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Pre-Chamber spark ignition: a reliability analysis of pre-chamber valve functions

Hazne öncesi kıvılcım ateşlemesi: ön yanma odalı valf fonksiyonlarının güvenilirlik analizi

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Abstract

A pre-chamber ignition allows spark-ignition engines to operate in lean air-fuel settings. It improves fuel efficiency and reduces emissions. In this study, a reliability analysis of a single GE Jenbacher J620 natural gas engine was done. It was operational on continuous load in the power generation sector in Karachi, Pakistan. The bathtub curve of GE J620 pre-chamber gas valve (PCV) was generated. The three-year industrial data comprised PCV failures that occurred between two overhauls. During infant mortality, the curve revealed 7 failures during 1000 hours. This decreased to a failure for the next two cycles of thousand hours each. The mean-time-to-failure (MTTF) of the gas valve at 2500 hours and 4500 hours was calculated. There was a 50% decrease in reliability after 1500 hours. Exponential distribution revealed that the mean time-to-failure (MTTF) was 545.5 hours. This study was the first of its kind in the facility. Previously, much time was lost in breakdown maintenance. Thus, it helped to increase the system's reliability.

Keywords: Bathtub curve, Exponential distribution, Fuel injection, Pre-Chamber valve, Reliability.

Öz

Ön oda ateşlemesi, kıvılcım ateşlemeli motorların zayıf hava yakıtı ayarlarında çalışmasına izin verir. Yakıt verimliliğini artırır ve emisyonları azaltır. Bu çalışmada tek bir GE Jenbacher J620 doğal gaz motorunun güvenilirlik analizi yapılmıştır. Pakistan, Karaçi'de elektrik üretim sektöründe sürekli yükte çalışıyordu. GE J620 ön oda gaz vanasının (PCV) bir küvet eğrisi oluşturuldu. Üç yıllık endüstriyel veriler, iki revizyon arasında meydana gelen PCV arızalarını içeriyordu. Bebek ölümleri sırasında, eğri 1000 saat boyunca 7 başarısızlık ortaya çıkardı. Bu, her biri bin saatlik sonraki iki döngü için başarısızlığa düştü. Gaz vanasının 2500 saat ve 4500 saatte ortalama arıza süresi (MTTF) hesaplandı. 1500 saat sonra güvenilirlikte %50 azalma oldu. Üstel dağılım, ortalama başarısızlık süresinin (MTTF) 545,5 saat olduğunu ortaya koydu. Bu çalışma, tesiste türünün ilk örneğiydi. Daha önce, arıza bakımında çok zaman kaybedildi. Böylece sistemin güvenilirliğinin artmasına yardımcı oldu.

Anahtar kelimeler: Küvet eğrisi, Üstel dağılım, Yakıt enjeksiyonu, Ön hazne valfi, Güvenilirlik.

1 Introduction

The majority of countries around the world rely on fossil fuels to supply their energy needs. 87% of the world's energy is met by non-renewable fossil fuels. These include coal, oil, and gas. The energy sources of Pakistan are thermal (87%), hydropower (11%), and nuclear power (1.7%). In 2013, Pakistan's total energy supply was 64.5 million tons of oil equivalent (MTOE). Oil (20.96 MTOE), gas (31.1 MTOE), LPG (0.3 MTOE), coal (3.8 MTOE), hydroelectricity (7.1 MTOE), nuclear electricity (1 MTOE), and imported energy (0.08 MTOE) were the principal energy sources [1]. Concern about the impact of greenhouse gas (GHG) emissions on climate change is driving the international community to pursue sustainable growth. This can be achieved by an economy that is less reliant on carbon-intensive industries. This concept is named "Low Carbon Society" (LCS). Therefore, for this goal to be realized, the current energy system must be restructured [2]-[3]. Most of the GHG emissions were attributed to the power sector in 2014. Of these, Carbon dioxide (CO_2) accounts for 90%. CO_2 emissions from fossil fuels are one of the most dangerous and complicated problems in the climate change debate [4]. The remaining GHG emissions are from methane (9%), nitrous oxide (1%) and other gases 14% [5]. Nearly a third of Pakistan's energy needs are met by imports. Energy imports totalled roughly US$ 14.4 billion in 2017-2018 [6]-[7].

