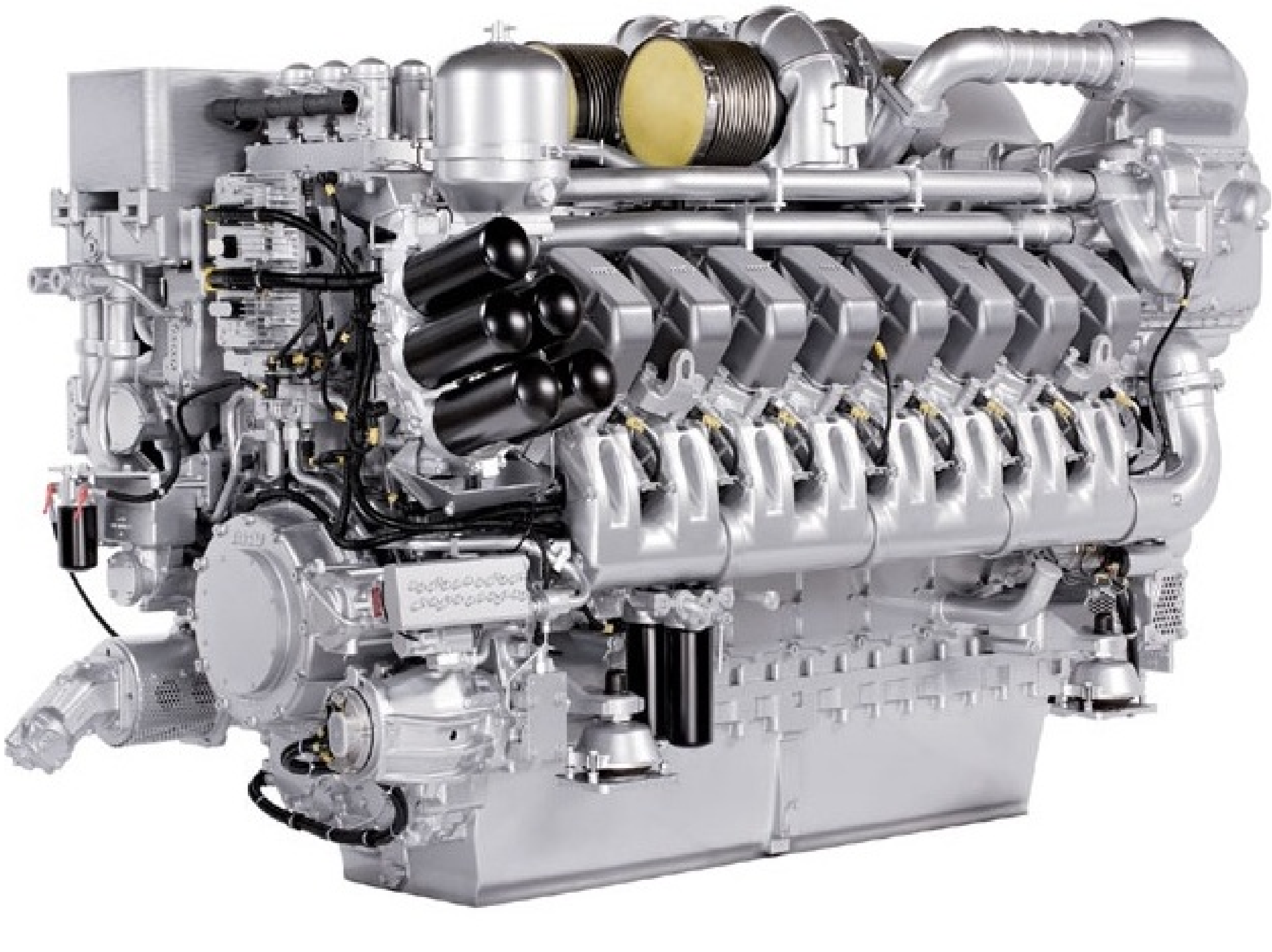
Optimizing diesel engine condition monitoring

Research on diagnostic representation techniques based on in-cylinder pressure measurement

LTZT3 G.J.J. Oskam

MSc Thesis



Delft University of Technology

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SDPO.14.005.m

For the degree of Master of Science in Mechanical Engineering at Delft University of Technology

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January 8, 2014

Faculty of Mechanical, Maritime and Materials Engineering (3mE)
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Abstract

The aim of this thesis is to investigate whether other representation techniques of the in-cylinder pressure signal, besides the current pressure-crank angle curve, have the potential of improving the diagnosis in a condition monitoring program.
Investigated are the quantitative representation of the heat release through Vibe parameters and the analysis of a temperature-specific entropy diagram. These two alternative techniques are being discussed theoretically in the first part and are tested through simulations in the second part. Two pre existing MatLab models, functioning as the selected 12SW28 benchmark engine, are used to analyse pressure measurements collected from the Marinebedrijf. Three different situations are being discussed: a reference dataset, a dataset diagnosed with leaking injectors, and simulated blowby by an implemented subsystem in the models. For all three of these situations, the outcome in terms of pα curve, Vibe parameters, and Ts curve are being compared.

The output of the simulations seemed promising at first but unfortunately the consistency of output abnormalities raises doubts on whether the input parameters are all valid. To test this, five possible input errors are simulated and the effects are studied. The cause of the abnormalities, whether diesel engine faults or systematic errors, can not be determined in this thesis. This means that the potential of Vibe parameters and the Ts diagram, in terms of condition monitoring diagnostics, can not be determined based on this data.

The current way of analysing the pressure signal is not really influenced by these possible errors. However, functioning as input for a heat release simulation model enlarges these errors, creating an unreliable output. Fixing these possible errors, and other structural shortcomings of the current condition monitoring program at the Marinebedrijf, will certainly improve the representation.

Table of Contents

List of Figures

List of Tables

Preface

This thesis report forms the last phase of my two years and four months at the Delft University of Technology, following a Master of Science program in Mechanical Engineering. I started of with the specialisation Mechanical Systems and Integration in September 2011, after completing my Bachelor of Science on Military Systems and Technology at the Netherlands Defence Academy in Den Helder. When I started my career in the Navy, more than six years ago, I never thought my education track would be this long but I am very glad and thankful they offered me the upportunity to get my MSc degree. Without the help and support of the people around me, I would have not made it to this point. First of all I would like to express my gratitude to my supervisors Klaas Visser, for his assistance, guidance and moral support during the graduating process, and Douwe Stapersma for his guidance and drive to get the most out of every student. From the Marinebedrijf I would like to thank Nick Stulen, L.G. Cuijpers and R.M. Angevare, and S. Portman from Wartsila for all their practical and useful information. Further thanks to my parents and Jasper, my boyfriend, for their constant support and strong believe in me. Finally I would like to take a moment to remember Hugo Grimmelius, a greatly valued member of the department, who tragically passed away too soon.

Introduction

Just like all types of machinery, diesel engines need maintenance to keep doing what they are intended to do. This diesel engine maintenance can be applied in a lot of different varieties but this thesis will focus on condition monitoring of maritime engines.
The benefit of this maintenance strategy is that it is a part of preventive maintenance that predicts the maintenance interval and prevents failures by analysing the current condition or trend. Condition monitoring is usually a combination of different sensors that try to detect symptoms of certain developing faults.
One of these sensors is an in-cylinder pressure sensor. In theory this parameter contains a lot of information about the combustion in the cylinder. In current diesel engine condition monitoring techniques this pressure analysis is widely applied and therefore has proven its usefulness.
Analysing the signal is usually done by presenting it in a pressure-time or pressure-crank angle diagram and studying its shape and maximum. The technique is known for being able to reveil a group of faults while others will stay unnoticed. This pressure signal might be more useful and present more information when it is post processed and represented in another way.
The scope of this research is to investigate whether other representation techniques, of the same pressure signal, contain the same, less or more information in terms of condition monitoring.
A constant strive in condition monitoring is to clearify the representation of the data leading to a more simple diagnostic method and less errors. That is why these alternative representation techniques are also tested on their quality of being unambiguous. The three techniques in this comparison are:

- Pressure versus crank angle diagram
- Heat release in terms of Vibe parameters
- Temperature versus specific entropy diagram

The investigated techniques are closely related to the heat release; the release of chemical energy from the fuel during the combustion process. Heat release can not be measured directly but can be computed from the in-cylinder pressure measurement combined with basic information about the engine. To do so, existing MatLab simulation models are used

in this thesis.
The theory investigated in the first part of this thesis will be simulated and tested in the second part by running the simulation models with existing pressure measurements taken from the diesel generators on board the Zr Ms Rotterdam. These measurements are collected from the database available at the non destructive testing department (NDO) of the Marinebedrijf.

