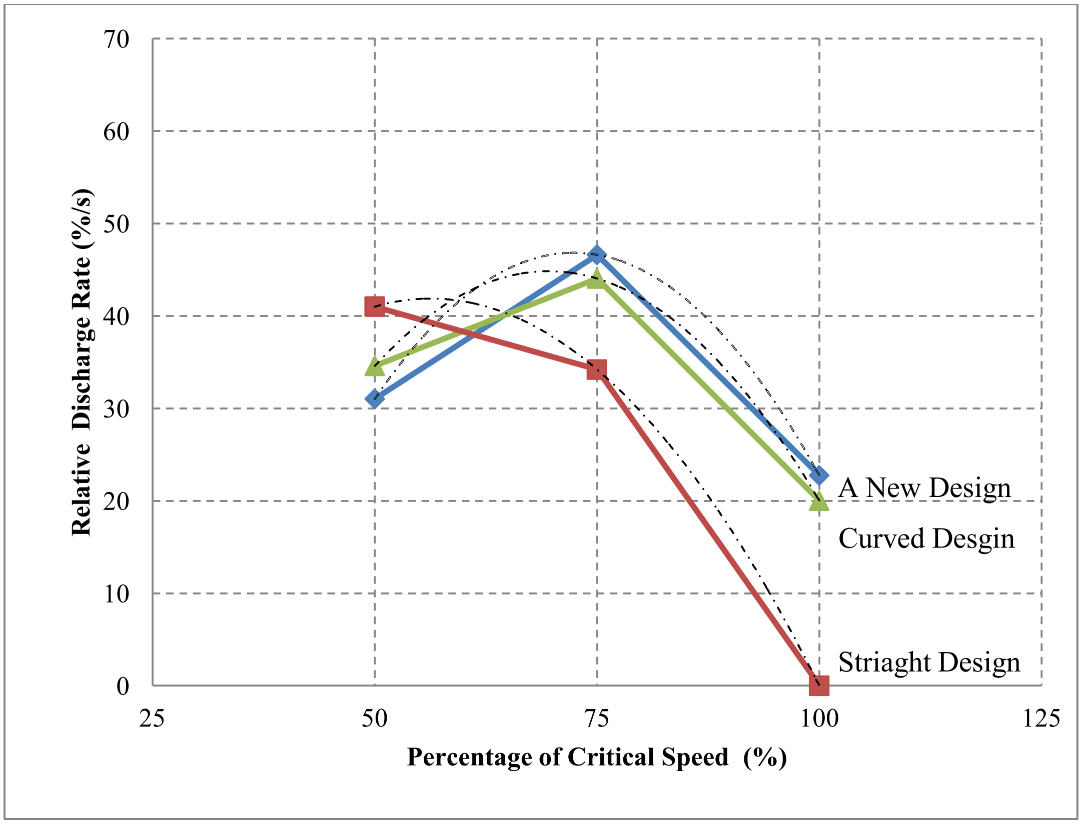


Figure 4.2: Discharge Rates of Three Designs Operated at 50%, 75% and 100% of the Critical Speed

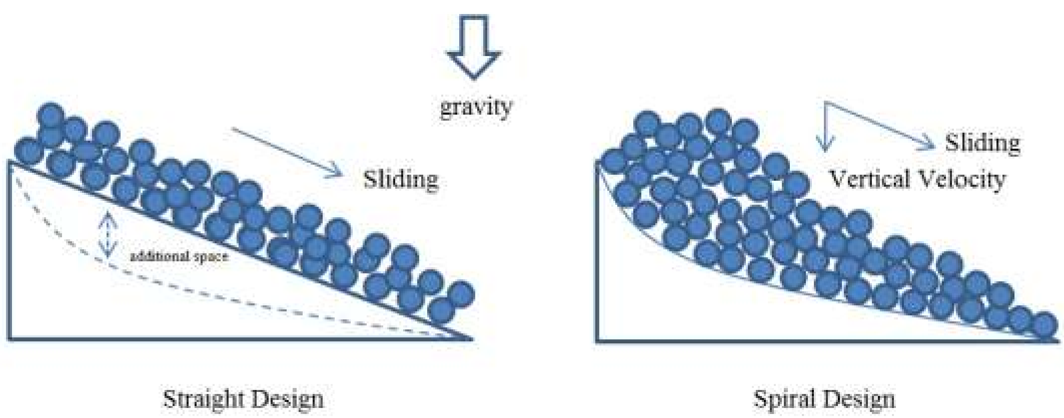


Figure 4.3: Schematic of Particle Move in a Cross Sectional View of Straight and Spiral Pulp Lifters

4.2.1.2 Variation in Coefficient of Friction

With the mill rotational speed controlled at 75% of critical speed, simulations were conducted on the three types of 18 ft pulp lifters to investigate the sensitivity of the relative discharge rate to the coefficient of friction. It should be mentioned that the friction in the actual operation is a very complex issue because it is a result of several other complicated parameters, such as geometries of particles, the material properties of particles and pulp lifter, the amount of particles. This study used a simplified model for which the particles were assumed to be uniform in terms of their geometry and material properties, and there existed two types of friction – particle to particle, particle to pulp lifters. To make the results comparable to those obtained in section 4.2.1.1 operated at 75% of critical speed, all simulation parameters were remained constant except the coefficient of friction were modified twice.

The results shown in Figure 4.4 indicate that the coefficient of friction has significant impact on the relative discharge rate for all three types of pulp lifter designs. At designated coefficient of friction provided – normalized coefficient of friction 1 on the graph, the new design shows the best discharge rate of about 47%, followed by 44% for the curved, and 34% for the straight. The superiority of designs which have spiral radial arms continues when the coefficient of friction increases. However, this is not the case for individual relative discharge rates. With 40% increase in the coefficient of friction, the relative discharge rate for the new design has lowered down to 43%, and it was 37% and 28% for the curved and straight, respectively. On the opposite side where the coefficient of friction decreased by 40%, it is observed that the relative discharge rates increase. The new design and the curved share an approximate same amount for about 63%, whereas the straight was 28%. If attention was paid to the variation in the relative discharge rate, one can notice that the most dramatic change was made by the curved design for 44% increase during decrease in coefficient of friction and the straight design for 18% decline during increase in coefficient of friction. The new design is less sensitive to either of the cases compared to the other designs.

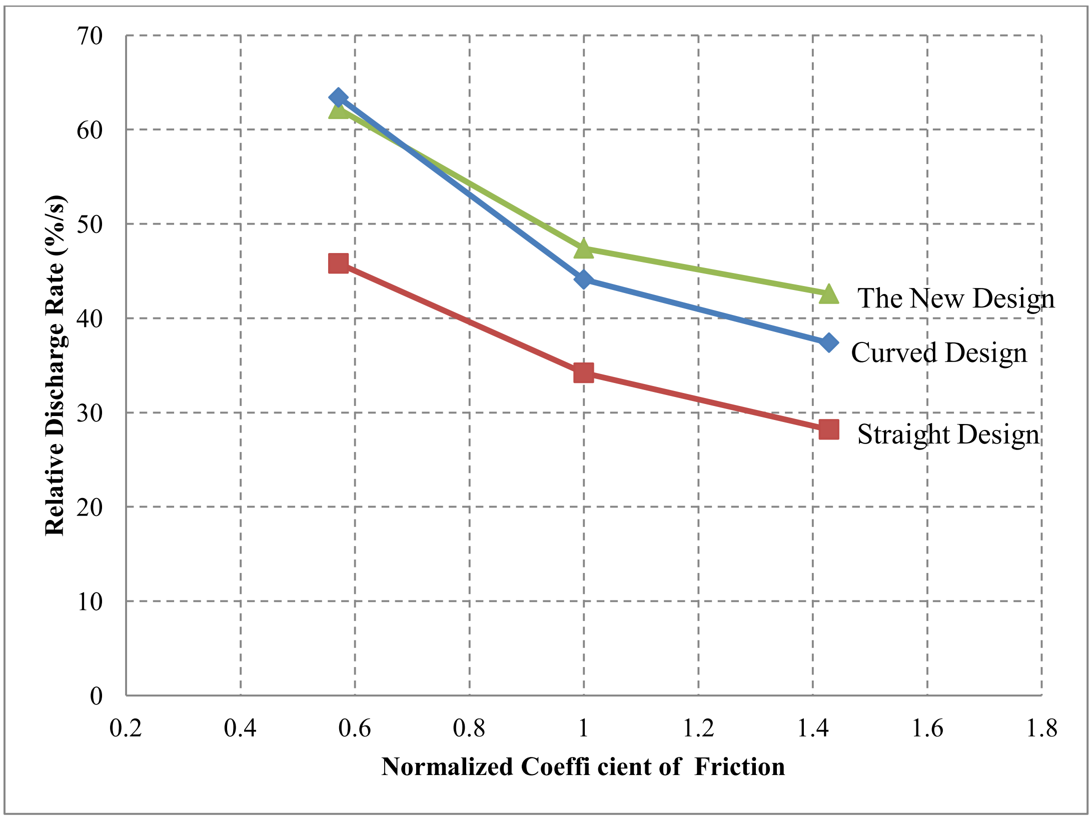


Figure 4.4 Discharge Rates of Three Designs with three different coefficients of friction

4.2.1.3 Variation in Particle Size

Simulations investigating the effects of variation in particle size on the discharge rate were preceded with three particle sizes, respectively. Depending on the designated grate design adopted for this work, all three particle sizes were chosen such that the particles were small than the diameter of grate holes. With the total volume of the particles kept constant and the particle size same as those in simulation operated at 75% of critical speed for an 18 ft mill, two additional particle sizes – one with 30% decrease and the other with 20% increase were chosen based. Figure 4.5 shows the results obtained for 18ft pulp lifters of the new design, curved design and straight design.

Similar to the influences of the coefficient of friction, the effect of variation in particles size on relative discharge rates is also observed. At 0.7 shown in Figure 4.5, the best discharge rate was achieved by the new design with about 53%, followed by the curved design with about 50%, and lastly the straight design for about 39%. When the size of particles increased to 1 as shown, the discharge rates have fallen to about 47%, 44%, and 33% for the new design, curved design, and straight design, respectively. If particles were continuously being enlarged, one can observe that the relative discharge rate also declines. It has been seen that with additional 20% increase, the discharge rate has deceased to about 33% for all three types of pulp lifters.

It is obvious that relative discharge rate increases as the particle size decreases regardless the types of pulp lifters. For particles with smaller sizes, it is the variation in particle size that mainly affects the relative discharge rate. If one compares the amount of decrease in relative discharge rate, it can be found that it was about 11% from 53% down to 47% for the new design when the particle size increased with 30%, and it was about 12% for both the curved and straight. Whereas the particle sizes increase, the relative discharge rates decreased differently but eventually merged to a common. This observation is very important from two aspects. First of all, it could be useful information on future design of grate such that only particles with optimum size would pass through the grate and subsequently get discharged by pulp lifters. Second is that it provides guidelines for operation of grinding to produce the desired size of particles for better mill operating efficiency.

