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Original Research Article

Reliability Prediction of a Mechanical Refiner

Mohammad Ali Farsi *

Aerospace Research Institute, Ministry of Science, Research and Technology, Tehran, Iran

*** Farsi@ari.ac.ir**

Abstract

Reliability refers to the quality during operation, the fulfillment of requirements, and the quality production of the final product by a system. A Refiner is also industrial equipment that is used to improve the properties of the raw material and prepare it for the production of the final product. In the mechanical pulp production industry, the role of the refiner in product production and its effect on product quality and total cost is very important. In this article, the structure of a mechanical refiner is introduced, and the main components effective in determining and improving reliability are investigated, and their reliability values are calculated. The most influential element of this equipment, based on the calculations, is the mechanical seal, which should be more careful than other elements in selecting and monitoring its condition to achieve the reliability of the target.

Keywords: Bearing; Gap control; Mechanical refiner; Mechanical seal; Reliability.

1. Instructions

Nowadays, all of us depend on a wide range of technical products and services in our everyday life. We expect our devices, such as home appliances, computers, gadgets and mobile phones, to function when we require them and to be reliable for a reasonable time. We expect services, such as electricity, computer networks, and transport, to be supplied without disruptions or delays. Factories to work continually without stoppage. When a product, machinery, or service fails, the consequences may be critical or catastrophic. More often, product flaws and service outages lead to customer dissatisfaction or stoppage in manufacturing processes. Stoppages increase the total cost and may reduce the final product quality. For many suppliers, reliability has become a matter of survival.

Reliability can be defined as the ability of an item to perform as required in a specified operating context and for a stated period [1].

The reliability concept is illustrated in Figure 1. The required performance is determined by laws and regulations, standards, customer requirements and expectations, and supplier requirements and is usually stated in a specification document, where delimitations of operating context are stated.

By operating context, the environmental conditions for the item can be defined by the usage patterns and mechanical, thermal, electrical, and chemical loads it is subjected to, how the item is serviced and maintained, and its location.

For some systems, this ordinary definition would be introduced as service reliability. Service reliability is the ability of a system (service) to meet its supply function with the required quality under specified conditions for an identified period [2]. According to this point of view, the required quality and specified condition should be considered the same as failure rates for components. We know that reliability is a basis for different applications in industry, such as maintenance planning, risk analysis, lifetime determination, warranty costing, technology qualification and so on. Therefore, the reliability definition and evaluation can be useful for engineers in different industries. In this paper, the reliability of a mechanical refiner is introduced and evaluated.

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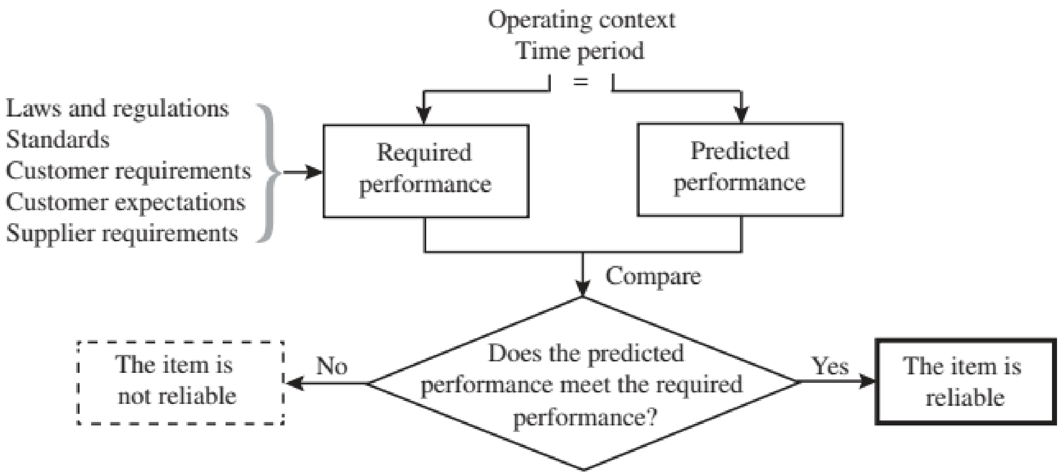