Outline

The research is devided in two parts: the literature survey and the thesis. In the literature survey background information from books, articles and other types of literature is used to discuss the important subjects of the thesis. The handled subjects are maintenance in Chapter 1, where the broader view of maintenance is being diverged to condition monitoring specifically, faults in diesel engines in Chapter 2, where faults and their effects will be discussed, and Chapter 3 discusses heat release, explaining some of the theory that is used in the rest of the thesis.

The second part starts with information about the modelling in Chapter 5, discussing the two used MatLab models and the way they are prepared to serve as the determined benchmark engine. Chapter 6 illustrates the different simulations and their verfication while Chapter 7 discusses the output and validation. The last two chapters contain the conclusions and recommendations, followed by some appendices.

Part I

Literature survey

Introduction

This literature survey forms the theoretical foundation of this thesis.

The survey is built up in different parts, all influencing the research in a different manner. All parts consist of an illustration of its basic subjects, the way in which these subjects are mentioned in the gathered literature and my opinion on these books or reports.

First of all the idea of maintenance is discussed and slowly narrowed down to the part important for this survey. This is done by discussing the general ways in which maintenance can be applied and converges to one specific type: condition monitoring. The reason why it is first discussed in a broader sense is to discover the framework in which condition monitoring can be placed and what role the other types of maintenance play in this. Towards the end of the condition monitoring part, the focus will be on process parameter monitoring because the research is about in-cylinder pressure measurement which is a part of this monitoring technique. In later chapters the application of this method on diesel engines specifically is mentioned.

The next part will cover the subject of faults in diesel engines. To come to a reliable condition monitoring system and be able to diagnose and quantify the output of such a system, the possible faults and its symptoms must be known. This is done by examining books and reports on fault diagnosis and combining these to construct a list of possible diesel engine faults. In the final list only the faults which can possibly be detected by examining the in-cylinder pressure signal are discussed.

The final part of this literature survey will cover the theory of heat release in the diesel engine combustion process. Based on this theory the thesis will examine the possiblity to develop a new maintenance technique in terms of diagnostics.

Chapter 1

Maintenance

Ever since the start of mechanisation people have tried to 'maintain' the machinery in the right operating condition. To achieve this, they had to perform maintenance work. In the beginning this maintenance work consisted mostly of repairing failures. Downside of this type of maintenance was that between the failure and finishing the repair the machinery could not function, called the downtime. Also the failure of a single component could cause the breakdown of other components resulting in the need for more complicated and prolonged repairs. With time, the machinery increased in complexity and in numbers, replacing more and more human tasks. In some applications people became dependant of it which demanded better reliability.

The need for a decrease of maintenance costs and downtime and increase of reliability forced the producer and user to come up with better maintenance concepts. The balance between costs, downtime and reliability has a different outcome for different fields of application resulting in diverse maintenance solutions. For instance, in aviation reliability has the top priority while in food production lowering the maintenance and thus production costs is more important. More about this in the next section.

In the next chapter the different existing maintenance concepts are discussed. After a more broad analysis the discussion will be narrowed down to the one concept applied in this research; condition monitoring. This model will be investigated more thoroughly, examining all the different ways in which it can be applied in several fields but most importantly on diesel engines. The occurring problems, shortcomings and benefits when applied on diesel engines are discussed resulting in a complete review of the current diesel engine condition monitoring programmes.

1-1 Maintenance strategy

Choosing the right strategy for a specific field, system or part can be intricate. The main goal is to keep the machinery at the optimum operating conditions with the least effort possible. But this goal is subdivided in several sub-goals all of varying importance for the different fields of application. These variations result in the before mentioned multiple solutions. The most important aspects in choosing a maintenance concept are listed and described below. The content of this chapter is based on *An Introduction to Predictive Maintenance* from R. Keith Mobley.

1-1-1 Costs

Of course an important goal will always be saving money and thus lowering maintenance costs. These costs do not only come from developing and executing maintenance and inspections but also the downtime is a significant cost driver.

The introduction showed a so called run-to-failure management technique; spending no money on maintenance until a system failed to operate. This reactive management technique is rather a ′no-maintenance′ approach since it is not maintaining but constantly restoring the system in its optimum operating conditions. Although money is saved since no management technique nor inspections are needed, the downtime resulting from the breakdowns is a huge cost driver. Unless machinery is redundant, which is obviously also very expensive, downtime will cause problems. For instance if we are talking about a production plant downtime results in nothing being produced although the rent for the production hall and the wages for the employees still need to be paid causing a net loss of money. But if we are talking about the propulsion plant of a carrier ship the consequence of downtime is that the ship is delayed risking a contract fee from the customer or floating out of control at sea.

Another downside of waiting till the machinery fails is that restoring it in perfect condition may be more expensive than maintaining its condition. It is possible that the specific component failure influences other surrounding components which will then also need restoring.

On the other hand, developing and executing maintenance is not for free. Replacing components before failure also causes downtime and it is hard to know how much operating time you are throwing away by removing the older component because maybe it could have run for a few more weeks.

The goal is always to reduce the total costs and thus a balance needs to be found between too much and too little maintenance. This will reduce the downtime on one side and the unneeded discard of machinery parts on the other. The balance is different for every application and can only be found if all the influencing costs are known and constantly weighed against each other, ultimately resulting in the optimum maintenance technique.

1-1-2 Optimal performance

Maintaining the optimal performance of the system is also an important factor in maintenance. Every producer promotes his products to be of top quality and wants to be able to guarantee his costumers he can live up to his promises. But if the condition of the producing machinery slowly starts to degrade this will certainly affect the quality of the products. Deterioration of the plant can be avoided if it is well maintained and thus continuously operates at the best running conditions. This type of maintenance requires a lot of effort which can be proven essential when for instance the producer is acting in a strong competitive branch.

Aside from the production plant, also a propulsion or power plant needs to be kept in optimal condition. In this case there is no direct product quality to be maintained but it is all about fuel economy and/or environmental aspects. If the engine of a propulsion plant is deteriorating it can influence the fuel economy and the emission of the exhaust gases. Depending on the emphasis, the engine needs to be optimized for one of these aspects.

Before society started to worry about environmental pollution and became self-conscious about emissions, the accent was mainly on reducing fuel consumption. The motive for this was reducing fuel costs and increasing the range of, for instance, ships and airplanes. But since the deployment of new environmental laws, such as the IMO MARPOL Annex VI for ships, the scope of optimal performance has shifted towards lowering hazardous emissions. The so called 'clean operation' of engines needs to be maintained, whether it is profitable or not, because if the companies do not live up to the regulations they eventually will have to close their doors. The older, dirtier engines have to be scrapped and the newer, cleaner engines need to be kept in optimal, low emission operating condition. Of course, within limits of the pollution regulations companies will always strive for optimal fuel economy but it is clear that this relatively new environmental motivation for adapting the right maintenance concept is gaining importance in almost all fields.

1-1-3 Reliability

The third aspect in choosing a maintenance model is determining the required level of reliability. It is obvious that not always the one system needs to be as reliable as the other. A confronting example of this is comparing the propulsion of an airplane with the packing machine in a cookie factory. Of course the producer wants its cookies to be packed as good and quickly as possible but there are no lives at stake with the failing of the packing machine. On the other hand, if the gas turbines of a Boeing 747 suddenly fail during flight it is likely to have a disastrous ending.

A lot of research has been done on the reliability and mean time to failure (MTTF) of systems. Although different for every type of system and its application it roughly looks the same. A company in need for high reliability can choose to investigate and map their systems failure rate and reliability level and adapt this in the maintenance concept. This type of maintenance is called reliability centred maintenance (RCM). Of course companies like the cookies factory do not want to spend the effort, time and money to do so and will cope with a few more failures due to the lack of insight in their equipment.

Another way to improve the systems reliability is a redundant implementation. In this way a failure of the system can be diverted by a second system that is standing by in case it is needed. Of course this is a very costly solution since there is constantly one system available but not producing. That is why this is only applied when there is a demand for extreme reliability.

In short, defining the level of desired reliability, determined by the type of system and its application, will help establishing the correct maintenance model.

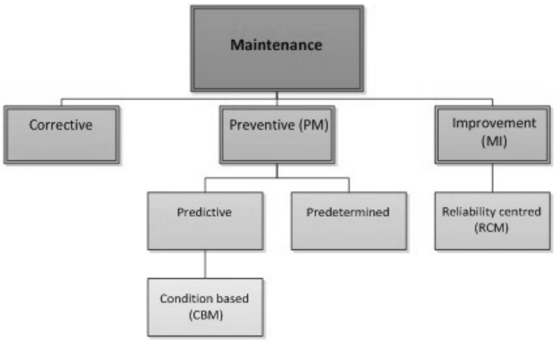


Figure 1-1: Division of maintenance concepts as used in this literature survey

1-1-4 Concepts

Maintenance strategy is the name of the study on maintenance concepts. Maintenance concept is quite an abstract term but is defined in an accurate and clear way by Fagerland, Rothaug and Tokle: *The maintenance concept is defined as the combination of all technical and corresponding administrative actions intended to restore an item to a state in which it can perform its required function*[1]

The partition into various maintenance concepts, also called types or models, is shown in Figure 1-1. Here it is shown that the major divisions are corrective maintenance, preventive maintenance and maintenance improvement in which preventive is sub divided in predictive and predetermined.