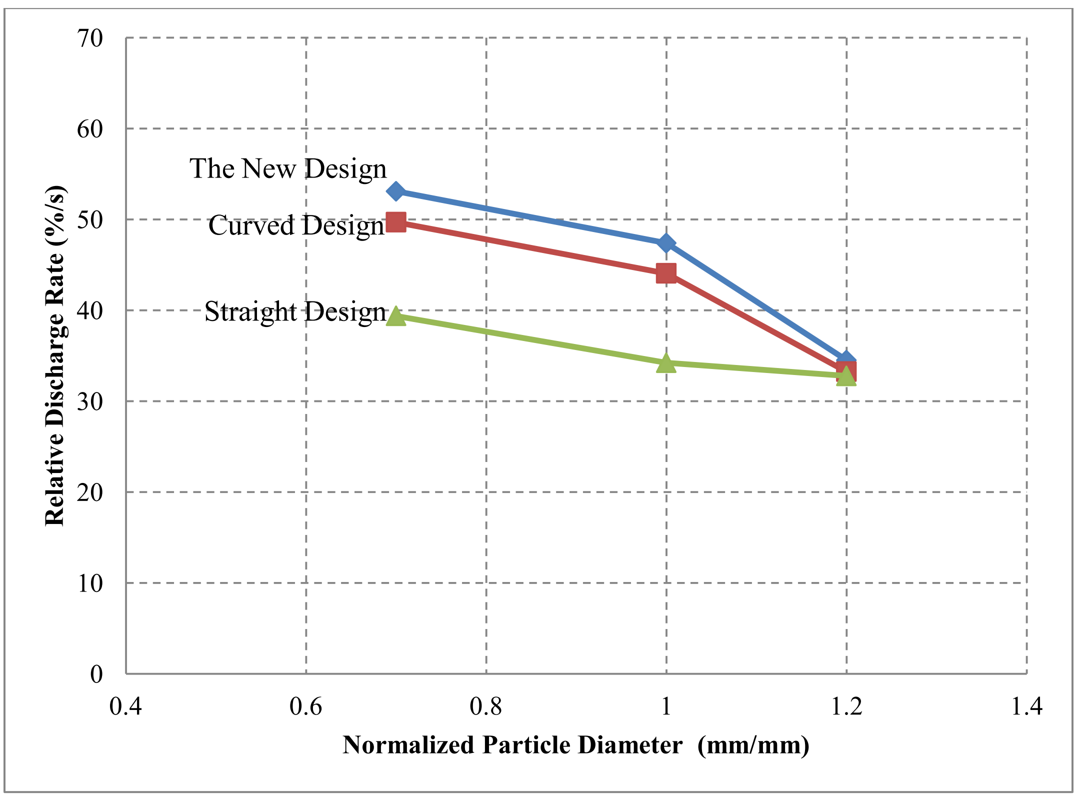


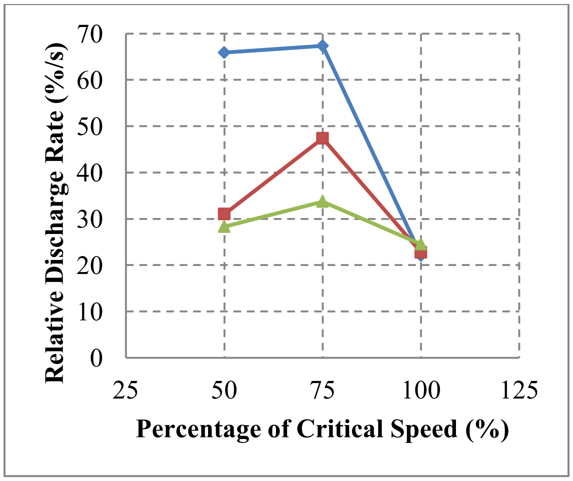
Figure 4.5: Discharge Rates with Variation on Particle Diameter

4.2.2 The Effect of Number of Vanes

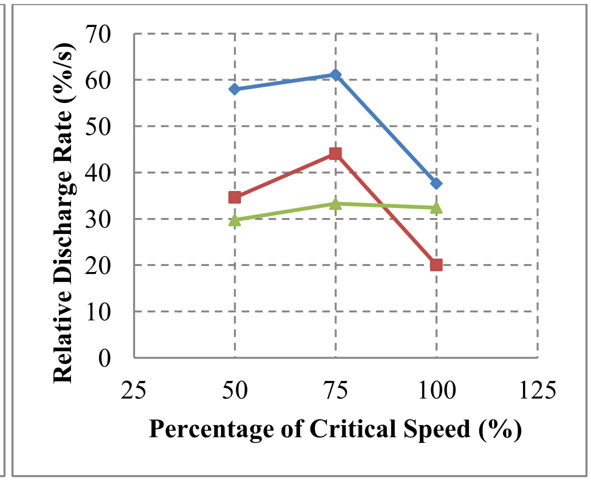
With the completion of investigating the effect of geometry of the radial arms, the next task of this work is to examine the influence of number of vanes on the relative discharge rate of pulp lifters. Three numbers of vanes, 16, 20 and 22 were integrated into three types of pulp lifters. During simulations, the diameter of the discharge end and the charge volume were not changed. Parametric studies similar to those completed in previous section were repeated.

4.2.2.1 Variation in Mill Rotational Speed

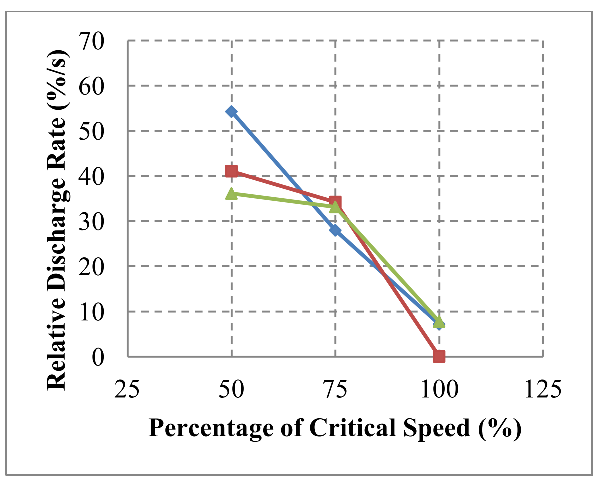
Same variations in mill rotational speed – 50%, 75% and 100% of critical speed for an 18 ft mill were chosen. The results for the new design, the curved, and the straight are shown in Figures 4.6, respectively. It was found that the number of vanes has tremendous influences on the relative discharge rate. The smaller number of vanes has positive impact on the relative discharge rate when the mill rotational speed is low. It assisted achieving discharge rates of 66%, 58%, and 54% for the new design, the curved, and straight, respectively. However, this positive construction did not maintain when the mill rotational speed increased. At 75% of critical speed, it was observed that the discharge performance of the new design and the curved which had 16 vanes configuration was superior to those which had larger numbers of vanes. This was however not true for the straight design. When the mill rotational speed continued increasing, the influences of number of vanes on the relative discharge rate became vague. At 100% of critical speed, the effect of number of vanes has produced no difference on the relative discharge rate for the new design. Yet it caused some variations for the curved. When it came to the straight pulp lifters, there were differences but not very significant.



(a) The New Design



(b) The Curved Design



(c) The Straight Design

16 Vanes 20 Vanes 22 Vanes

Figure 4.6: Effect of Number of Vanes on the Relative Discharge Rate at Different Mill Rotational Speed

One important observation made during this set of study is that at 75% of mill critical speed, the relative discharge rates were the same for three types of pulp lifters which had 22 vanes configuration. This indicates that when the pulp lifter consists of higher number of vanes, the mill rotational speed dominates to determine the best discharge performance.

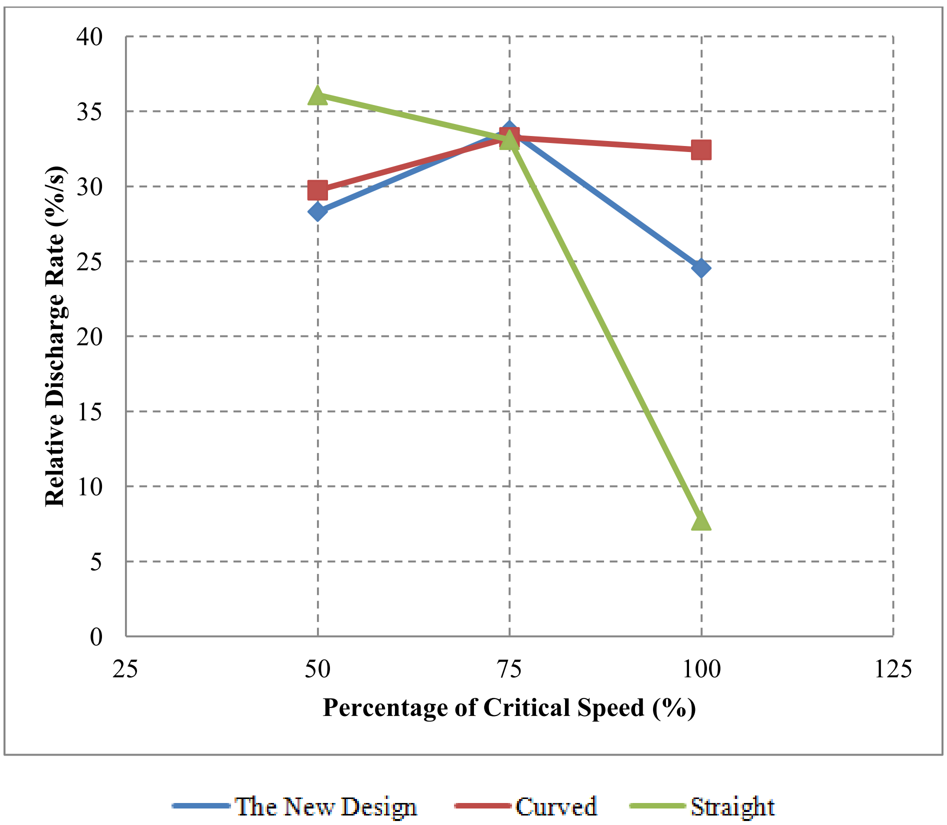
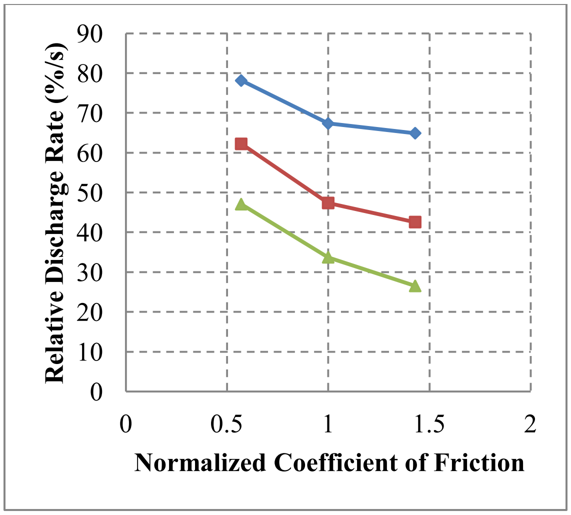


Figure 4.7: Effect of 22 Vanes Configuration on the Relative Discharge Rate at Different Mill Rotational Speed

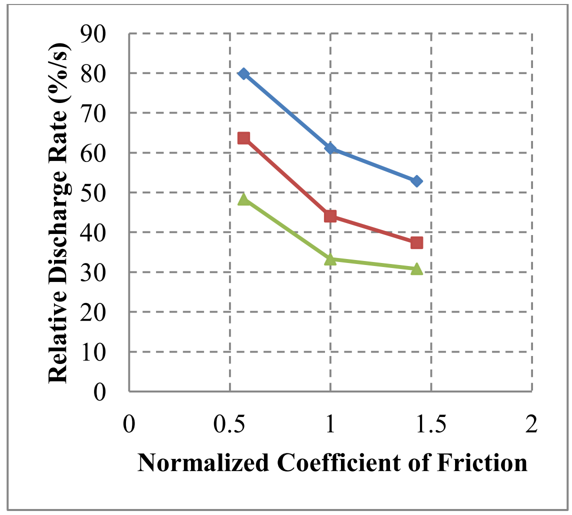
4.2.2.2 Variation in Coefficient of Friction

Same coefficients of friction used in previous sections were adopted for this specific study. The results obtained are shown in Figure 4.8. It was observed that the highest relative discharge rate, about 80%, occurred at the lowest coefficient of friction for the new design and the curved which had 16 vanes configuration. At normalized coefficient of friction 1, the advantages of the higher number of vanes maintained for the new design and the curved, and it even continued for higher coefficients of friction. However, this positive construction did not reflect on the straight design. At the lowest coefficient of friction, the highest relative discharge rate for the straight design, approximate 47%, occurred for 20 vanes configuration. Unlike the new design and the curved, the discharge performance of the straight pulp lifter seemed to receive less affection from the variation of its number of vanes when coefficient of friction increased.