Figure 1. The reliability concept [2]

Refiners are the heart of a pulp-making mill that uses a thermal-mechanical scheme to produce the pulp. The pulp making is an energy-intensive process. Therefore, for the reduction and management of energy consumption in this process, several studies have been conducted. In the refining section, the raw materials are beaten, and the physical shape is changed to make or increase the connection among fibers to improve pulp quality [3]. Reliability is a vital aspect of pulp mills to make an economical product since any stoppage will result in financial loss. For example, in a mill that produces 500 tons per day, when it is stopped for one hour by an undesired event, about 5% of the production is reduced, and the loss is about $25000.

Reliability and maintenance are critical items for these systems management. Production systems are repairable systems that consist of different machines. Some studies were performed for reliability modelling of these systems [4-8]. In this paper, only studies conducted to evaluate or improve the reliability of pulp mills are considered. Sachdeva et al. [9] used Petri net to evaluate the reliability of a pulping system in a paper factory. This work helps the management to decide upon the maintenance strategy to be adopted to improve the performance of the system and consequently reduce the operation and maintenance costs. Kumar et al. [10] calculated the reliability and availability function and mean time to failure (MTTF) of a feeding system. Availability and MTTF of a washing system in a pulp mill has been studied [11]. Zaidi and Goyal [12] tried to model a pulping system and used the Markov method to evaluate availability and mean time to failure. Kumar and Goel [13] discussed the fuzzy reliability of a pulping system which consists of four subsystems such as digester, knotter, deckers, and openers. They compared Exponential, Rayleigh, and Weibull distributions and indicated that paper industry management should involve Weibull-distributed random variables for the pulping system to attain higher reliability. Saini et al. [14] considered an industrial system that consists of six subsystems: conveyor belt, crusher, froth flotation, rotary disc filter, balling disc and rolling screen. The distribution of failure times and repair times are arbitrary distributions for all subsystems. The availability of this system is calculated. Gurunathan [15] used generalized stochastic Petri nets (GSPNs) to estimate the availability of a process plant. These references show that pulp systems have been deeply investigated in the past, but refiners have not received much attention. Thus, in this research, we consider this type of machine.

2. Product performance

Product performance is defined as a vector of variables, where each variable is a measurable property of the product or its elements. The variables may be functional properties, form, durability, price, and market. The performance of an item depends on several factors. These include usage mode, usage intensity, usage environment, skills of the operator involved, and so on. Suppliers and customers consider different performance variables, and there are different notions of performance in the context of the product life cycle. Various and uncertain factors beyond the control of the supplier influence the actual performance.

Important factors in determining the predicted performance are the following: (1) design properties, (2) models utilized for prediction, and (3) the quality of the data utilized in the prediction. Figure 1 shows factors influencing product performance. Thus, in the performance evaluation process, these factors should be considered.

