ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Sadık ÜNAL

THE TRANSFORMATION OF POWER GENERATION FROM GEAR SYSTEM TO THE HYDRAULIC SYSTEM AT ROTARY KILN

DEPARTMENT OF MECHANICAL ENGINEERING

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DEPARTMENT OF MECHANICAL ENGINEERING

We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 09.09.2019.

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ABSTRACT

MSc THESIS

THE TRANSFORMATION OF POWER GENERATION FROM GEAR SYSTEM TO THE HYDRAULIC SYSTEM AT ROTARY KILN

Sadık ÜNAL

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INSTITUTE OF NATURAL AND APPLIED SCIENCES
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The aim of this thesis is to transform the reducer system of rotary kiln to the hydraulic system. In this way, load strength is increased and consequently equipment failure is reduced, material expenses are decreased, loss of manpower in maintenance is reduced and the continuity of production is ensured. At the rotary kiln, the loads which affect to the gear system is very irregular and mixed. So, these loads cause unstable deformation and stress. For this reason, gears and pinions can wear in a short time however very kindly different materials are chosen. However, the hydraulic system brings us strength to the irregular load effects. For this reason, power generation of gear system rotary kiln is transformed to hydraulic system for obtaining high strength. In this thesis, the comparison between the reductor systems and the hydraulic systems are analysed. The advantages and disadvantages are explained. The function and working principle of rotary kiln is explained. The loads acting on the geared system of rotary kiln is analysed. Deformation and stress analysis are carried out according to incoming loads. In line with the load analysis, the necessary calculations are made for the design of the hydraulic system. Based on the calculations, hydraulic elements are selected and hydraulic system is modelled. Moreover, reliability analysis of proposed system were performed by failure mode and effect analysis.

Keywords: Power Generation System, Hydraulic System, Rotary Kiln, Load Analysis

ÖZ

YÜKSEK LİSANS TEZİ

DÖNER FIRINLARDAKİ GÜÇ ÜRETİM SİSTEMİNİN DİŞLİ SİSTEMDEN HİDROLİK SİSTEME ÇEVRİLMESİ

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Bu tezin amacı, döner fırının redüktör sisteminin hidrolik sisteme çevrilmesidir. Böylece yük dayanımının arttırılması ve buna bağlı olarak ekipman arızalarının azaltılması, malzeme giderlerinin düşürülmesi, bakımda harcanan iş gücü kaybının azaltılması ve üretimin sürekliliğinin sağlanmasıdır. Döner fırında, dişli sistemini etkileyen yükler çok düzensiz ve karışıktır. Yani, bu yükler dengesiz deformasyona ve strese neden olur. Bu nedenle ne kadar farklı malzeme seçilirse seçilsin, dişliler kısa sürede aşınabilir. Ancak, hidrolik sistem düzensiz yük etkilerine karşı dayanım kazandırır. Bu nedenle, dişli sistemli döner fırına sağlanan güç yüksek mukavemet elde etmek için hidrolik sisteme dönüştürülmüştür. Bu tez çalışmasında redüktör sistemi ile hidrolik sistemler arasındaki karşılaştırma incelenmiştir. Avantaj ve dezavantajları açıklanmaktadır. Döner fırının işlevi ve çalışma prensibi açıklanmaktadır. Dişli sistemli döner fırınlara etkiyen yükler analiz edilmektedir. Gelen yükler doğrultusunda oluşan deformasyon ve stres analizi yapılmaktadır. Yük analizi doğrultusunda hidrolik sistem dizaynı için gerekli hesaplamalar yapılmaktadır. Hesaplamalara bağlı kalınarak da hidrolik elemanlar seçilmektedir ve hidrolik sistem modellemesi yapılmaktadır. Ayrıca önerilen sistemin güvenilirlik analizi hata modu ve etkileri analizi ile yapılmıştır.

Anahtar Kelimeler: Güç Üretim Sistemi, Hidrolik Sistem, Döner Fırın, Yük Analizi

EXTENDED ABSTRACT

The rotary kilns provide the product to crystallize in high temperatures. The sodium monochromate fed into the rotary kiln and heated with natural gas. The reaction accelerates and the blending takes place.

The first action and move of rotary kiln achieved and produced by electrical power. The electric motor converts electrical energy into mechanical energy. The rotation operation takes place and the mechanical movement starts. At this stage, the speed is high but the torque is low. The motion of rotary kiln transmits by the gear system. The electric motor transfers the movement to the gearbox by means of a coupling connection. The reducer system consists of staged gear groups and this stages show the reducer character. Large and small gears connected to each other throughout the stages. The gear diameters enlarged from the electric motor input to the gear unit output. In this direction, the speed of the system decreases and the torque increases. The torque value increases between the gearbox stages from inlet to outside. Increased torque also provides to increase the load-carrying capacity. Each of the gearbox has the characteristics of reducing the speeds to a certain extent due to their design. The rate of decrease in speed also gives the ratio of the reducer. Therefore, the first movement which is produced from the electric motor and transmitted by the coupling to the gear unit, causing to lose speed and increase its torque with the ratio of the reducer. The gearbox output shaft connected to the pinion gear. The pinion acts as a bridge between the point where the motion generated and the point at which the movement finally wants to transferred. The high torqued and low speed pinion transfers motion to the rotary kiln body. There is a gear, which covers all around the body of the rotary kiln called girth gear. The pinion gear and girth gear are in contact with each other. The pinion gear transfers the movement to the girth gear. Therefore, the process of calcination obtain which the rotation occurred in the rotary kiln. When the rotary

kiln movement is obtained, the body of rotary kiln is carried by rollers and these rollers called as tyres and tyres provide guiding to the rotary kiln. These guide rollers, the other name of tyres determine the number of stations of the rotary kiln. For example, if there are four rollers in the rotary kiln, which has group of rollers, each point with these rolls is one station and referred to as four station rotary kiln. There are also the rotary kilns, which do not use a gear system and rotate with a direct roll drive. However, the rollers are usually does not provide rotating and only used as guide. In addition to this, there is a small angle between the surface in the rotary kiln and allows to flow the calcined material into the pour. This angle is extremely important which will be included in the calculations and will affect the design of the hydraulic system. The angle will change the loads coming to the gear and rolls in the hydraulic system design.

During the calcination process, sodium monochromatite starts to melt and stick. The molten sodium monochromatite sticks to the wall of the rotary kiln. The product, which sticks to the wall of rotary kiln, causes a large layer on the kiln wall. This is due to the stick of the molten product and the stickness force, which occurs. The stickness force on the calcined product helps for a period of time to keep on the surface of kiln wall. However, after a certain point the stick product layer becomes too thick and falls. This fall causes a sudden and large load to the rotary kiln drive system. This load can cause inversion of the gearbox and motor. This situation causes the wear of the reducer gears, the impact of the electric motor, and abnormally increases the mechanical stress of the whole system. The mechanical failures occur and there are production losses due to mechanical failure. For this reason, the incoming large load must be absorbed. The hydraulic system is advantageous at this point. The sudden load is absorbed from the hydraulic system by the relief valve. The sudden load passed through the hydraulic system and the excess pressure released to the outside by the relief valve. Therefore, the damage acts on the system prevented and absorbed.

The hydraulic system consists of reservoir, hydraulic pump, hydraulic pipe, filters, hydraulic fluid and hydraulic motor system. The hydraulic energy produced by the hydraulic pump converted into mechanical energy by means of a hydraulic motor. In this thesis, the current state and load, which acts on the rotary kiln system, will be analysed. The points of the loads, which acts the rotary kiln, was determined and examined with the help of the ANSYS program. The loads were calculated with the aid of the software and analytically. The hydraulic components of the system were analysed by utilizing these loads and the existing design. The rotary kiln is a case study for the transformation of redactor system to the hydraulic system for this thesis, but also the application can be applicable for all other systems, which have sudden load.

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NOMENCLATURE

D	:	Diameter of the pump
d	:	Pitch diameter of the rotary kiln and the pinion
d_c	:	The center diameter
d_p	:	Pitch diameter of pinion
d_r	:	Pitch diameter of rotary kiln
F^t	:	Tangential force
H	:	Power
ISO	:	International Standards Organization
m	:	Module
N	:	Number of teeth
n	:	Rotational speed
T	:	Torque
V	:	Displacement
v	:	Flow velocity (m/s)
W_t	:	Transmitted load
η_m	:	Mechanical efficiency
η_t	:	Overall efficiency
η_v	:	Volumetric efficiency
Δp	:	Differential pressure

1. INTRODUCTION

Production of sodium monochromate is a difficult and expensive process. However, if a production line is installed once the process would result with a valuable product which can be easily export to the countries in all over the world. Sodium monochromate is generally used for production of raw chromium compound which is application area in chemical industry, drugs, and detergent etc.. The chemical structure of the sodium monochromate was illustrated in Figure 1.1.

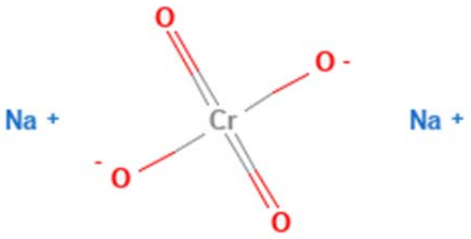


Figure 1.1.The chemical structure of the sodium monochromate

The production of sodium monochromate consists by calcination of a mixture. The mixture contains calcined soda, chromium ore and leaching the obtained sinter and filtering the sinter pulp. In the process, the rotary kiln is used to crystallization of sodium monochromate. Sodium monochromate fills into the rotating tube. Sodium Monochromat (Na_2CrO_4) is the first +6 valued chromium compound obtained by the processing of chromite ore. The total reaction resulting from a series of reaction in the tube is as follows:

$$Cr_2O_3 + 2Na_2CO_3 + 1/2O_2 \Rightarrow 2Na_2CrO_4 + 2CO_2 \quad (1.1)$$

A rotary kiln is a cylinder shape furnace and it continuously rotates around its axis. The rotary kiln is a pyroprocesing device to increase temperature of

materials in a continuous process. The alignment and construction of rotary kiln is very important for the operation of the process. Slight inclination with the horizontal axis makes the movement of solid bed towards the discharge head. The operational efficiency of the rotary kiln based on several parameters. These are rotation speed, temperature, inclination angle, material flow rate and discharge rate (Vijayan and Sendhilkumar, 2014). A rotary kiln on the field was illustrated in Figure 1.2.

The rotating tube working principle is geared system. Electrical motor feeds the gearbox and gives first move. After that, gear system transfer the motion to the other gears until reaching the large pinion on the tube. So, rotation obtained by using electrical power. The material, sodium monochromate, and hot gas are fed. The material rotates with high level of heat and crystal form of sodium monochromate obtained.



Figure 1.2. Rotary kiln

Sodium monochromate filled into the rotating tube with large pieces. This causes sudden loads. In addition to this, sodium monochromate sticks to the rotating tube walls under high temperatures. This creates layer on the rotating tube wall. When the kiln rotates, this layer breaks and falls suddenly. The loads, which affect to the gear system is very irregular and mixed. So, this loads cause unstable

deformation and stress. For this reason, gears and pinions can wear in a short time however very kindly different materials are chosen. But, the hydraulic system brings strength to the irregular load effects. However, hydraulic system compensates sudden loads. The other comparison between these systems were given below and in Table 1.1:

- Hydraulic system runs quieter than gear system.
- Vibration-free movement is obtained at hydraulic system because they are considered incompressible.
- High operating pressures may be obtained at hydraulic system compared to gear system.
- When the system is running, speed of system can be changed at hydraulic system.
- The components of system is lubricated at hydraulic system because of oil is used as hydraulic fluid.
- Safe working system is obtained with the help of safety valves at hydraulic system.
- Precision speed can be adjusted at hydraulic system.
- Hydraulic fluid allows the heat generated into the environment, so system heating is prevented.
- Hydraulic circuit components are long lasting compared to gear system.

But;

- Hydraulic fluid is sensitive at high temperatures.
- Hydraulic circuit components must be solid and have high strength because of working under high pressures. For this reason, hydraulic system components are more expensive than gear system components.

- Connection of the hydraulic circuit must be firm and tight.
- Hydraulic system cannot be transported to long distance because of hydraulic fluid friction is high.
- Hydraulic system is sensitive to air. It causes cavitation and harms the system.
- Hydraulic system need large space because of oil reservoir and other components.

Table 1.1. Comparison of hydraulic, electric, and pneumatic systems

	Hydraulic	**Electric**	**Pneumatic**
Energy transfer	1000 m/s	Unlimited	40 m/s
Energy storage	Limited	Limited but capacity is high	Limited
Energy cost	Expensive	Cheap	Cheap
Temperature effect	Important	Non- Important	Important
Linear motion	Sensitive	Not-Effected	Sensitive
Rotary motion	Very strong	Strong	Very strong
Positional sensitive	Adjustable to ±1 μm	Adjustable to ±1 μm	Adjustable to ±10 mm
Strength	Reliable to high loads	Non-Reliable to high loads	Reliable to high loads but limited load
Unstable loadings	Very reliable	Non-reliable	Reliable

Therefore, in this thesis the transformation of a gear system to a hydraulic system on a rotary kiln was evaluated in details. For this, 3D model of the system was prepared in order to determinations of components based on force, stress, deformation, etc. calculations. After the findings of these parameters, hydraulic

motor was selected according to torque output. Pump was determined according to selected hydraulic motor and electric motor was determined according to selected pump. Moreover, the required diameter of the pipes and the reservoir capacity, type hydraulic fluid were settled.

2. PREVIOUS STUDIES

There have been studies in literature for hydraulic systems and gearbox systems since each system has its own advantages and disadvantages. Therefore, applications area of the systems are different according to their physical characterises.

There is no system directly driven at rotary kiln. Generally, mechanical driven rotary kiln system is preferred. Because, hydraulic requires expertise compared to other systems. High capacity of force can be obtained. For this reason, it is difficult to control. If the engineers have easy to control of system and this system meets the requirements, firstly the engineers prefer hydraulic system. Moreover, high capacity forces can be obtained by using hydraulic systems. On the other hand, hydraulic system has disadvantages such as difficult on control. Various studies are available for the design of rotary kiln in literature. Almost all works related to gear system. Working principles are similar to each other. However, every work was done by putting something on the front.

Dmitrij Ramanenka et al. (2015, 2017a, 2017b) has analysed the effects on the rotary kiln. They were modelled the rotary kiln with respect to these effects. Especially, it has been about drive unit. Because, the drive unit is most affected by the external influences of the rotary kiln. They were categorized the effects under three main title. These are mechanical effects, thermal effects and chemical effects. They found out that there are many factors that can cause sudden loads on the furnace such as a load due to the product, sodium monochromate, in the rotary kiln and layer on the wall. In addition to this, brick lining is fitted to the casing of the kiln very tightly. Whenever starting, stopping or rotating of the kiln, the casing and brick lining are subjected to radial bending, longitudinal bending, vibrations and torsion forces. Additional stresses can typically arise from misalignment of the kiln or other abnormalities. They explained the loads to effect on rotary kiln stress-

controlled loads, external loads, gravity load, and pressure load. In addition, they showed that the size of rotary kiln effects stress on rotary kiln surface. If the size is too large, the sudden load effect on rotary kiln surface creates more stress. Because, loads fall from more height and have more potential energy. Therefore, when the load is falling during the rotating, this potential energy transform completely to kinetic energy. Then the load impacts the rotary kiln surface and creates stress. For this reason, the size of rotary kiln effects the deformation on rotary kiln surface. Where σL is the compressive induce of stress on the inner wall, E_L Young's modulus and t_L is the thickness of rotary kiln surface.

Heydenrych (2001) have modeled a rotary kiln to investigate the mass transfer. According to their studies, despite the other effects such as thermal and chemical effects, mass transfer and loads are the most important factors for designing the gales. If the bed fill is high or rotational speed is fast, the momentum of the particles increases. Momentum depends on mass and speed. So, the particles which are in rotary kiln, fall down during the rotation and reach the inner surface of rotary kiln. Distortion obtains in the kiln bed surface.