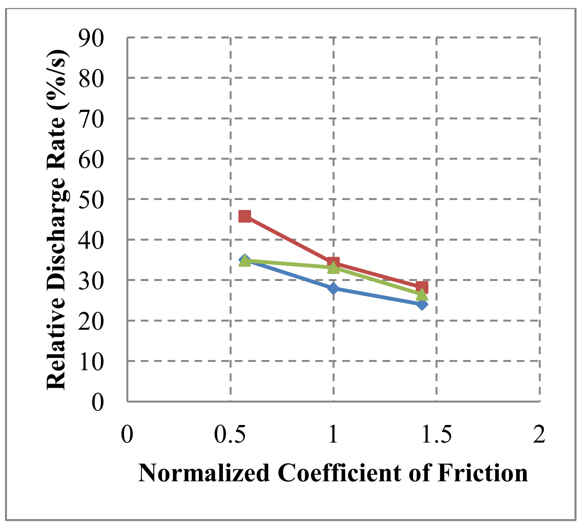
It can be concluded that the larger number of vanes has significant positive impact on the relative discharge rate for the new design and the curved regardless the coefficient of friction. This may be contributed by the fact that the trunnion opening is wider for the spiral design with larger number of vanes. Larger exit area allows more particles to discharge and hence increase the discharge capacity. Figure 4.9 shows illustrations of the trunnion openings for a pulp lifters assembly with 16 and 20 vanes configurations.



(a) The New Design



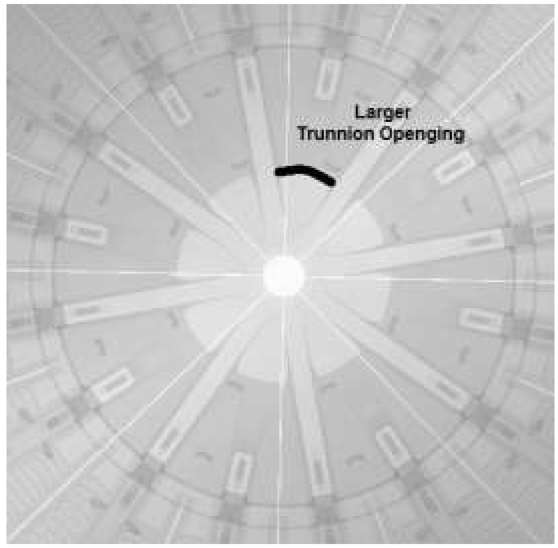
(b) The Curved Design



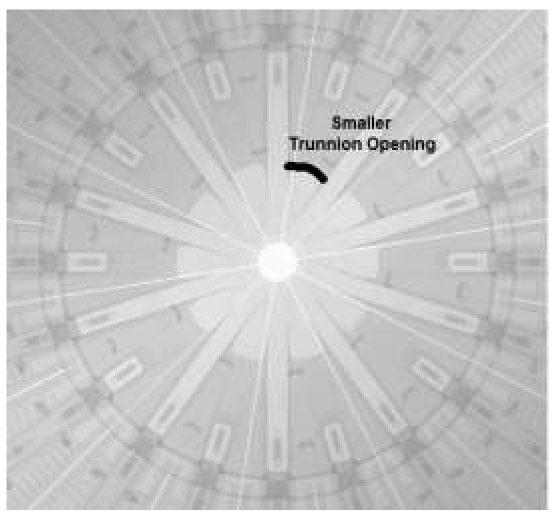
(c) The Straight Design

16 Vanes 20 Vanes 22 Vanes

Figure 4.8: Effect of Number of Vanes on the Relative Discharge Rate at Different Mill Rotational Speed



(a) 16 Vanes Configuration



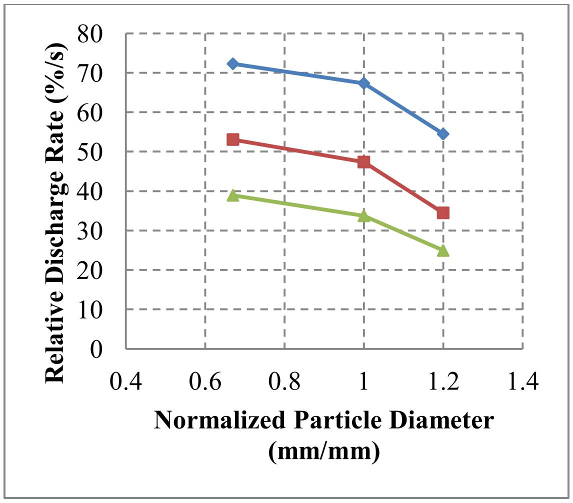
(b) 20 Vanes Configuration

Figure 4.9: Trunnion Opening for Pulp Lifter with 16 and 20 Vanes Configurations

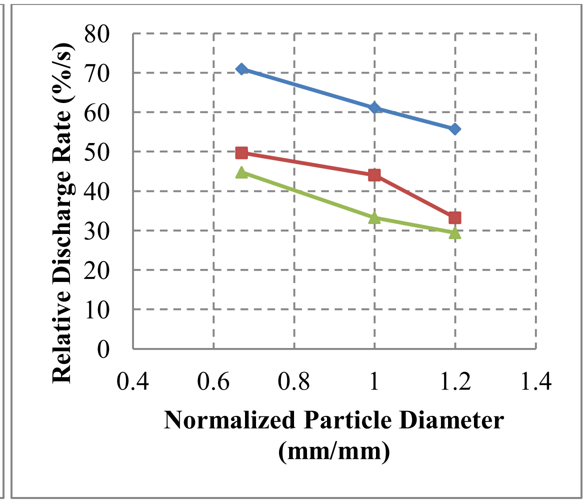
4.2.2.3 Variation in Particle Size

All other simulation parameter, except the particle sizes, for this section are kept the same as those adopted in section 4.2.1.3 for study of effect of radial arm geometry on relative discharge rate with different particle sizes. The discharge rates for the new design, the curved, and straight are shown in Figure 4.10 (a), (b), and (c), respectively. Similar to the variation of coefficient of friction, similar discharge patterns have been seen. It was observed from the graphs that the highest relative discharge rate, about 70%, occurred for the new design and the curved with 16 vanes configuration when the particle diameter is the minimum. Even though the discharge performance of spiraled 22 vanes configuration was weak compared to those of other configurations, it still showed its superiority when particles were small.

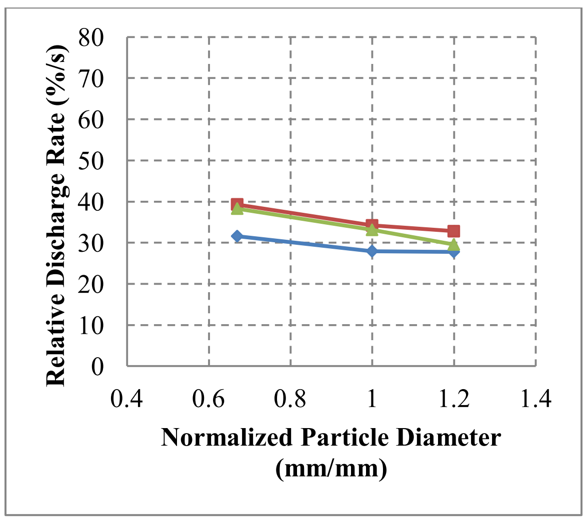
For the straight pulp lifters, the variation of particle size caused some differences on the relative discharge rate but their amounts were not significant. The variation of number of vanes on the relative discharge rate was not particularly following the same trend as those of the new design and the curved. In this case, the 20 and 22 vanes configurations dominated to produce the better discharge performance, whereas the 16 vanes configuration was the least.



(a) The New Design



(b) The Curved Design



(c) The Straight Design

16 Vanes 20 Vanes 22 Vanes

Figure 4.10: Effect of Number of Vanes on the Relative Discharge Rate at Different Particle Sizes

4.2.3 The Effect of Mill Diameter

Repeatedly observed from the previous simulations, two confident confirmations can be drawn. First of all, pulp lifters with spiraled radial arms are able to discharge more materials than the ones with straight radial arms. Second, the improvement of the relative discharge rate of the new design and the curved design happens at three situations, increase on number of vanes, decrease on coefficient of friction, and decrease on particle size. No formal conclusions can be made for the straight pulp lifters, except the fact that it has the weakest performance in terms of relative discharge rate.

With the above two confirmations understood and also to expedite the work progress, the ongoing simulations will focus on effect of the mill diameter with variation in mill rotational speed. The size of the pulp lifters adopted in this section was increased to 30 ft, and this consequently decreased the critical mill rotational speed according to the equation provided in section 3.3. Similar to the previous simulations, three mill rotational speeds, 50%, 75%, and 100% of the critical speed was chosen. It has been observed from Figure 4.11_1 that the relative discharge rate decreased as the mill rotational speed increased. The strongest performance for the relative discharge rate was still dominated by the new design, while the weakest was made by the straight. Different from the 18ft mill, the optimum rotational speed of this larger mill was seemed to occur at lower percentage of its critical speed. This may be due to the fact that the radial arms of larger pulp lifters are longer, and therefore it requires slower rotation for the particles to have enough time travel from the mill periphery to the discharge trunnion. The increased mill diameter has not caused significant variations on relative discharge rates when the mill rotational speeds were or above 75% of their critical speeds. The comparison with results obtained for 18ft pulp lifters are shown in Figure 4.11.