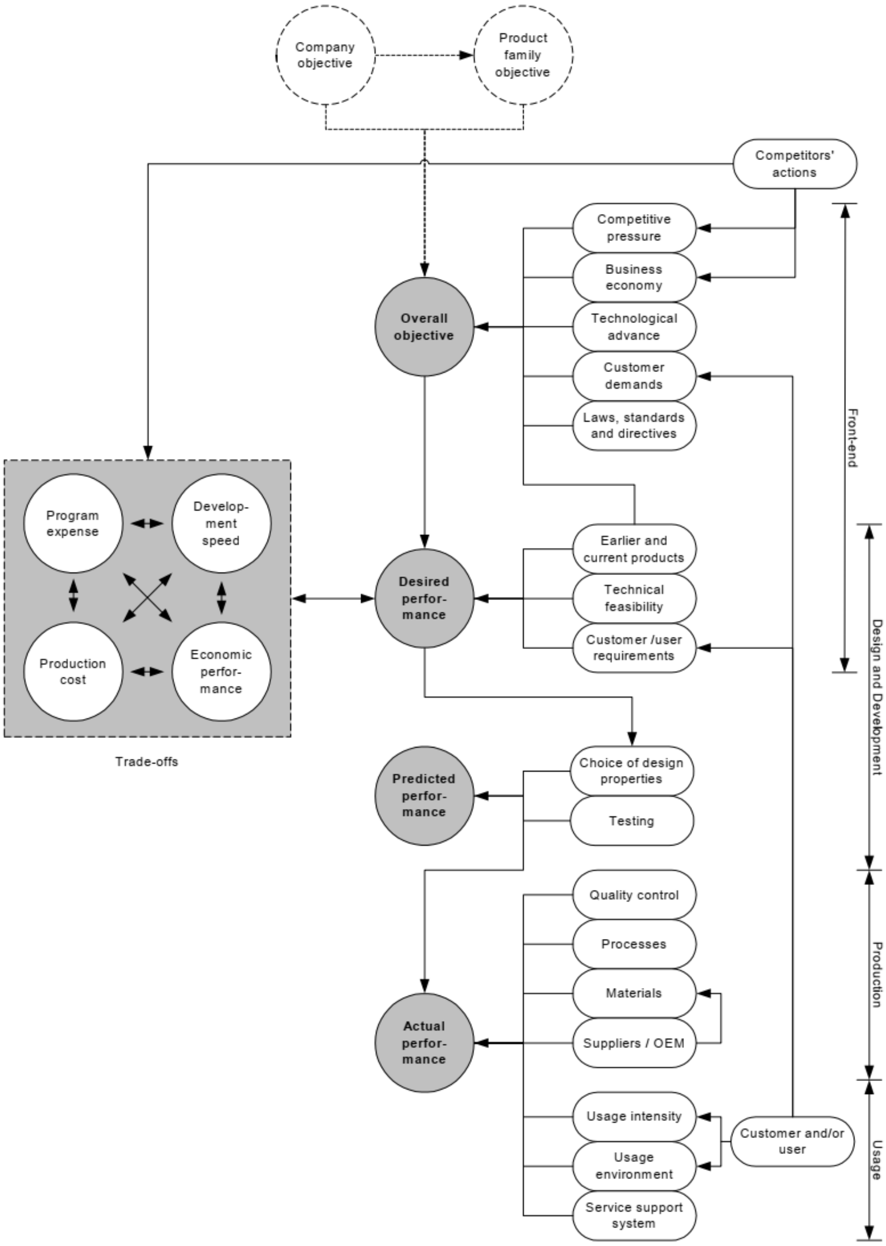

Figure 2. Overview of factors influencing product performance

3. Mechanical Refiner

Different schemes can be utilized to make pulp or paper. The manufacturing process is designed based on raw material properties and final product applications. Chemical treatment and mechanical refining are the most common methods for this purpose. The pulp-making process usually includes several stages, such as cooking, washing, refining, screening, forming, and drying. These stages should be performed in a series layout. The refining process influences final product quality, and its quality effect on the performance of a production line is important.

Refining or beating of chemical pulps is the mechanical treatment, and it modifies fibers so that they can be formed into paper or board with the desired properties. It is one of the most significant operations when preparing fibers for the production of high-quality paper or paperboard.

Treating fibers in the presence of water with metallic bars is the most commonly used refining or beating method. The plates or fillings are grooved so that the bars that treat fibers and the grooves between bars allow fiber transportation through the refining machine. During this fiber pick-up stage, the consistency is typically 3%−5% (sometimes, in special applications, 2%−6%), and the fiber flocs comprise mainly water. The most important refiner mechanical pulping process today is thermomechanical pulping (TMP) [16].

Refiners can be grouped into Hollander beaters, Conical refiners and Disk refiners. Today, disk refiners are commonly utilized in industry due to their capability and production requirements. Figure 3 shows the disk refiner. The main components of disc refiners are the electrical motor, shaft, disks, bearings and mechanical seal. The distance between two disks or surfaces in a refiner is called a gap and is controlled by a manual mechanism or an automatic system. In this study, it is assumed that a manual mechanism was used.