This division of maintenance in different concepts can also be found in literature. A more extensive diagram is found in the book *Principles of Loads and Failure Mechanisms* by Tiedo Tinga[2] and depicted in Figure 1-2. Although the terms are a bit different from Figure 1-1, the division stays the same.

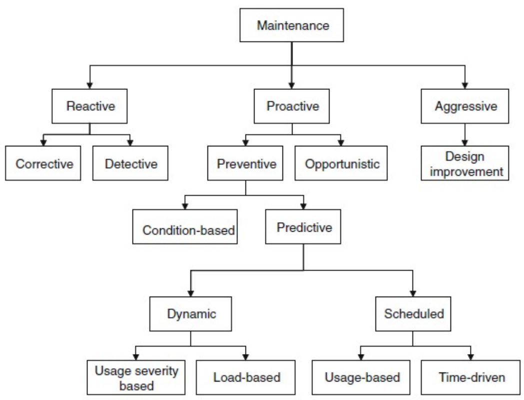


Figure 1-2: Maintenance concepts

[1]Fagerland, H., Rothaug, K., Tokle, P. *Monitoring and Diagnosing Process Deviations in Marine Diesel Engines.* Ship Research Institute of Norway, 1978

[2]Tinga, T. *Principles of Loads and Failure Mechanisms.* Springer, 2013

Corrective maintenance

If this concept is applied on a system it means that no effort is put in preventing a failure or maintaining the operating condition. As previously discussed it is a 'run-to-failure', rather non-maintenance technique, also called 'breakdown maintenance'. If chosen wisely, the benefits lay in the costs and the main weakness is the reliability. It simply deals with the breakdowns which can be beneficial in some applications, for instance changing a lightbulb only when it fails. Specific key terms of these applications are non-critical, easy to repair, no safety risk, and limited failure consequences. This concept was dominating maintenance prior to the mid 1960's.

Although corrective maintenance is a maintenance concept on itself it is still applied in situations where another concept has failed. This is because corrective maintenance stands for emergency repairs of sudden breakdowns and if another concept is inadequately chosen or applied, that is exactly what will happen. These type of unexpected failures are very problematic because in most cases there is a reason why another maintenance type than the corrective one is applied. Probably it is the opposite of the above mentioned description; whether the system is critical, difficult to repair, has high safety risks, or failing has tremendous consequences the failure will cause serious problems. Furthermore, it is highly possible that there is no or not the right capacity for emergency repairs because according to the applied concept there will not be any. Therefore improvement of the used maintenance concept, other than the corrective one, is vital to reduce this problem to a minimum.

Maintenance improvement

Maintenance improvement (MI) does not immediately sound like a maintenance type but more like a continuing strive, applicable on all sorts of maintenance. The underlying principle is to eliminate the need of maintenance at its source. Based on reliability engineering it tries to preact instead of react; prevent any need of maintenance. This means finding and strengthening the weak points of a system to not only eliminate the probability of failure but moreover the need for maintenance. This concept requires a lot of inside knowledge about the system and must be implemented during the design phase.

An example of such an MI system is RCM. This maintenance concept is based on the idea that every system degrades and ultimately will fail due to its deterioration. It works with probability tables and Weibull distributions to anticipate on upcoming failures. The concept assumes proper design, installation, operation, and maintenance and therefore abnormal deviations are excluded from these calculations. The concept can only be beneficial if the actual failure trend and degradation of the system is accurately determined with a statistical approach.

Preventive maintenance

The scope of preventive maintenance (PM) is to prevent failures from occurring by applying maintenance beforehand and thus avoiding system breakdown causing downtime. This can be done in a predetermined and a predictive way.

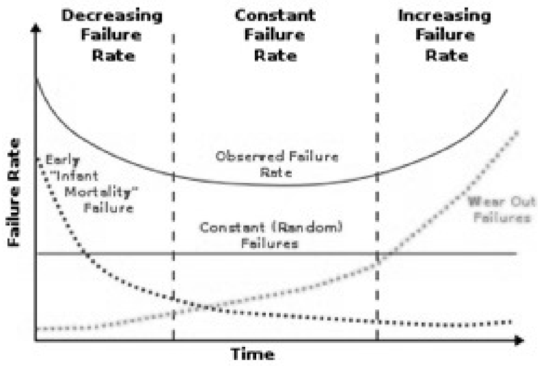


Figure 1-3: Bathtub curve

The predetermined way of PM is based on maintenance schedules without any monitoring activities. In most cases the builder constructs a maintenance schedule during the design phase and the machinery is sold including this maintenance programme with build in safety margins. The programme contains a detailed description of the different maintenance tasks and when they have to be executed. The 'when' can be purely time-based but it can also be based on running hours, start-ups or covered kilometres. So the only responsibility of the user is to record the above mentioned data and execute the maintenance on the prescribed moments. This concept is suitable for tasks like lubrication, inspections and adjustments. The interval for these tasks is determined by the criticality of the component or, as before mentioned, the desired reliability. Depending on this the task interval can be short, *effective* maintenance for high reliability, or long, *efficient* maintenance for lower desired reliability.[3]

The predetermined PM concept assumes that the component will fail after a fixed timespan, the mean time to failure (MTTF). This MTTF is based on the widely applied bathtub curve, depicted in Figure 1-3[4].

The curve can be constructed for every component when a thorough knowledge about the failure behaviour is established. According to this curve the MTTF of this specific component can be estimated as long as the current failure rate is known which is fixed by the position in the lifetime interval. Conclusively a safety margin is applied and the maintenance interval for this component is determined.

The downside of this approach is that although very well substantiated, not every component will obey such a trend. It is possible that the curve is constructed based on faulty facts or the component behaves very unpredictable. Also the constructor of the maintenance programme assumes certain operating conditions which can differ strongly from the actual conditions, influencing the MTTF. It is imaginable that under lighter conditions the prescribed maintenance intervals are too short, resulting in unneeded maintenance and maybe the discard of perfectly functioning components. On the other hand heavier operating conditions than assumed result in much shorter failure intervals and thus a more intensive need for maintenance than prescribed.

The other PM method is a condition-driven preventive maintenance approach. This predictive

[3]Tinga, T. *Principles of Loads and Failure Mechanisms.* Springer, 2013
[4]http://en.wikipedia.org/wiki/Bathtub_curve

maintenance model uses dynamic intervals instead of fixed ones. It literally predicts the need of maintenance by examining the current state and developing trend of the machinery. It is best described as follows:

The common premise of predictive maintenance is that regular monitoring of the actual mechanical condition, operating efficiency, and other indicators of the operating condition of machine-trains and process systems will provide the data required to ensure the maximum interval between repairs and minimize the number and cost of unscheduled outages created by machine-train failures.[5]

One way of doing this is through condition monitoring in condition based maintenance (CBM). In the next chapters these subjects will be discussed in detail. Concluding this chapter it needs to be said that there is no good or bad maintenance concept in general. The right implementation of maintenance lays in knowing the system and its application inside out. Methodical consideration of all the facts and figures may result in a combination of the above mentioned concept. One part or task may be candidate for corrective maintenance while another more crucial one is better off with one of the other maintenance concepts. And of course, if problems are arising during utilization the concept may be changed to another one. Although quite intricate, choosing the right maintenance concept for the field of application or even specific system component is crucial in avoiding costs, downtime, quality decrease, and risks.

Predictive maintenance As a part of preventive maintenance, predictive maintenance will be discussed in this part of the chapter. The reason that this specific maintenance concept is highlighted is because the research can be encountered to this concept.

Because this report focuses on condition based maintenance (CBM) the terms predictive maintenance and CBM will be used interchangeably. It was introduced in the early 1970's. The goal of predictive or condition based maintenance is to observe the system's condition and, according to this observation, the necessary maintenance can be planned. To establish the right representation of the current condition, condition monitoring has to be applied. More information about the ways in which this can be done will follow in the next chapter.

Just like the other reviewed concepts predictive maintenance has advantages and disadvantages and is not suitable for all sorts of systems. This, and some examples of condition monitoring techniques and applications, will be further discussed in the next chapters.

One of the benefits of predictive maintenance is that it can prevent failures. By detecting a developing failure or fault a breakdown can be prevented. Consequently this is more a pre-active than a reactive management technique. Furthermore the developing fault can be analysed and by following and extrapolating the trend an estimate can be made when maintenance needs to be scheduled. This means that the timing of the maintenance can be planned on the most convenient moment. Also by predicting not only the moment but also the maintenance tasks the parts inventory can be minimized. Besides, by applying predictive maintenance the reliability of the system can be improved without the need of redundancy.