A gas engine is a type of internal combustion (IC) reciprocating engine. Its principal application includes heavy-duty industrial use for electric power generation. It can continuously undertake heavy loads for larger periods [8]. It is classified on a variety of factors; including mixture preparation, ignition type, and engine cycle. The mixture can either be premixed or non-premixed. The ignition type can be spark ignition (SI engines), or diesel pilot. Engine cycle may be Otto, diesel, or mixed cycle [9].

To implement the LCS vision, natural gas (SI engines) is preferred over gasoline and diesel. This is because natural gas emits approximately 25% to 30% less CO_2 per energy unit [10]-[11]. However, problems arise when the fuel-air mixture is either rich or stoichiometric [12]. In a rich air-fuel mixture, the quantity of air is less than required for the complete combustion of fuel [13]. In a stoichiometric air-fuel combination, complete fuel is burned without any additional air. It has an optimal air-fuel ratio [14].

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The problems faced when the engine operates at these air-fuel mixtures include low compression ratio, losses due to throttling, engine knock, high emissions and lower thermal efficiency [15]. Thus, it is recommended to burn the fuel in excess air, i.e. having a higher concentration of air to fuel [16]-[17].

Such a type of air-fuel mixture is known as lean fuel [18]-[19]. Lean-premixed combustion can reduce fuel consumption, flame temperature and NOx emissions [17]. It also shortens the combustion process and increases combustion efficiency and stability [20]. However, flame instabilities escalated critical ignition and flame propagation [21], greater cycle-to-cycle variability, a high likelihood of flame quenching, misfire, and partial burning [22], and increased unburned hydrocarbons (UHC) are the drawbacks [20],[23].

To address these concerns, advanced ignition methods, like diesel pilot-fuel injections or pre-chamber spark ignition (PCSI), can be employed [24]-[25]. Turbulent jet ignition system (TJIS) is another name for PCSI. A traditional electrical spark mechanism is employed in the PCSI system. It ignites a specific volume of the air-fuel mixture in a pre-chamber through a series of orifices [26]. It results in high pressure [27], and faster combustion which mitigates the knock tendency. It presents a reduction in vehicle exhaust level and fuel usage [28]. So, the compression ratio rises, enhancing the thermal efficiency of the engine [29]-[30]. The present study focuses on a gas engine. The working fluid is natural gas. It is the most widely used alternative fuel for an IC engine. This is due to its lower carbon content and high octane number [31]. But as fossil fuels' reserves get depleted and GHG emissions increase, emission reduction must be incorporated. The industrial data of a pre-chamber gas valve (PCV) of General Electric's (GE) single Jenbacher J620 is used. A Jenbacher gas engine has a power range of 200 kW to 10 MW.

In this study, a reliability analysis is done of a single GE Jenbacher J620 natural gas (NG) engine. It is operational on continuous load in the power generation sector in Karachi, Pakistan. A bathtub curve of GE J620 PCV is generated. A three-year failure data of PCVs is collected. These failures occurred in between two complete overhauls. A bathtub curve is generated. It helps to identify the maximum failures occurring in different stages of life. Another study is underway to eliminate these failures. The probability density function (PDF) of the NG engine helps to predict when the next maintenance is due. Moreover, a reliability analysis is carried out by applying exponential distribution. Mean-time-to-failure (MTTF) of the gas valve at 2500 hours and 4500 hours is also calculated.

2 Research methodology

2.1 Pre-chamber combustion structure

Gas engines have a broader deviation in peak firing pressure per cycle than diesel engines. It might be due to firing or misfiring. This would hamper betterment in performance. So, combustion deviation control would be critical for ensuring engine reliability [9]. Figure 1 illustrates the structure of the pre-chamber [32]. It includes a body forming a pre-combustion chamber. It is used for the pre-combustion of fuel gas. A spark plug is installed in the body to ignite the fuel gas. There is a check valve in the main body. It controls the flow path of gas supply passage to prevent the reverse flow of combustion gas [33].