Mass transfer was measured during the drying process by Jauhari (1997). In the study, large particles were used for obtaining evaporation until the particles were dry. 0,15 m diameter and 0,041m length steel rotating drum was used and 0,052 radians/s and 0,266 radians/s speeds were applied. So, the factors, which effect momentum, were iterated. Different speeds were also used and momentum created distortion on the rotary kiln surface.

Boateng and Barr (1997) have analysed the behaviour of a partially filled rotating cylinder tube in the transverse plane. They performed an experimental study to improve prediction of the rheological behaviour of materials granulite in partially filled rotating cylinder.

Kritzinger and Kingsley (2009) have analysed optimum conditions for designing the rotary kiln. The most suitable gear combination, gear material

selection, and equipment placing have analysed in the study. Basic modelling notion were explained, because of approach of optimization description. We understand from the results that how the combining methods with respect to modern computing power, may generate large number of viable design and operating candidates. An Excel-based calculation and FORTRAN program were used to determine mass transfer of kiln with the aid of one-dimensional model.

Karacan (1982) has worked about the hydraulic systems in the industrial applications. Hydraulic pump and hydraulic power have analysed and made calculations. In the study, selection of hydraulic type, calculation of reservoir capacity, determining of diameter of hydraulic hose, selection of filter type, calculation of hydraulic pump and hydraulic motor capacity were explained.

Şimşek et al. (2013) worked about heat loss from surface of rotary kiln tube by using empirical and statistical modelling. In addition to this, stresses were analysed. Cement rotary kiln working principle and working conditions were same with sodium monochromate rotary kiln.

Dekkiche et al. (1980) have worked about different mathematical modelling computer programs, cybernetic approach. The art industry process has a lot of interactions with the environment on subjects such as information, material and energy. The progress of a series of retro actions was checked. The system modelling is a representation of the fact that reality is partially perceived. They proposed a new methodology for the development of the autonomous approach. They decided the control variables such as temperature, heat, feed rate, fuel rate, recycling fan speed, induced draft fan speed, kiln rotational speed, kiln motor intensity, air rate. Then, they change these variables and measure the reaction of rotary kiln. But, they neglect uncontrolling variables such as sudden loading, kiln bed thickness, kiln bed stickness, elongation, ovality, thermal stress. These variables created certain changes on rotary kiln design. Our design was about driven system. So, these variables change driven system, too. For this reason, in

our design, first of all the most active parameter can be handled. This active parameter is load, especially sudden load.

Öven and Bogoçlu (2015) worked about hydraulic system design, especially designing of hydraulic pump. Most of time, gear pumps are used as hydraulic pump. Gear pump which is used in rotary kiln hydraulic pump systems was designed with CAD Program and program develops additional features about the working condition parameters. The program was calculated and compared the fluid values with different surface widths.

Murakami and Takada (1998) analysed the effect of quenching and tempering processes on the fatigue life. Load factors were analysed as approach of fatigue life. They focused on loads on rotary kiln and analysed the fatigue behaviour. Stress, strain analysis, and work analysis were applied. The load which affect gale and girth gear has been analysed, as well.

3. MATERIAL AND METHOD

3.1. Material

The rotary kiln is calcination device by using continuous heating to raise high temperature of materials for obtaining chemical reaction. The rotary kiln shape is cylindrical vessel tube and inclined to the horizontally and rotates slowly about its own axis. Electrical motor is used as power source of the system and the power transmits by gear system. The cylindrical vessel of kiln covers all around with huge gear and this is called girth gear. Girth gear is contacted with pinion. So, pinion translates revolution and torque to the girth gear. Therefore, rotation is obtained on cylindrical vessel of the kiln. Rotation must be slow to obtained enough calcination. In addition to this, the kiln must be inclined to the horizontally for streaming from feeding to the discharge of kiln. Feeding of the rotary kiln is very unstable. Amount of materials can be changed in time and this situation creates unstable loads. For this reason, unstable loads create fatigue on gear system. The material, which is calcinated, is fed into the upper end of the cylinder rotary kiln tube. During the kiln rotation process, material which will be calcinated slowly moves down towards from upper end to the lower end, and during the moving process stirring and mixing are obtained at the material. Energy source is necessary to reach high temperatures for obtaining calcination. For this reason, different types of energy sources are used to obtain hot gases. Hot gases pass along the rotary kiln tube. Flow of hot gases can be in same direction with the process material and it is called co-current flow. However, hot gases generally pass along the kiln tube in the opposite direction for obtaining effective heat transfer, so effective calcination and it is called counter-current flow. The energy source can be different and generated in an external furnace, or can be generated by burner inside the rotary kiln. The burner is extended into the rotary kiln by means of a pipe.

Different type of fuels can be used such as natural gas, pulverized coal, oil, or petroleum (Peray, 1986). Flow diagram of rotary kiln was shown in Figure 3.1.

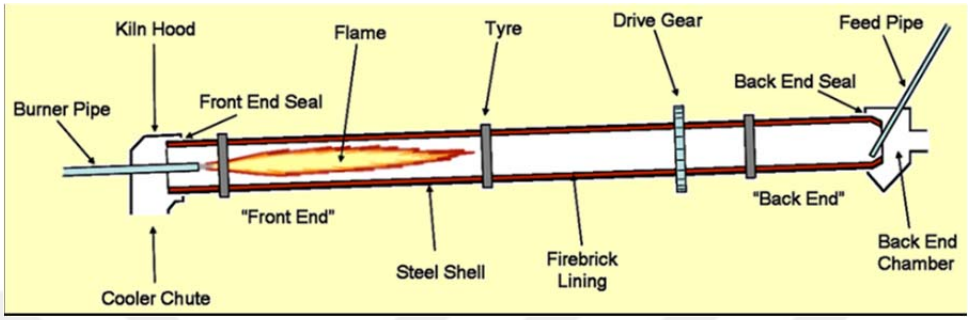


Figure 3.1. Rotary kiln flow diagram (Moore, 2012)

The basic components of a rotary kiln are the shell of vessel tube, the refractory lining, tyres, and rollers for supporting, drive gear, or the other name of girth gear, drive unit, and internal heat exchangers. Drive gear or girth gear is driven by drive unit. Drive unit consist pinion gear, reducer, housings, coupling, and electrical motor. General representation of gear system of rotary kiln is shown in Figure 3.2 at below.

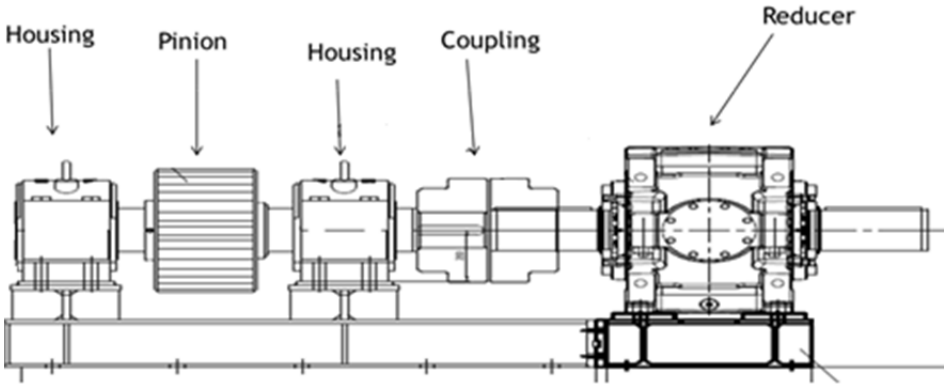


Figure 3.2. Drive Unit of Rotary Kiln

Electrical motors give motion to the reducer. Reducer decreases speed and increases torque to rotate rotary kiln. So, reducer transmits high torque values to the pinion gear. Pinion gear is contact point with rotary kiln. Pinion gear transmits torque to the girth gear on rotary kiln shell. Electrical motor produces a rotary motion and translate to reducer. Then, reducer decreases the speed of rotary motion and increases torque of the system. Then, reducer feeds the pinion gear. Pinion gear is connected drive gear. The kiln is generally turned around with single gear and this gear is called girth gear. Girth gear surrounds a cooler part of the rotary kiln shell. Nevertheless, sometimes, rotary kiln is turned by driven rollers. Tyres and rollers are connected with each other. Rollers directly driven by electrical motor and transmits motion to the tyres, so rotation is obtained. But, this type of system is used under low loads therefore it is not functional. Generally, gear system driven units are selected. At the gear system driven systems, the girth gear is connected through a gear train to a variable-speed electric motor. The drive unit must have high starting torque in order to start rotation of the kiln with huge eccentric load.

In the designing of rotary kiln, spur type gear is selected, because spur gears are simple in construction, easy to manufacture and cost less. Spur gear means that straight-cut gear. The edge of tooth is straight at spur gears. Tooth of spur gears are aligned parallel to the rotation axis. These types of gears are assembled to the parallel shafts for correct fitting. For this reason, axial thrust loads on the tooth absorbed. Furthermore, they have highest efficiency compared to other type of gears. In addition to this, spur gears have excellent precision rating. The spur gears are used in high load application. Also, they can be used in all types of trains and wide range of velocity ratios. But, spur gears are not suitable at high speeds. Because during the tooth interaction, tooth collide and impact force causes noise. This noise means that increment of stresses. For this type of application, generally helical gear is selected in some applications such as cars. The pinion gear material is alloy special steel. In addition to this, heat treatment processes are

applied. Inside of the gear must be tough and outside of the gear must be hardened. Because, tough body of gear provides high load absorption. Hardened gear surface provides wear resistance. The grade is 34CrNiMo6 and the material number is 1.6582. The hardness of the gear is between 270 to 330 HB (Brinell Hardness Number). The module of pinion gear is 25 and the number of teeth (z) is 23. The technical drawing of pinion gear is shown in Figure 3.3.

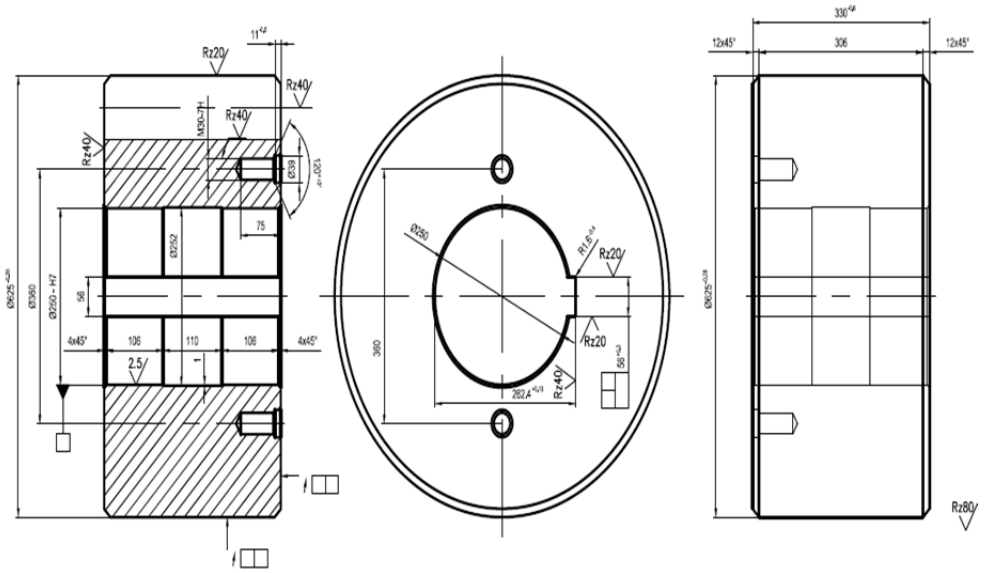


Figure 3.3. Technical drawing of pinion gear

Table 3.1. Mechanical Properties of EN/DIN 34CrNiMo6 / 1.6582 Alloy Steel

Physical Properties	Value
Density	7.73 kg/dm^3
Young's modulus	210 GPa
Poisson's ratio	0,29
Yield strength	600 MPa
Tensile strength	800 MPa
Elongation	13%
Reduction of area	55%
Toughness	45 J

Table 3.2. Chemical Composition Properties of EN/DIN 34CrNiM06 / 1.6582 Alloy Steel

	C	Mn	Si	P	S	Cr	Mo	Ni
Min.	**0.3**	**0.5**	**-**	**-**	**-**	**1.3**	**0.15**	**1.3**
Max.	**0.38**	**0.8**	**0.4**	**0.025**	**0.035**	**1.7**	**0.3**	**1.7**

Rotary kiln reducer system works with auxiliary drive because it is overloaded at the moment of first take-off. The main drive should be 90 kW and the auxiliary drive should be 7.5 kW. Generally, drive system is made from reducer, main drive electrical motor (90 kW), auxiliary drive electrical motor (7,5 kW), couplings and housings. Reducer has been differentiated with two types of shafts. These are High Speed Shaft (HSS) and Low Speed Shaft (LSS) by the effect of different capacity of electrical motors. The gear type inside the gearbox is helical gear. Because, helical gears are preferred for heavy load applications. The gear type of transmission between gearbox and rotary kiln is spur gear. The gearbox works under high loads so the temperature may reach up to 150 ^{o}C. Gear ratio was chosen as 10 with respect to inlet rotation and outlet speed. 1500 rpm of electric motor inlet speed was reduced to 150 rpm in two equal stage. The teeth were finished by hobbing or shaping. Cycles life is reach up to 10^8 and reliability is about 99%-99,9%. It is high precision shaved or ground tooth (Budynas and Nisbett, 2014). General assembly of drive system and specifications of rotary kiln gear system–reducer were given Figure 3.4 and Table 3.3, respectively.

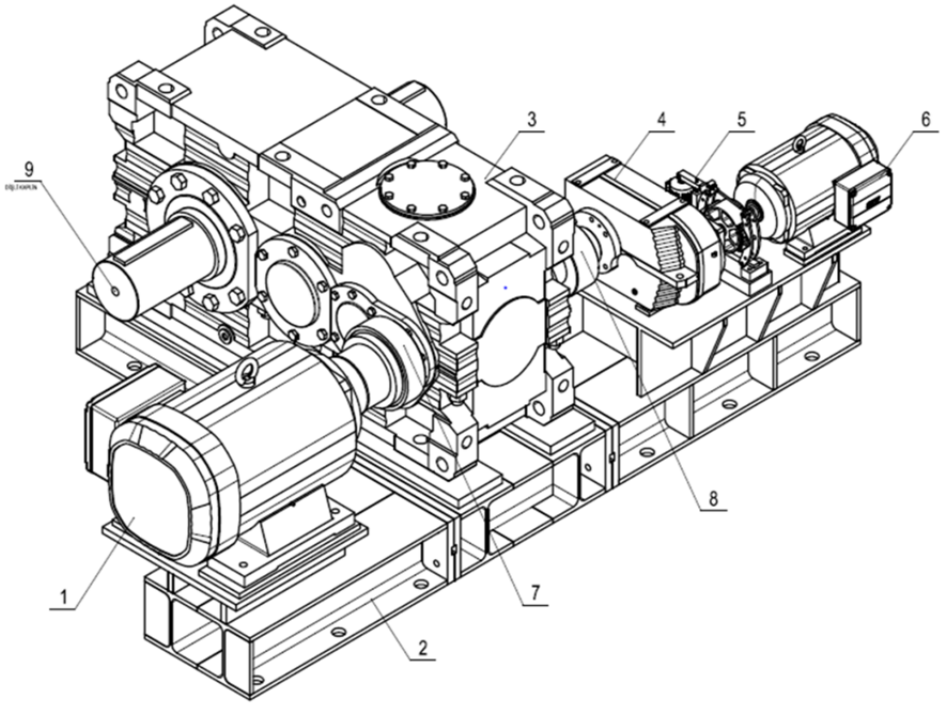


Figure 3.4. General assembly of drive system (Sew Eurodrive Catalog, 2007).

Table 3.3. The gearbox parameters of rotary kiln

Power	90 kW + 7,5 Kw
Input Speed	1500 rpm
Output Speed	150 rpm
Gear Type Transmission Between Gear Box and Rotary Kiln	Spur
Gear Type Inside The Gear Box	Helical
Working Temperature	150 ^{0}C
Power Source	Electrical Motor

The gearbox which is used at rotary kiln was Sew Eurodrive X2F220 consists of helical gears with parallel shafts. Two-stage of gear set reduce torque output to 150 rpm from 1500 rpm. Mounting position is horizontal shaft and horizontally aligned housing which fixation is flanged. Nominal torque class of the gearbox is 112 kNm and the efficiency is 97,5%.