Nevertheless, predictive maintenance also has some downsides. One of them is best explained by the slogan 'if it isn't broken, don't fix it'. According to the predictive maintenance concept

[5] Mobley, R.K. *An Introduction to Predictive Maintenance.* Butterworth Heinemann, 2002

all maintenance should be performed on components that are not broken which can inflict potential damage due to ignorance or incorrect procedures. Another disadvantage of this approach is that by replacing or fixing non-broken components, potential useful life is thrown away. But still the main disadvantage for applying this maintenance concept is costs. Setting up a predictive maintenance programme is expensive compared to the other concepts and the system user needs to make a cost/benefit analysis to see whether it can be beneficial. A greater part of these costs comes from the fact that establishing a predictive maintenance program for a system requires thorough system knowledge. Still, even if the analysis shows clear benefits the initial costs are large which prevents a lot of users of adapting this concept.[6]

[6] Rasmussen, M., Lippe, J. *Condition Monitoring on Ships.* ICMES, 1987

1-2 Condition monitoring

As mentioned before condition monitoring is the foundation of predictive maintenance: it extracts information concerning the health of the system from the measured condition and based on this information the need for maintenance in the future can be predicted. Its purpose is to detect and follow-up developing faults and anticipate to upcoming failures and possible breakdowns. In that way maintenance can be planned just in time to prevent extra costs and optimise the operation. From a survey for the British Department of Industry in 1975 it has been estimated that condition monitoring can usually lead to a cost saving of 1.2% of a companies added value output[7]. This corresponds with another report[8] stating this cost saving is 1% of the turnover of a plant. These savings are said to arise from reduced consequential damage and reduced downtime. Another survey, dating from 1986[9], states that in comparison with scheduled maintenance, CBM can reduce manhours by 37%.

Although the CM methodology seems pretty modern compared to the other concepts it is just an extension of the initial, old principle of engineers to obtain some general information about the system's condition using their own senses. While human senses remain a useful CM tool it is impossible for human beings to look into the system whilst operating or accurately sense the littlest difference in vibration. Rapidly developing techniques do make this possible and that is why condition monitoring has been gaining popularity.

Of course not all faults can be detected with CM neither can all failures be prevented. Some failures will occur suddenly, without any warning symptoms or the symptoms could have been missed. The first type of failures, in which no symptoms are present, cannot be prevented by CM. The second type however can be reduced by optimizing the CM methods to a maximum so that symptoms can be detected earlier and more easily.

The detection of faults by CM can be done in two different ways, by trend monitoring and condition checking. Trend monitoring holds that the condition is monitored in a quite continuous matter to detect the trend of the fault and extrapolate this to plan the maintenance. Condition checking can be done if the failure of the system is quite predictive and sufficient data has already been gathered. In that way the condition on one specific moment can be automatically linked to an estimation of the maintenance interval. Also condition checking can be useful if several systems of the same type are present. The measurements of the different systems can be compared to see what their relative conditions are.

The most crucial part in applying condition monitoring, with respect to the predictive maintenance concept, is that the system is known from inside and out. Only if the possible faults and their symptoms are identified, a proper CM programme can be utilized. This programme consists of several condition measurement techniques which all must be applied in the right manner to be able to detect the known possible symptoms. Regarding this techniques the remainder of this chapter will be about the different types, their applications and some examples. These subjects will be discussed in a universal manner because the techniques discussed are widely applied in all fields of engineering. After this general explanation, the parts concerning the specific subject of the survey are discussed in the next chapter.

[7] Woodley, B.J. *Failure Prediction by Condition Monitoring.* Materials in Engineering Applications Vol. 1, 1978

[8] Neal, M.J. *Condition Monitoring Methods and Economics.* Maintenance Vol. 1, 1986

[9] Hind, M. *Advanced Maintenance in Ships.* Maintenance Vol. 1, 1986

1-2-1 Condition monitoring versus performance monitoring

The similarities between these two techniques are considerably large in terms of the monitoring system components and parameters but the objectives are completely different. It must be noted that performance monitoring only consists of the process parameter method while condition monitoring can use all sorts of techniques, as seen in this chapter.

A 1982 report dictates the objectives as follows[10]:

Diesel propulsion plant performance monitoring, (PM), as applied in this report, is defined as:

- *The monitoring, indication and subsequent assessment, (either automatically or manually), of the operational efficiency and performance levels of the diesel propulsion engine and its respective subsystems*

The objectives of this form of performance monitoring are:

- *To effect the efficient, economic and optimal operation of the diesel propulsion plant*
- *To reduce the possibility of "off design" operation degrading both the individual components and the overall system reliability and service life*

Diesel propulsion plant condition monitoring, (CM), with its objectives as applied in this report, is defined as:

- *The monitoring of component or system wear and degradation in order to predict scheduled maintenance or at least to avoid catastrophic failure. Condition monitoring is meant to supplement, not supplant, the traditional high/low limit alarm systems.*

This is contrary to the way in which the term performance monitoring is used in another the report or Woodley. Here, performance monitoring is taken up in the list of machine condition monitoring methods between vibration monitoring, visual monitoring and wear debris and contaminant monitoring (previously discussed as tribology). Referring to the definition of performance monitoring: *The condition of a machine or component is assessed by measuring how well it is performing its intended duty*[11], it sounds more like a combination of the above mentioned definitions and just another name for process parameter monitoring, which will be discussed in the next section. When studying the rest of the report it becomes obvious that what is meant is the same as the here called process parameter monitoring.

Rasmussen relates the economical advantages to performance monitoring and mechanical condition monitoring as showed in Figure 1-4. Here the term condition monitoring is used as a collective noun for both performance and mechanical condition monitoring. In which performance monitoring leads to a reduction in fuel cost and an increase of efficiency, and mechanical condition monitoring reduces the maintenance cost by preventing unnecessary

[10] United States Department of Transportation Maritime Administration *An Assesment of Performance and Condition Monitoring Requirements of Foreign Marine Diesel Propulsion Systems.* 1982

[11] Woodley, B.J. *Failure Prediction by Condition Monitoring.* Materials in Engineering Applications Vol. 1, 1978

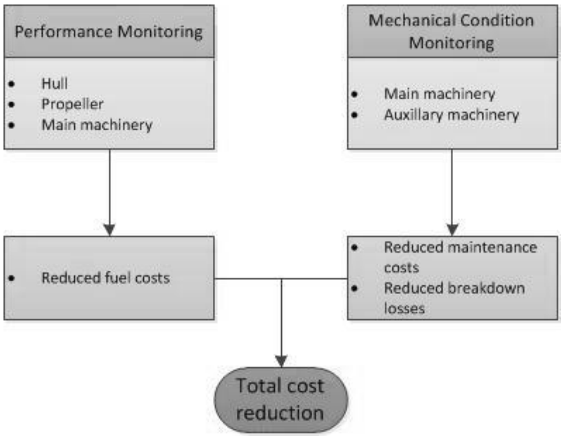


Figure 1-4: Flowdiagram of economical benefits of PM and CM

maintenance. Also the picture makes clear that the author is of the opinion that the different components of, in this case a ship, are candidate for one of these CM techniques, only the main machinery, later explained as the diesel engine in specific, is suitable for both methods. This corresponds with the before mentioned idea that both systems can be applied together. Although this explanation of condition monitoring seems fitting for this report it will not be applied in this literature survey. What is mentioned as mechanical condition monitoring will be assumed as condition monitoring in this research, and performance monitoring will not be a part in this.

A CIMAC report partly originating from the Delft University of Technology and written by Woud and Boot mentions 'condition monitoring' in its title while in most of the article the term 'performance monitoring'. For instance *'The performance of the engine can be checked by comparing the actual behaviour to that of the healthy engine.'*[12] In this sentence the term 'performance' can without any problem being replaced by 'condition', which is being done in whole of the article.

As seen above a lot of different interpretations of condition and performance monitoring are used in literature. In the scope of this survey, an attempt to finding new quantitative methods for condition assessment, the definition of condition monitoring as a way in which condition based maintenance is being implemented through sensoric data seems more suitable. The intention is to find a way of preventing failure and schedule maintance, not to optimize efficiency in the current point of operation. On the other hand, when talking about the monitoring system and the monitored parameters, the methods are almost completely identical, which is the reason these two are often combined in one system. The only essential difference is the way the output of the system is implemented; the diagnostics. In condition monitoring the output of the system is examined for trends in degradation of the components, to plan maintenance and prevent failure, while in performance monitoring the constant strive is for economical or environmental efficiency. This difference in diagnostics is imminent for this survey because the implementation of the output in terms of preventing failures is what it is trying to improve. That is why, by adapting the definitions of CM and PM mentioned above, this survey is about condition monitoring in terms of condition based maintenance and not

[12]Woud, J.K., Boot, Ph. *Diesel Engine Condition Monitoring and Fault Diagnosis Based on Process Models.* 20^{th} CIMAC, 1993

about performance monitoring. Though a marginal note needs to be placed here because to a certain degree the methods overlap. Through performance monitoring the process parameters in different operational points can be determined and can be used as a reference value in the assessment of the condition during condition monitoring.