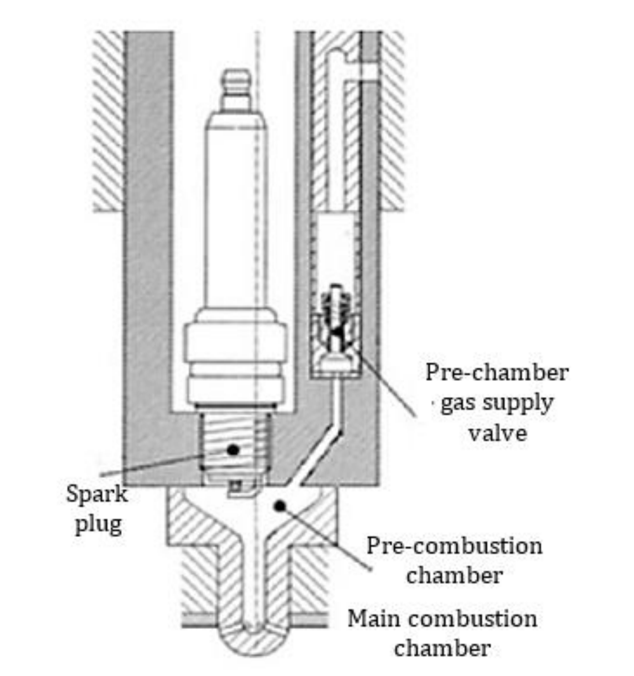

Figure 1. Pre-Chamber Structure [32].

Figure 2 illustrates the structure of the pre-chamber combustion style [32]. A pre-chamber combustion controls the deviations in combustion by stabilizing it. There are four steps, as shown in Figure 2. These are: (1) Fuel gas is fed into the pre-chamber; (2) Lean mixture from the main chamber flows into the pre-chamber, to create a stoichiometric mixture; (3) A spark plug ignites the mixture in the pre-chamber to start combustion, and (4) Flame from pre-chamber shoots into the main chamber to burn the lean mixture. These four phases take place in a single cycle.

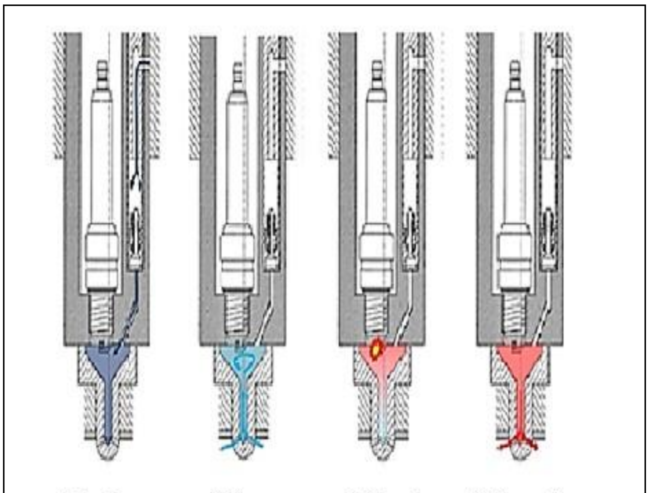

Figure 2. Pre-Chamber Combustion Method [32].

The thermal efficiency of gas engines can be increased significantly if high compression ratios are used and lean mixtures are combusted. Therefore, the mixture inside the pre-chamber must be ignitable. It is necessary for pre-chamber ignition devices to function properly. When there is a lean mixture in the combustion chamber, fuel must be added to the pre-chamber. A crucial design factor is the fuel required to enrich the pre-chamber. A challenge occurs to accurately measure the needed amount of fuel when the pre-chamber is small. Nonetheless, mixture formation with liquid fuels is exceedingly difficult. This is due to small dimensions and charge motion in the pre-chamber. So gaseous fuels are preferred [34]-[36].

2.2 Fundamentals of pre-chamber combustion structure

For an extremely lean mixture, with a φ factor greater than 2.0, a pre-chamber system is used [28]. It is shown in Equation (1):

$$\varphi = \frac{\text{Amount of Oxygen actually present in combustion chamber}}{\text{Amount of Oxygen that should be present to get perfect combustion}} \quad (1)$$

Where φ is air-fuel equivalence ratio.

The mixture enters the intake port. Here it is aspirated into the cylinder. A near-stoichiometric mixture is added in the pre-chamber [37]. Large volumes of Carbon monoxide (CO) and hydrocarbons (HC) are created when this combination is burnt. A flame is pushed out from the connecting channel into the cylinder as pressure escalates [38].

The charge distribution is characterized as homogenous or stratified. This is based on the mixture entering the pre-chamber. Fuel injection occurs exclusively in the main chamber in a homogeneous charge. The air-fuel mixture then enters the pre-chamber by interconnected orifices. Thus, the geometry of orifices and pre-chamber is critical for combustion development.