3.1.1. The Hydraulic Systems

In the industry, it is demanded that the load applied to the parts and the movement resulting from this load is controlled. The movement control is usually required with electric machines or the machine which carriers that use diesel, gasoline or steam. The movement control equipment, the other name of movers, are used mechanical attachments such as screw, rack, pinion, lever etc. However, these are not the only movement control equipment or prime movers. In addition to this, enclosed fluids which can be liquids and gases, can also be movers to control and provide motion and applied force to substances. Hydraulic system liquids are transmitted and distributed forces to evenly all surfaces which is contacted. Liquids cannot be compressed for this reason, they transmit the load on each surface which is contacted. Pascal's Law said that pressure applied to any part of confined liquid is transmitted with to every other part (Bannister, 1996).

3.1.1.1. Hydraulic Type

When the hydraulic system is designed, firstly, type of hydraulic must be determined. So, every hydraulics has different physical properties. Hydraulic fluids are used to transmit hydraulic power. In addition to lubricating and cooling the hydraulic circuit elements. When water is used as a hydraulic fluid, problems such as corrosion, boiling point, freezing point and low viscosity are encountered. Some blends (such as oil, glycol) are added to remove these problems. Mineral oils are the most used fluid. Additives are added to increase the service life and duration. Hydraulic fluids fulfil three important functions, which are transferring power, protecting the hydraulic system, and dealing with operational conditions (Givens and Michael, 2003)

In a hydraulic system, efficient transmission of power occurs with a liquid having the following characteristics.

- Low Compressibility; so that pressure and other power can be transmitted immediately and efficiently;
- Good Air Removal Features; so that compressibility will not increase due to air bubbles remaining in the liquid;
- Good anti-foaming properties; so that the foam does not enter the hydraulic system;
- Appropriate Viscosity; so that it will be viscous so that you can comfortably navigate through the system while at the same time lubricating it (Placek, 2006).

Mineral oils are ideal liquids for hydraulic systems due to lubrication, cooling and protection. For lubrication between moving parts in the circuit oil, pumps, motors, and valves requires an oil with suitable flow characteristics and anti-wear properties. Cooling distributes the heat generated in the system where viscosity is an important criterion. Protection is necessary for protect the system from corrosion and protect moving parts such as pumps, motors and valves from wear and tear (Canada National Research Council, 1986).

Synthetic hydraulic fluid combines the properties of the synthetic base with the properties of the lithium complex thickener. Paraffin-free structures of synthetic fluids and have low drag coefficients, excellent pump ability at low temperatures and very low initial start-up and torque when compared to mineral oils. These products potentially save energy and reduce operating temperatures in the load areas of spherical and ball bearings. Lithium complex thickener adds adhesion to the surface, structural stability and water resistance. With a high level of chemical stability, this grease has a working viscosity suitable for high and low temperatures; it is also formulated with a special additive combination to provide excellent protection against abrasion, rust and corrosion.

3.1.1.2. Physical Properties of Hydraulics

For the efficiency of a hydraulic system, it is very important that the components of the hydraulic system have a good quality. But hydraulic oil is the biggest cause of defects in hydraulic systems. Even in a hydraulic system made from the best materials in the world, it is inevitable that failures will occur in a very short time if a suitable and high quality hydraulic oil is used. For this reason, the physical properties of hydraulic fluids are very sensitive and important (Makine Eğitimi, 2018).

Viscosity: The viscosity of a fluid is measure of resistance to deformation which is created by shear stress or tensile stress. For liquids, generally viscosity can be defined as thickness. Thick fluids have less fluidity. In addition to this, most important characteristic of a hydraulic fluid is the viscosity when considering the lubrication of the system. The viscosity of the hydraulic fluid should be efficient to lubricate the system components, especially the pump and effective sealing element to prevent leakage of pumps, motors and valves between operating tolerances.

In practice, the choice of a low viscosity hydraulic fluid that can adequately lubricate the system pump is made by leaving a suitable safety clearance (Canada National Research Council, 1986).

The requirement for viscosity of a hydraulic fluid is complicated by the fact that the viscosity changes with temperature and pressure. The change in temperature with a viscosity of hydraulic fluid depends on the viscosity index of the hydraulic fluid. With an increase in the viscosity of a high viscosity index hydraulic, it exhibits less change in viscosity than a fluid with a lower viscosity index. Temperature changes the viscosity logarithmically. The viscosity index of a fluid should be selected high enough, considering the operating temperature range of the hydraulic system in which the hydraulic fluid is used. The fluid must be able to flow smoothly even at the lowest operating temperatures, while satisfying the

lubrication characteristic even at the highest operating temperatures, and should not cause difficulties in cold, especially during initial work. Many liquids have a viscosity index of around 100, but in areas such as aviation where very large operating temperature changes are required, viscosity indexes of 150 and above are required.

The viscosity index improvers in hydraulic oils can be used as additives. These should be carefully selected because they can affect the physical stability of the oil (Debra Light, 2005).

Oxidation: The components of hydraulic react with oxygen in air and transform to state of mug. This can be called oxidation on hydraulic. It causes to corrosion on metal layers. The oxidation of mineral oils leads to sludge formation; which causes clogging in the valves and filters, leading to corrosion and lacquer formation. High temperatures and pressure in many hydraulic systems cause oxidation. Pollutants in hydraulic oils; for example, the presence of water and metal components fuel oxidation, because they trigger reactions that cause mineral oil properties to deteriorate. Hydraulic fluids must be resistant to oxidation, so normally there are antioxidant additives in them to prevent oxidation and prolong the working life. Oxidation endurance is measured by the Turbine Oil Stability Test (TOST). This test has more severe conditions than normal hydraulic systems. However, the factors that most disturb a hydraulic fluid are considered in the test. In the test, 300 ml oil sample and 60 ml water are placed together with a scrap of copper and steel coils (serving as catalyst). The tube is heated to 95 °C and bubbled into the liquid at an oxygen controlled rate. The acidity of the solution is constantly monitored. The time taken for the fat to reach the 2 mg KOH/gr neutralization number is determined as the life of the TOST. In addition, the sample is checked after 1000 hours for precipitate formation or for changes in appearance in oil, water, copper and steel (Gatto et al., 2005).

Ability of Lubrication: Ability of lubrication can be defined as ability to make film layer on metal surface. So, it is related with friction. At high temperatures, zinc type additives create protective film layer between metal surfaces to prevent friction.

Bubble Formation: The bubbles occur that when the oil molecule flows with high velocity, impacts to the air molecule. For this reason, sealing method important for hydraulic system. The hydraulic fluid must be viscous enough for providing effective sealing in valves, pumps and motors. This will minimize the leakage and ensure that these parts work efficiently. At the same time, the materials used in the hydraulic fluid system must also be compatible with the gaskets. Compliance with the seals can be determined by immersing a nitrile rubber ring in the oil and waiting for 24 hours at 100 °C. The inner diameter of the seal is measured before and after the test and is designated as the gasket compatibility index. In addition to this, the pipe shall not be sharp (90°) angled. It should be curved with large curves. The sections should not be narrowed suddenly; their internal surfaces should be smooth. The appropriate filter should be selected in the tank and the turbulence should not be allowed by inserting a curtain between the suction and return line with the pipe's mouth (45°) inclined. For this, there must be ventilation elements in the circuit (Gatto et al., 2005).

Yield Point: It is related with temperature. Hydraulic losses the fluidity at low temperatures. For this reason, heaters can be used at hydraulic system. The heat that the hydraulic circuit oils lose their fluidity and start to thicken is called the yield point. For hydraulic circuits, the hydraulic fluid operating temperature is between 50 °C and 100 °C. As the working temperatures drop, the viscosity of the hydraulic fluid increases, the fluidity decreases. In such cases, the efficiency of the system decreases. The yield point is the lowest temperature of the activity of a mineral oil. Most mineral oils contain some dissolved wax. When the oil is cooled, the wax forms a solid crystalline structure which prevents the remaining liquid

from flowing. The operation of a hydraulic fluid must be at least 10 °C lower than the expected temperature. Yield point additives can be added to mineral oils (Suzuki et al., 1998).

Flashing Point: The temperature of ambient is important. Normally, hydraulic can flash over 150 ^{0}C. So, temperature measurement devices are used at hydraulic system. It is the point where the oils start burning when they are sprayed in the temperature between 160 °C and 200 °C.

Polymerization: If the different types of hydraulics are used in same system, polymerization can be obtained and loss of physical properties are seen. In hydraulic circuits, it maintains high pressure and high temperature oil properties. If the oil does not deteriorate under these adverse conditions and does not dissociate to its molecules, the polymerization property is good.

These different properties in hydraulic fluids have created designations for their identification. Therefore, physical properties of hydraulic fluids can be understood easily by looking at their abbreviations. These abbreviations also explain their application areas. Therefore, some institutions have standardized these physical properties, one of which is The International Organization for Standardization (ISO). ISO standards has set broad categories for the classification of mineral hydraulic oils as it shown in Table 3.4 (Michael et al., 2000).

Table 3.4. ISO Classes of hydraulic fluids

DESIGNATION	IMPORTANT PROPERTIES	APPLICATION AREAS
HL	Resistance to corrosion	Work under water
HLP	Resistance to abrasion	Work under high load
HV	Resistance to temperature	Work under high temperature
HH	Flat mineral oils - do not contain additive	They are low cost products. It is suitable for use in non-critical systems
HM	Resistance to corrosion & abrasion	Work under water and high load
HR	Resistance to corrosion & viscosity index is high	Work under water and high life expectancy
HS	Unresistance to flame	Cannot work under fire
HG	Resistance to stick	Work slide systems

3.1.1.3. Hydraulic System Components

The main hydraulic system consist reservoir, filter, hydraulic pump, hydraulic motor and hydraulic fluid. But, different control and measurement devices can be added the hydraulic system.

The hydraulic system includes the following elements:

- piston connected to the output shaft and moving in a closed system
- storage tank (reservoir)
- filter
- electric pump (hydraulic pump)
- pressure regulator
- control valve
- leak proof closed loop piping
- hydraulic motor
- connecting devices
- measurement devices (manometer, flowmeter … etc.)
- sealing parts
- hydraulic fluid
- check valves

The piston and connected output shaft are used to transfer the motion and force. However, all other parts are used to help for controlling the system. The storage/fluid tank is a reservoir for the fluid which is used as transmission media. The hydraulic oil is generally used as transmission media because of high density incompressible. Transmission media or the other name of hydraulic fluid must be filtered for removing dust or any other unwanted particles. After filtration process, the hydraulic fluid is pumped by the hydraulic pump. The capacity of hydraulic pump is directly related with the hydraulic system design.

The hydraulic pump design is generally designed as constant volume for each revolution of the pump shaft. For this reason, until the system fails, the fluid pressure can increase indefinitely at the dead end of the piston. The pressure regulator is used to regulate system pressure and redirect the excess fluid back to the storage tank.

The leak proof piping is also important for the safety, environmental hazards and economical gains. In addition to this, autonomic control systems such as overload protector, limit controller, electric motor starter can also be used to control flow in hydraulic systems. Reservoir, filter, pump and hydraulic motor are explained in the following subsections.

Reservoir (Storage Tank): The reservoir is the hydraulic unit that will be needed for the system to store hydraulic fluid and ready to send when needed. Hydraulic fluid does not just store in the tank, it is filtered and cooled. The lower part of the reservoir should be designed to generate air flow so that the cooling hydraulic fluid can easily be cooled. To prevent the fluid returning to the tank to be absorbed without resting, a tilting plate should be placed.

The storage capacity is selected according to the amount of fluid required in the hydraulic system and the size of the distribution system.

The oil reservoir contains a suction filter and suction pipe, which is formed on the suction line and separates the returning oil. The oil reservoir discharges this heat as the oil from the suction line is heated backwards. Unwanted materials such as dust, dirt, sediment passing through the system are cleaned by means of return filters. The oil reservoir of the hydraulic systems should be made of acid type compounds.

Filter: The filter is a hydraulic element that can catch the particles before they enter the system which damages the hydraulic system, clog the hydraulic pipes and lock the hydraulic pump and therefore protect the system. It is used to clean the fluid to protect the hydraulic elements from wear and tear. Pollution is

changing the elements such as pipe, hose; Due to the presence of new hydraulic fluid or impairment of the sealing elements (The Handbook of Hydraulic Filtration, 2018)

Fluid contaminants in the fluid become four anticipated obstacles in the hydraulic flow direction. These are supply of energy transmission, lubricating duty between moving inner parts, delivery of heat transfer, and providing sealing tolerance between moving parts.

ISO 4406 (International Standards Organization) cleanliness standards are widely accepted throughout the industry. Manufacturers of all machinery and hydraulic equipment must specify the target ISO cleanliness level standards in order to ensure that their equipment can achieve optimum standard performance. The comparisons of cleanliness standards are shown Table 3.5.

Table 3.5. Cleaning level standards comparison

ISO Code	**Particle / Millimetres**			**NAS 1638 (1964)**	**SAE Level (1963)**
	≥2 micron	**≥5 micron**	**≥15 micron**		
23/21/18	80000	20000	2500	12	-
22/20/18	40000	10000	1300	-	-
22/20/17	40000	10000	640	11	-
22/20/16	40000	10000	640	-	-
21/19/16	20000	5000	320	10	-
20/18/15	10000	2500	160	9	6
19/17/14	5000	1300	160	8	5
18/16/13	2500	640	80	7	4
17/15/12	1300	640	40	6	3
16/14/12	640	320	40	-	-
16/14/11	640	160	20	5	2
15/13/10	320	160	10	4	1

The material of the filter element; the main part of the filter is the pollution. The filter element is generally fabricated in sheet form, thereby forming

a large, spun bonded structure through which the fluid can pass. This increases the dirt holding capacity, reducing the pressure differential. In some applications, the filter element is multi-layered to support precise performance criteria and is supported by mesh. Once the folds of the element have been made, they are cut to the appropriate lengths and are connected, glued or otherwise sewn by using special hooks from both ends. All filter elements include wire mesh, paper, fiberglass composites or synthetic materials. Comparison of filter elements according to certain criteria is shown in Table 3.6 below.

Table 3.6. General comparison of filter elements

Material	**Capture Efficiency**	**Dirt Holding Capacity**	**Pressure Drop**	**Life**	**Inıtial Cost**
Fiberglass	High	High	Medium	High	Medium
Cellulose (or paper)	Medium	Medium	Medium	Medium	Medium
Wire	Medium	Medium	Medium	Medium	Medium

Hydraulic Pump: It is the circuit element that sends the fluid in the tank to set the pressure and outgoing system. The pumps convert mechanical energy into hydraulic energy. The pump takes its rotational motion from the electric motor. Pumps do not create pressure. Pressure builds up when a barrier is encountered in the fluid system.

Hydraulic pumps are generally classified into two categories: Non-positive displacement pumps and positive displacement pumps. The non-positive displacement pump unit is the centrifugal pump whose transmission is reduced by the increase of the working pressure. If the outlet of the centrifugal pump is completely closed, the flow stops and the flow rate is drop to zero. In these pumps the flow rate varies in proportion to the pressure resistance encountered. The

operating pressures of the devices in the power hydraulics are very high. The pumps to be used in these arrangements should be in the structure to provide the continuity of the flow of the pressure that is met as mentioned. For this reason, positive displacement pumps which do not change the pressure despite the pressure resistance are used in hydraulic assemblies. Positive displacement pumps are used as the main pump in hydraulic installations. In positive-displacement pumps, the inlet is completely insulated from the outlet. The unpressurized fluid in the section of inlet and the pressurized fluid in the section of outlet are separated from each other by a structure within the pump. Pump types and their sub-types were presented in Figure 3.5.