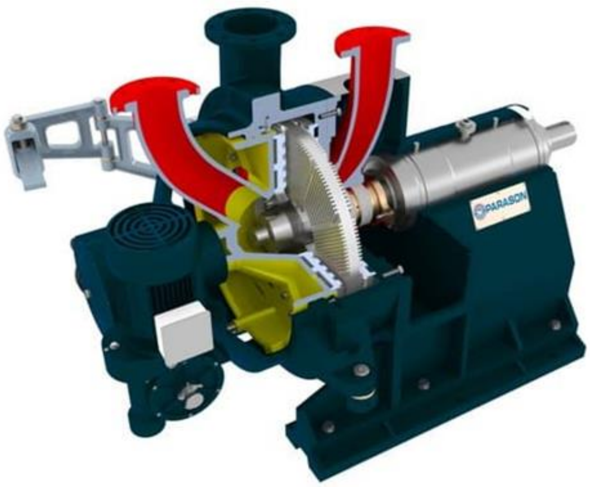

Figure 3. Disk refiner structure

Refiners are utilized to achieve the desired quality. The final product quality is not acceptable, When the pulp quality is reduced, thus it can be said that the desired function has failed. According to this subject, the refiner is terminated from predefined performance. Also, when a component of the refiner is failed, we deal with a stoppage in production. According to this definition, the reliability of the refiner is determined as follows:

$$R = Rs \times Rq \tag{1}$$

where Rs defines the probability of working without component failure, and Rq defines the probability of making a product with acceptable quality.

The quality and result of a refiner depend on the amount of refining, nature of refining, length of impact, fibers, process condition (PH, Temperature, Pressure, consistency and slushing), refining system, refiner filling, and refiner parameters (geometry, Gap clearance, stability and so on.). Some of these items, same as all fiber-based variables, are predefined and cannot be changed during the refining process. Process conditions such as consistency, pH, temperature, and pressure can, to some extent, be controlled. Some items, such as refiner type, refining system and refiner filling, are selected in the factory design process. In practice, flow rate and gap are controlled in a refiner so that these can be changed during a process. Flow rate can be adopted by a centrifugal pump or a screw pump installed in the inner line. The quality and stability of this pump impress the final product quality.

The refiner is controlled by adjusting the gap between disks or plates. This gap variation creates some signals that can be detected and indicated. The signal for automatic or manual control may be selected as main motor load, the amount of the refining energy, temperature rise of the stock, freeness, vacuum from a flat box or couch roll, or air permeability of the paper. The main motor monitoring is the simplest way to detect abnormal situations and adjust this gap.

The accuracy of the produced signal measurement guides the accuracy of the control system. Noise, false signals, and errors in a signal collection usually exist. Therefore, collected signals should be calculated as an average for better management. Also, when a signal monitoring device fails, the quality of the final product may be changed to an undesired situation. According to the mentioned items, the probability of rejection of the final product may depend on the monitoring system. For the evaluation of a measurement system, we can use the stress-strength model as follows [1]:

$$R = \Phi(SM)$$

$$SM = \frac{E(S)-E(c)}{\sqrt{var(S)+var(c)}} \rightarrow SM = \frac{\mu_S-\mu_C}{\sqrt{\sigma_S^2+\sigma_C^2}} \tag{2}$$

where E(S) and E(c) define the mean of strength and stress (challenge), respectively, Var defines variance, and Φ is the normal distribution parameter.

For this, several tests should be performed and according to records, the reliability is determined. In measurement devices, the reliability value is usually 0.97. On the other hand, the failure rate of the control system can be applied to determine the reliability value.

Another aspect to determine the reliability of a refiner is the MTBF (Mean Time Between Failures) calculation. This value depends on components and sub-systems failure rate.

The refiner consists of plates, a shaft, a bearing, a mechanical seal, and a body. These components work together as a series system since the failure of each of them leads to the stoppage of the refiner. In the rest of the paper, the behavior of these components is considered.