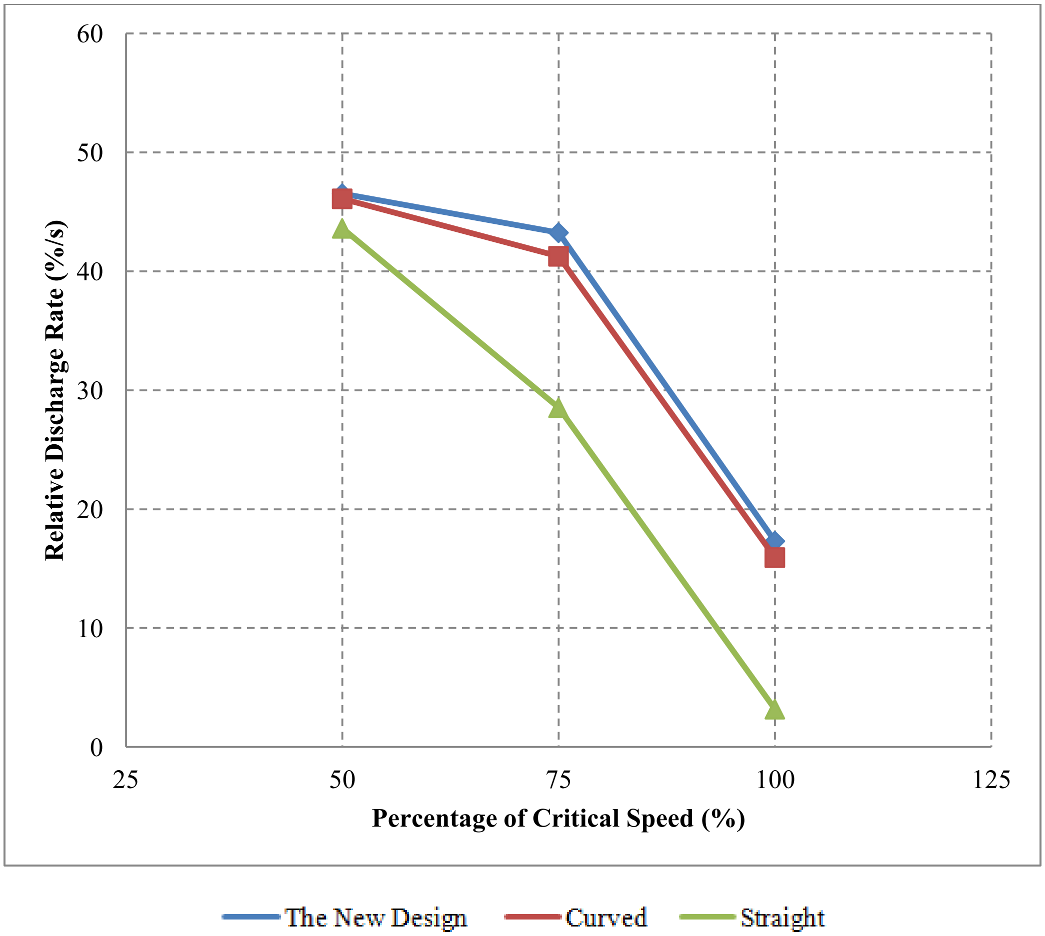
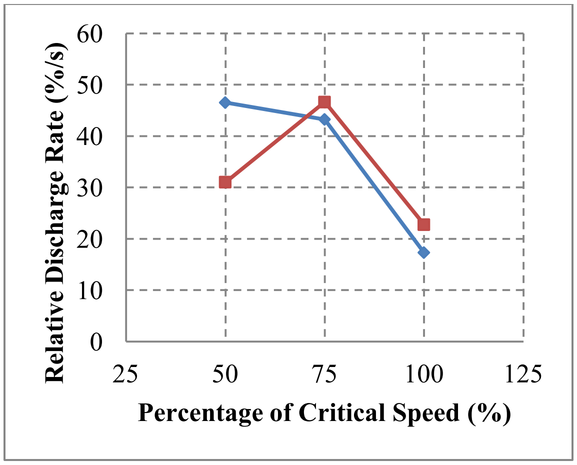
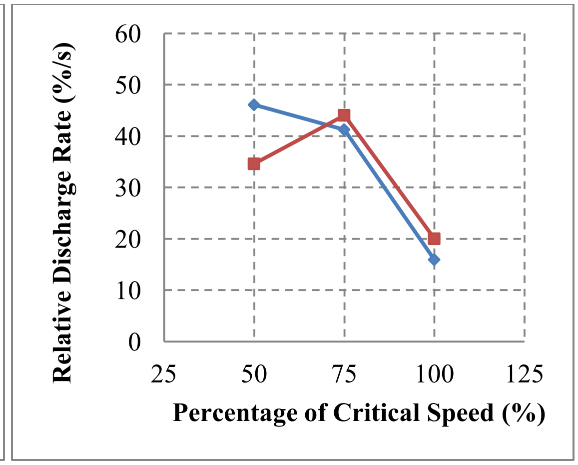


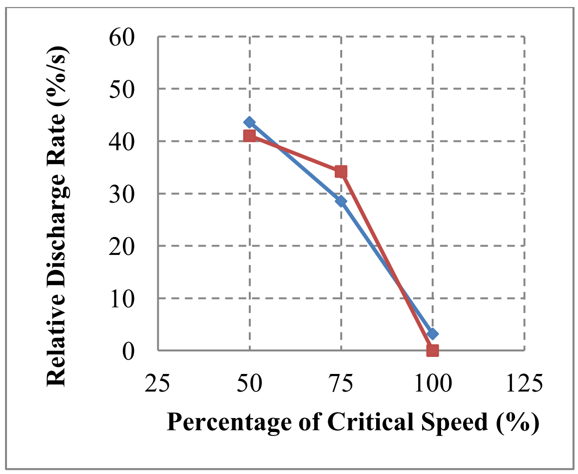
Figure 4.11_1: Relative Discharge Rate for 30 ft Mill



(a) The New Design



(b) The Curved Design



(d) The Straight Design

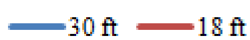


Figure 4.11: Effect of Mill Diameter on the Relative Discharge Rate – 18ft and 30ft

4.3 POWER CONSUMPTION

The power consumption is another consideration that is of great interest to this study. Because rotation is the only type of motion involved, the power consumption can be obtained by the product of torque and mill rotational speed. The results shown in this section are only concerning about torque consumptions. The reason of not presenting power consumption is because of the adopted methodology for which variation in results only comes from the types of design when mill rotates at certain specific speed. For instance, the torque consumptions among the new design, the curved, and the straight when mill is 18ft in diameter and rotate at 75% of its critical speed. With the understanding of this content, the behavior of torque consumption is therefore equivalent to that of the power consumption.

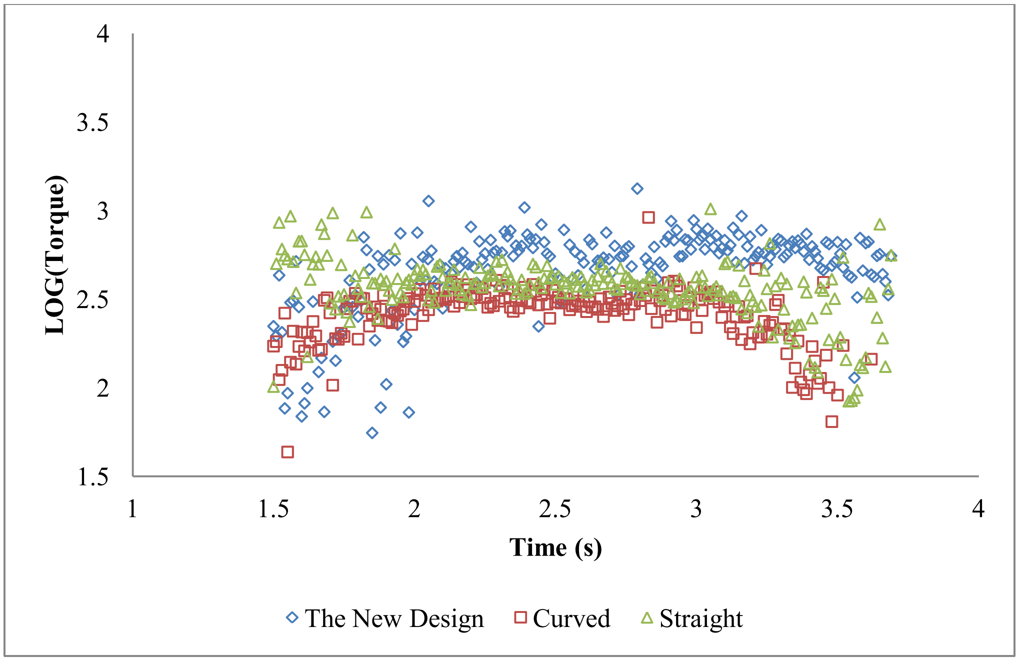
4.3.1 The Effect of Radial Arms' Geometry

Similar to the analysis of relative discharge rate, the performance of torque consumption for all three types of pulp lifters were evaluated against three factors, the mill rotational speed, the coefficient of friction, and the particle size. It has been concluded that pulp lifters with spiral radial arms consume less energy than the straight radial armed pulp lifters. The following section presents the detailed results.

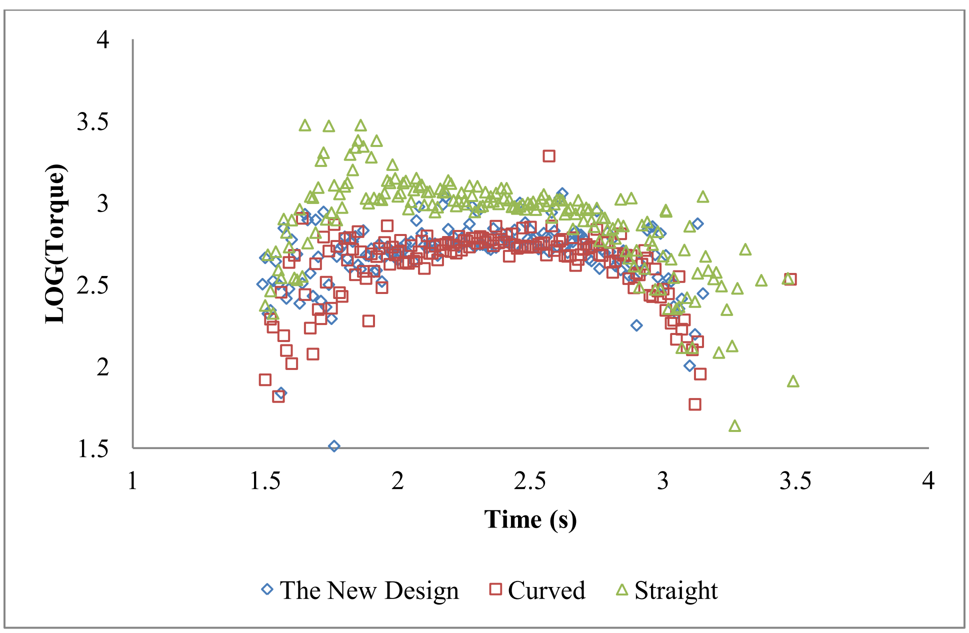
4.3.1.1 Variation in Mill Rotational Speed

The simulations were based on 18ft pulp lifters with three types of design for one discharge cycle. The variation of mill rotational speed was 50%, 75%, and 100% of the critical speed.

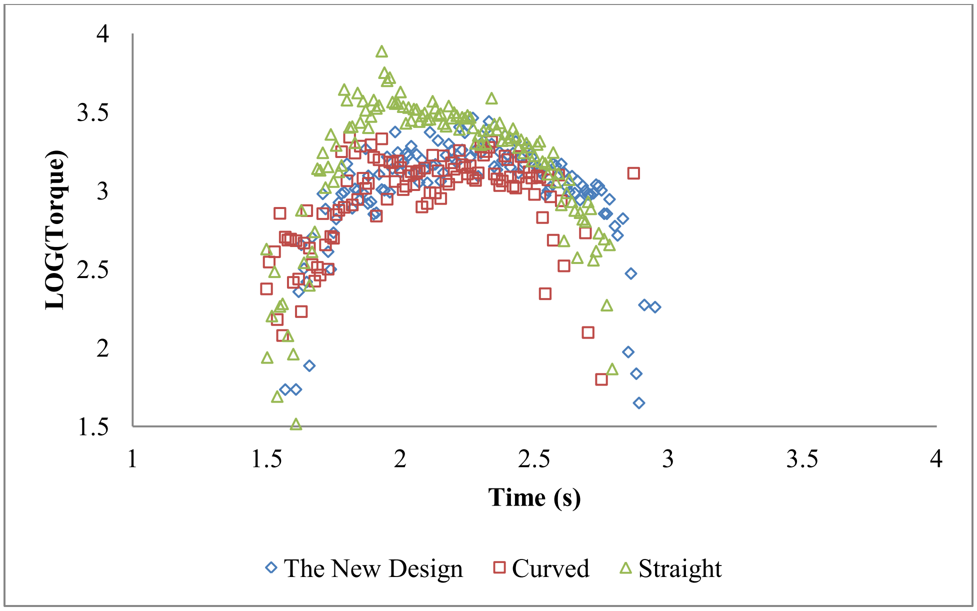
All other simulation parameters were kept constant. There are two observations made from Figure 4.12. First of all, the torque consumption, regardless the type of pulp lifters, is sensitive to the mill rotational speed. If attention was paid to geometry of the torque consumption curves, one can notice that it was somehow flattened at the lower mill rotational speed. It looks like a downward parabola when the mill rotational speed increased. The reason associated with this change is probably due to the fact that the discharge locations of pulp lifters are primarily occurring between 10 to 2 o'clock for which faster mill rotation will need less time to travel through, and thus results in a sharp change in the behavior of its torque consumption. Second observation is that there exist an approximately reverse relationship between the torque consumption and the relative discharge rate. Recall conclusions made from Figure 4.2, the strongest performance of the relative discharge rate at 50% of mill critical rotational speed was accomplished by the straight pulp lifters. While for the torque consumption, the straight design was not the biggest. As shown in Figure 4.12 (a), the maximum energy consumption was dominated by the new design whose relative discharge performance was the weakest. The straight and the curved almost overlapped with each other but with the former slightly higher. When mill rotational speed was approaching the optimum, the advantages of pulp lifters with spiral radial arms started appearing. The new design and the curved design achieved much better performance reflected on the high relative discharge rates and low energy consumptions. After passing the optimum mill rotational speed, the torque consumptions were all increased but still with the observation that spiraled designs consumed less than the straight design. Together with the reduced relative discharge rates, this was consistent with the expected reserve relationship.