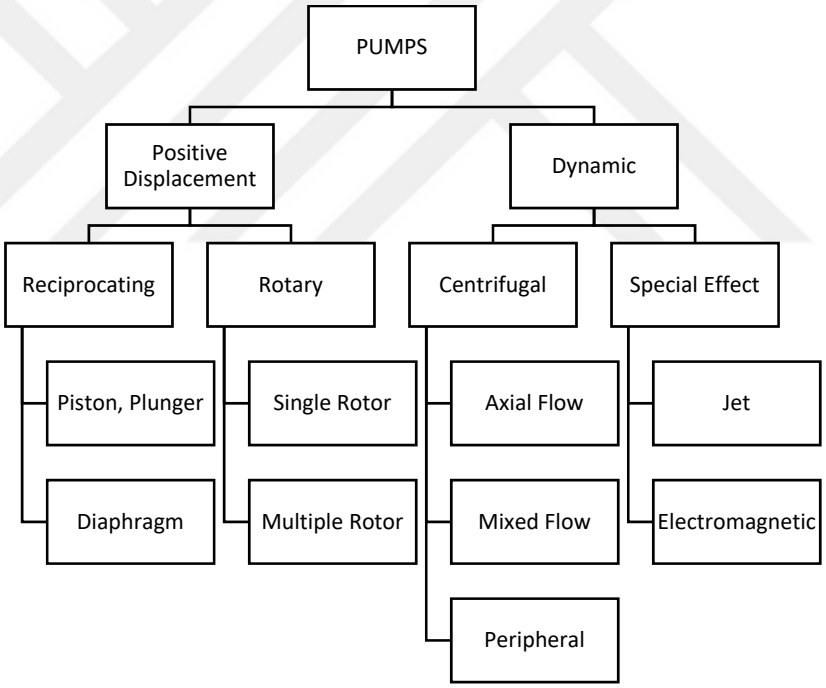


Figure 3.5. Types of pumps

Gear pump can be defined as simple and sturdy positive displacement pump. Gear pump systems consist two meshed gears rotating about own axes. At

the gear pump system, rotating gears are the only moving parts. The gear pumps are relatively inexpensive compared to the other pump types, compact and have less moving parts (Pinches, 2000). The gear pumps can be categorized by the position of gears like external and internal. External gear pump is meshed with two gears housed in a pump. It works like reducer system, driving and driven (Manring and Kasaragadda, 2003).

Lobe pump working principle is similar to external gear pump. But lobe pump is different from external gear pump in one point that at the external gear pump, gears are contacted with each other, but at the lobe pump, lobes does not have any contact with each other.

Internal gear pumps can be used widely different production processes. The internal gear pumps are generally used for low or medium viscosity fluids. In addition to this, they can be used in wide range of temperature. The internal gear pump is basic gear pump for variation. They can be used as self-priming, non-pulsing and running dry in short periods.

The internal gear pump systems consist basic components such as internal gear, regular spur gear, crescent-shaped seal and casing of the pump (external housing).

Gerotor pump type is a positive displacement pump. The gerotor pump working principle is similar to the internal gear pump. But, at the gerotor pump the crescent is not available compared to the internal gear pump. The gerotor pump consists of two main parts which is called rotors. These are inner rotor and outer rotor. The outer rotor has one more tooth compared to the inner rotor. Precedence and limitations of the hydraulic gerotor motor was presented in Table 3.7.

Table 3.7. Precedence and limitations of the hydraulic gerotor motor

Precedence	Limitations
Compared to other types of hydraulic motors, relatively simple construction	Low sealing ability of lobes between the inner rotor and outer ring
Low speed	Low total efficiency
Relatively small and light	Friction
Relatively cheap	Wear
High torque	
Self-braking ability	

Vane configurations can be changed at the vane pumps such as sliding vane, flexible vane, swinging vane, rolling vane, and external vane with respect to number of vane configurations. The vane pump is different from external vane pumps not to pump solid particles. The flexible vane pump performance can be low for only pumping the small solids but this type of pumps create effective vacuum. (Majumdar, 2001). Unbalanced vane pumps are similar to the vane pumps. But the unbalanced vane pumps have one more vane compared to the vane pumps.

The balanced van pump is different from the unbalanced vane pump with respect to cam shape. The balanced pump has an elliptical cam ring and this pump has two inlet sections and two outlet sections. The pressure is created by the effect of vanes but the difference of this pump compared to the other types of pump is having two pump halves identically creates equal and opposite forces on the rotor. Some type of vane pumps can be used as adjustable capacity. This type of pumps are called adjustable vane pumps. The adjusting process can be applied by using the position of rotor and the inner casing of the pump.

The piston type pumps are suitable and available for the high pressure applications. The piston pump has some advantages such as high efficiency, simple and basic design and maintenance need is low. The piston pump converts the rotary motion to the linear and reciprocating motion.

3.1.1.4. Hydraulic Motor

Different types of motors can be used at the hydraulic systems but the most commonly used one is the piston type motors. The characteristics of the piston type motors are the same as the other pumps. The piston type is separated from the others, especially in the direction of converting hydraulic energy into mechanical energy.

As a result, power source is substance of hydraulic, reservoir and hydraulic pump instead of the electrical motor at gear system. Hydraulic motor is a transmission device instead of a reducer at gear system. Hydraulic motor has high torque and moment values compered to reducer at gear system. In addition to this, velocity adjustment can be obtained without stages at gear system reducer. Also, during the working velocity can be increased or rotation direction can be changed at hydraulic system.

Hydraulic motor types are similar to hydraulic pump types. These are gear type, vane type and piston hydraulic motor. Gear type hydraulic motor is used under low load applications. It must be produced as constant displacement. Vane type hydraulic motor is used under low load applications too but it can be produced variable displacement compared to gear type hydraulic motor system. The piston type hydraulic motor is the most commonly used inside the hydraulic motor types. It can be used under high load applications and it can be produced constant and variable displacement.

3.2. Method

Analytic and numerical calculations were performed throughout the study. The force transmitted between the gears were determined in both approach in order to confirm the transmitted force. Acting force on the gears were also calculated and compared with the analytical solution to validate the numeric approach on the

system. Moreover, stress distribution and deformation were calculated by numeric calculations.

Before the numerical approach, full model of the system was modelled in 3D environment in order to observe the system in details. The 3D model of the system was illustrated in Figures 3.14, 3.15, 3.16, and 3.17. The dimensions of the rotary kiln was given in Figure 3.18.

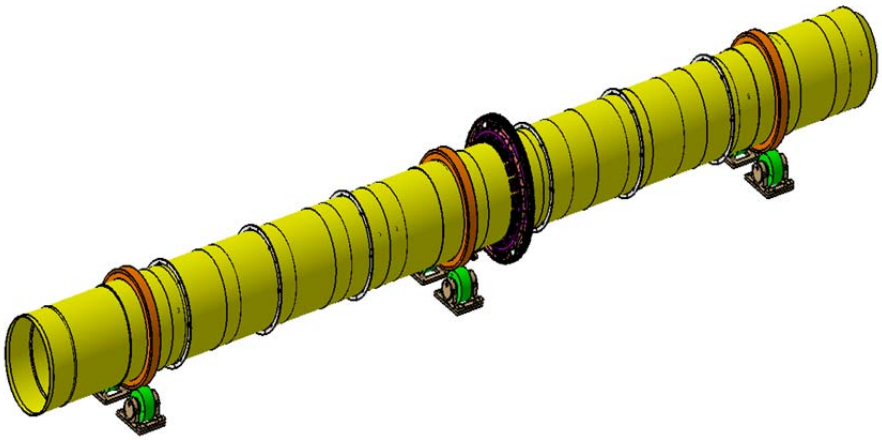


Figure 3.6. 3D model of the system

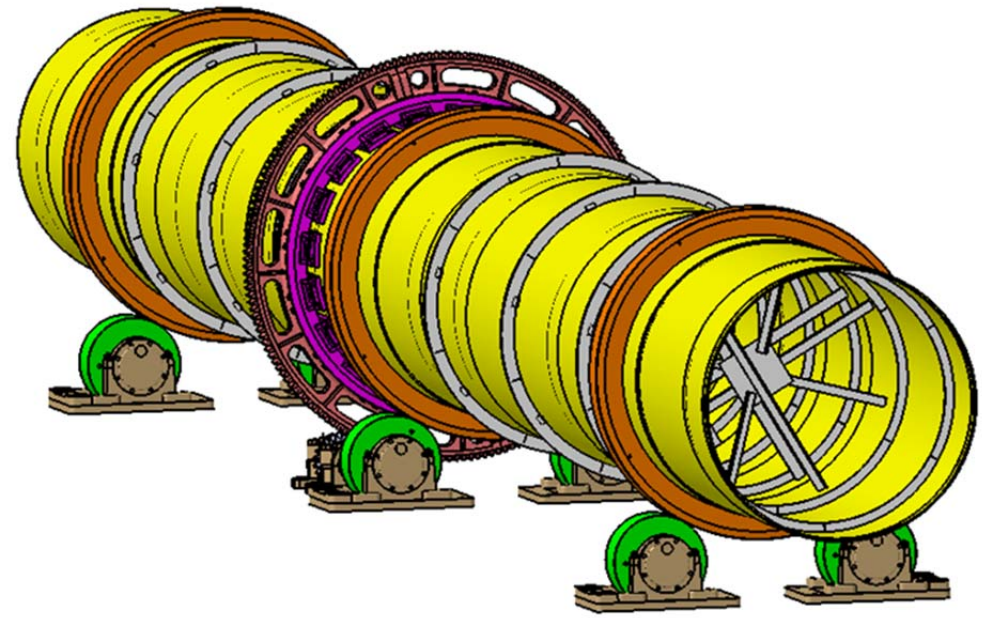


Figure 3.7. 3D model of the system

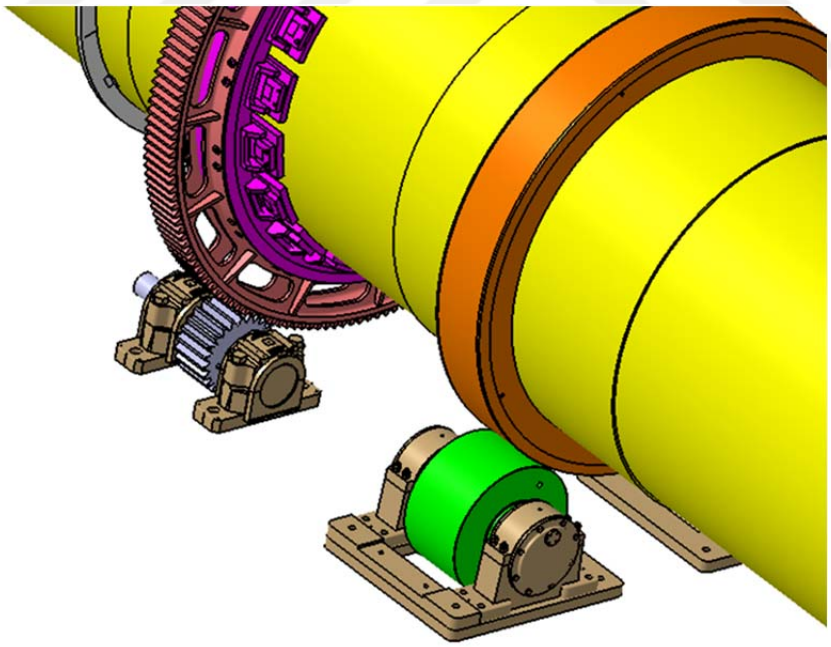


Figure 3.8. 3D model of the system

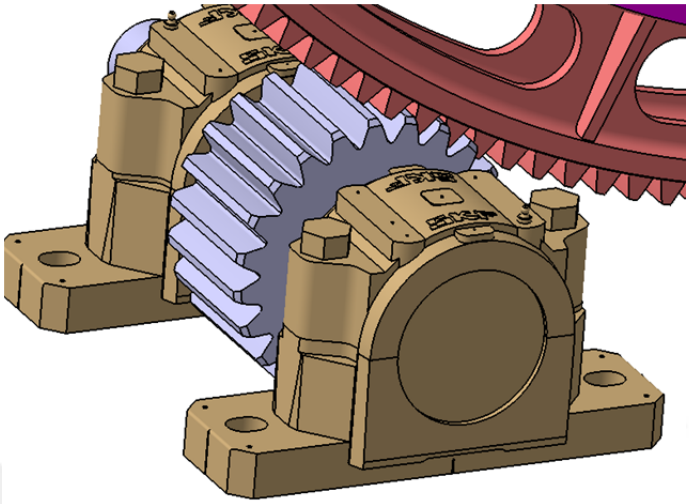


Figure 3.9. Details of 3D model of the system

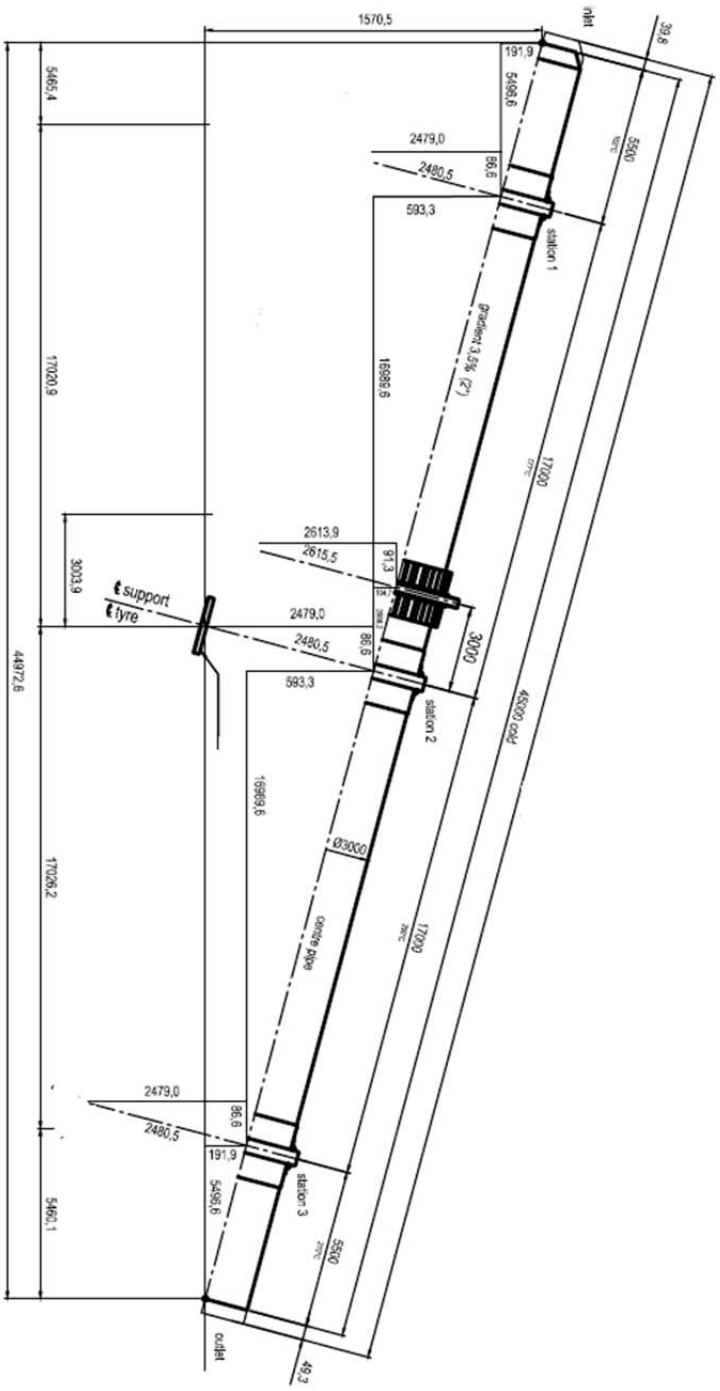


Figure 3.10. Dimensions of the rotary kiln

After detailed modelling, the gear parts were simplified for numerical solution. The simplified model was shown in Figure 3.19. Finite element analysis was carried out with 2387151 nodes and 1532433 elements on simplified model. The dense of mesh were increased at contact regions of pinion and rotary kiln by reducing element size to 2 mm. The view of the mesh was shown in Figure 3.20. Boundary condtiıns which were applied on the model was shown in Figure 3.21. The contact between pinion and the rotary kiln was assigned as no separation.