Fuel injection in the auxiliary chamber distinguishes stratified charged pre-chambers. Since the volume of the pre-chamber is less, it creates a richer zone around the spark [39]. During compression, the lean mixture of the main chamber enters the pre-chamber [40]. This results in zones with differing air-fuel ratios within the primary combustion chamber. The richest mixture is around the spark plug [41].

[42] performed an in-depth study about power generation technologies. The analysis is under different scenarios with gas turbines, IC and other engines. The study proves that an IC engine has the best economic performance over gas turbines, including higher efficiency. In a different research, engine design is improved. One modification made is installing the engine with a pre-chamber [43]. This controls the engine knocking. The results show that by adding a pre-chamber, the break-thermal efficiency of the engine is improved. In their study, [44] investigate the technical parameters needed to convert an NG engine to burn associated petroleum gas. This is done based on real, sampled data. From the experiments, it is seen that the optimal percentage of gas in the pre-chamber for the NG engine is 1%. At this percentage, the thermal efficiency of the engine is approximately 99.3%. At 0.6% of gas in the pre-chamber, the thermal efficiency of the engine rises to a perfect 100%. It is also deduced that peak pressure majorly affects the thermal efficiency of the engine having a pre-chamber. However, if a pre-chamber is added to an engine, this would increase cost and maintenance, and an additional pressure line and a gas train would also be needed. However, if a pre-chamber is not used, then the overall thermal efficiency of the thermodynamic engine decreases. However, incorporating different technological advancements can overcome this decreased efficiency. These advancements are out of the scope of this paper.

2.3 Pre-chamber gas valve or check valve

The reliability of pre-chamber constituents requires extra attention due to the high temperature. The structure of the check valve is depicted in Figure 3 [32]. It prevents combustion gas from returning to the fuel supply line. It is turned on by a spring. A check valve with a valve body and valve springs is shown in Figure 3. In the operational condition, the valve body has a lower gap. It is acted upon by gas. The valve spring is positioned in a space above the valve. A pressed plug closes the upper space [45].

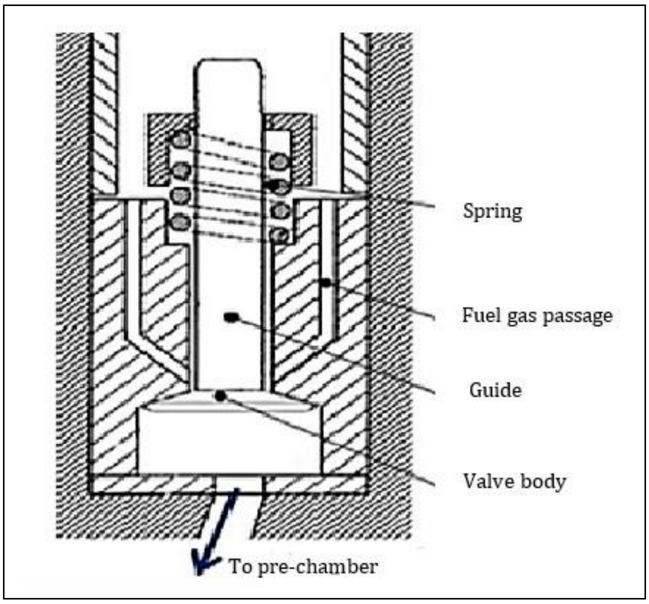

Figure 3. Structure of pre-chamber gas supply valve [32].

Figure 4 shows the check valve of a single GE Jenbacher J620 NG engine. Figure 5 shows its spark plug. The gas engine under consideration is operational on continuous load in the power generation sector in Karachi, Pakistan.