(a) Torque Consumption (N·m) with Variation in Mill Rotational Speed – 50% of the Mill Critical Speed



(b) Torque Consumption (N·m) with Variation in Mill Rotational Speed – 75% of the Mill Critical Speed

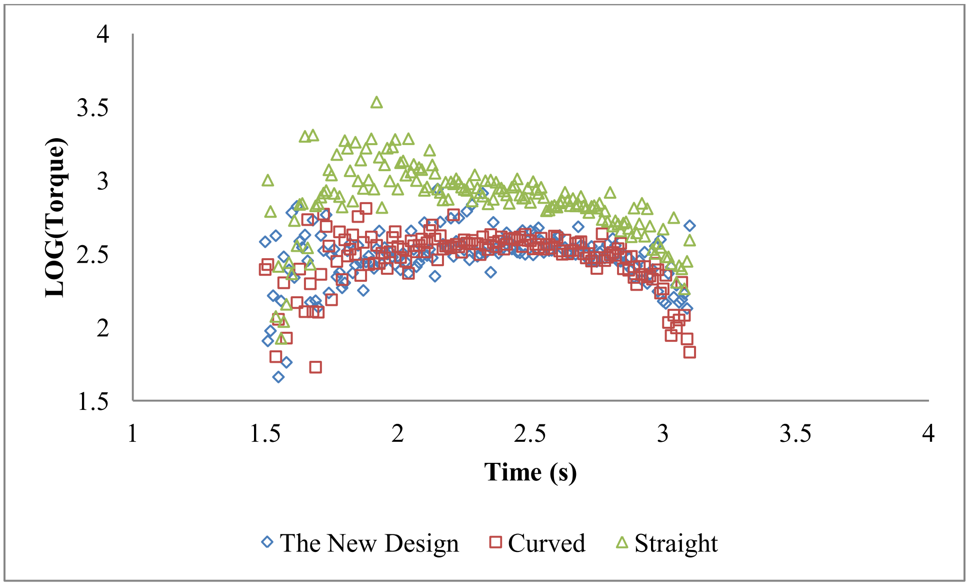


(c) Torque Consumption (N·m) with Variation in Mill Rotational Speed – 100% of the Mill Critical Speed

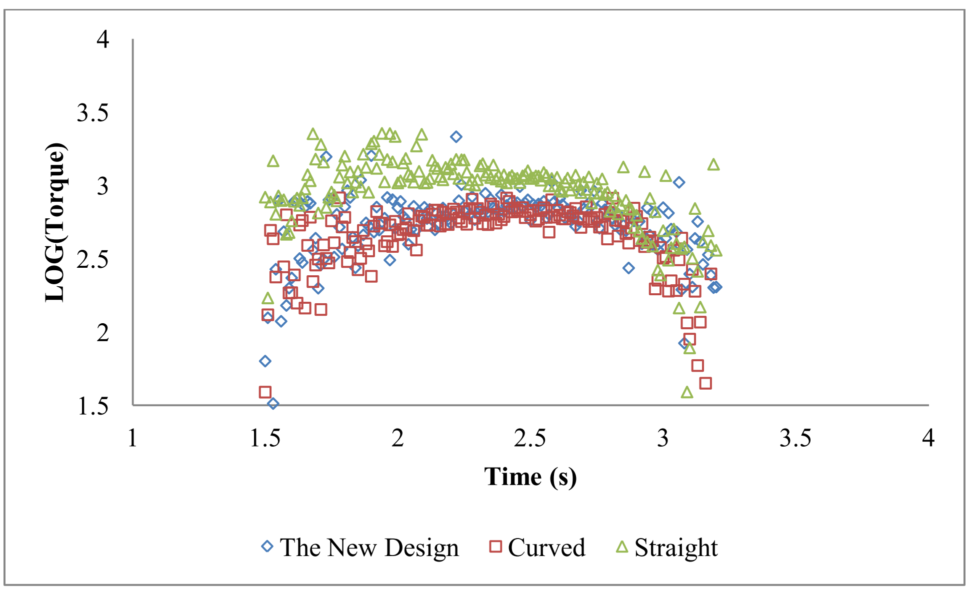
Figure 4.12: Torque Consumptions for Variation on Radial Arms' Geometry with Change in Mill Rotational Speed

4.3.1.2 Variation in Coefficient of Friction

Figure 4.13 shows the results obtained with variations in coefficient of friction relative to simulation operated at 75% of critical speed of 18ft mill. Two variations in coefficient of friction, 40% relative decrease and 40% relative increase, were adopted. The neutralized results were the same as those shown in Figure 4.12 (b). It has been seen that the torque consumption increased as the coefficient of friction increased. For individual energy consumption, the straight design was always the biggest. With consideration of the performance on relative discharge rate for each of the designs, one can concluded one more time that lower torque consumption associated with stronger performance on relative discharge rate.



(a) Torque Consumption (N·m) with Variation in Coefficient of Friction – 40% less than the Normalized 1

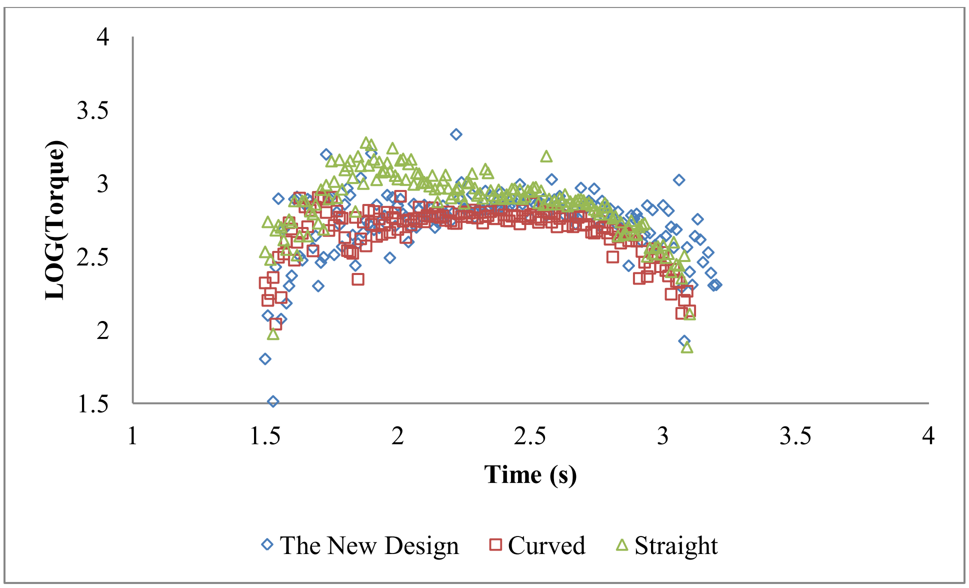


(b) Torque Consumption (N·m) with Variation in Coefficient of Friction – 40% higher than the Normalized 1

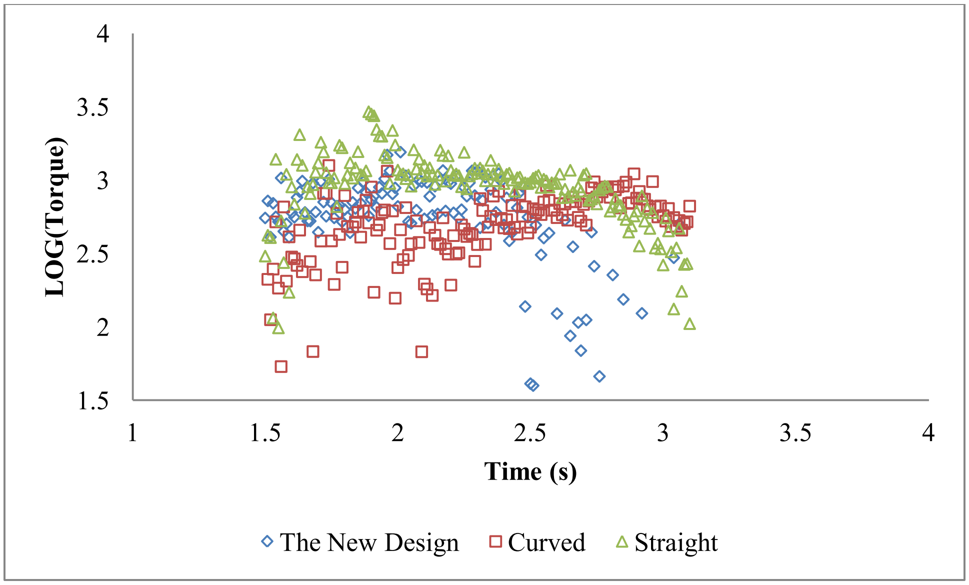
Figure 4.13: Torque Consumptions for Variation on Radial Arms' Geometry with Change in Coefficient of Friction

4.3.1.3 Variation in Particle Size

Similar to previous section, the base simulation results of this section were the same as those shown in Figure 4.12 (b). The particle diameter was relatively changed twice, a 33% decrease and a 20% increase. It seems that the increase in diameter would cause some changes in average torque consumption. But more significantly, it brought rougher fluctuations during discharge activity, which can be easily seen in Figure 4.14 (c). However, this did not alter the fact that pulp lifters with straight radial arms consume more energy.



(a) Torque Consumption (N·m) with Variation in Particle Diameter – 33% decrease



(b) Torque Consumption (N·m) with Variation in Particle Diameter – 20% increase

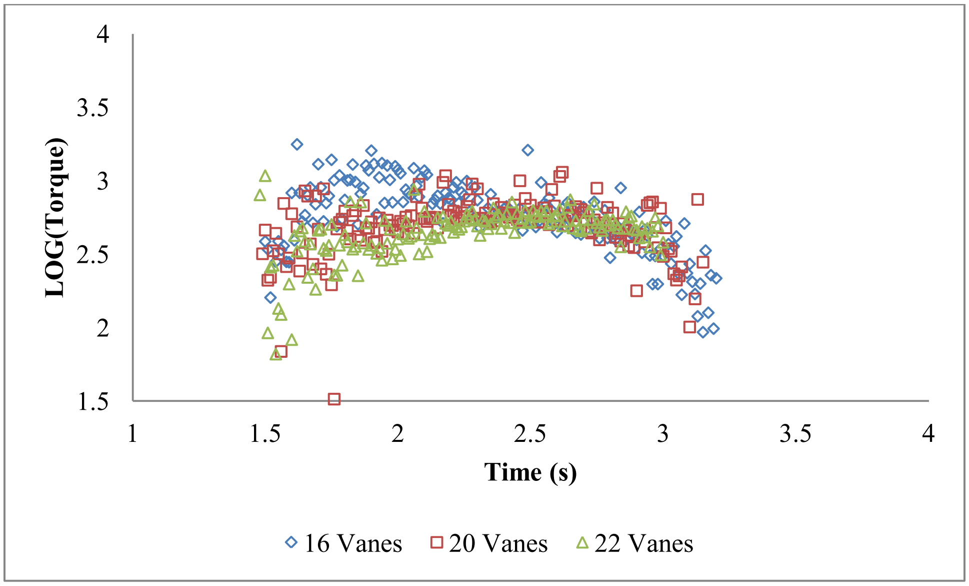
Figure 4.14: Torque Consumptions for Variation on Radial Arms' Geometry with Change in Particle Size