1-2-2 Monitoring techniques

As mentioned above, predictive maintenance assesses the current state of the investigated system and thus proper condition monitoring tools are needed. The required characteristics of these tools are that they need to be easy to apply, produce a useful representation of the state of the system, as cheap as possible, and of course not destructive and not disturbing the system's functioning. Probably the most crucial requirement is that it needs to produce a useful representation of the current state of the system. Because when it does not, what is the use of it? In most cases, the best representation is achieved by monitoring as close to the potential failing component as possible. This seems straightforward as a lot of noise and uncertainties can be eliminated from the signal, but cannot always be realized.

Some examples that are most commonly used in CM are vibration monitoring, process parameter monitoring, visual inspection, tribology and thermography. These techniques can be subdivided in direct and indirect ways of condition assessment; indirect methods monitor the process parameters of the system while direct techniques use sensors that measure directly monitor the condition of a specific component.[13] When it has been decided that CM will be applied, the monitoring technique or techniques need to be chosen. It has been proven that covering all the possible faults of a complete system is in most cases only possible when multiple techniques are selected. A combination of techniques can cover more faults and can simplify the diagnosis of a fault by combining the symptoms. Electing the best techniques for the application can be tricky. The fault behaviour of the system must be investigated and the system knowledge needs to be at the highest level possible. Considerations need to be done on where the tools must be placed and which faults they can expose. Also a very significant factor in the selection are the initial costs. Every technique needs specific tools and the information provided by these tools needs to be digitalised, processed, analysed and presented to the user. It is understandable that the whole condition monitoring system is very expensive but if applied correctly it will most certainly pay back the initial costs. In the remainder of this paragraph the before mentioned techniques will be discussed one by one.

Vibration monitoring

Vibration monitoring is one of the more dominating CM techniques. It is used as a primary diagnostic tool for most mechanical system, whether rotating, reciprocating or other mechanical motion. It is predicated on the fact that all mechanical equipment in motion generates a vibration profile that contains a lot of information about its operating condition. Every moving component of the system contributes to the profile with its own signature vibration. If one or several components contain a fault this characteristic signature changes, consequently altering the monitored vibration profile. In regard of this sum of vibration profiles it is also

[13] Tinga, T. *Principles of Loads and Failure Mechanisms.* Springer, 2013

possible to monitor not the overall level but only one specific component by spectral analysis. Figure 1-5[14] shows an example of such a profile in the frequency domain.

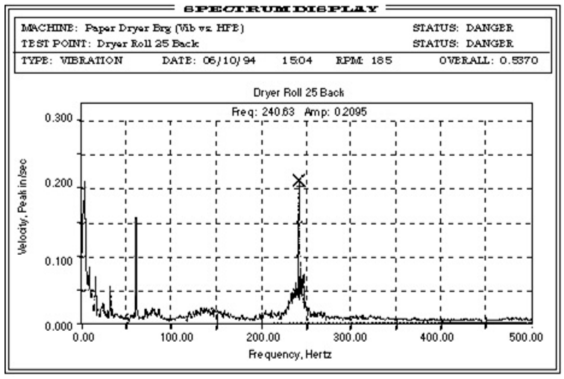


Figure 1-5: Example of a vibration profile

Depending on the type and complexity of the system analysing such a profile can be tricky. Seeing something is wrong in the overall analysis is relatively simple but isolating the specific fault is not an easy task. Vibration detectors can be placed on multiple locations on the system and several vibration directions can be measured, such as horizontal, vertical but also torsional. That is why it is crucial in vibration monitoring to use the right sensors, on the right place and with the right mounting. If a mistake is made in any of these steps the monitoring will not be optimal and possibly a fault is overlooked. Types of detectors which are often used are displacement probes, which measure the displacement of for instance a shaft relative to its central position, velocity transducers, which records the rate of displacement, accelerometers measuring the acceleration, and cables, which measure vibration through their extension. Each of these detectors has its own benefits and downsides and thus cannot be used in all applications.

Besides the use in predictive maintenance, vibration monitoring has additional applications. It can for instance be used to detect leaks in pipelines and to isolate sources of undesirable noise. These subjects are beyond the scope of this report and therefore will not be discussed any further.

Thermography

Since vibration monitoring cannot monitor all aspects of a system's functioning it is generally combined with other predictive methods.

Figure 1-6: Example of an infrared image

One of these other methods can for instance be thermography. Some older reports, for instance the one from Woodley, classify thermography as a visual monitoring aid but its development and increasing importance in the recent years contribute to it being a condition monitoring technique on itself. This predictive maintenance technique monitors the infrared energy emission of a system. It is based on the fact that all items with a temperature of above absolute zero emit infrared energy. Faults in a system can cause thermal irregularities which, if monitored through thermography, can be discovered by an experienced inspector. The types of faults which can be detected through this technique are mechanical looseness, load problems and failure of a specific component.

[14] http://rtreport.ksc.nasa.gov/techreports/95report/instf/inst01b.gif

Because infrared light cannot be seen with the naked eye, special infrared equipment is required. Some criteria for this type equipment are that it needs to be portable and easy to use. Besides these criteria a consideration needs to be made on what type of equipment is best to obtain the desired result. If the temperature at one or several specific spots is needed the best piece of equipment would be an infrared thermometer. It displays the exact temperature of the relatively small spot it is aimed on and therefore is suitable to monitor critical points of a system such as bearing caps. Less frequently used is the line scanner which provides a one dimensional line of comparative radiation. Best applicable in CBM is infrared imaging. Unlike the other instruments it can display the infrared profile of a complete system. Several types of imaging devices are available varying from relatively cheap black and white versions which are unable to store or recall images, and the expensive coloured scanners which are microprocessor-based. An example of the image such a system can produce is shown in Figure 1-6, which contains a fault with an industrial electrical fuse block.

Analysing an infrared image is the most difficult part of this monitoring technique. First of all choosing the right setup for the image is important because thermal sources or other disturbances in the environment can make it futile. Furthermore the transmitted and reflected part of the energy must be filtered out so that only the emitted part remains and is visualised in the image. The interpretation of the constructed image requires extensive training and thus special employees need to be trained for this purpose or a specialized company must be hired.

Tribology

The third condition monitoring technique discussed focusses on unwanted friction between surfaces in motion. It consists mainly of lubricant analysis to investigate the properties of the oil and even indicate wear problems in the system. Moving parts which are in contact with the lubricant can be monitored for wear by analysing the amount and nature of debris contained in the lubricant. The main use of tribology in a predictive maintenance programme is to schedule the oil change intervals based on its condition. Although this may seem of less importance for the condition of the system it most certainly is not. Deterioration of, for instance, lube oil can cause the whole system to fail and therefore its condition is a vital characteristic of the system. An example of systems in which tribology plays an important role is hydraulics.

Visual inspection

This technique is essential in every predictive maintenance programme. A fault which can be missed by all the other techniques can be detected by regular visual inspections. Besides that it is probably the least expensive technique of all and therefore should be incorporated in every predictive maintenance programme. During inspections the most unique and most difficult to copy instrument are the human senses and the way in which the gained information is processed and combined in our brain; an experienced inspector can sense a fault in the system. Another advantage is that visual inspection, executed by a trained engineer, will give an immediate indication of the condition without any processing time or signal analysis.

Besides the senses, tools are used during the inspections to support them and make an accurate analysis of the system's running conditions. Some of these tools can be light probes, boroscopes and stroboscopes. Not all these visual monitoring techniques can be executed during operation and thus systems may have to shut down for visual inspection.

Visual inspection is widely applied as a condition checking tool but can be recorded as well to serve trend monitoring purposes.

Process parameters

This monitoring technique covers the tracking of a process parameter by using sensor technology to monitor a systems condition. The monitoring can cover the measurement of all possible process parameters which can indicate a fault and/or the current status of the engine. For instance pressure, temperature, torque or strain. The most basic way is measuring the useful output of a system and determine whether it is within the desired limits. If it is not, this may indicate that something is wrong in the system and a developing fault may be present or that the settings should be changed.

Besides the process parameters mentioned above, some literature mentions others, like vibration. Since vibration monitoring is such an important monitoring technique and it is more of an external output of the system than an internal one, it is found in this survey that vibration monitoring is a monitoring technique on itself and not a part of process parameter monitoring. Other external outputs measured within condition monitoring are thermography and aspects of visual inspection. If vibration monitoring were to be a part of process parameter monitoring, these methods will have to make the same move. That is why in this survey the line is drawn before vibration monitoring and when talking about process parameter monitoring only the internal parameters are addressed.

Process parameter monitoring is versatile in its application because besides the fact that it can uncover a fault, it can also indicate the status of the system in terms of efficiency. In most cases these two applications are used simultaneously as a condition and performance monitoring system and therefore these terms are sometimes, not completely just, used interchangeably. In the next chapters this discussion will be further addressed.