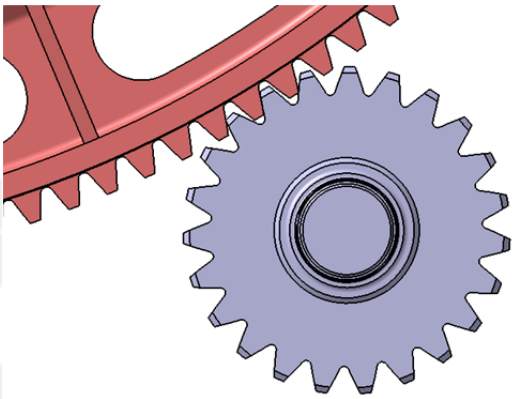


Figure 3.11. Simplified model of the gears

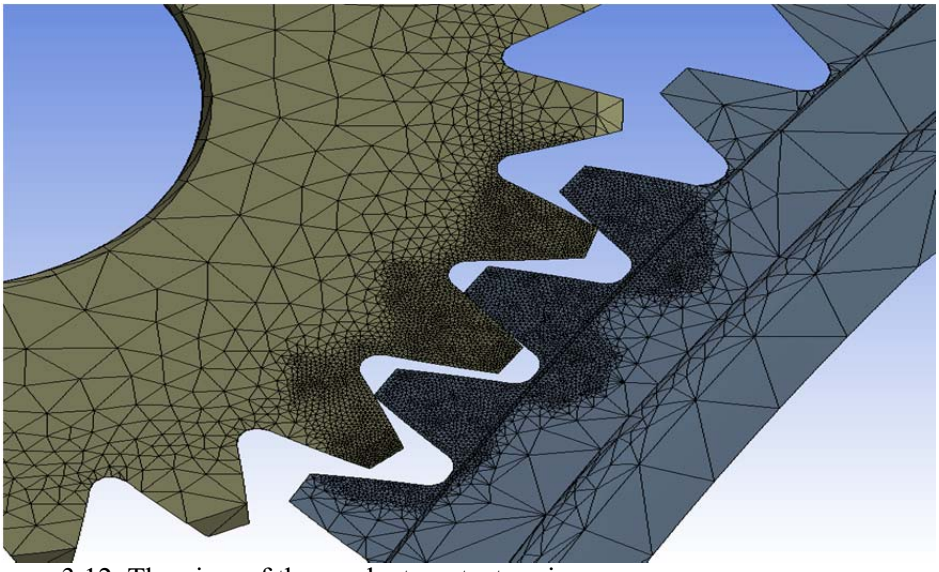


Figure 3.12. The view of the mesh at contact region

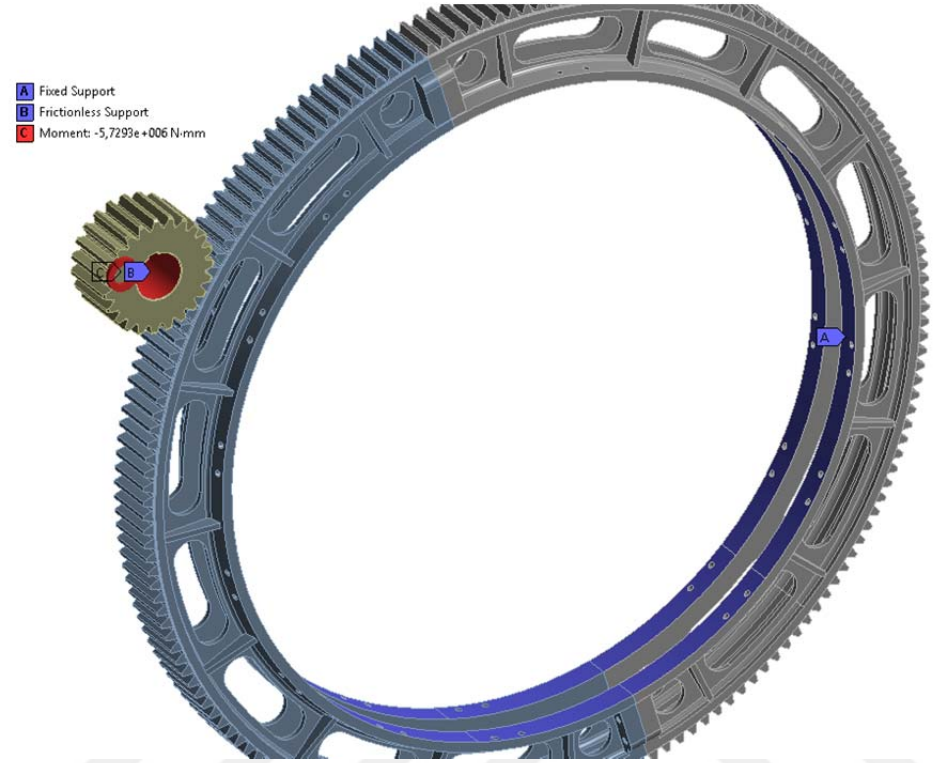


Figure 3.13. Boundary conditions

3.2.1. Selection of Hydraulic Motor

Hydraulic motor should be decided according to torque which applies on the gear mechanism. The analytical calculation of force and torque on the gear can be calculated as follows:

The Pitch Diameters of Gears

$$d_r = N_r * m \quad (1)$$

$$d_p = N_p * m \quad (2)$$

Where;

d is the pitch diameter of the rotary kiln and the pinion (mm)

m is the module

N is the number of teeth

Sub-index r and p indicates rotary kiln and pinion, respectively.

The Center Diameter

$$\frac{d_r + d_p}{2} = d_c \tag{3}$$

Where;

d_r is the pitch diameter of rotary kiln,

d_p is the pitch diameter of pinion,

d_c is the center diameter

Transmitted Load

The corresponding equation of transmitted load is expressed by following equation;

$$W_t = \frac{60000 * H}{\pi * d_p * n_p} \tag{4}$$

Where;

W_t is the transmitted load (kN)

H is the power (kW)

n is the speed (rev/min)

Thus, the tangential force of pinion on rotary kiln is $F^t = W_t$

Therefore;

$$F = \frac{F^t}{\cos 20^o} \quad (5)$$

Stress on the gears

Stress on the gear may calculate by the Eq. 6.

$$\sigma = \frac{K_v * F^t}{Fw * m * Y} \quad (6)$$

In Equation 6;

Fw = Face width

Y = Lewis form factor

K_v = Barth equation, which was modified by AGMA and can be expressed as Eq. 7 for hobbed and shaved profile;

$$K_v = \frac{3{,}56 + \sqrt{V}}{3{,}56} \quad (7)$$

Where;

V = pitch line velocity (m/s)

Stress concentration factor should be calculated by the Mitchiner and Mabie (1982).

$$K_f = H + \left(\frac{t}{r}\right)^L \left(\frac{t}{l}\right)^M \quad (8)$$

Where;

$$H = 0{,}34 - 0{,}4583662\emptyset \quad (9)$$

$$L = 0{,}316 - 0{,}4583662\emptyset \quad (10)$$

$$M = 0{,}290 + 0{,}4583662\emptyset \tag{11}$$

$$r = \frac{\left(b - r_f\right)^2}{\frac{d}{2} + b - r_f} \tag{12}$$

In the equation l, r_f, and t are as showed in Figure 3.22. $\emptyset$ is the pressure angle, b is the dedendum, and d is the pitch diameter.

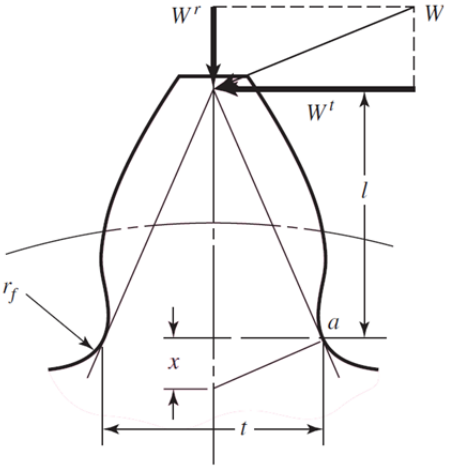


Figure 3.14. Visualization of l, r_f, and t (Budynas and Nisbett, 2014)

Surface Durability

Surface durability of the gears should calculated by using Equation 13.

$$\sigma_c = -C_p * \left[\frac{K_v * F^t * \left(\frac{1}{r_1} + \frac{1}{r_2}\right)}{Fw * \cos\emptyset}\right]^{\frac{1}{2}} \tag{13}$$

In the equation;

C_p = elastic coefficient defined by AGMA which described in Equation 9.

$$C_p = \left[\frac{1}{\pi \left(\frac{1 - v_P^2}{E_P} + \frac{1 - v_G^2}{E_G} \right)} \right]^{\frac{1}{2}} \quad (14)$$

And r_1 and r_2 are;

$$r_1 = \frac{d_P * \sin \emptyset}{2} \quad (15)$$

$$r_2 = \frac{d_G * \sin \emptyset}{2} \quad (16)$$

Torque of the Gear

Torque T of the gear is;

$$T = F * \frac{d_p}{2} \quad (17)$$

For the design of the hydraulic system, the motor can be selected by using the formula given in Equation 18.

Torque output ;

$$\mathrm{M} = \frac{\mathrm{V} * \Delta \mathrm{p} * \eta_m}{62{,}8} \ (\mathrm{Nm}) \quad (18)$$

Where;

V = displacement (cm^3/rev)

Δp = differential pressure (bar)

η_m = mechanical efficiency

3.2.2. Hydraulic Pump Selection

The piston type pumps produce the flow with the movement of the piston in the piston pumps and perform the pumping process. The piston pumps should not only be considered as single-piston. There are also many different piston combination types of piston pumps. In the piston pumps, the flow is regulated according to the movement of the piston in the cylinder. As the piston enters the cylinder, the fluid in the cylinder is discharged and pumping is performed. As the piston exits through the cylinder, the fluid is fed into the cylinder and the fluid is ready to be pumped. The piston pumps can be categorized in two basic types, axial and radial piston. Both types of the piston pumps can be available as fixed and variable displacement pumps.

Required flow for the pump can be decided by using Equation 19.

Required flow ;

$$Q = \frac{V * n}{1000 * \eta_v} \ (l/min) \tag{19}$$

Where;

V = displacement (cm^3/rev)

n = speed (rpm)

η_v = volumetric efficiency

3.2.3. Electric Motor Selection

Maximum power can be calculated from Equation 20 as below:

Output power;

$$P = \frac{Q * \Delta p * \eta_t}{600} \ (kW) \tag{20}$$

Where;

Δp = differential pressure (bar)

η_t = overall efficiency

$$P = \frac{Q.V}{510} \tag{21}$$

3.2.4. Hydraulic Fluid Selection

For the fluid, superior quality hydraulic mineral fluid is preferable such as HLP oils with respect to DIN 51524, part 2. A certain greasiness is formed by the film layer formed by the hydraulic fluid which is between the two metals. The measure of greasiness is called brugger value. Brugger value can be change the load and the application area such as if the application is general, brugger value should be more than 30 N/mm^2 and if the application is heavily loaded, fast cycling machines or high dynamic loads, brugger value should be more than 50 N/mm^2. Brugger value is measured by the standard of DIN 51 347-2. The normal operating viscosity should range between 16 and 100 mm^2/s (cSt) whereas maximum start-up viscosity should be 800 mm^2/s (cSt).

Effective filtration should be performed in order to protect the system from contamination for maximum pump and system component functionality and life. Fluid cleanliness should be with respect to ISO classification ISO 4406:1999. The quality of filter elements should be as required with ISO standards. General hydraulic systems for satisfactory operation is class 20/18/15, considering to ISO 4406:1999. Suggested cleanliness for obtaining maximum life of the component and component functionality Class 18/16/13, considering to ISO 4406:1999 should be used. The cleaning process is applied by using hydraulic filters. These standards are available and necessary for determining the hydraulic filter type. The classes

explain that the application parameters and compatibility of the current system at the hydraulic filters.

When selecting hydraulic fluid, chemical resistance should also be considered. Especially, seal material is effected from chemical items and temperature. During the selection of the hydraulic fluid and sealing material, chemical resistance and temperatures must be compared. In addition to this, physical conditions and the properties of hydraulic fluids should be considered. Generally, nitride is chosen to have wide temperature range with respect to other types. N- Nitride which is able to resist between -40…+90 ^{O}C is preferable.

3.2.5. Calculation of the Inner Diameter of the Pipe

The lowest inner diameter for flow of hydraulic can be determined by Equation 22.

$$D = \sqrt{((Q * 21{,}22)/v)} \quad (22)$$

D = diameter of the pump (mm)

v = flow velocity (m/s)

3.2.6. Calculation of the Reservoir Capacity

The reservoir can be defined as the place where the hydraulic fluid is stored in order to operation of the system and transfer the energy. The reservoir capacity should be more than the volume of motor displacement, pump displacement and pipes in the system.

4. RESULTS AND DISCUSSIONS

4.1. Force and Stress Calculations of the System

4.1.1. Analytical Approach

In the study, analytic and finite element solutions of gear system were performed to calculate the reaction forces and stress on the system.

For the analytic solution, firstly, the pitch diameters of gears were calculated. 575 mm for pinion and 4400 mm for rotary gears were calculated as pitch diameters of the gears. The equations for pinion and rotary gears were presented in Equations 23 and 24, respectively.

$$d_r = N_r * m = 176 * 25 = 4400\ mm \tag{23}$$

$$d_p = N_p * m = 23 * 25 = 575\ mm \tag{24}$$

Secondly, the center diameter of the gears was calculated by Equation 25.

$$\frac{d_r + d_p}{2} = \frac{4400 + 575}{2} = 2487{,}5\ mm \tag{25}$$

The corresponding equation of transmitted load was expressed by following Equation 26. Calculations were made with respect to main drive which is 90 kW electrical motor; 7,5 kW electrical motor was neglected in the calculation since it is auxiliary drive.

$$W_t = \frac{60000 * H}{\pi * d_p * n_p} = \frac{60000 * 90.0}{\pi * 575 * 150} = 19{,}929\ \text{kN} \tag{26}$$

Thus, the tangential force of pinion on rotary kiln is $F^t = 19{,}929$ kN. Therefore;

$$F = \frac{F^t}{\cos 20^o} = \frac{19{,}929}{\cos 20^o} = 21{,}208 \text{ kN} \tag{27}$$

Torque T of the gear is;

$$T = F * \frac{d_p}{2} = 21{,}208 * \frac{575}{2} = 6097{,}3 \text{ N. m} \tag{28}$$

Contact stress on the gear is

$$K_v = \frac{3{,}56 + \sqrt{4{,}516}}{3{,}56} = 1{,}6 \tag{29}$$

$$\sigma = \frac{1{,}6 * 19929\ N}{306{,}18\ mm * 25\ mm * 0{,}334} = 12{,}47\ MPa \tag{30}$$

Stress concentration factor should be calculated according to Mitchiner and Mabie (1982).

$$H = 0{,}34 - 0{,}4583662\emptyset = 0{,}18 \tag{31}$$

$$L = 0{,}316 - 0{,}4583662\emptyset = 0{,}156 \tag{32}$$

$$M = 0{,}290 + 0{,}4583662\emptyset = 0{,}45 \tag{33}$$

$$r = \frac{\left(b - r_f\right)^2}{\frac{d}{2} + b - r_f} = \frac{(261{,}5 - 10)^2}{\frac{575}{2} + 261{,}5 - 10} = 117{,}35 \tag{34}$$

$$K_f = H + \left(\frac{t}{r}\right)^L \left(\frac{t}{l}\right)^M = 0{,}18 + \left(\frac{58{,}234}{117{,}35}\right)^{0{,}156} \left(\frac{58{,}234}{50{,}1}\right)^{0{,}45} = 1{,}139 \tag{35}$$

The result of contact stress on the gear with stress concentration factor is 14,2 MPa.