The plates are grooved elements so that the bars on the plate treat fibers, and the grooves between bars allow fiber transportation through the refining machine. Geometry and material are preselected for a special fiber, but in the refining process, its geometry may be changed, or a part of it is torn off. Wear is the dominant process that determines the life of plates. The previous studies demonstrated that the wear on the rotor is greater than the stator section, and the Archard relation can be used to evaluate wear on plates in a refiner [17].

$$W = kNL/H \quad (3)$$

where k is a dimensionless wear coefficient, in this relation, wear volume, W, depends on the hardness of the wearing material, H, applied normal load, N, and sliding distance L.

To determine the plates' lifetime, it should be defined a threshold for wear, and a normal distribution can be calculated this time.

In the worst case, two plates collide, but this situation should be avoided. In normal conditions, wear occurs due to pulp flow and fiber contact with the plate's surface. Wear rate is governed by fiber material since the fiber hardness and its morphology define normal load value and wear coefficient. According to Frazier's study [18], the wear rate is slow, and after 2 years, about 13 to 23 percent of plate surfaces are damaged. In Iranian factories, unfortunately, the replacement time for these plates is very long, and consequently, the quality and availability of the system are low. Thus, replacement time and inspection are necessary.

Another component that can influence the refiner's lifetime is the main shaft. Stainless steel materials are utilized to make this shaft. Thus, corrosion can be ignored, and only fatigue loads may disturb this. Fatigue is one of the main failure mechanisms in mechanical elements that has been deeply investigated in the literature. The fatigue life of a component may be divided into (1) the time required to initiate a crack and (2) the time required for that crack to propagate to the final fracture. Life-stress or strain-life methods usually determine the life. For a refiner shaft design, the life-stress method is applicable, and the life can be determined as below:

$$N = exp\left(\frac{Log\ S - Log\ A}{B}\right) \quad (4)$$

where S is the applied alternating stress, and A and B are constants to be determined. For example, if s=206 MPa, A=886, and B=-0.14. Then N=3.32 x 10^4 cycles. Also, this notice should be reminded that the shaft design can be performed based on ASME or API codes. In this situation, the reliability can be determined by the stress-strength model.

A bearing is used as a support for a shaft in a rotary machine. Bearing as a mechanical element has different failure modes, such as fatigue, fracture, wear, fretting, and so on. When a failure mode appears on a bearing, it should be replaced. Determining the life of a bearing is a complex problem, and this life depends on several parameters such as working load, temperature, humidity, etc. Health monitoring via acoustic or vibration measurement is a common solution to manage advanced rotary machines. For this purpose, several methods have been proposed for health monitoring [19-20]. Also, Different formulas have been proposed to determine bearing lifetime. For instance, B10 defines a time that ten percent of bearings will be failed. B10 can be determined as follows [21]:

$$B_{10} = \left(\frac{C}{P}\right)^n \left(\frac{16667}{RPN}\right) \quad (5)$$

where C is dynamic capacity, P defines equivalent load, 3.0 for ball bearings, and 10/3 for roller bearings. For example, in general industrial machinery, B10 is 2 - 3 years.

Although Weibull distribution is useful for bearing lifetime determination, for simplification, exponential distribution is often used for this. Thus, the failure rate can be determined by B10.

Sealing for a hydraulic machine and any unit dealing with liquid is very crucial. In a refiner, water and fiber flocs are pumped, and after the refining process, they exit through a pipe. Fibers are beaten, and temperature is increased during this process. Pressure between disks and shaft rotation in fluid creates a situation where pulp would like to exit from this volume. Leakage is the main failure of the refiner that reduces its capability and causes pollution. Therefore, designing a correct sealing mechanism is significant. A dynamic seal is a mechanical device applied to control the leakage of fluid from one place to another when there is a rotating or reciprocating motion between the sealing interfaces. The integrity of a seal depends upon the compatibility of the fluid and sealing components, conditions of the sealing environment, and the applied load during application. Thus, different sealing mechanisms can be utilized here, it is recommended that a mechanical seal with double cartridges is applied in a refiner Because of its durability and capability.