Monitoring can be done on a system level, called machine monitoring in which the presence of a fault can be detected but the location is often hard to point out, or a component level, called component monitoring which makes finding the exact location of the fault much more straightforward. Of course, the latter one is relatively expensive and the system knowledge should be very thorough in order to correctly place the sensors.

When a process parameter monitoring system is to be applied, the success rate is determined by choosing the right parameter to monitor, select an accurate sensor and signal processing system and implement the output of the processing system.

Choosing a process parameter to be monitored depends on which faults you want to discover. In most cases there is not one parameter which can reveal all the possible faults and thus the operator needs to know the possible faults, divide them in groups and choose a parameter to monitor such a group. The chosen parameter has to be able to reveal the group of faults and preferably each of these faults should be distinguishable through the parameter output. When choosing a parameter the operator should realise that some parameters may be impossible to monitor because of costs, inability of existing sensors and difficulties in the physical placing of a sensor. Also, when looking for advice on which parameter gives the best status indication, the opinions may vary. This opinion variation will be illustrated in a later chapter of this literature survey.

Expert opinions on performance and condition monitoring may also vary in time because of the constant technological development of sensing and processing systems. For example, a parameter which is thought to be very representative some decades ago but was not considered because of the lack of adequate technology can be revised again after some technological development. One of these examples can be in-cylinder pressure measurement. At the start of condition monitoring techniques, around 1970, the existing pressure sensors were unable to endure the high temperatures inside the cylinder. Therefor this seemingly important parameter could not be directly used in monitoring systems. Nowadays, the development of pressure sensors has made it possible to adapt pressure sensing inside the cylinder in a condition monitoring program. Although a note should be made that the high temperatures and quickly fluctuating pressures still make it a very sensitive component.

When the right parameter has been found and an accurate sensor and processing system has been placed it is crucial for the functioning of the monitoring system to correctly implement the supplied output. This part is called the diagnostics of the condition monitoring system. The output of the system has to be represented in such a way that conclusions can be drawn about the current operational state of the system. First aim of diagnositics is always to determine the state, and if this shows a deviation, the second aim is to identify the cause of this deviation, called fault diagnosis. The subject of fault diagnosis is extensively addressed in all sorts of literature and is a condition monitoring topic on itself. More on this is found in part two of this literature survey.

The diagnosis can be done automatically by the monitoring system or manually by the operators. When done automatically, the system will provide the operator with the possible faults in order of likeliness with the help of models or fuzzy logic theory. Downside of this diagnosis automation is that the underlying information, models and software is very complex and thus money and time consuming. The positive side of it is that almost everyone can be the operator because he will not have to think for himself and gets the answer presented by the system. This upside of automation also reveals the downside of manual diagnosis: the operator will have to interpret and filter the presented information by himself and thus has to be educated and trained to do so. This operator can not always be available and may even switch jobs, in which case the knowledge and experience will have to be transferred to a new operator. Also, every operator will have different ways of looking at the information which may mean that, although both educated and trained, two operators can have different diagnosis for the same output. All these reasons feed the need for automation and the elimination of the human factor from condition monitoring diagnosis techniques. But there is also a mean between these two options: the system can also be partly automated in which case the presented information does not contain the most likely faults, but *will* give a quantitative representation of the sensor output. In this way, the operator can be provided with standard procedures to follow if the presented values are diverging. This advance in diagnosis technique is the underlying goal of this survey; to find a quantative way of representing the supplied output from the transducers in order to simplify the fault diagnosis. This idea has been proposed much earlier, in 1978, by the Ship Research Institute of Norway by stating that *"condition monitoring system should not be allowed to replace the engineers' experience, intuition and understanding of system behaviour, but should be a supplementary to these human qualities. The main goal is to increase the information level upon which the engineer* *makes his decisions, and thereby increase the probability of the decision being correct"*[15] More on this in later chapters.

After diagnosing, the prognosing phase begins. This holds that the way in which the fault will develop in the near future will be predicted. The results of this prediction will serve as a directory for the maintenance work planning. Prognosis is not always seen as a part of condition monitoring but is a crucial last step when applying condition monitoring as a maintenance concept. Since the subject of this survey is about diagnosing, this last step will not be further addressed.

As the title of this survey already suggests, the process parameter technique is the only condition monitoring method considered in this survey and thus when using the term condition monitoring only the process parameter technique is being addressed. The reason that some of the articles and books used are refering to performance monitoring although they are used in this condition monitoring topic is because process parameter monitoring is a condition monitoring but also the only performance monitoring technique available. With respect to the fact that this report is on process parameter monitoring, certain parts of performance monitoring are applicable too.

[15]Fagerland, H., Rothaug, K., Tokle, P. *Monitoring and Diagnosing Process Deviations in Marine Diesel Engines.* Ship Research Institute of Norway, 1978

1-3 Diesel engine condition monitoring

In this chapter the items discussed in the previous chapter about condition monitoring in general will be discussed in the context of diesel engine diagnostics. First the general methods applied on diesel engines are discussed. These methods concern all aspects of condition monitoring: from the monitored parameters to the fault diagnosis. After that a few examples of existing diesel engine condition monitoring systems will be given.

1-3-1 Methods for Diesel engine condition monitoring

The CM methods mentioned in section 1-2-2 can be applied on several types of machinery and are therfor a more universal list. For diesel engines specifically some methods are more suitable than others and for every component another monitoring method can be more applicable. That is why the division into different methods is made according to the different components to be monitored. Every component has its own parameters, faults and failure consequences. The division into components is roughly the same in all literature and can be listed as follows: [16][17][18]

1. Fuel injection process
2. Cylinder combustion process
3. Lubrication system
4. Mechanical components
5. Heat exchanger
6. Air and gas path processes

In the following sections these components will be discussed one by one in terms of the CM methods.

Fuel injection process

This process is crucial for the functioning of the engine because if the injection timing is incorrect or the valves are leaking, problems such as thermal overload may occur. Thermal overloading increases the rate of degradation processes and excessive emissions. This means that thermal overloading is not only a concern in condition monitoring but also plays a role in performance monitoring. The reason why the fuel injection process is a separate component in terms of monitoring methods is because it contains some delicate parts like the valves, injector and spring. If any of these fail the engine may experience a complete failure in

[16] United States Department of Transportation Maritime Administration *An Assesment of Performance and Condition Monitoring Requirements of Foreign Marine Diesel Propulsion Systems.* 1982

[17] Jones, N.B., Li, Y.H. *A Review of Condition Monitoring and Fault Diagnosis for Diesel Engines.* Tribotest Journal Vol. 6, 2000

[18] Fagerland, H., Rothaug, K., Tokle, P. *Monitoring and Diagnosing Process Deviations in Marine Diesel Engines.* Ship Research Institute of Norway, 1978

which other components may likely get damaged to. A problem arising in the condition monitoring of the fuel injection equipment is the fact that it is all very small spaced and thus placing sensors can be difficult. Also the pressure, temperature and frequency are high which makes it difficult to find a sensor that can survive this harsh environment. That is why an indirect way of measuring is often applied. An indirect method could be to measure the injection pressure with a clamp-on pressure sensor. The operation of this piezoelectric sensor is based on the idea that the pipe expands when high-pressure fuel flows through it.

When the pressure inside the fuel injector is measured a diagram such as Figure 1-7 can be made.[19] From such diagrams parameters such as the opening pressure, pressure rise before opening, maximum injection pressure, injection crank angle and injection duration can be derived.

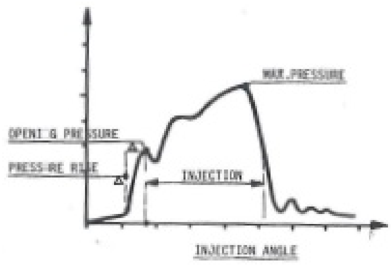


Figure 1-7: Example of an injector pressure diagram

Some authors, like Fagerland et al, see the fuel injection process as a part of the combustion process because they influence eachother to a high degree but in this survey these process will be separated in terms of CM because in that way the faults are easier to distinguish.

