

Integrated FMEA approach for analyzing cylinder head failure due to thermal mechanisms in internal combustion engines

Wilarso

Universitas Muhammadiyah Cileungsi, Indonesia

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ABSTRAK

Cylinder head is a critical component in internal combustion engines that operates under extreme thermal and mechanical conditions, making it highly susceptible to failure. One of the most common failure modes is cracking, which is primarily associated with overheating and thermal fatigue. However, existing studies often analyze failures descriptively without integrating causal relationships and quantitative risk assessment. This study aims to analyze the failure mechanism of a cylinder head in unit BMGS1740 using an Failure Mode and Effects Analysis (FMEA) approach. FMEA is applied to evaluate and prioritize risks based on Severity (S), Occurrence (O), and Detection (D), resulting in the Risk Priority Number (RPN). The analysis is based on operational data, inspection results, and thermal performance indicators. The results show that cylinder head failure is driven by a progressive thermal mechanism initiated by cooling system degradation, leading to overheating, thermal stress, and ultimately crack formation. The highest risk factors identified are radiator fouling, water pump failure, and thermal fatigue, each with RPN values ≥ 300 , indicating their dominant contribution to failure. Medium-risk factors include thermostat malfunction, loose fan belt, and poor atomization, while overfueling is categorized as a low-risk contributing factor. The findings indicate that cooling system performance is the primary triggering factor, while thermal fatigue acts as the main damage propagation mechanism. Therefore, preventive strategies should focus on improving cooling system efficiency and optimizing combustion processes to minimize thermal loading. This integrated approach provides a more comprehensive framework for failure analysis and supports risk-based maintenance decision-making.

*Corresponding Author:

Wilarso

Universitas Muhammadiyah Cileungsi, Jawa Barat, Indonesia

Email: wilarso@umci.ac.id

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1. INTRODUCTION

The cylinder head is a critical component in internal combustion engines, functioning as the combustion chamber enclosure, as well as a pathway for coolant and lubrication systems [1]. During operation, the cylinder head is subjected to extreme conditions involving high temperature, high pressure, and repeated thermal cycles [2]. These conditions make it highly susceptible to material degradation and structural failure when thermal and mechanical loads are not properly balanced [3].

One of the most common and critical failures in cylinder heads is cracking (*crack*), which can lead to compression leakage, reduced engine efficiency, and potentially catastrophic engine damage [4]. Among the various contributing factors, overheating is widely recognized as a dominant trigger of such failures, primarily associated with the degradation or malfunction of the cooling system [5].

In practical operation, failure cases often show a combination of symptoms such as elevated exhaust gas temperature, increased jacket water temperature, and abnormal combustion behavior. In the case of unit BMGS1740, cracks in the cylinder head were identified during a General Overhaul (GOH), preceded by abnormal increases in jacket water and exhaust temperatures based on

operational data. These observations indicate the presence of thermal imbalance, suggesting overheating as a potential root cause of failure.

However, most existing analyses of cylinder head failure are still largely descriptive and tend to focus on individual components rather than examining the failure mechanism in a systematic and integrated manner [4]. In particular, there is a lack of approaches that simultaneously model the causal relationship between failure factors and quantify their relative contribution to the overall system failure [6].

To address this gap, this study proposes an integrated analytical approach *Failure Mode and Effects Analysis* (FMEA). FMEA is used to evaluate and prioritize the associated risks based on quantitative parameters [7]. The objectives of this study are: (1) to analyze the failure mechanism of the cylinder head based on operational and inspection data, (2) to determine the priority of failure factors using FMEA based on Risk Priority Number (RPN). This integrated approach is expected to provide a more comprehensive understanding of failure mechanisms and to support effective maintenance strategies based on risk prioritization.

FMEA is a structured method used to identify and prioritize potential failure modes based on Severity, Occurrence, and Detection parameters [8]. Although widely applied, conventional FMEA has limitations in risk ranking consistency. Recent developments such as fuzzy FMEA. In this study, FMEA is applied using operational data to evaluate the risk of cylinder head failure and to determine priority corrective actions. Failure of cylinder head components in internal combustion engines has been widely studied due to its critical role in engine performance and reliability. Several studies have identified overheating and thermal fatigue as dominant factors contributing to crack initiation and propagation in engine components operating under high thermal and mechanical loads.

Highlighted that cylinder head failures are strongly associated with excessive thermal gradients, which induce thermal stresses exceeding the material strength, particularly under repeated heating and cooling cycles. This phenomenon is commonly referred to as thermal fatigue, which significantly reduces the structural integrity of metallic components.