Failure stress of the surface was calculated from the Equation 39 by calculating Equations. 36, 37, and 38.

$$r_1 = \frac{575\ mm * \sin 20}{2} = 98{,}33\ mm \tag{36}$$

$$r_2 = \frac{4400 * \sin 20}{2} = 752{,}44\ mm \tag{37}$$

$$C_p = \left[\frac{1}{\pi\left(\frac{1-0{,}29^2}{210 * 10^3 MPa} + \frac{1-0{,}29^2}{210 * 10^3 MPa}\right)}\right]^{\frac{1}{2}} = 191{,}03 \tag{38}$$

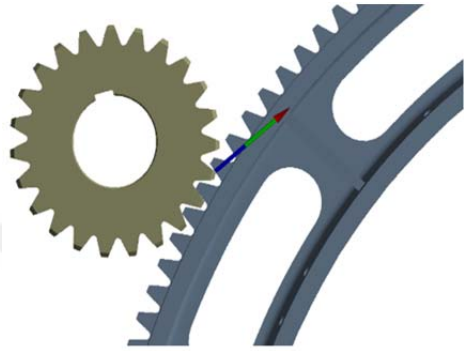
$$\sigma_c = -191{,}03 * \left[\frac{1{,}6 * 19929\ N * \left(\frac{1}{98{,}33\ mm} + \frac{1}{752{,}44\ mm}\right)}{306{,}18\ mm * \cos 20}\right]^{\frac{1}{2}} = -215{,}65\ MPa \tag{39}$$

4.1.2. Numerical Approach

After the calculation of force and torque, the motor capacity, pump capacity, electric motor and reservoir could be evaluated according to results of analytical solution, however, finite element method was also performed on the system. Firstly, the force reaction was solved on the system. Then stress, deformation and safety factor results were found by finite element method.

On the model, the pinion gear was forced to rotate while rotary gear was fixed. As a result of the numerical solution, the total force was calculated as 21327 N which was found as 21208 N in analytical solution. After the validation of the exerted force, the von-Mises stresses were obtained. The result of the force and stress of the gears was illustrated in Figure 4.1 to 4.5. Moreover, Figure 4.6, 4.7, 4.8 and 4.9 illustrate the minimum principle stress, maximum principle stress, maximum shear stress and deformation of the gears, respectively. maximum von-mises stress on pinion which were calculated as 14,2 MPa, by theoretically was

found as 14,844 MPa by finite element analysis. The small movement of the pinion caused the colour of the gear as red in contour whereas, since the rotary gear was fixed, the colour was in blue that indicates a small or no deformation.



Type	Force Reaction
Location Method	Contact Region
Contact Region	No Separation - Fener_disli\PartBody To pinyon\PartBody
Orientation	Global Coordinate System
Extraction	Contact (Underlying Element)
Suppressed	No
Options	
Result Selection	All
Display Time	End Time
Results	
X Axis	-16870 N
Y Axis	-1,3134e-007 N
Z Axis	13047 N
Total	21327 N

Figure 4.1. Force reaction between the gears

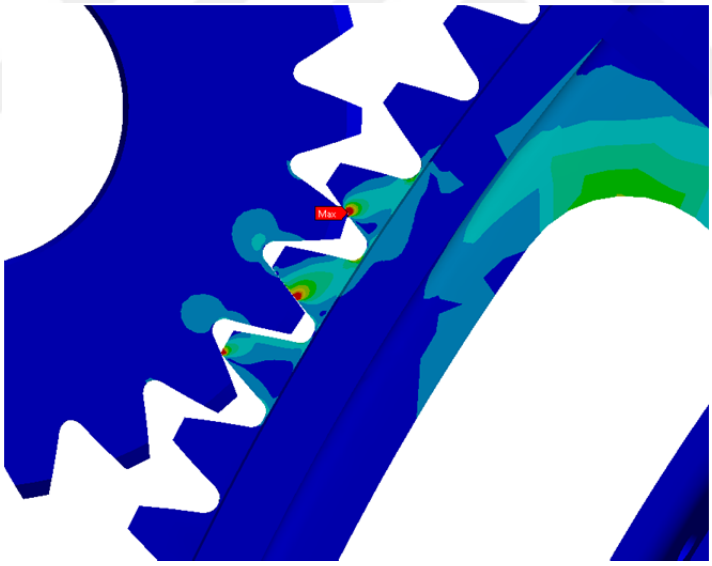


Figure 4.2. von-Mises stress distribution of the gears

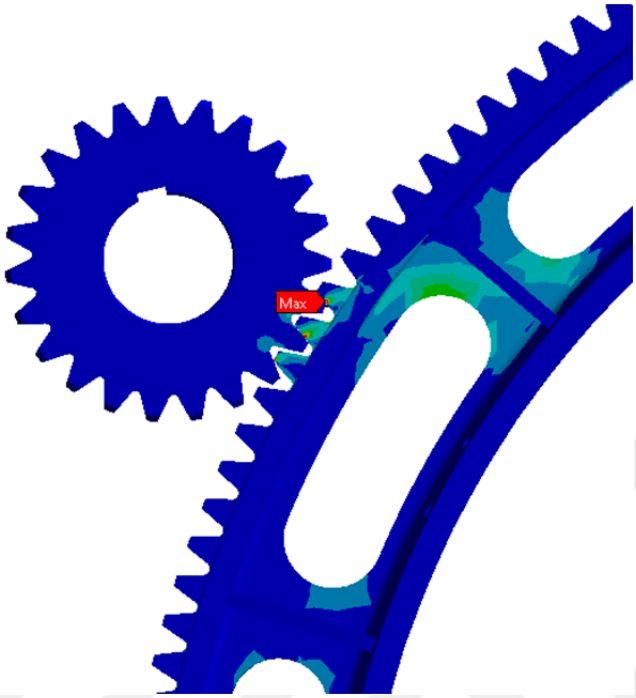


Figure 4.3. von-Mises stress distribution of the gears

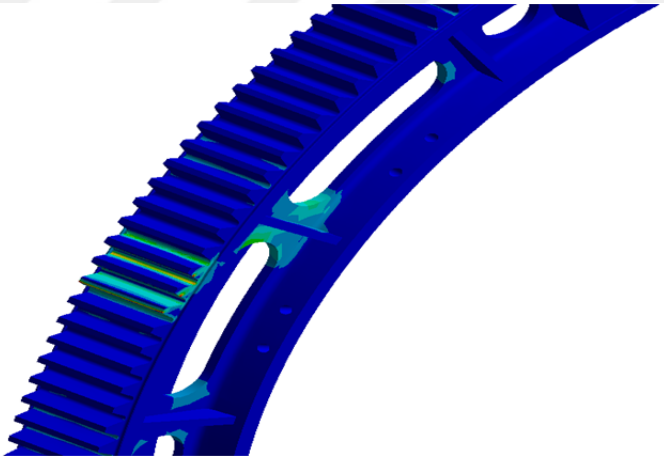


Figure 4.4. von-Mises stress distribution on the rotary gear

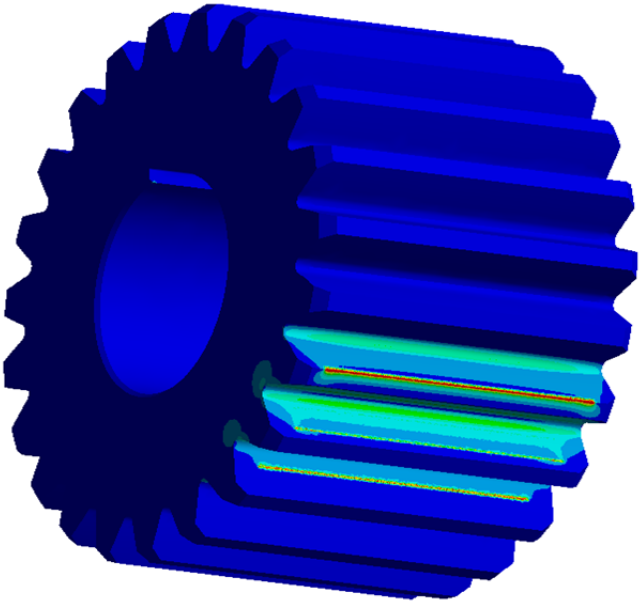


Figure 4.5. von-Mises stress distribution on pinion gear

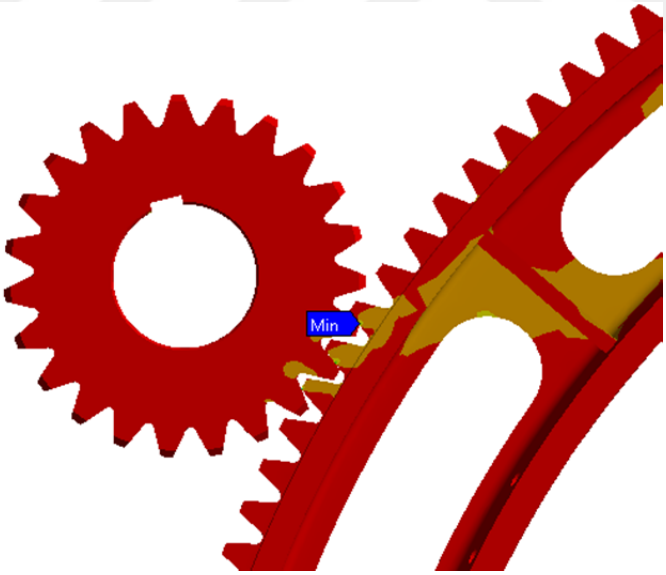


Figure 4.6. Minimum principle stress distribution between the gears

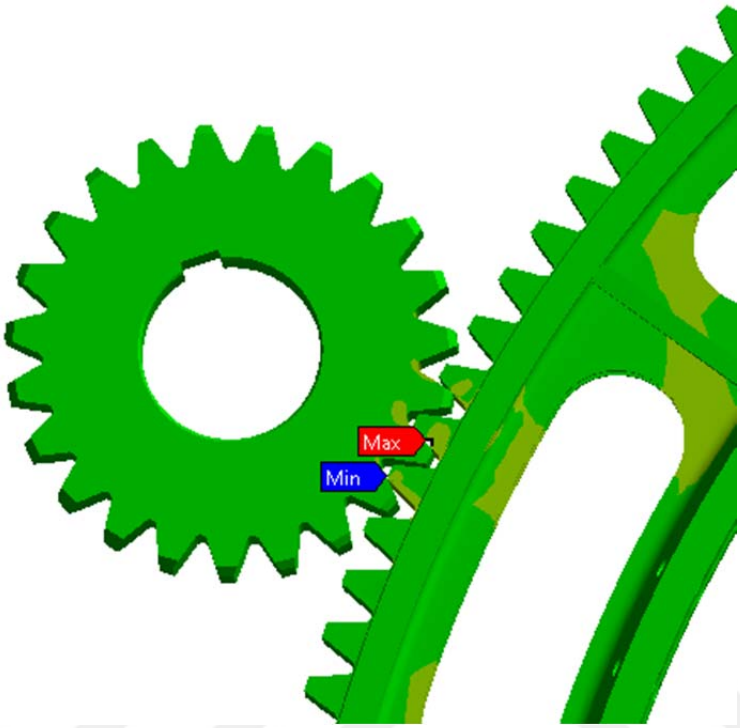


Figure 4.7. Maximum principle stress distribution between the gears

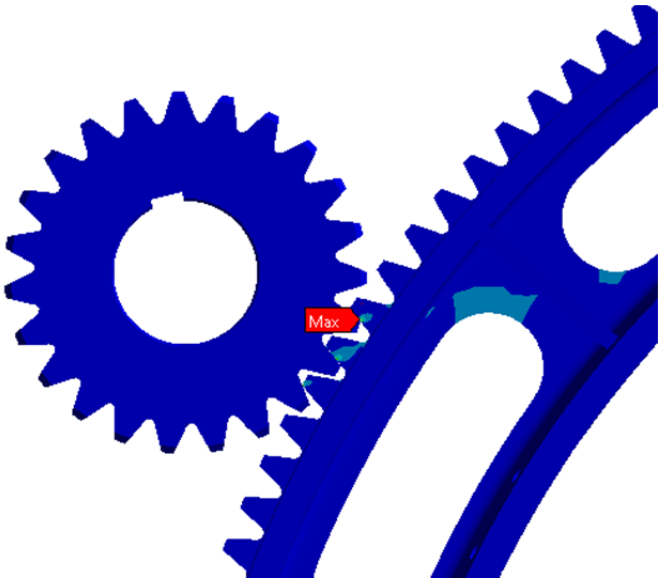


Figure 4.8. Maximum shear stress distribution between the gears



Figure 4.9. Deformation of the gears

According to the static test, the safety factor exceeds 15, so the colour was appeared as red in the contour. The result can also be calculated by the yield strength of the material divided by the maximum stress, which are 600 MPa and 14,844 MPa, respectively for the gears that evaluated in this study. The result of the factor of safety was presented in Figure 4.10. In Figure 4.11, life of the gears were presented. According to Gerber Mean Stress Theory, the life of the gears exeated 10^6 cycles with 0,4 K_f factor. Thus, it can be said that the gears have infinite life.



Figure 4.10. Safety factor of the gears



Figure 4.11. The Fatigue Life of The Gear

4.2. Selection of Hydraulic Motor

After the calculation of forces and torque by analytically and numerically, the motor, pump, electric motor, reservoir were evaluated as follows:
By assuming the system mechanical efficiency is 0,9;

$$6097{,}3 \approx 6100 = \frac{V * \Delta p * 0{,}9}{62{,}8} = V * \Delta p = 425644{,}4 \text{ Nm} \quad (30)$$

The selection hydraulic motor must be confirmed $V * \Delta p = 425644{,}4 \text{ N.m}$. The different type of hydraulic motors can be selected in Figure 4.10 from MR 1800 H to MRE 5400 L. In decision process, flushing of the hydraulic motors should also be considered. According to calculations, the motor from 1800 H to MRE 5400 L can be used. However, in order to avoid flushing, the motor MR 2400 I and the rest should be selected. To be more secure, in this study, MRE 3100 I was selected as motor. The diagrams of the motor MRA 2400 H, MR 2400 H and MRE 3100 I were presented in Appendix. In Appendix , diagrams of hydraulic motors were also given.

In the figure each diagram shows the these following definitions:

1. The out power which is maximum with flushing or without flushing
2. Scattered operating and working area
3. Continuous operating area with flushing
4. Continuous operating area without flushing
5. Constant pressure curves

For each motor, the curves which is blue color in the diagrams left position represent to the motor total efficiency η_T and the curves which is light blue color in

the diagrams right position represent to the volumetric efficiency η_V. In addition to this, the evaluated mechanical efficiency η_M can be calculated by dividing the total efficiency by the volumetric efficiency value ($\eta_M = \eta_T/\eta_V$).

According to selection of the hydraulic motor:

$$6097{,}3 \approx 6100 = \frac{V * \Delta p * \eta_m}{62{,}8} = V * \Delta p = 425644{,}4 \text{ Nm} \quad (31)$$

$$\eta_m = \frac{\eta_t}{\eta_v} = \frac{0{,}86}{0{,}99} = 0{,}87 \quad (32)$$

$$6097{,}3 \approx 6100 = \frac{3103{,}7 * \Delta p * 0{,}87}{62{,}8} = \Delta p = 141{,}87 \text{ bar} \quad (33)$$

$\Delta p = 141{,}87$ bar $\approx$ 145 bar

Max speed = 215 rpm

Torque = 49,4 Nm/bar

Pressure of the system is as in Equation 34:

$$\frac{6100}{49{,}4} = 123{,}5 \text{ bar} \quad (34)$$

4.3. Pump Selection

The gerotor internal gear pump contains pair of gears and the gerotor internal pump's gears are always in sliding contact. This type of pump consists the internal gear and gerotor gear. These type of gears are different to each other with respect to number of teeth. The gerotor gear has one less tooth than the internal gear. The internal and gerotor gears rotate with the same direction. During the

rotation process, the teeth are separating and meshed. If the teeth are separating, the hydraulic oil is drawn into the chamber. If the teeth are meshed, the hydraulic oil is ejected. Therefore, sealing surface is provided by the sliding contact. Generally, piston pumps and gerotor internal gear pump are preferred at hydraulic application. Because, these types of pumps provide high pressure, high torque and high speed by using smaller body. Therefore, efficiency is increased. It also provides better performance and longer life.