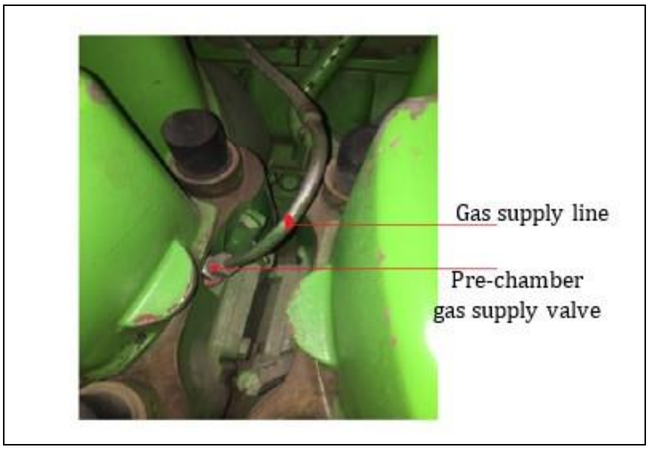

Figure 4. Pre-Chamber Gas Valve of GE Jenbacher J620 NG Engine

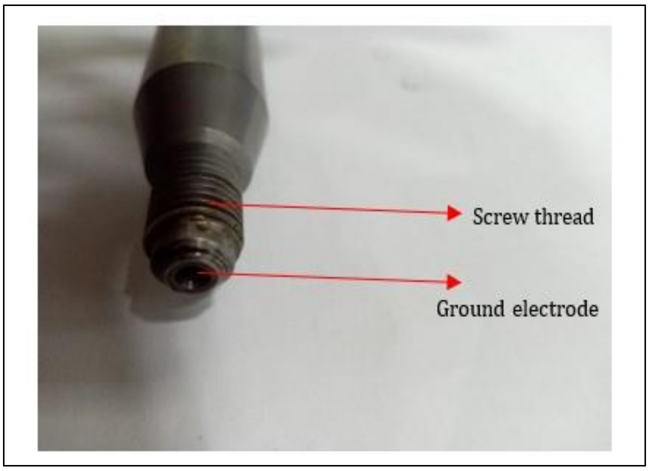

Figure 5. GE Jenbacher J620 NG Engine Spark Plug.

2.4 Bathtub or life cycle curve

The bathtub curve, also known as the life cycle curve, represents the failure pattern of any product. There are three stages to it. These include (1) the infant mortality stage; (2) the useful life stage; and (3) the wear-out stage. Figure 6 presented below shows a typical life cycle curve [46].

The infant mortality stage begins when the product is manufactured. The failure rate is the highest. With time, the failure or hazard rate of the product decreases. The curve falls rapidly. This stage is the infant mortality stage. In this stage, failures can be due to manufacturing defects, installation issues, or even improper start-up problems.

As the curve straightens, the failure rate becomes the least during the whole life cycle. Here, the failure probability of the product is minimum. This stage is the useful life stage. The breakdowns which occur during this stage are random failures mostly. This stage forms most of the useful life of the product. Timely maintenance or overhaul can increase this stage.

As the useful life stage of the product nears its end, breakdowns and failures start to increase. The slope of the life cycle curve shoots up. This is the wear-out region. With time, the curve again peaks up to reach a maximum. This warrants that the useful life of the product is ended, and it can no longer be used.

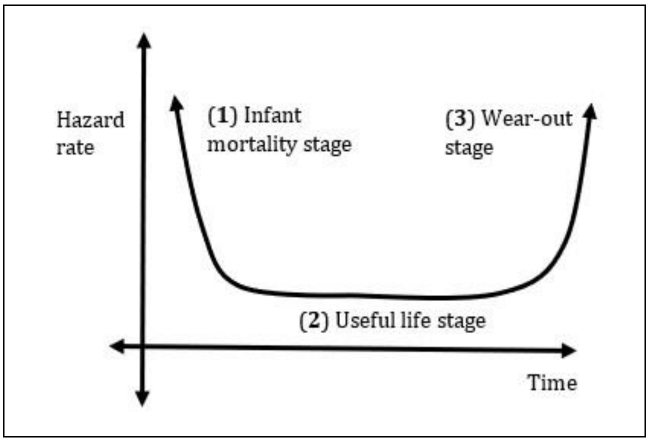

Figure 6. Bathtub (life cycle) curve [46].

3 Reliability terms

A few of the basic reliability terms are explained. This is necessary to understand the succeeding paper. The terms are explained in context to the exponential distribution only. This distribution is most widely used in reliability work. It is used nearly exclusively in the reliability prediction of electronic equipment. The terms are:

3.1 Reliability

It is the probability that a component will perform its intended function over time, under the provided conditions. In simple words, reliability is the probability of success, and how well the component averts breakdowns during its useful life. It depends on time. The formula is shown in Equation (2):

$$R(t) = \frac{\text{Number of working products till time 't'}}{\text{Total number of products tested at time t=0}} \quad (2)$$

For exponential distribution, refer to Equation (3) below:

$$R(t) = e^{-\lambda t} \quad (3)$$

where, $R(t)$ is reliability as a function of time, e is the natural logarithm and λ is the rate parameter of the exponential distribution. It determines the constant average rate at which failure occurs, and "t" is time.