4.3.2 The Effect of Number of Vanes

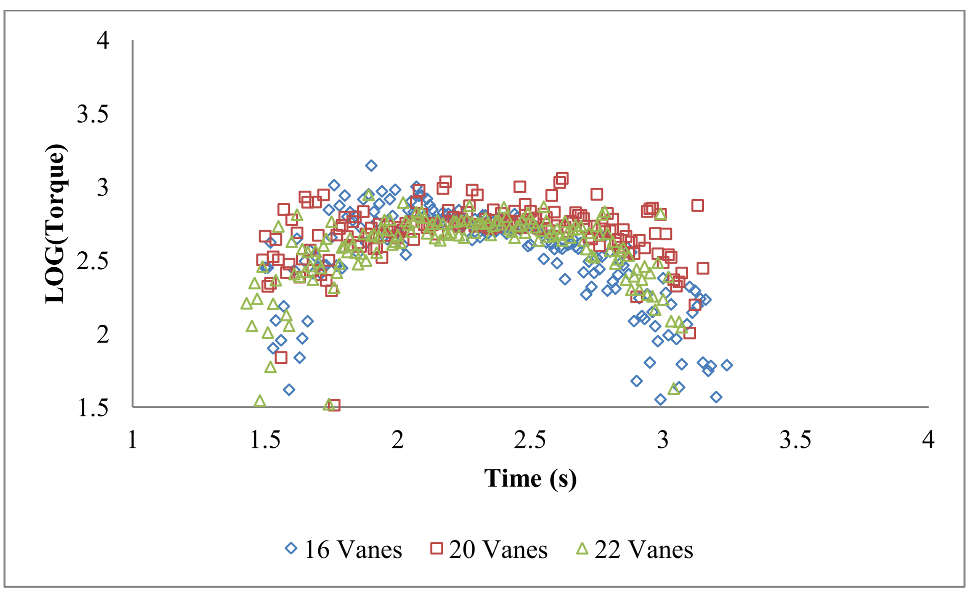
With the fact that a better relative discharge rate associates with a lower consumption understood well, the next task of this section was to examine the effect of number of vanes on the torque consumption during discharge. Since it has been shown in section 4.2 that the new design has the best relative discharge performance for which the straight has the least, the study of variation of number of vanes was preceded with focus on each of the pulp lifter designs. It should be noted the simulation parameters, such as 75% of mill critical speed, the normalized particle diameter 1, and the normalized coefficient of friction 1, were kept constant during simulations.

There are some adverse observations seen in Figure 4.15. Contradicted to the previous finding that stronger relative discharge performance accompanied with lower energy consumption, it has been observed that the torque consumptions for small number of vanes which achieved better relative discharge performance were higher than those for higher number of vanes which showed weaker relative discharger performance. This observation was particularly significant at the first half of one discharge cycle. One reason that could possibly explain this phenomenon was the assumption made for this study. It was assumed the mass of the to-be-discharged particles was fixed for three types of pulp lifters. When the number of vanes changed, the amount of particles that each vane can hold consequently changed. It was then obvious that vane capacity for 16 vanes configuration was the highest among other designs. Since the pulp lifter assembly is a complete revolved and symmetrical geometry, it therefore does not consume any torque. Because the power consumption equals to the product of torque and mill rotational speed, the variation of power consumption in this specific situation is then determined by the variation of the contained mass. With this understood, the adverse observations are accordingly logical. It is expected more energy is needed to lift a larger quantity of mass, and less for a smaller. These are exactly consistent with the findings that 16 vanes configuration is more energy costive than others. Compare with other factors that cause variation in torque consumption, one can conclude that the effect of number of vanes is more dominating.

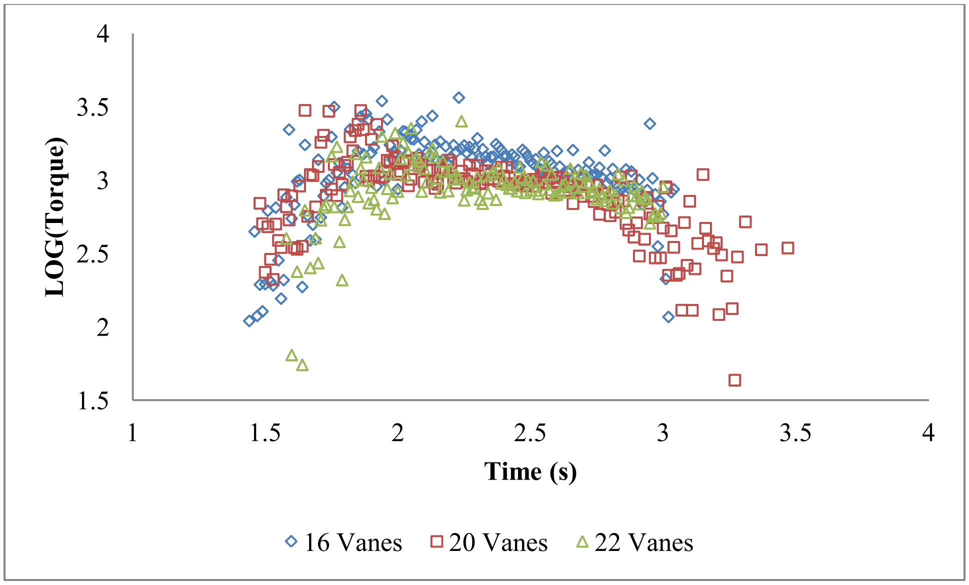
The adverse trend only occurred during the first half discharge cycle. After the materials were lifted to the designated height, the behavior of the torque consumption seemed to retrieve the previous trend. This is observable from Figures 4.6 and 4.15 for smaller torque consumptions with higher relative discharge rate for spiraled design with 16 vanes configuration, and for bigger torque consumption with lower relative discharge rate for straight design with same vanes configuration.



(a) The New Design at 75% of Critical Speed



(b) Curved Design at 75% of Critical Speed

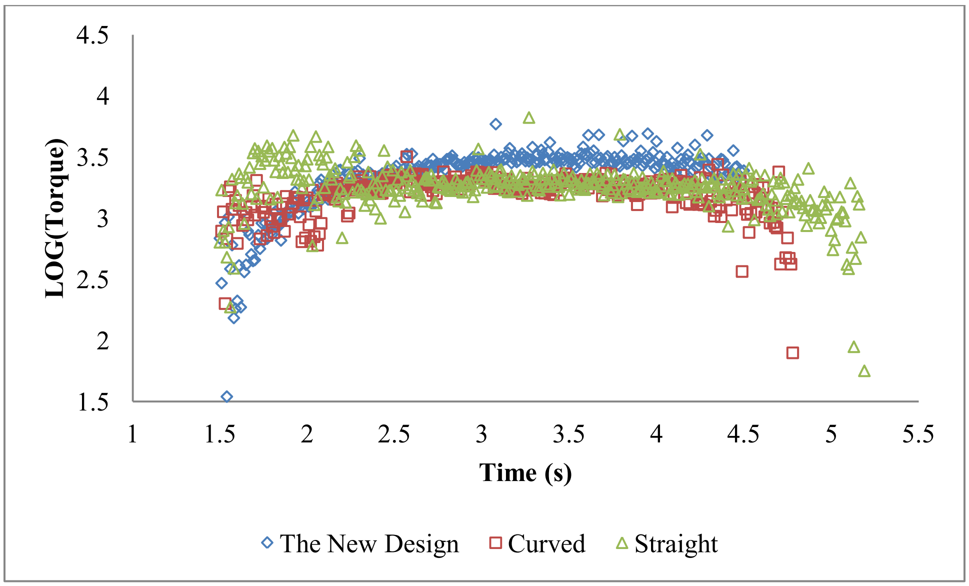


(c) Straight Design at 75% of Critical Speed

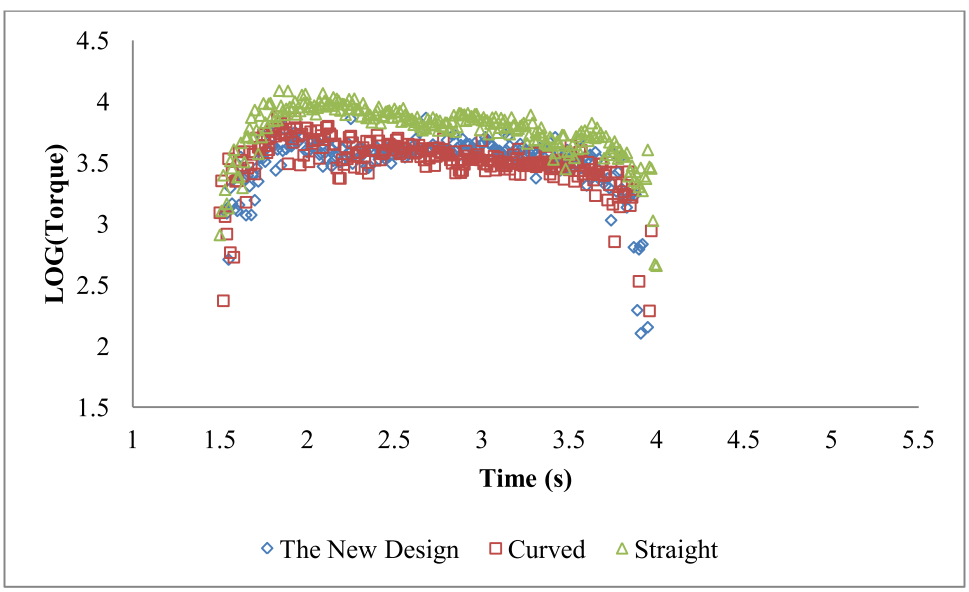
Figure 4.15: Torque Consumption (N·m) for Variation on Number of Vanes

4.3.3 The Effect of Mill Diameter

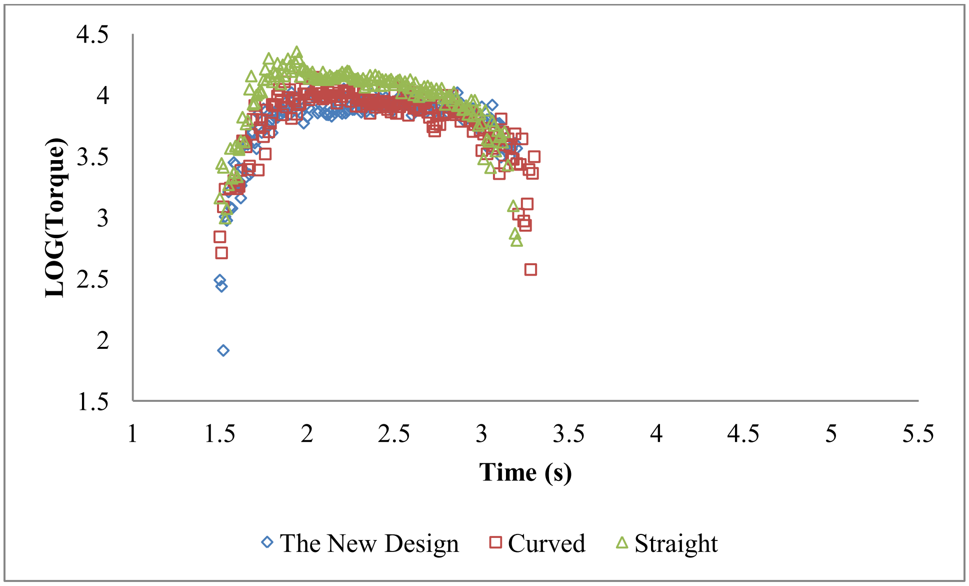
The parameter settings of simulations in this section were the same as those in section 4.2.3. Similar to the 18ft pulp lifters, the first observation made from Figure 4.16 was that the discharge cycle for lower mill rotation speed was longer than those for higher mill rotational speeds. It also showed the torque consumption of a larger pulp lifter assembly increased as the mill rotational speed increased. Compared with results obtained for the small diameter, it has been found that increase in mill diameter also caused increase in torque consumption. The spiraled designs still show their better performance over three mill rotational speeds except at 50% of critical speed, the torque consumption for the new design was a bit higher than those of others. This inconsistency is probably due to the contradiction between the slow mill rotational speed and the design nature of the new design which aims for better operating efficiency at higher mill rotational speed.