Emphasized that uneven heat distribution and localized overheating can lead to microstructural degradation, resulting in crack initiation at stress concentration points [9]. The presence of hot spots due to incomplete combustion further accelerates material degradation and crack propagation [10]. From a system perspective, demonstrate that cooling system degradation such as radiator fouling, water pump failure, and thermostat malfunction plays a significant role in engine overheating [11]. These failures reduce heat dissipation efficiency and disrupt coolant circulation, leading to elevated operating temperatures [12].

To systematically analyze such complex failure mechanisms, Fault Tree Analysis (FTA) has been widely applied as a qualitative tool for modeling cause–effect relationships [13]. According to FTA enables the identification of logical pathways leading to system failure by decomposing the top event into intermediate and basic events using Boolean logic [14]. This approach is particularly useful in complex engineering systems with multiple interacting failure modes.

In addition to qualitative analysis, quantitative risk assessment methods such as Failure Mode and Effects Analysis (FMEA) have been extensively utilized. That FMEA provides a structured framework to evaluate failure modes based on Severity, Occurrence, and Detection, enabling prioritization through the Risk Priority Number (RPN) [15]. This method is widely adopted in reliability engineering and maintenance optimization.

Recent studies have shown that integrating FTA and FMEA provides a more comprehensive failure analysis framework. Reported that the combination of FTA and FMEA improves the accuracy of root cause identification and enhances decision making in maintenance planning by linking causal relationships with risk prioritization. Furthermore, demonstrated that the integration of these methods is effective in identifying dominant failure factors in thermal systems, particularly in cases involving overheating and cyclic thermal loading.

Despite these advancements, there remains a gap in the application of integrated FTA – FMEA approaches specifically for analyzing cylinder head failure based on real operational data. Most studies focus either on material behavior or system reliability independently, without combining both perspectives into a unified analytical framework. Therefore, this study aims to fill this gap by

applying an integrated FTA – FMEA approach to analyze cylinder head failure in a real operational context, combining thermal analysis, system failure modeling, and quantitative risk assessment. However, several researchers have identified limitations in the conventional FMEA approach. Pointed out that the traditional RPN method may produce ambiguous rankings due to the multiplicative nature of S, O, and D, where different combinations of values can yield identical RPN results [16]. This limitation can reduce the accuracy of risk prioritization.

To address these issues, proposed modifications to the FMEA framework by introducing alternative ranking methods and weighting schemes to improve decision-making accuracy. These enhancements aim to overcome inconsistencies in traditional RPN evaluation. In addition, introduced fuzzy logic-based FMEA to handle uncertainty and subjectivity in the evaluation of Severity, Occurrence, and Detection. This approach allows for more flexible and realistic modeling of complex engineering systems, particularly when precise data is unavailable. From an application perspective, A. Stamatis emphasized that FMEA is particularly effective in identifying critical components in complex systems and supporting preventive maintenance strategies. By prioritizing high-risk failure modes, organizations can allocate resources more efficiently and reduce system downtime.

Recent studies have also highlighted the benefits of integrating FMEA with other analytical methods. M. Sharma demonstrated that combining FMEA with Fault Tree Analysis (FTA) enhances failure analysis by linking causal relationships with risk prioritization [17]. This integrated approach provides a more comprehensive understanding of system failures [18]. Furthermore, S. K. Tyagi reported that FMEA is highly effective in thermal system analysis, particularly in identifying risk factors associated with overheating and cyclic thermal loading [19]. The method enables the identification of dominant failure contributors and supports the development of targeted mitigation strategies.

Despite its widespread application, there is still a need for applying FMEA in conjunction with real operational data to improve the accuracy of risk evaluation. Many studies rely on theoretical assumptions, whereas practical implementation based on field data can provide more reliable and applicable results. Therefore, in this study, FMEA is applied using actual operational and inspection data to evaluate the risk of failure modes associated with cylinder head damage. The integration of FMEA with FTA is expected to enhance the reliability of the analysis by combining causal modeling with quantitative risk prioritization.

2. METHOD

Failure Mode and Effects Analysis (FMEA) was used in this study to evaluate the risk level of each failure mode identified through Fault Tree Analysis (FTA) [20]. This method was chosen because it provides a quantitative assessment of the severity and probability of failure, allowing it to be used to systematically prioritize corrective actions. Each failure mode is analyzed based on three main parameters: Severity (S), Occurrence (O), and Detection (D) [21]. The Severity parameter represents the level of impact of the failure on system performance, Occurrence indicates the likelihood of failure occurring, while Detection describes the system's ability to detect failure before it occurs [22].