3.2 Failure rate

The failure rate of a product is the probability of the product failing at time "t". The formula is stated in Equation (4):

$$F(t) = \frac{\text{Number of product failures between time 't' and } \Delta t}{\text{(Number of products that have not failed by time 't')}(\Delta t)} \quad (4)$$

For exponential distribution, refer to Equation (5) below:

$$h(t) = \lambda \quad (5)$$

where, λ is the rate parameter of the exponential distribution.

3.3 Mean time to failure (MTTF)

It is the duration of time during which an irreparable asset operates before failing. For exponential distribution, it can be stated as mentioned in Equation (6):

$$MTTF = \frac{1}{\lambda} \quad (6)$$

where, λ is the rate parameter of the exponential distribution.

4 Results and discussion

4.1 Reliability analysis

A three-year data of a single Jenbacher J620 NG engine is collected. The engine is operational on continuous load in the power generation sector in Karachi, Pakistan. The data comprised PCV failures that occurred after a complete overhaul until the next complete overhaul. The characteristics of a Jenbacher J620 NG engine are given below in Table 1. Basic characteristics and technical characteristics, both are mentioned for full load. J620 is a type 6 engine. It can be operational on natural gas, flare gas, bio gas, landfill gas, sewage gas, coal gas, wood gas, pyrolysis gas, coal mine gas, etc. A few of the reference sites where J620 has been installed include Eisenhower Hospital, California; at Wijnen Paprika; Egchel, The Netherlands; and Barakatullah Electro Dynamics Ltd, Bangladesh.

Table 1. Technical data of Jenbacher J620 NG Engine [47]-[48].

TECHNICAL DATA	VALUES
Configuration	V 60°
Bore	190 mm
Stroke	220 mm
Displacement/ cylinder	6.24 L
Speed	1500 rpm at 50 Hz 1500 rpm with gearbox at 60 Hz
Mean piston speed	11 m/s
No. of cylinders	20
At NOx emissions less than 1.0 g/bhp.hr:	
Electrical power	3325 kW
Electrical efficiency	45.2 %
Thermal power	10,692 MBTU/hr
Thermal efficiency	42.6 %
Total efficiency	87.8 %
At NOx emissions less than 0.5 g/bhp.hr:	
Electrical power	3325 kW
Electrical efficiency	44.4 %
Thermal power	10,717 MBTU/hr
Thermal efficiency	41.9 %
Total efficiency	86.3 %

The following bar chart (Figure 7) shows the number of failures of the gas engine in the three years. A sample size of 20 PCVs is used. On X-axis is the time interval, i.e. lifetime in hours. Y-axis shows the number of failures.

The bar chart shows that the slope of the life cycle curve is at a maximum during the initial life cycle. There are 7 failures during the first 1000 hours. This is the infant mortality stage. These failures are reduced to a minimum during subsequent hours, with around one failure during the next 2000 hours of operation. Since the gas engine is continuously operated, this is equivalent to 83 days of operation, with only two failures during this time. This is the stage of useful life.

As the operation of Jenbacher J620 exceeded 3000 hours, the number of failures increase to twice during that of the useful life stage. This certifies that the next overhaul is due for the gas engine to operate effectively. This is the wear-out stage.

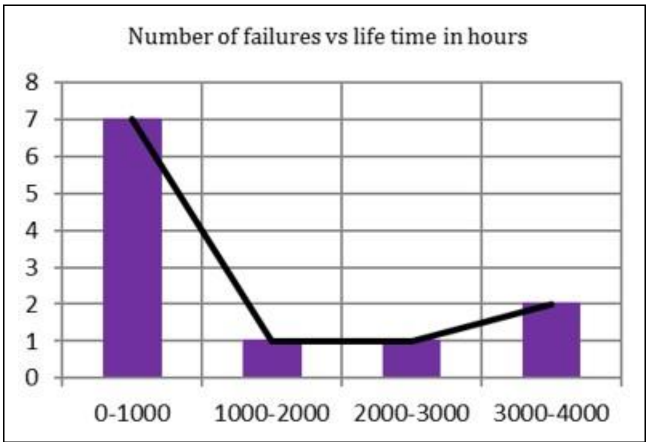

Figure 7. Number of Failures of J620.