(a) 50% of Critical Speed



(b) 75% of Critical Speed



(c) 100% of Critical Speed

Figure 4.16: Torque Consumption (N·m) for Variation in Mill Diameter

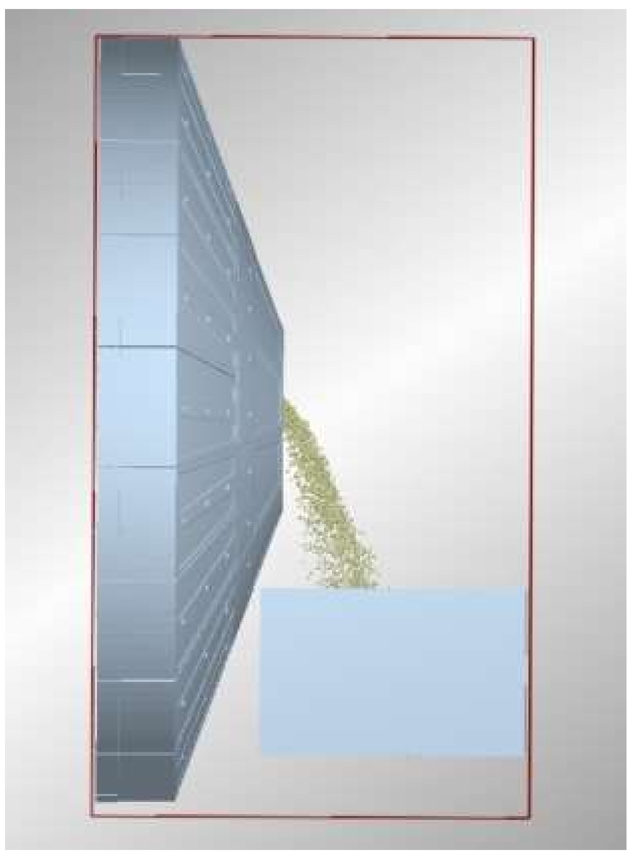
4.4 FLOW-BACK AND CARRY-OVER

As described in section 2.2.3, flow-back and carry-over are inevitable phenomena that occur simultaneously during discharge of grate-discharge grinding mills. The former occurs as a result of the latter. The process is that the particles that have been collected by vanes are not completely discharged out through the trunnion, rather they pass through the grates and falls back into the grinding chamber. This causes inefficient operation. Even though these phenomena are much dependable on the design of grate, they are still relevant to the design of pulp lifters. In this work, analysis was carried out to examine the three types of pulp lifter designs on this particular perspective.

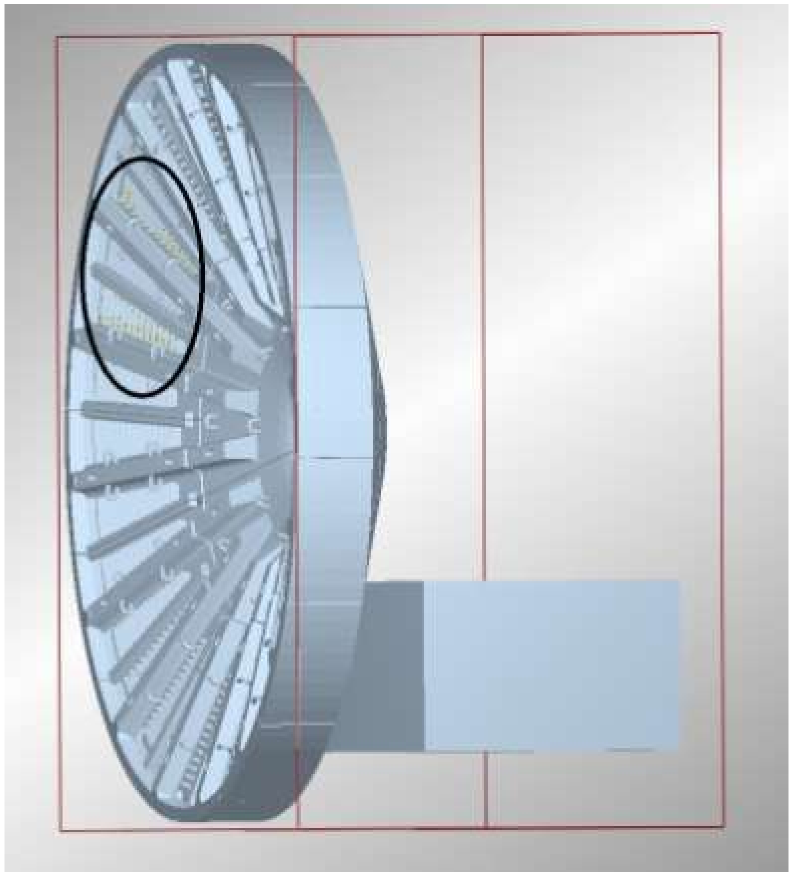
EDEM tracks the number of particles within a specific domain; any particle that is out of the domain will be disregarded. With the use of this feature, a simulation process is designed to count the number of particles that flow back due to carry-over. Figure 4.17 illustrates this process. As shown in (a), the specific domain is a rectangular box which consists of a pulp lifter assembly and a particle collection box. With the left face of the domain coincides with the grate side of the pulp lifters, any particles that pass through that face will be eliminated by the system (particles are grey as shown in (b)). Since the total number of to-be-discharged particles is known at the beginning, the number of the flow-backed particles can be obtained by differencing the initial total number of particles and the new total number of particles remaining in the domain after discharge.

From all the simulations that were conducted in previous sections, flow-back and carry-over were only seen for the straight pulp lifters when the particle diameter was the minimum and the assembly experienced variation in number of vanes. Figure 4.18 shows the percentage of the flow-backed particles for straight pulp lifters with 16, 20, and 22 vanes configuration during one discharge cycle. It was observed that all three curves were started at 0% which means the flow-back occurred simultaneously with the discharge. Noted that the conventional definition of carry-over only comes into effect after 12 o'clock position, therefore it was not referred until the second half discharge cycle. While at that critical location which was shown at 3.25s in the figure, it was found the flow-back was experienced a sharp increase for all three situations. This is expected since the carried-over particles experienced the maximum pressure from the effect of gradational force. The increase of the flow-back slowed down and eventually reached to a stop when the discharge cycle completed. Another observation was that the magnitude of the flow-back and carry-over increased as the number of vanes decreased. This is primarily due to the fact that the vane of small number of vanes configuration can hold more particles which increase the probability for flow-back/carry-over.

According to Latchireddi and Morrell (2003), the curved pulp lifers should also experience flow-back and carry-over. However, these were not observed in this study. The study of the new design has neither reported any flow-back and carry-over.



(a) Particles Discharge into Particle Collection Box



(b) Particles Flow-Back Due to Carry-Over

Figure 4.17: Simulation Setup for Examination of Flow-Back and Carry-Over

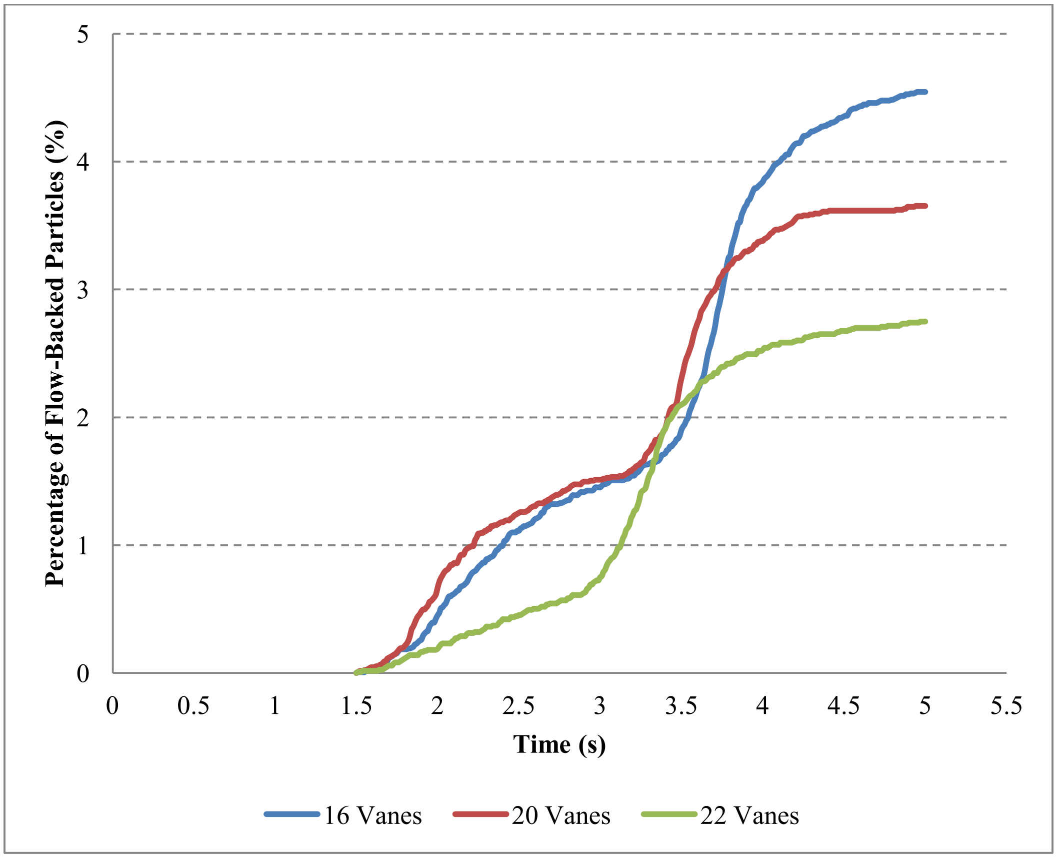


Figure 4.18: Flow-Back and Carry-Over for Straight Pulp Lifters

4.5 SUMMARY

The preliminary tests have shown the simulation results generated by EDEM software were consistent and reproducible.

The relative discharge rates with variations in radial arm geometry, number of vanes, and mill diameter were obtained through changes in operating conditions which include the mill rotational speed, particle size, and the coefficient of friction. The results have shown that radial arm geometry has significant impact on the relative discharge rate. Pulp lifter designs which have their radial arms spiraled apparently show better relative discharge rate than those with straight radial arms. The number of vanes is another significant design parameter than bring changes to the relative discharge rate. It has been found the smaller number of vanes configuration can lead to a larger relative discharge rate, which is particularly true for the curved and the new designs. The increase in mill diameter has not caused significant change in relative discharge rate. The relative discharge rate is also observed to be sensitive to operating conditions. It increases as the coefficient of friction decrease, or when the particle size decrease. The influence of mill rotational speed is different. For spiraled radial arm design, an optimum relative discharge rate can be obtained at a higher mill rotational speed. However, this is not the case for pulp lifter with straight radial arms.

The torque/power consumption was the second topic in this chapter. Similar to the situation of relative discharge rate, the results have shown that at most of the times the curved and the new design consume less energy than the straight. The torque consumption is about found to be relevant to the other design parameters. Higher energy cost associates with smaller number of vanes configuration and large mill diameters. As for the operation factors, the torque consumption actively responded to the mill rotational speed and the coefficient of friction. The change in particle size only brings large fluctuations.

The flow-back/carry-over was only observed from straight design. It was found that these drawbacks are especially significant when particles are small and there existed a smaller number of vanes configuration. Noted that the new design and the curved have been seen any flow-back/carry-over.

.

Chapter 5

Conclusions and Future Work

This chapter summarizes findings made in previous chapter. Given detailed considerations to the effect of each of the interested parameters on the discharge performance of pulp lifters, this chapter establishes five guidelines for future design and operation of such equipment. Recommendations for future work are also presented.