Cylinder combustion process

The combustion is the engine driving process and therefore the heart of the diesel engine. If a failure occurs inside the cylinder, complete breakdown is inevitable. Besides the fact that monitoring the cylinder combustion process can reveal problems inside the cylinder, in some occasions also other problems can be found via the parameters of this process. That is because every fault that occurs before the air or fuel arrives in the cylinder influences the operation during the combustion process. If this influence is big enough it can be traced back from the process parameters. So just as the human heart, the engines heart can also tell a lot about its overall condition. In some older articles, like Rasmussen et al, the combustion monitoring process is mentioned as a good way to analyse the fuel quality. Although this is a good example of how combustion monitoring can unveil a wide range of problems this is not realy relevant nowadays since international regulations in terms of fuel quality became very strict.
A lot of information can be measured from the combustion process such as the temperature and pressure in relation to time, angle and volume. Also the output of the engine tells a lot about what is happening in the cylinder.
Although monitoring is the best option the environment in the cylinder is the roughest in all the engine which requires a good monitoring strategy. In the early days of combustion process monitoring measuring the in-cylinder pressure and temperature was a big issue because the existing hardware could not function in this environment. Therefor no permanent sensors could be placed and only manually obtained "indicator" and "draw" diagrams were obtained. These diagrams expressed pressure versus volume and pressure versus time in a graphical

[19] Fagerland, H., Rothaug, K., Tokle, P. *Monitoring and Diagnosing Process Deviations in Marine Diesel Engines.* Ship Research Institute of Norway, 1978

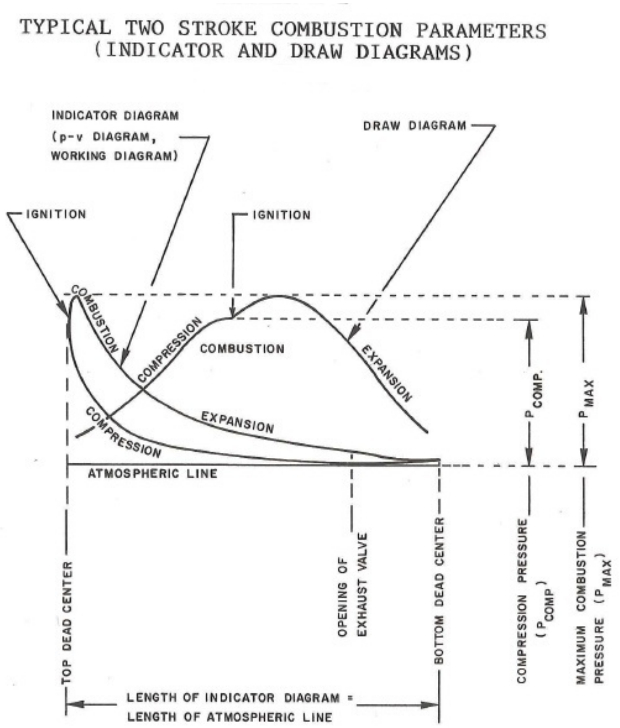


Figure 1-8: Example of an indicator and draw diagram

way. An example of such a set of diagrams is given in Figure 1-8 [20]

From these diagrams information can be extracted like the maximum cylinder pressure, compression pressure, expansion pressure and the angles at which these pressures occured. In addition the mean indicated pressure (MIP) can be determined.
The maximum pressure is related to the ignition delay and the rate of heat release during the initial combustion period. Expansion pressure is hard to point out because the expansion phase is stretched over a wide pressure range. The easiest way to compare expansion pressures is to choose a fixed crank angle during this phase and define the pressure at that moment as the expansion pressure. Delayed combustion and after burning can be recognised with this parameter. Also the start of ignition in terms of crank angle or volume can contain some information about combustion delay. The MIP serves as a comparison method for the different cylinders. If the cylinder loads are unevenly distributed this can result in thermal overload and failure but when comparing the cylinders MIP's this distribution can be quantified.
Considering the information extracted from the diagrams and the problems they can reveal it becomes more clear that combustion process monitoring is besides a CM, also a succesful PM technique. For instance, in-cylinder pressure measurements can serve as a monitoring tool to pursue a good fuel economy and cleaner emissions.
As seen above, these values can tell a lot about the current state of the engine but the deviations indicating a fault are often very small and it is hard to recognise them. The easiest way would be if simple alarm values could be set but this is not possible due to many factors

[20] United States Department of Transportation Maritime Administration *An Assesment of Performance and Condition Monitoring Requirements of Foreign Marine Diesel Propulsion Systems.* 1982

influencing the measurements. Small fluctuations are normal but can also denote an upcoming failure. Therefore the diagrams are often hard to implement, even for experts.
Nowadays indicator and draw diagrams are still being used to evaluate the combustion process although it is no longer done manually. In most cases pressure measurements can be obtained continuously through permanently mounted sensor systems. These systems can measure and log the pressure in a direct or an indirect manner. The direct method holds that pressure transducers are being installed inside the cylinder which produces a quite reliable and accurate measurement after some filtering. The downside is ofcourse that installing the sensors in inconvenient and uneconomic since they are intrusive.
To improve the efficiency researchers have been seeking for methods to measure the pressure indirectly. Till now two methods are known; through vibration and through crankshaft speed. The measured vibration and speed signals are being filtered to obtain the pressure signal indirectly. Both direct and indirect pressure measurement have their benefits and downsides and therefore the choice depends on its application.

Lubrication system

The lubricant system is sometimes called the vein system of the engine. Most of the moving components inside the engine but also the surrounding parts need to be lubricated. The quality of the lubrication oil influences the wear on the parts and therefore can lead to an indirect failure. Also contaminants in the lubricant can be transported through the engine and deposit elsewhere, causing damage to other components. To monitor the oil quality the temperature and pressure are measured and also tribology tests need to be carried out periodically.

Mechanical components

When talking about the mechanical system of a diesel engine in the scope of condition monitoring this mainly concerns the bearings and piston rings. The bearings are experiencing high loads and they are continuously exposed to wear. This can lead to cracks and eventually failure of the component. A bearing in a marine diesel plant that has failed can force the vessel to stop. The difficulty in monitoring the bearing wear is its inaccessibility during operation. Monitoring wear can be done in different ways, through a wear sensor, surface temperature sensor or tribology. The piston ring prevents leakages and blow-by of combustion gases and is therefore a vital part of the engine. Degradation of piston rings can be monitored with proximity sensors indicating the distance between the ring and the liner surface.

Heat exchanger

Monitoring the heat exchanger is more in terms of performance than condition monitoring. If the heat exchanger contains a fault this will harm the performance of the engine but will not likely lead to a failure. The parameter which should be monitored is the air temperature before entering the heat exchanger and the temperature after the heat exchanger.

Table 1-1: Summary of diesel engine condition monitoring parameters

Diesel engine components and their monitoring methods			
Engine component	Measurands	Performance monitoring	Condition monitoring
Fuel injection process	Pressures	PM	CM
	Angles	PM	
	Temperature	PM	
Cylinder combustion process	Pressures	PM	CM
	Angles	PM	
	Outputs	PM	CM
	Rotational speed	PM	CM
	Vibration		CM
Lubrication system	Tribology		CM
	Pressures		CM
	Viscosity		CM
	Temperatures		CM
Mechanical components	Temperatures		CM
	Visual inspection		CM
	Tribology		CM
Heat exchanger	Temperatures	PM	CM
	Pressures	PM	CM
Air and gas path processes	Visual inspection	PM	CM
	Vibration	PM	CM
	Composition	PM	
	Temperatures	PM	CM
	Pressures	PM	CM
	Air flow	PM	CM

Air and gas path processes

When monitoring the air and gas path processes inside the engine the aim is to reveal possible faults but also optimize the performance. In the first case the airflow and leakage are the main concerns and in the other case emissions and scavenge quality are being monitored. Reduced air flow can cause problems like thermal overload, leading to degradation of the materials. The flow paterns are difficult to monitor but new technology makes it possible to simulate the flow path through the engine. Placing sensors in the flow path is less usefull since the pressures are highly fluctuating per region and have extremely small values. Besides that, the temperatures are very high which makes it an harsh environment for the sensors. That is why some of the parts, like filters and compressor and turbine blades, are more often subject to scheduled maintenance. Some parameters more more suitable for monitoring purposes are the efficiencies of the turbocharger turbine and compressor, the pressure drop across the air cooler and engine, and the k-value of the air cooler. Also, by measuring the composition of the exhaust gases a range of malfunctions can be uncovered like timing and fuel quality.

Table 1-1 shows a summary of the different components of a diesel engine with their relevant monitoring parameters and whether they are suitable for condition or performance monitoring.[21]

1-3-2 Examples of Diesel engine monitoring systems

Over the years many different diesel engine condition monitoring systems have been presented by a lot of companies. Some systems may look alike but most of them use dissimilar techniques, hardware and software. These differences are caused by the time and the then available technology but also the underlying ideas can be very diverse. Parameters one company finds extremely important and representative may seem useless for others. That is why several systems are listed and discussed below. Most of these systems have been established for maritime employment. The reason most systems are developed for this sector is because high reliablity is demanded on board to prevent loss of propulsion and also maintenance should be carefully planned to match the sailing program. These two demands can justify the high costs of such a monitoring system. That is also why for example in the automotive industry a CM system is not profitable.

Friskaa mentions some of the first CM systems:

- PREDIKT I
- DATATREND - DIESEL
- CIPAN

According to the more recent report of Jones and Li, some of the maritime CM systems are:

- CYLDET-CM system
- DEFD system
- KBMED
- CPMPS

In the following sections a few of these systems will be discussed.