Figure 7 is further elaborated in Figure 8. The curve is plotted between failure rate and lifetime (in hours) during the two overhauls. The bathtub curve is obtained in a continuous form. The shape of the curve is the same as that obtained from the exponential distribution.

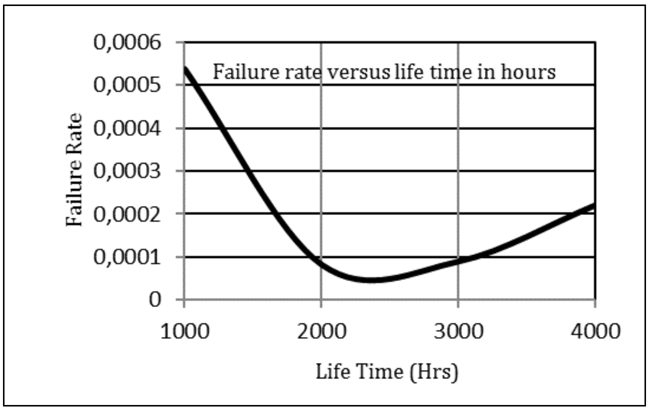

Figure 8. Failure Rate VS life time in hours.

Figure 9 depicts the probability density function (PDF) plot, against the lifetime (in hours). It shows the probability that the failure will occur.

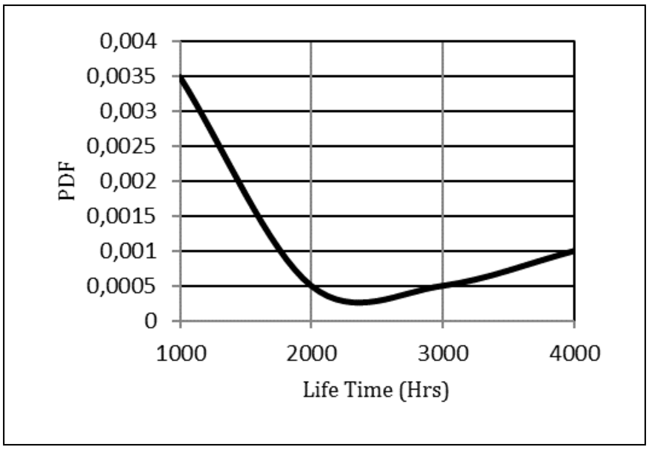

Figure 9. PDF VS life time in hours.

Figure 10 shows the plot of reliability versus lifetime. There are four legends: (1) the manufacturer data, which is established from the manufacturer's specifications; (2) calculated data; (3) Mean Time to Failure (MTTF) at 2500 hours; and (4) MTTF at 4500 hours. It can be seen that the reliability of calculated data decreases with time. From 1500 hours onwards, the reliability becomes nearly zero. If we compare this curve with the curve obtained from the manufacturer's specifications, it can be seen that there is a 0.5 or 50% increase in reliability at 1500 hours. This much deterrence from calculated data is a sign of concern. The reasons are many. The most pronounced reason is environmental. As the engine was manufactured in a Western country, the ambient temperature, pressure and humidity differed from that in Karachi. Since Karachi is a coastal area, pressure and humidity values are different. The climate of Karachi is very hot. Thus, increased failures due to corrosion, and wear-out occur in the facility. This requires additional and frequent over haulings, thereby decreasing the reliability of the system. However, if assumed that the MTTF of the J620 is 2500 hours, the reliability curve is in between that obtained from formed and calculated data. The MTTF at 4500 hours show the highest reliability, with a reliability of about 45% at 4000 hours. From the available data, the reliability of the PCV from 4500 to 6000 hours is 45%. Also, Jenbacher J620 PCV has a warranty time period of 6 months. An operating life of 60,000 hours is common before the first overhaul becomes mandatory, under ideal conditions. One complete over-hauling of PCVs usually takes 30 working hours. For subsequent over-haulings, the overall plant life decreases each time. However, timely maintenance is required in between [47]-[48]. Since the plant under consideration is operational on continuous load, 60,000 hours approximate 81 months, or 6 years of operation. However, since the ideal conditions are not present on the plant site, corrosion prevails in Karachi's atmosphere, and the plant was installed decades ago, therefore routine maintenance is done every 4000 to 6000 operating hours. This is equivalent to approximately 5.5 to 8 months respectively. However, major over-hauling is done every three years. Thus, this study incorporates 4500 hours in the research.