Required flow for pump selection can be calculated by using Equations 35 and 30.

$$Q = \frac{3103{,}7 * 150}{1000 * 0{,}99} = 470{,}26 \text{ (l/min)} \tag{35}$$

$$Q = \frac{470{,}26 \text{ l/min}}{1{,}50} = 313{,}51 \text{ cm}^3/\text{rev} \tag{36}$$

The properties of various pumps were given in Appendix. According to properties, only PV360 can provide required flow. The selected pump (PV360) gives $360 * 1{,}50 = 540\ l/min$

4.4. Selection of Electric motor

Electric motor should also be determined. For this, power and maximum power should be calculated by using Equations 37 and 38, respectively.

$$P = \frac{Q.V}{510} = \frac{145 * 540}{510} = 153{,}53 \text{ kW} \tag{37}$$

$$P = \frac{Q.V}{510} = \frac{350 * 540}{510} = 370{,}59 \text{ kW} \tag{38}$$

The electric motor should have the following specifications:

Power = 153,53 kW

Speed = 1500 rpm

4.5. Hydraulic Fluid Selection

Premium quality hydraulic mineral fluid such as HLP oils to DIN 51524, part 2 is recommended for hydraulic fluid. Brugger value has to be 30 N/mm^2 minimum for general application and 50 N/mm^2 for heavily loaded hydraulic equipment and fast cycling machines and/or high dynamic loads, measured in accordance with DIN 51 347-2. The normal operating viscosity range of hydraulic fluid should between 16 and 100 mm^2/s (cSt). Maximum start-up viscosity should be 800 mm^2/s (cSt). Filtration is suggest for pump and system component functionality and life, the system should also be protected from contamination by effective filtration.

Fluid cleanness should be in accordance with ISO classification ISO 4406:1999. The quality of filter elements should be in accordance with ISO standards. General hydraulic systems for satisfactory operation: Class 20/18/15, according to ISO 4406:1999 recommended cleanliness for maximum component life and functionality. Hydraulic fluid specification should be check for chemical resistance of seal material. Resistance of seal material must also be checked for maximum operating temperature and ambient temperature.

4.6. Calculation of the Inner Diameter of the Pipe

Other specification of hydraulic system must also be decided for the optimum design of the system. Inner diameter of the pipe is calculate.

$$D = \sqrt{((Q * 21{,}22)/v)} \tag{39}$$

Where;

D = diameter of the pump (mm)

v = flow velocity (m/s)

$$D = \sqrt{((517{,}28 * 21{,}22)/2)} = 74{,}08 \text{ mm} \approx 75 \text{ mm}$$

4.7. Calculation of the Reservoir Capacity

Reservoir capacity must be decided according to inner volume of motor, pump and pipes. Therefore, the capacity should be calculated by using Eq.40.

$$Displacement\ of\ motor + displacement\ of\ pump + pipe\ dia * length \quad (40)$$

$$3103{,}7\ cm^3 + 360\ cm^3 + 44{,}2\ cm^2 = 12303{,}7\ cm^3$$

However, in the field, to compensate fluid leakage and supply continues flow in the system, reservoir capacity should be 2.5 times larger than the theoretical capacity. Therefore, required reservoir capacity is:

$$12303{,}7\ cm^3 * 2{,}5 = 30759{,}25\ cm^3 \approx 3{,}125 * 10^7 mm^3 \quad (41)$$

General dimensions with respect to volume is shown in Figure 4.13 below. All dimensions in the figure illustrated in millimetre.

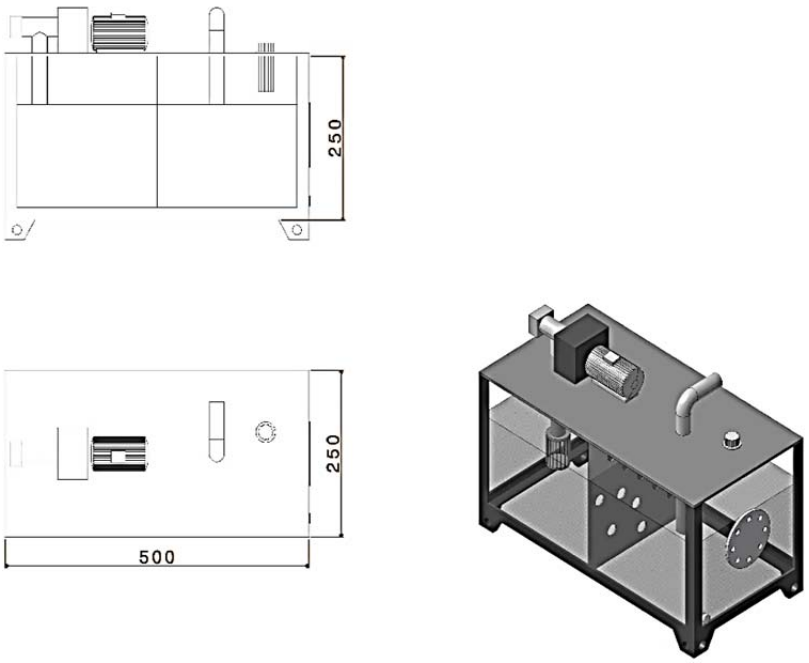


Figure 4.12. General dimension of reservoir

4.8. Reliability Analysis of the Hydraulic System

Lots of factors affect the system and cause failures. In the gear system, several factors create failure. For this reason, maintenance must be applied. The gear system is wanted to transform to hydraulic system because of having different parameters to cause failure. In the gear system, failure causes and frequency should be analyzed. In the RCM (Reliability Centered Maintenance) applications, failure analyzing tools and methods are used for evaluating the cause of failures and their effects. Different type of methods can be used to evaluate failure mode. FMEA (Failure Mode and Effect Analysis) method is one of the tools in the failure analysis and equipment condition monitoring.

In the FMEA method, each potential failures are determined and scaled from 1 to 10, low to high with respect to three factors, these are severity, occurrence and detection. The RPN (Risk Priority Number) can be determined by multiplying

these factors. RPN is calculated to determine root failure for our system. Lots of failures can be determined in the system but one of these is the most powerful one and solution of the most powerful failure provides effective recovery in the system. Comparison of the failures are obtained and the root failure can be determined by calculating of the RPN. RPN can be calculated by using the formula which is given below:

$$RPN = Severity \times Occurrence \times Detection \quad (42)$$

The gear system and hydraulic system will be analyzed by building of RCM application with the support of FMEA method. In the rotary kiln which is driven by gear system power source, failure analysis for each component of the system and main factors, severity, occurrence and detection scales are given below in Tables 4.1, 4.2, and 4.3.

Table 4.1. Failure points

	SEVERITY
1	Create simple and unimportant effect, fault can be found and solved easily by operator
2	Create simple and unimportant effect, fault can be found by maintenance
3	Create moderate effect, fault can be found and solved easily by operator
4	Create moderate effect, fault can be solved by maintenance without to stop the machine
5	Create moderate effect, fault can be solved by maintenance by stopping the machine for less than one day
6	Create moderate effect, fault can be solved by maintenance by stopping the machine for less than three days
7	Create critical effect, fault can be solved by maintenance by stopping the machine for less than one day
8	Create critical effect, fault can be solved by maintenance by stopping the machine for more than one day
9	Create very critical effect, fault can be solved by maintenance by stopping the machine for more than one day
10	Create catastrophic effect, fault can damage the system and people

	OCCURRENCE
1	Without failure in the last 4 years
2	2 or 3 failures in the last 4 years
3	4 or 5 failures in the last 4 years
4	6 or 7 failures in the last 4 years
5	8 failures in the last 4 years
6	9 failures in the last 4 years
7	10 failures in the last 4 years
8	11 or 12 failures in the last 4 years
9	13 or 14 failures in the last 4 years
10	15 or more failures in the last 4 years
	DETECTION
1	Failure can be determined by instrumentation
3	Failure can be determined by daily controls
5	Failure can be determined by abnormal effects such as noise, vibration, heating, etc.
7	Impossible to detect failure by operator

Table 4.2. FMEA form for gear system power source

Functional Failure	Failure Mode	Failure Cause	Failure Effect
The tooth surface of the gears have gaps and pitting are determined	1.1Excessive wearing	1. The gear tooth surfaces do not fully contact each other 2. Unstable or excessive loading 3. No oil film layer, insufficient gear oil, dirty oil 4. Foreign bodies between the tooth such as rust, sand, weld spatter etc. 5. Chemical action (acidic effect) on tooth surface 6. Wrong material alloy or heat treatment application 7. Completion of the mechanical life of the material	Risk that tooth break
The tooth surface of the gears have cracks, oxidation or melting are determined	1.2 Corrosion	1. Chemical action (acidic effect) on tooth surface 2. Wrong material alloy or heat treatment application 3. Completion of the mechanical life of the material 4. Reaching high temperatures 5. Excessive humidity or moisture	Risk that degration of contacting points and vibration
The rupture of teeth or cracks on gear surfaces are determined	1.3 Fatigue	1. Unstable or excessive loading 2. Wrong material alloy or heat treatment application 3. Completion of the mechanical life of the material 4. Reaching high temperatures	Risk that vibration of system even stopping rotation
The plastic deformation on gear surfaces is determined	1.4 Loss of material property	1. Wrong material alloy or heat treatment application 2. Completion of the mechanical life of the material 3. Reaching high temperatures 4. Chemical action (acidic effect) on tooth surface	Risk that system can be escaped from measurement, vibration and noise are seen.

Table 4.3. RPN calculation of gear system power source

Failure Mode	Severity	Occurrence	Detection	RPN
1.1	9	10	3	270
1.2	8	10	3	240
1.3	9	2	5	90
1.4	8	5	5	200

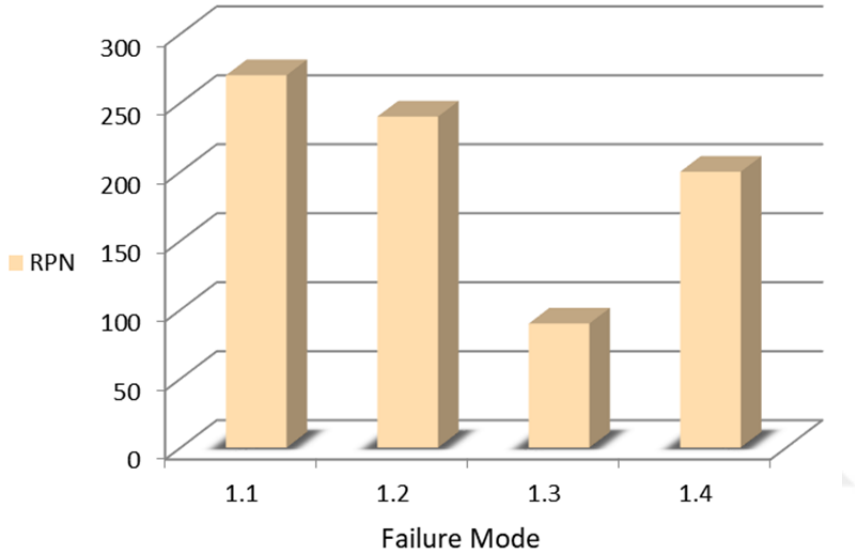


Figure 4.13. RPN-Failure modes (gear system)

The FMEA method is applied to hydraulic power source rotary kiln is supposed with respect the life of hydraulic components because this type of system is designed theoretically. FMEA form, RPN calculation, and RPN-Failure modes were given in Tables 4.4, 4.5, and 4,6, respectively.

Table 4.4. FMEA form for hydraulic system power source

Functional Failure	Failure Mode	Failure Cause	Failure Effect
The hydraulic pump or hydraulic motor runs noisy	1.1 Excessive noises	1. The hydraulic fluid level is too low 2. The temperature of the system is too low. So, the viscosity of the hydraulic fluid is too high 3. The hydraulic fluid is foamed 4. Foreign bodies in the hydraulic oil such as rust, sand, weld spatter etc. 5. The equipment has bearing failure 6. The capacity of the equipment is insufficient 7. Completion of the mechanical life of the material	Risk that hydraulic pump or hydraulic motor break
The pressure of the system decreases to low levels and fluid can not be transferred	1.2 Low pressure	1. Excessive leakages are seen at the system 2. Excessive flow resistance is obtained because of too high viscosity 3. The hydraulic fluid is foamed 4. Reaching high temperatures 5. Excessive humidity or moisture 6. Foreign bodies in the hydraulic oil such as rust, sand, weld spatter etc.	Risk that hydraulic fluid can not be transferred and hydraulic motor can not produce motion
The hydraulic oil temperature is measured above 80^0 C	1.3 Excessive temperature	1. Excessive leakages are seen at the system 2. Excessive flow resistance is obtained because of too high viscosity 3. Completion of the mechanical life of the material in the system equipments 4. The hydraulic fluid is foamed 5. Foreign bodies in the hydraulic oil such as rust, sand, weld spatter etc. 6. The hydraulic fluid level is too low 7. The equipment has bearing failure 8. The capacity of the equipment is insufficient	Risk that all of system equipments break. The hydraulic oil loss the properties. Hydraulic lines break, too
The directional control valves do not work	1.4 Excessive compression	1. The temperature of the system is too low. So, the viscosity of the hydraulic fluid is too high 2. Excessive flow resistance is obtained because of too high viscosity 3. Very tight connection bolts 4. Valve slide jamming due to contamination 5. Coil failure or no power to the coil	Risk that the hydraulic lines break

Table 4.5. RPN calculation of hydraulic system power source

Failure Mode	Severity	Occurrence	Detection	RPN
1.1	7	3	5	105
1.2	6	7	3	126
1.3	7	7	3	147
1.4	5	6	3	90

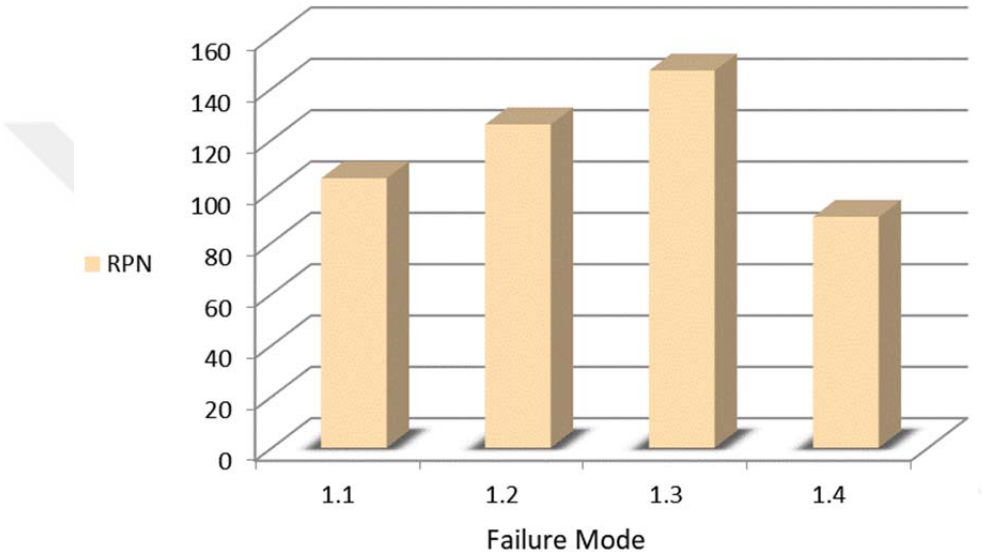


Figure 4.14. RPN-Failure modes (hydraulic system)

Hydraulic system provides great savings in failure rate and maintenance. The equipment dimensions are much smaller than the gear systems. The weights are also much less than the gear systems. Therefore, it provides ease of maintenance. However, in terms of occupational safety, more precautions would be taken in the hydraulic system. Because, it works at high pressure and poses a risk. In addition, the rotary kiln is a hot system. Therefore, no leakage in the hydraulic system because of the fire hazard. If all precautions are taken in terms of occupational safety, low maintenance and labor cost would be obtained. The energy consumption of the hydraulic system is also slightly higher than the gear system. However, the energy consumption differences are negligible with the gain

to be achieved by reducing the production loss time. In addition, if more than one rotary kiln is to be driven by a single hydraulic system, profitability is achieved in terms of energy consumption. Some failures types of gear system were illustrated in Figures 4.15, 4.16, 4,17, and 4.18.