According to the movement between sealed surfaces. The dynamic seal should be used. The main mechanisms for failure and leakage in this unit are wear, dynamic instability and embrittlement. The wear mechanism is more important than others. Seal face pressure and liquid velocity are two parameters that control the wear. The failure rate of a dynamic seal can be determined by [21]:

$$\lambda = \lambda_{sb} \prod_{i=1}^{n} C_i \quad (6)$$

The failure rate is determined by failures/million hours. λ_{sb} is the base failure rate, 2.4 failures/million hours. Ci is a multiplier factor that considers the effect of operational factors such as contact stress and hardness, allowable leakage, fluid viscosity, pressure, fluid velocity and seal face temperature. A specified relation should determine each factor. For instance, the multiplying factor of material hardness/contact pressure is determined by [22]:

$$C_H = \left(\frac{M/C}{0.55}\right)^{4.3} \quad (7)$$

where M is Meyer hardness, lbs/in^{2,} and C defines contact pressure, PSI.

In this section, the main parts of a mechanical refiner were introduced and physic of failure relations were introduced. In the rest of the paper, a small refiner that can be used in a small production line or laboratory is considered, and its reliability is predicted.

4. Case study

Setareh Etemad Iranian would like to produce a small refiner that can be utilized to make 20 TPD paper pulp from palm date waste. In this section, this system is introduced, and its reliability is predicted.

This machine can beat one-tone pulp per hour. This machine has double disks, and its revolution speed is 1400 RPM. Plates are made of cast iron, and their diameter is 375 mm. Also, an electrical motor is utilized to provide power equal to 75 Hp. The system produces 100 cubic meters of liquid per hour at one to three bar pressure.

4.1 Control system

In this machine, we consider a simple control system to adjust the distance between plates. The main motor current is monitored, and power consumption is calculated. A threshold is defined for this purpose. When the power is increased to over this limitation, an alarm light indicates this condition, and the operator adjusts the gap between plates. The reliability of this scheme depends on current measurement reliability. According to MIL-217 Plus, this system failure rate is determined as below:

In the first step, a block diagram is created the main electronic and electrical components are defined, and according to mission target, failure rates are calculated. For example, the failure rate model for displays is [23]

$$\lambda = \lambda_0 \times \left\{1 + 2.5 \times 10^{-3} \times \left[\sum_{i=1}^{j} (\pi_n)_i \times (\Delta T_i)^{0.68}\right]\right\}. Fit \quad (8)$$

or, the failure rate model for dielectric capacitors is

$$\lambda = \pi \left\{\left[\frac{\sum_{i=1}^{y} (\pi_t)_i \times \tau_i}{\tau_{on} + \tau_{off}}\right] \times \pi_A + \pi_{type-II} \times \left[\sum_{i=1}^{j} (\pi_n)_i \times (\Delta T_i)^{0.68}\right]\right\}. Fit \quad (9)$$

Then, the system failure rate is determined. According to system configuration and components, the designed system failure rate is 40 FIT (Failure in Time). Consequently, the mean time to failure is 25000 hours. Thus, for 700 hours (equal to one month), reliability is 0.9725.

In a pulp & paper factory, the production process is often stopped for 2 days per month for planned maintenance.

4.2 Refiner plates

Refiner plates provide maximum uniformity in the refining zone when they are manufactured using special casting and CNC technology. These plates are made of alloy cast iron, which is resistant to wear and corrosion. The outer diameter is 375 mm, and the thickness is 20 mm. The groove depth is 5 mm. That is assumed that when groove depth is reduced to 4 mm, the plates should be replaced. Thus, according to the Achard equation and working conditions, the predicted lifetime is 18 months or 83 failures per one million hours. This lifetime follows the normal distribution. Thus, the reliability for one month is very close to 1.0.

4.3 Shaft

In the mentioned machine, a shaft with a 60 mm diameter is utilized. This part material is SS 304. According to the power and torque produced by the main motor, shaft material and dimensions, the induced stress is 45 MPa, and the material fatigue threshold is 60 MPa. Thus, the reliability is predicted by the stress-strength model as follows:

$$SM = \frac{E(S) - E(c)}{\sqrt{var(S) + var(c)}} = \frac{60 - 45}{\sqrt{1 + 4}} = 6.7082$$

$$Reli = 0.99999$$

In this relation, the variance of stress and strength are assumed to be 1 and 4, respectively.