These three parameters are assessed using a numeric scale of 1–10, with higher values indicating greater severity, frequency of occurrence, or difficulty of detection [23]. Determination of the S, O, and D values is based on a combination of operational data, inspection results, and reference standards for risk evaluation in machine systems [24]. Failure Mode and Effects Analysis (FMEA) is conducted to evaluate the risk level of each failure mode that has been identified through FTA [25]. The failure modes analyzed included overheating, hot spots, and thermal fatigue, with specific causes such as stuck thermostat, clogged radiator, loose fan belt, water pump failure, poor atomization, and over fueling.

The assessment is carried out using three parameters:

- Severity (S): the impact of failure on machine performance
- Occurrence (O): frequency of occurrence based on operational data
- Detection (D): the system's ability to detect failures

The S, O, and D assessments use a scale of 1–10 which is determined based on:

- Temperature data (FROM)
- Visual inspection results
- Technical literature related to diesel engine systems

The Risk Priority Number (RPN) value is calculated using the following equation:

$$RPN=S \times O \times DRPN$$

The RPN value is used to determine the risk priority level of each failure mode [26]. The higher the RPN value, the greater the risk, thus requiring higher priority corrective action [27]. To facilitate interpretation, RPN values are classified into three categories: high risk ($RPN \geq 300$), medium risk ($200 \leq RPN < 300$), and low risk ($RPN < 200$). This classification is used as a basis for developing improvement strategies and risk-based decision-making.

3. RESULTS AND DISCUSSION

Integration of Failure Mode and Effects Analysis (FMEA)

Based on the results of the Failure Mode and Effects Analysis (FMEA) in Table 1, cylinder head failure was identified as a result of a series of thermal phenomena starting from the degradation of the cooling system, which caused overheating, then developed into thermal stress, and finally triggered cracks in the material. To quantify the risk level of each failure cause, a further analysis was conducted using Failure Mode and Effects Analysis (FMEA) with the parameters Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) value was calculated to determine repair priority.

Table 1. Results of Failure Mode and Effects Analysis (FMEA).

No	Failure Mode	Effect	Cause	S	O	D	RPN
1	Overheating	Crack cylinder head	Stuck thermostat	9	6	5	270
2	Overheating	Crack cylinder head	Clogged radiator	9	7	6	370
3	Overheating	Crack cylinder head	Loose fan belt	8	6	5	240
4	Overheating	Crack cylinder head	Damaged water pump	9	7	6	378
5	Hot spot	Local crack	Poor atomization	8	5	6	240
6	Hot spot	Local crack	Overfueling	8	5	5	200
7	Thermal fatigue	Crack propagation	Thermal cycling	9	6	7	378

Figure 1 shows the Risk Priority Number (RPN) ranking of each factor causing cylinder head failure. A clogged radiator, a faulty water pump, and thermal fatigue have the highest RPN values (378), indicating that these three factors are the dominant causes of failure. Meanwhile, factors such as a stuck thermostat, a loose fan belt, and poor atomization are at a medium risk level, while overfueling has the lowest RPN value. This distribution indicates that cylinder head failure is more influenced by cooling system performance than combustion factors alone.

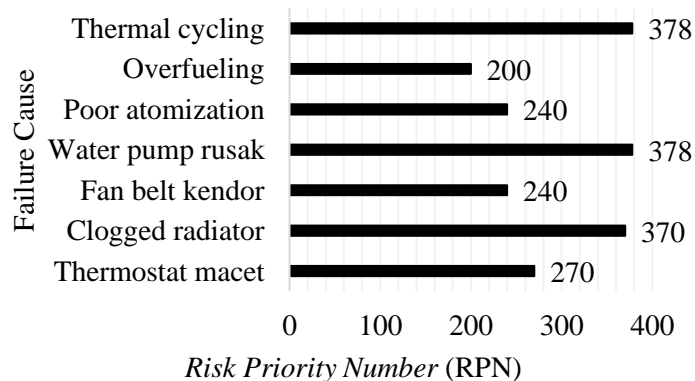


Figure 1. Risk Priority Number (RPN) value ranking.
Risk Priority Analysis

Based on the Risk Priority Number (RPN) calculation results, failures with the highest risk level ($RPN \geq 300$) consist of a clogged radiator (378), water pump failure (378), and thermal fatigue (378). High RPN values for these three factors indicate that cooling system failure and the resulting thermal effects are the main contributors to cylinder head damage.

A fouled radiator significantly reduces heat transfer efficiency, preventing the heat generated during combustion from being released optimally into the environment. This condition is exacerbated by a damaged water pump, which disrupts coolant circulation. The combination of these two factors leads to heat buildup in the system, ultimately leading to overheating.