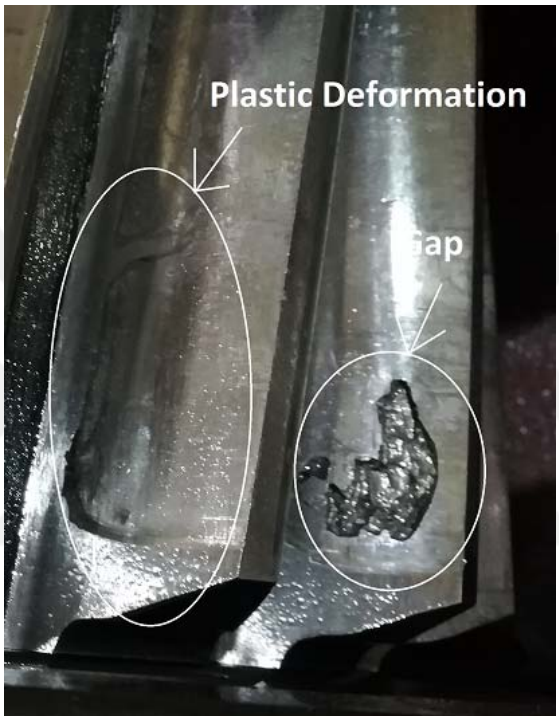


Figure 4.15. Plastic deformation and gap on the system



Figure 4.16. Crack failure on the system

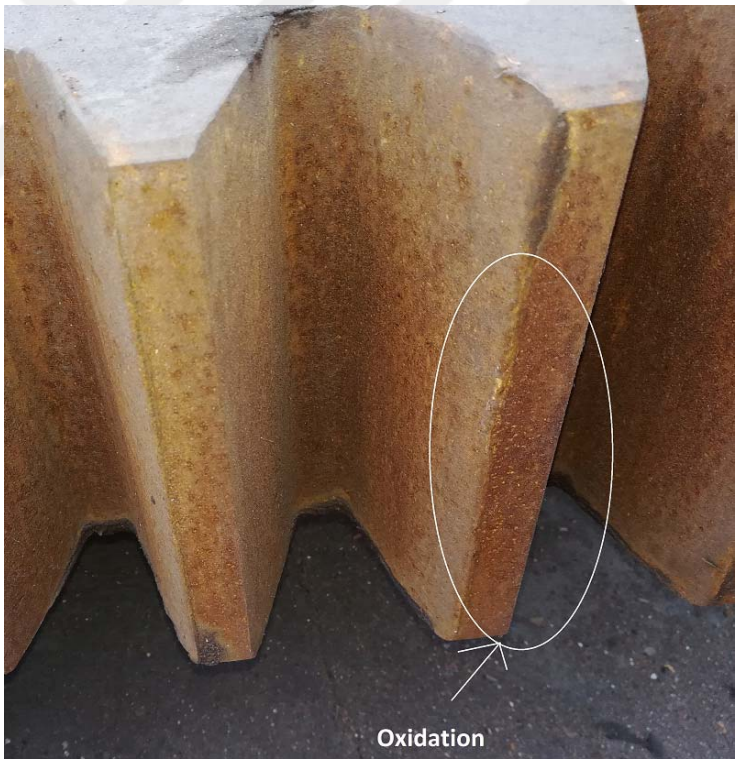


Figure 4.17. Oxidation on the surface

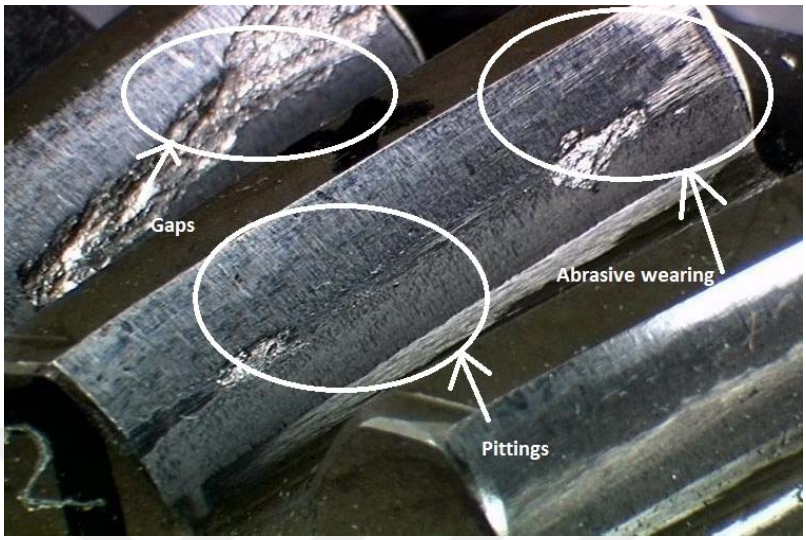


Figure 4.18. Gap, pitting and abrasive wearing on the system

5. CONCLUSION

In this thesis, the transformation of a reducer system to a hydraulic system on a rotary kiln was evaluated in details. For the alteration, firstly, 3D model of the system was prepared for further modifications and calculations. Then the force on gear system were calculated as analytically and numerically. In the numerical solution, finite element analysis was performed via a software program. As a result of analytical solution 21208 N was found, while 21327 N was calculated via numerical solution. The error was 0,56% per cent between the solutions. Therefore, rest of the structural analysis was performed via numerical calculations. In the analysis maximum von-Mises stress was found as 14,844 MPa which occurred on the contact teeth of the gears and it was found as 14,2 MPa theoretically. Moreover, maximum shear stress was calculated as 8,4145 MPa. The stresses are suitable for surface durability which is 215,65 MPa compression stress. According to calculations, the gears have infinite life.

After the force calculation on the system torque output and output power were determined for selection of hydraulic motor. Motor with a slightly larger displacement than the result indicated was selected as a hydraulic motor in order to optimize the safety increment and cost of the system. In the decision of hydraulic motor MRE 3100 I type motor was selected. For the pump selection, only PV360 type of pump was provide required flow. Then the required flow and output power for electric motor were determined for pump and electrical motor selection. Required properties of electric motor was found as 153.53 kW power and 1500 rpm rotational speed. Moreover, premium quality hydraulic mineral fluid which has normal operating viscosity between 16 and 100 mm^2/s (cSt) range and be 800 mm^2/s (cSt) maximum start-up viscosity was selected. After all, required pipe diameter and reservoir capacity were calculated as 75 mm and 30759,25 cm^3.

Even though the rotary kiln application was studied as case study throughout this thesis, transformation of reducer system to hydraulic system would expand to other similar applications.

The properties of hydraulic fluid which should be use in the system was also presented. Finally, the required diameter of the pipe and the reservoir capacity was calculated and declared in the thesis.

In the future, the application of transformation to hydraulic power system of a rotary kiln that performed throughout the study may also apply to the other systems in academic and industry fields. After the conversation, field measurements could be added and compare with the numerical and theoretical calculations.

Due to smaller equipment system, hydraulic system would provide savings in failure rate and maintenance. However, since the system has high pressure, precautions should be taken in the system and in terms of leakage from the system. If all precautions are taken in terms of occupational safety, lower maintenance and labor cost would obtained. Profitability may also achieved in terms of energy consumption in some applications.

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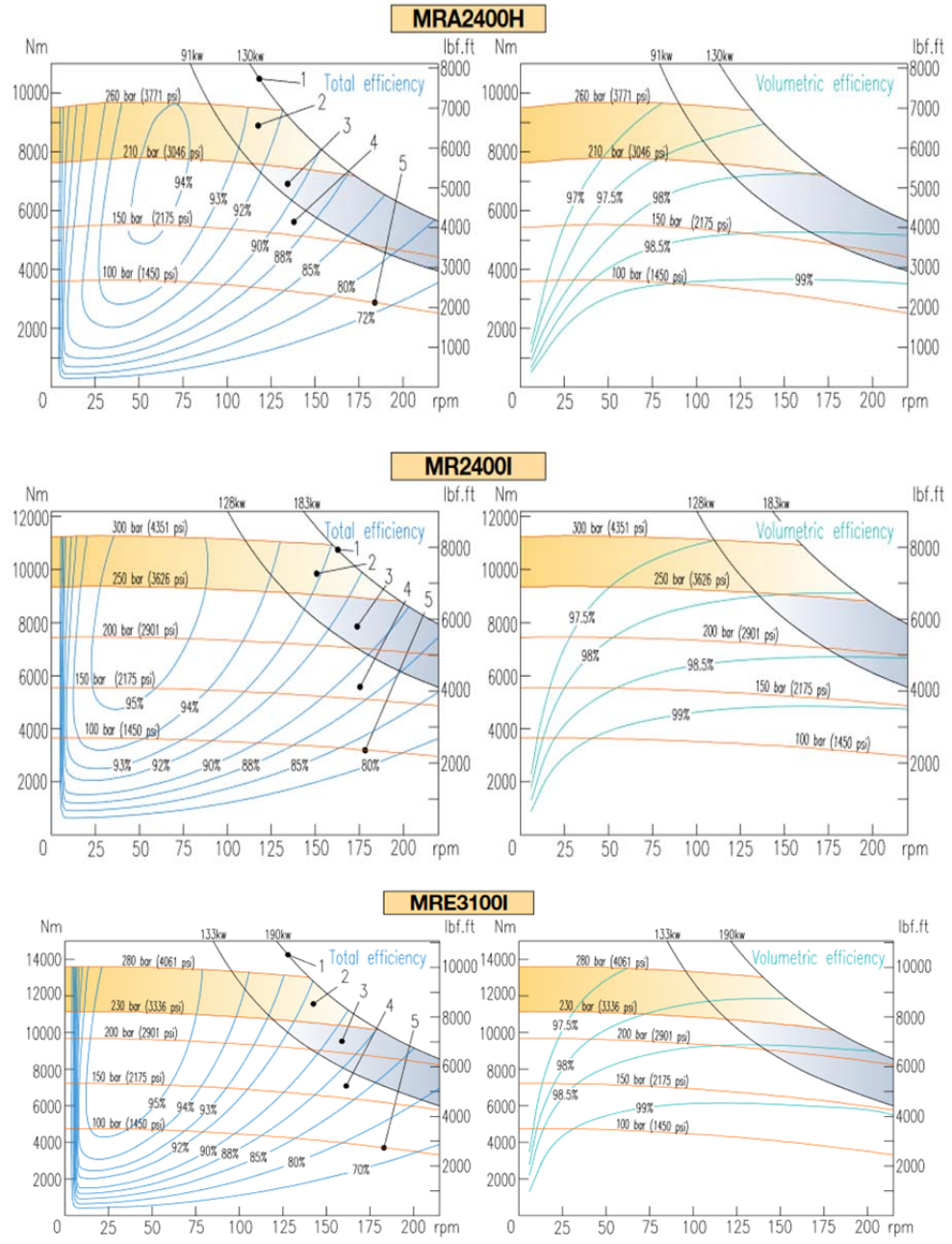
CURRICULUM VITAE

Sadık ÜNAL was born on 06.08.1989 in Ağrı. He graduated from Adana İ.M.K.B. Anatolian Teacher Training High School in 2007. He started in Çukurova University Mechanical Engineering Department in 2008. He got a high score from the English exam prepared by the university and started first year without reading the preparatory class. He finished the university in four years. He graduated from Çukurova University Mechanical Engineering Department in 2012. He completed his military service in the same year at Erzurum Palandöken. After finishing military service, he began his engineering career at Sabancı Holding SASA Polyester Sanayi A.Ş. He worked at SASA as mechanical maintenance engineer between 2013 and 2015. Then, he has been continuing his career at Şişecam Holding Soda Sanayi A.Ş. as project engineer, investment engineer and maintenance engineer from 2015. The articles was written and presented at Gazi University 7th International Powder Metallurgy Conference and Exhibition in 2014 as subjects of ‘’The Fatigue Properties of The Machine Elements Produced by Powder Metallurgy Method’’ and ‘’Manufacturing of Dental Implants Using Powder Metallurgy (P/M) Process’’. In addition to this, the article was written and shown as poster display at Çukurova University 1st International Mediterranean Science and Engineering Congress as subject of ‘The Transformation of Power Generation From Gear System to the Hydraulic System at Rotary Kiln’’ Also the article was written at faculty journal as subject of ‘’Analysis of The Loads Acting on Rotary Kiln & Hydraulic Design’’.

APPENDIX

Motor type	Displace-ment	Specific Torque	Speed		Maximum pressure				Max power
			Min	Max	Continuous	Intermittent	Peak	A+B	
-	V	T_s	n_{min}	n_{max}	$p_{cont.}$	$p_{int.}$	p_{peak}	p_{A+B}	$P_{max.}$
-	cm^3/rev	Nm/bar	rpm	rpm	bar	bar	bar	bar	kW
MR 1100 G	1125.8	17.9	0,5	330	250	300	420	400	119
MRE 1400 G	1369.5	21.8	0,5	280	230	280	400	400	102
MRA 1600 G	1536.7	24.5	0,5	260	210	260	380	400	96
MR 1600 H	1598.4	25.4	0,5	260	250	300	420	400	144
MR 1800 H	1809.6	28.8	0,5	250	250	300	420	400	153
MRE 2100 H	2091.2	33.3	0,5	250	230	280	400	400	148
MRA 2400 H	2401.4	38.2	0,5	220	210	260	380	400	130
MR 2400 I	2393.0	38.1	0,5	220	250	300	420	400	183
MR 2800 I	2792.0	44.5	0,5	215	250	300	420	400	194
MRE 3100 I	3103.7	49.4	0,5	215	230	280	400	400	190
MRA 3500 I	3490.4	55.6	0,5	180	210	260	380	400	175
MR 3600 L	3636.8	57.9	0,5	180	250	300	420	400	185
MR 4100 L	4104.4	65.3	0,5	175	250	300	420	400	190
MR 4500 L	4502.7	71.7	0,5	170	250	300	420	400	210
MRE 5400 L	5401.2	86.0	0,5	160	230	280	400	400	210
MRA 6000 L	6005.9	95.6	0,5	140	210	260	380	400	190
MR 6500 M	6460.5	103.6	0,5	130	250	300	420	400	240
MR 7000 M	6967.2	111.4	0,5	130	250	300	420	400	250
MRE 7600 M	7628.1	121.4	0,5	130	230	280	400	400	250
MRE 8200 M	8226.4	130.9	0,5	120	230	280	400	400	250
MRA 9000 M	9040.4	143.9	0,5	110	210	260	380	400	230

Properties of hydraulic motors



Diagrams of hydraulic motors

		PV063	PV080	PV092	PV140	PV180	PV270	PV360
Frame size		3	3	3	4	4	5	6
Max. Displacement	[cm^3/rev.]	63	80	92	140	180	270	360
Output flow at 1500 rpm	[l/min]	94.5	120	138	210	270	405	540
Nominal pressure pN	[bar]	350	350	350	350	350	350	350
Min. outlet pressure	[bar]	15	15	15	15	15	15	15
Max. pressure pmax at 20% working cycle[1)]	[bar]	420	420	420	420	420	420	420
Case drain pressure, continuous	[bar]	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Case drain pressure, max. peak	[bar]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Min. Inlet pressure, abs.	[bar]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Max. Inlet pressure	[bar]	16	16	16	16	16	16	16
Input power at 1500 rpm and 350 bar	[kW]	61.5	78	89.5	136	175	263	350
Max speed at 1 bar, abs, inlet pressure	[rpm]	2800	2500	2300	2400	2200	1800	1750
Min. speed	[rpm]	400	400	400	400	400	400	400
Moment of inertia	[kgm^2]	0.018	0.018	0.018	0.030	0.030	0.098	0.103
Weight	[kg]	59	59	59	90	90	172	180

The properties of various pumps