4.4 Bearing

Other components used in this machine are two bearings utilized to support the main shaft. These are tapered roller bearings. According to predicted values of dynamic load and axial and radial loads, the basic rotating life is 1500 million revolutions or 80 failures in a million hours.

4.5 Mechanical seal

A seal is a device placed between two surfaces to restrict the flow of fluid from one region to another. A dynamic seal is a mechanical device used to control the leakage of fluid from one region to another when there is a rotating or reciprocating motion between the sealing interfaces. There are several types of dynamic seals to be considered, including the contacting types, such as lip seals and non-contacting types, such as labyrinth seals.

The most common modes of seal failure are fatigue-like surface embrittlement, abrasive removal of material, and corrosion. The wear and sealing efficiency of fluid system seals is related to the characteristics of the surrounding operating fluid.

The failure rate of a mechanical seal can be determined by equation 6. For this purpose, multiple factors should be calculated. *CQ* is a multiplying factor that considers the effect of allowable leakage on the base failure rate; leakage in this system cannot be accepted. Thus, this factor is 4.2. *CH* is a multiplier factor that considers the effect of contact stress and seal hardness. According to elastic material hardness, this factor is 10. CF defines the effect of surface finish; this factor is equal to 1 since a grinding machine has finished the shaft. The effect of fluid viscosity is indicated by CV. This factor is 19 since the liquid is water-based and the working temperature is lower than 50 ^{0}C. CT defines the effect of seal face temperature. It is 0.21 due to the utilization of neoprene, and the rated temperature of the seal is greater than the operating temperature.

CPV indicates the effect of the pressure velocity coefficient. This factor calculates the relation between the actual and design conditions of a sealing mechanism. This factor value is equal to 1.

The effect of contaminants on the sealing is very vital, CN defines this effect. The number of contaminants depends upon the design, the enclosure surrounding the seal, its physical placement within the system, maintenance practices and quality control. The number of contaminants may have to be estimated from experience with similar system designs and operating conditions. Also, this factor can be estimated by [21]:

$$CN = \left(\frac{C0}{C10}\right)^3 N_{10}\, LPM \tag{10}$$

LPM defines the flow rate as a liter per minute. N_{10} indicated the number of particles under 10 microns produced in an hour when a system works. The filtration system effect is determined by $\left(\frac{C0}{C10}\right)$. According to system design parameters, CN is 27.

Consequently, the failure rate of the designed mechanical seal is 679 failures/million hours. The mean time to failure is 1472 hours.

4.6 The system

A mechanical refiner consists of different components in a series structure. The failure rate of this system is calculated as follows:

$$\lambda_{refiner} = \lambda_{plates} + \lambda_{bearing} + \lambda_{mechanical\ seal} + \lambda_{shaft} + \lambda_{control}$$

thus,

$$\lambda_{refiner} = 83 + 80 + 679 + 10 + 40 = 892\ failures\ per\ 10^6\ hours$$

Therefore, the mean time to failure is 1121 hours equal to two months working. In other words, we expect every two months, this machine will be stopped for a repair process. According to this study, the mechanical seal is a critical item with the lowest lifetime and the highest failure rate. Shaft is the best from a reliability point of view.

5. Conclusions

Mechanical refiners are the main part of a pulp mill, and in mechanical pulp processing, they are the heart of a factory. This device has been considered and evaluated from the point of the pulp quality; several studies have been conducted to improve pulp quality by the mechanism changing or parameters setting. The study of reliability and maintenance attracted little attention; thus, in this paper, the reliability of a mechanical refiner was considered. The principle of a refiner machine was studied, and the main components were introduced. This machine consists of different sections that work as a series structure. In this paper, the reliability of components was determined and failure rates and mean time to failure are predicted. The mechanical seal is the critical element, and its failure rate is very high compared to other elements. Bearing and plates have the greatest failure rate in the next step. To refiner health monitoring, it is suggested that these elements to monitored. Also, according to the influence of mechanical seals and plates on the reliability and quality of the final product, reliability modeling of these via the physics of failure methods is recommended for the next studies.

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