Furthermore, high RPN values for thermal fatigue indicate that failure is triggered not only by transient overheating but also by repeated heating and cooling cycles that cause the accumulation of material damage. Under these conditions, repeated thermal stress reduces material strength and triggers crack initiation and propagation in the cylinder head.

These findings indicate that cylinder head failure is progressive and multifactorial, with the cooling system acting as the primary triggering factor, while thermal fatigue acts as the damage propagation mechanism. Therefore, temperature control by improving cooling system performance is a critical aspect in preventing failure.

Medium Risk (RPN 200–299)

The medium risk category (RPN 200–299) consists of thermostat failure (270), loose fan belt (240), and poor atomization (240). The RPN values in this category indicate that these factors significantly contribute to overheating and hot spot formation, but are not as dominant as the high-risk factors.

Thermostat failure, particularly when stuck closed, impedes coolant circulation, resulting in suboptimal heat distribution. While not as severe as a clogged radiator or a damaged water pump, this condition still contributes to a gradual increase in system temperature. Meanwhile, a loose fan belt causes a decrease in cooling fan speed, reducing airflow through the radiator. This reduces the efficiency of heat dissipation to the environment, especially under high load conditions or high ambient temperatures.

On the other hand, poor atomization is related to imperfect combustion where inhomogeneous fuel distribution leads to uneven combustion. This condition triggers the formation of localized hot spots that can increase local temperatures in the cylinder head. Although localized, this effect can accelerate crack initiation if it occurs repeatedly.

Overall, factors in the medium-risk category act as contributing factors that worsen system conditions, particularly by increasing thermal loads. In terms of failure mechanisms, these factors are not always the primary cause, but they can accelerate overheating and increase the likelihood of thermal fatigue when combined with high-risk factors.

Low Risk

The low-risk category in this study is indicated by the overfueling phenomenon with an RPN value of 200. Although the RPN value is relatively lower compared to other factors, this condition still contributes to increasing local temperatures in the combustion chamber.

Overfueling causes an excessive fuel supply, resulting in inefficient combustion and uneven heat distribution. This condition has the potential to trigger the formation of localized hot spots on the cylinder head surface. However, these effects tend to be localized and do not directly cause overall system failure.

In the context of failure mechanisms, overfueling acts as a minor contributing factor that worsens thermal conditions when combined with other factors, such as cooling system degradation. In other words, overfueling is not strong enough to be the root cause, but it can accelerate material degradation through repeated local temperature increases.

Therefore, even though it is in the low-risk category, overfueling control is still necessary as part of efforts to optimize the combustion system to prevent the accumulation of thermal loads that can accelerate the occurrence of thermal fatigue.

Discussion of failure mechanisms

The analysis shows that cylinder head failure is not caused by a single factor, but rather the result of a complex interaction between the cooling system and the combustion process. The highest RPN values for the radiator and water pump indicate that the cooling system's inability to control temperature is the primary factor triggering overheating. This condition causes an increased thermal gradient in the material, resulting in high thermal stress.

Furthermore, high RPN values for thermal fatigue indicate that repeated heating and cooling cycles accelerate crack initiation and propagation. This is supported by visual findings of deformation, thermal erosion, and cracks on the cylinder head surface. On the other hand, combustion factors such as poor atomization and overfueling contribute to the formation of local hot spots, which worsen heat distribution. Although the RPN values are lower than those of the cooling system, these factors still play an accelerating role in the material failure process.

4. CONCLUSION

Based on the analysis results using the Failure Mode and Effects Analysis (FMEA) approach, cylinder head failure in the BMGS unit is caused by a progressive thermal mechanism, which begins with the degradation of the cooling system, triggers overheating conditions, produces thermal stress, and culminates in the initiation and propagation of cracks in the material. The results of the Risk Priority Number (RPN) calculation show that the dominant factors causing failure are a clogged radiator, water pump damage, and thermal fatigue, which has the highest RPN value (≥ 300). This indicates that the inability of the cooling system to control temperature is the main root cause of cylinder head failure. In addition, medium risk factors such as thermostat failure, loose fan belts, and poor atomization act as contributing factors that worsen the thermal conditions of the system, while overfueling acts as a minor contributing factor that accelerates material degradation through the formation of localized hot spots. Overall, cylinder head failure is multi-factorial and involves interactions between the cooling system and the combustion process. The cooling system acts as a triggering factor, while thermal fatigue acts as the main mechanism in the propagation of material damage. Therefore, failure prevention strategies should be focused on improving the performance of the cooling system, particularly through controlling radiator efficiency and water pump performance, and supported by optimizing the combustion system to minimize the formation of hot spots.

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