5.1 CONCLUSIONS

The first important finding is that pulp lifters with spiraled radial arms show better performance than pulp lifters with straight radial arms. With influences from grate kept constant, the performances of three types of design, a new design inspired by TCPL, a curved design, and a straight design, have been thoroughly evaluated against some critical design and operating factors.

It has been confirmed that the discharge performance of pulp lifters is sensitive to the mill rotational speed. Depending on the type of design, each pulp lifter assembly associates with a unique optimum rotational speed. According to the simulation results, it is expected that the smaller pulp lifters with spiraled radial arms achieve their best discharge rate at higher mill rotational speed. However, this advantage does not appear significantly when the mill diameter increases. The straight pulp lifter assembly also has its optimum rotational speed except it is slower than those of other designs when the mill diameter is small. The influence of the mill rotational speed is also reflected on the torque/power consumptions. As expected, a higher mill rotational speed will result in relative larger torque/power consumption for all three types of design.

For grinding operated in dry condition, the coefficients of friction have significant impacts on the performance of pulp lifters. The change of coefficients of friction is complicated and yet not understood well. But in this study, it has been shown that the increase in coefficients of friction will causes decreases in discharge performance. This is always valid, regardless the type of design. Similar to the effect of mill rotational speed, the increase in coefficients of friction also causes increase in torque/power consumptions.

Particle size is another important influential factor that is of interest to this study. Analysis has shown that pulp lifter assemblies with spiraled radial arms are more sensitive to the change in particle size. To accomplish better discharge performance, a smaller particle size is preferred. However, the effect of the particle size is not significant for straight radial armed pulp lifters. When comes to the consideration of the average energy consumed, it has found that the variation of particle size within a constant mass has little influences. The enlarged particles will rather bring rougher behaviors to the power consumptions, and which may be reflected as larger acoustic during discharge.

Considerations are also made from the design perspective. First of all, the change of number of vanes brings changes to the discharge performance. A smaller number of vanes configuration is able to generate a stronger discharge performance for the spiraled designs. However, this positive construction is not observed for the pulp lifters with straight radial arms. Since more particles are held in vane of a smaller number of vanes configuration, there associates one consequence for which more energy is required to lift the materials to the designated height to be discharged.

Second design consideration is the mill diameter. It has been seen that the increase in mill diameter will not cause significant variation in discharge performance except it delays the happening of optimum mill rotational speed for spiraled pulp lifters. The enlarged mill diameter suggests the vane capacity is increased and therefore causes larger energy consumption.

The drawback of the straight radial armed pulp lifters are evidently seen in this study. The flow-back and carry-over are especially significant when the particle size is small. They also related to the vane configurations. Smaller of vanes will cause worse flow-back and carry-over. These disadvantages are supposedly seen for the curved pulp lifter assembly. However, it is not the case. Flow-back and carry-over are neither seen for the new design.

It has been concluded that the objectives of this work have been met. The first objective, the defined pulp lifter performance criteria which include the discharge rate, the torque/power consumption, and flow-back/carry-over have been good indicators during analysis of the results. The second and third objectives are accomplished through studies with pulp lifter assemblies with industry conventional designs whose diameters are 18ft and 30ft. A new design inspired by TCPL has also been investigated as a partial fulfillment of these objectives. The successful completion of objective four is reflected in chapter four where thorough analyses of obtained results were given. The five established guidelines to be presented in the following section satisfy the last objective of this work.

5.2 DESIGN AND OPERATING GUIDELINES

Based on the conclusions of this study, the following five guidelines are established. It is the hope that these guidelines will provide insights and assist the industry on future designs and operations of pulp lifter systems.

1. Spiraled radial arm is a favored design for smaller size of pulp lifter assembly aimed for better discharge performance and low energy consumption.
2. The number of vanes should be slightly less the diameter of the mill, e.g. 16 vanes for an 18ft mill, in order to achieve a better discharge performance. However, it should

be always kept in mind that smaller number of vanes also associates with higher power consumption.

3. Pulp lifter assembly with larger diameter will result more discharged materials. But its discharge rate is not significantly faster than that of a smaller pulp lifter assembly. Large diameter also results in more energy consumption. Tradeoff needs to be considered carefully.
4. For smaller pulp lifter assemblies with spiraled radial arms, the mill should rotate at a faster but not fastest speed in order to achieve the best discharge performance. For example, 75% of critical speed for an 18ft mill. For mill with larger size, the rotational speed should be controlled slowly, such as around 50% of critical speed for a 30ft mill. If selection was the straight pulp lifters, the mill rotational speed should be kept low but other considerations should be also taken into account.
5. The straight pulp lifter design should be avoided if flow-back and carry-over are great concern. If selected, one has to combine the consideration of guideline 2, the design of grate, and the composition of particles or materials. Keep in mind that flow-back and carry-over is worse when the vane capacity is large and in which contains smaller particles.

5.3 RECOMMENDATIONS FOR FUTURE WORK

As an extension to this work, several issues are worth to be investigated in the future.

- First of all, since the discharge end of grate-discharge mill consists of grates and pulp lifters, it is important to conduct studies to examine the influences caused by types of grate design.
- Even thought this work assumes the geometry of particles was sphere, it is more complicated in reality. Therefore, the variation in particle geometry could be recommended as a future continuing task.
- This work was based on mills operated in DRY condition. However, there are mills operated in WET condition. Therefore, it is also desirable to investigate the effect of WET condition.
- Though wear of the radial arms of pulp lifters is comparably less significant than those of shell liners, it could cause some operational inefficiency. An investigation of this phenomenon is recommended.

References

Abouzeid, A.-Z.M., Fuerstenau, D.W., 1980. "A study of the hold-up in rotary drums with discharge end constrictions". Powder Technology 25, 21-29.

Afacan, A. and Masliyah, J.H., 1990. "Solids hold-up in rotary drums", Powder Technology 61,179-184.

Berkel, R., 2007. "Eco-efficiency in the Australian minerals processing sector", Journal of Cleaner Productions 15, 772-781.

Bond, F.C., 1985. "History of autogenous grinding", SME Mineral Processing Handbook N.L.Weiss (Ed) 1, SME, New York, 3c-57-3c-60.

Chenje, T.W., Simbi, D.J., and Navara, E.,2003. "Wear performance and cost effectiveness – a criterion for the selection of grinding media for wet milling in mineral processing operations", Minerals Engineering 16, 1387-1390.

Cleary, P.W., 1998. "Predicting charge motion, power draw, segregation and wear in ball mils using discrete element methods', Minerals Engineering 11, 1061-1080.

Cleary, P.W., 2001. "Charge behavior and power consumption in ball mills: sensitivity to mill operating conditions, liner geometry and charge composition", International Journal of Mineral Processing 63, 79-114.

Cleary, P.W., Morrison, R. and Morrell, S., 2003. "Comparison of DEM and experiment for a scale model SAG mill", International Journal of Mineral Processing 68, 129-165.

Cleary, P.W., Sinnott, M. and Morrison, R., 2006. "Predication of slurry transport in SAG mills using SPH fluid flow in a dynamic DEM based porous media", Minerals Engineering 19, 1517-1527.

Djordjevic, N., Shi, F.N., and Morrison, R., 2004. "Determination of lifter design, speed and filling effects in AG mills by 3D DEM", Minerals Engineering 17, 1135-1142.

DOE, 2004. Profile of Total Energy Use for US Industry, Industrial Technologies Program, US Department of Energy, Energy Efficiency and Renewable Energy, Decemeber.

EDEM Software Manual, DEM Solutions.

Fang H., Wu J., and Zeng C., 2009. "Comparative study on efficiency performance of listed coal mining companies in China and the US", Energy Policy 37, 5140-5148.

Karr, C.L. and Weck, B., 1996. "Computer modeling of mineral processing equipment using fuzzy mathematics", Minerals Engineering 9, 183-194.

Kjos, D.M.,1985. "Wet autogenous mills", SME Mineral Processing Handbook N.L.Weiss (Ed) 1, SME, New York, 3c-60-3c-75.

Kotake, N., Kawaguchi, T., Koizumi, H., and Kanda, Y., 2004. "A fundamental study of dry and wet grinding in bending tests on glass-effect of repeated impact on fracture probability", Minerals Engineering 17, 1281-1285.

Latchireddi, S. and Morrell, S., 1997. "A laboratory study of the performance characteristics fo mill pulp lifters", Minerals Engineering 10, 1233-1244.

Latchireddi, S. and Morrell, S., 2003. "Slurry flow in mills: grate-only discharge mechanism (Part -1)", International Journal of Mineral Processing 16, 625-633.

Latchireddi, S. and Morrell, S., 2003. "Slurry flow in mills: grate-pulp lifter discharge systems (Part 2)", International Journal of Mineral Processing 16, 635-642.

Latchireddi, S. and Rajamani, R.J., 2005. "Optimizing performance of AG/SAG mills – A design approach", Proceedings of the Canadian Mineral Processors 2005, 251-266.

Latchireddi, S. and Morrell, S., 2006. "Slurry flow in mills with TCPL – An efficient pulp lifter for ag/sag mills", International Journal of Mineral Processing 79, 174-187.

Levanaho, J. and Koivistonien, P., 2001. "Use of base mill units to predict mill power efficiency", 2001 SAG Conference 3, 124-136.

Lynch, A.J., Oner, M. and Benzer, H., 2000. "Simulation of a closed cement grinding circuit", ZKG International 10, 560-567.

Makokha, A.B. and Moys, M., 2007. "Effect of cone-lifter on the discharge capacity of the mill product: Case study of a dry laboratory scale air-swept ball mill", Minerals Engineering 20, 124-131.

Mokken, A.,Blendulf, G. and Young, G., 1975. "A study of the arrangements for pulp discharge on pebble mills and their influence on mill performance", J.S.A. Inst. Min. Metal., May., 257-280.

Morrell, S., Finch, W.M., Kojovic, T., and Delboni Jr., H., 1996. "Modelling and simulation of large diameter autogeneous and semi-autogeneous mills", International Journal of Mineral Processing 44-55, 298-300.

Morrell, S. and Stephenson, I., 1996. "Slurry discharge capacity of autogenous and semi-autogenous mills and the effect of grate design", International Journal of Mineral Processing 46, 53-72.

Moys, M.H., 1986. "The effect of grate design on the behavior of grate-discharge grinding mills", International Journal of Mineral Processing 18, 85-105.

Morrison, R.D., Cleary, P.W. and Sinnott, M.D., 2009. "Using DEM to compare energy efficiency of pilot ball and tower mills", Minerals Engineering 22, 665-672.

Morrsion, R.D. and Cleary, P.W., 2011. “Understanding fine ore breakage in a laboratory scale ball mill using DEM”, Minerals Engineering 24, 352-366.

Napier-Munn, T.J. 1997. “Invention and innovation in mineral processing”, Minerals Engineering 10, 757-733.

Onate, E. and Rojek J., 2004. “Combination of discrete element and finite element methods for dynamic analysis of geomechanics problems”, Computer methods in applied mechanics and engineering, 193, 3087-3128.

Ozer, C.E., Ergun, S.L. and Benzer, A.H., 2006. “Modeling of the classification behavior of the diaphragms used in multi-chamber cement mills”, International Journal of Mineral Processing 80, 58-70.

Powell, M.S., 1991. “The effect of liner design on the motion of the outer grinding elements in a rotary mill”, International Journal of Mineral Processing 31, 163-193.

Powell, M. and Valery, W., 2006. “Slurry pooling and trasnsport issues in SAG mills”, 2006 SAG Conference 1, 133-152.

Riezinger, F.M., Knecht, J., Patzelt, N. and Errath, R.A., 2001. “How big is big – exploring today’s limits of SAG and ball mill”, 2001 SAG Conference 2, 25-43.

Wills B. A. and Napier-Munn T. J., 2006. “Mineral Processing Technology”, 7th Edition, Published by Oxford, 146-185.