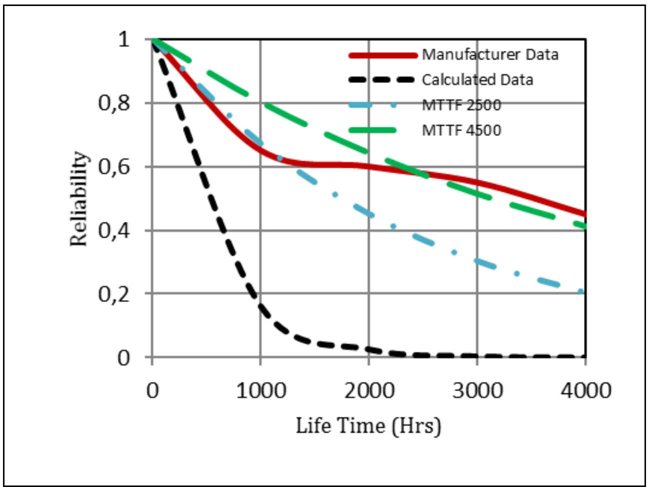

Figure 10: Reliability VS Life Time (in Hours)

The reliability curve declines with time after initially being at 100%. This curve closely resembles the form expressed by an exponential distribution, which has the expression as shown in Equation (7):

$$R(t) = e^{-\left(\frac{t}{\theta}\right)} \tag{7}$$

where $R(t)$ is reliability as a function of time and θ is MTTF.

From this curve, MTTF is found to be 545.5 hours. The calculated curve follows the data plot but drops off sharply. This is explained as the OEM's expected life cycle has yet not been achieved.

Figure 11 shows the plot of unreliability versus lifetime. The unreliability of the calculated data peaks at around 2000 hours, achieving the value of 1. On the contrary, if the manufacturer's data is considered, there is unreliability of only 0.4 at 2000 hours, which reaches the maximum value of 0.55 at 4000 hours.

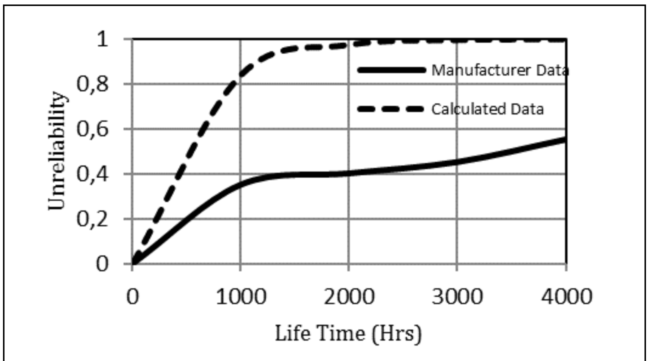

Figure 11: Unreliability VS life time (in Hours).

5 Conclusion

The bathtub curve obtained from a Jenbacher J620 gas engine is established. The data comprised PCV failures that occurred between two overhauls, over three years. The sample size was of 20 PCVs. The faults were due to exhaust gas temperature showing positive or negative deviations. Considering the faults between two routine (preventive) maintenances of PCVs, the industrial data showed that 14 problems occurred. Of them, 8 were due to high exhaust gas temperature, and 3 faults occurred due to negative temperature. The bathtub curve indicated several failures during infant mortality. This may be credited to improper fitting or improper lubrication. This caused the PCV to fail prematurely. In the reliability curve, initial high reliability was found. However, it was deduced that a reliability of 45% was the cut-off point for the said equipment and was to be replaced. The difference in reliability obtained from the manufacturer's data and actual data was due to environmental reasons mostly. Using exponential distribution, it was found that single-engine GE J620 Jenbacher has a MTTF of 545.5 hours. Since 11 of 14 issues related to exhaust gas temperature deviations, by resolving them the reliability of the system will also be increased. The cheapest and easiest solution would be to provide proper attention to fittings and doing timely lubrications.

6 Author contribution statements

In the scope of this study, Faraz AKBAR contributed in the formation of the idea, design and in the assessment of obtained results. In the scope of this study, Sarah ZAKI contributed in literature review, writing, reviewing and editing of the paper.

7 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared". "There is no conflict of interest with any person / institution in the article prepared".

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