PREDIKT

One of the earliest deployed condition monitoring systems is the PREDIKT I[22] which was first delivered in the sixties. It was designed for the monitoring of large bore 2-stroke diesel engines. The parameters monitored by PREDIKT I are:

1. Air filter pressure drop
2. Compressor efficiency

[21] Mobley, R.K. *An Introduction to Predictive Maintenance.* Butterworth Heinemann, 2002

[22] Fagerland, H., Rothaug, K., Tokle, P. *Monitoring and Diagnosing Process Deviations in Marine Diesel Engines.* Ship Research Institute of Norway, 1978

3. Air cooler thermal conductivity
4. Air cooler pressure drop
5. Engine pressure drop (scavenging air pressure)
6. Exhaust turbine efficiency
7. Metal temperature cylinder cover
8. Metal temperature cylinder liner manifold side
9. Metal temperature cylinder liner exhaust side
10. Piston ring functioning

During deployment the system did not function very well. Most complains were about the amount of work needed to carry out a condition test, the lack of information about the system and the large scatter in parameters in plots. But besides all these complaints the thermal load and piston ring monitoring has been quite succesful. That is why later on the system has been used only for measuring parameters number 7 till 10. The developers of PREDIKT I made a second attempt after the partial failure of this system by developing PREDIKT II.

CIPAN

In 1975 the prototype of the CIPAN system, developped by the Ship Research Institute of Norway, was installed on a ship with two medium speed four stroke diesel engines[23]. This instrumentation system is intended to monitor the state of the cylinder and the injector pressure sequences in an on-line measurement configuration. The system was available in different forms but the basic was always formed by the cylinder pressure measurement and analysis. It computed the mean indicated pressure, maximum pressure, ignition angle, compression pressure and a characteristic pressure during the expansion phase which all could be stored and recalled later on. The system consisted of a pressure pick-up with amplifier, a shaft encoder, converters, a mini computer and a control panel. Some of the extensions available were:

- *Continuous combustion monitoring* where the pressure sensor could be mounted permanently to enable continuous monitoring
- *Injection system monitoring*, both portable as permanently mounted, to monitor the maximum injection pressure, angle of maximum pressure and the angle at the start of injection
- *Thermal load monitoring*, applied on the cylinder liners and/or covers
- *Condition monitoring* is a software package, together with some additional instrumentation, which computes the expected value of some of the most important parameters under present conditions and presents these on the screen together with the measured values for immediate comparison

[23] Friskaa, G. *Condition Monitoring Methodology and Experience on Diesel Engines.* Ship Research Institue of Norway, 1975

- *Alarm reporting* is an addition to the condition monitoring module which automatically prints alarms if the deviations between the computed and measured values are beyond the preset alarm limits
- *Presentation on hard copy* which enabled the operator to print every report needed
- *Monitoring of specified measurement*, if the user desires to measure other parameters
- *Plot of measured and computed values* which is again an addition to the condition monitoring package and enables the user to plot the trends of the measured and computed values

Although nowadays this does not seem to be a very thorough CM system, especially without the extensions, it was quite revolutionary at that time. This was caused by the mini computer and its storage space but also the great emphasis laid upon designing a well functioning man/machine interface.

CYLDET-CM system

The trigger for developing this diesel engine CM system was the upcoming price trend for petroleum in 1978[24]. Operators were fearing that the quality of the petroleum used in diesel engines would deteriorate to such a degree that wear, fouling and scuffing of the combustion chambers would become a serious problem in the near future. Therefore an easier way for inspection was required in the form of a continuous condition monitoring system. Besides the goal of preventing break downs this system was also presented as a way of lowering fuel consumption and thus, in the before adapted terminology, was also monitoring the performance of the engine.

Jones and Li refer to this system as if it *'only monitors the piston assembly and cannot be called a condition monitoring system for engine'*[25]. When reading the system illustration written by ASEA (Allmaenna Svenska Elektriska Aktiebolaget), the developing authorities, this seems a legit statement. In their explanation the ASEA states that analysis show the costdrivers of maintenance are the cylinder units and the fuel system. That is the reason why ASEA has chosen for a CM system only monitoring these two components of the engine. Therefore it is a rightful claim that the CYLDET-CM system is not a diesel engine condition monitoring system but exclusively monitors the cylinder and fuel system.

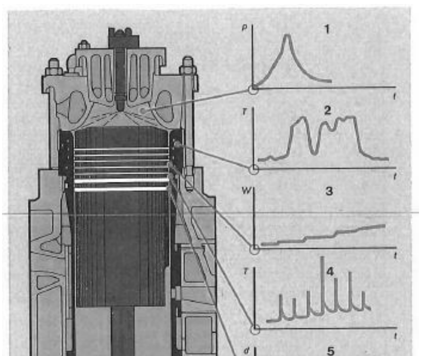


Figure 1-9: Measurands of the CYLDET-CM system

The system has a modular design with respect to the number of transducers and the degree of signal processing, which would make it suitable for different types of diesel engines and can live up to various data processing demands.

[24] Sletmo, K. *Condition Monitoring of Marine Diesel Engines.* ASEA Journal Vol. 51, 1978

[25] Jones, N.B., Li, Y.H. *A Review of Condition Monitoring and Fault Diagnosis for Diesel Engines.* Tribotest Journal Vol. 6, 2000

In Figure 1-9[26] the measuring points of the system are presented. The various sensors placed in the cylinder unit are:

1. Cylinder pressure
2. Cylinder liner temperature
3. Cylinder liner wear
4. Surface temperature of cylinder liner
5. Condition of piston ring

Because of the scope of this survey only number 1 will be further addressed.
The CYLDET system uses the pressure signal for two purposes: maintaining a good fuel economy and preventing breakdown. Consequently, the pressure parameter is used for both performance and condition monitoring. This combination was to be expected when considering section 1-2-2. The pressure signal is fed to a signal processing unit together with the crank angle information. Subsequently it presents the work developed per cylinder, ignition point and maximum pressure. Sletmo adds an 'etc' to this summation which insinuates that more information is extracted from these signals. Though what information specifically is not being discussed. The results are presented on a display and an oscilloscope screen.

CPMPS

The full name of CPMPS is *Condition/Performance Monitoring and Predictive System*[27], which already gives some information about the issue discussed in section 1-2-1. CPMPS is based on existing techniques but focusses more on fault diagnostics, performance optimisation, and predictive maintenance. It has been developed around 1988 by a project group led by the Performance Technology Department of Lloyd's Register of Shipping. The functions the project group was aiming for were:

1. Condition monitoring
2. Performance monitoring
3. Fault diagnosis
4. Predictive maintenance
5. Performance optimization

These functions were deduced from a list of requirements which were, in the opinion of the authors, necessary improvements of the current monitoring systems. The aim was to reduce maintenance, improve availability and reliability, optimise control, improve fuel economy and optimise the utilisation of engineers.

[26] Sletmo, K. *Condition Monitoring of Marine Diesel Engines.* ASEA Journal Vol. 51, 1978

[27] Katsoulakos, P., Banisoleiman, K., Hornsby, C, Vekaria, A., Morgan, D., Ruxton, T. *Design and Development of CPMPS: A New Generation of Engine Management Systems.* CIMAC, 1988

The relative new aspect of this system was that it used simulation and knowledge-based methods for the purpose of fault diagnosis. Although this method may have been considered before the adaptation would have been a problem because of the low processing and storage capacity of computers at that time. The rapid technological development led to new opportunities for the CPMPS project group allowing them to adapt the fault diagnosis simulation program into their CM system. The simulations were used to determine the reference value of the measurands and were therefore not static but adjusted to the actual engine's operating environment.
In a small review of condition monitoring systems the project group responsible for the CPMPS mentions three types: traditional condition monitoring systems, state estimation and knowledge-based systems for condition monitoring. The first type consists of performance monitoring, vibration monitoring and wear monitoring. In this part the authors state that performance monitoring systems are based on recordings of cylinder gas pressure but a reliable technique for continuous in-cylinder pressure monitoring has not yet been established. This corresponds to the assumption that the information contained in the pressure signal has been recognised before the technological development enabled to monitor it.
CPMPS contained a module named the maintenance planning system (MPS) which, as the name already suggests, *'provides on-line predictions of future maintenance activity according to engine condition'*[28]. The three aspects considered in these predicitions were normal wear/-fouling, accelerated wear/fouling due to fuel effects and accelerated wear due to faults and off design engine operation. Four specific goals of the MPS are listed below[29]

1. *Produce a system which would run on a day-by-day basis, for those maintenance instructions which can and should be carried out at sea, and for revising the plan for maintenance activities which can only be carried out in port.*

2. *To provide a maintenance instructions database for the appropriate engine components including manhours, location, spares and tools requirements.*

3. *To keep an updated record of total machine running hours and maintenance completion data.*

4. *To provide a five year maintenance schedule for each of the maintenance instructions according to the actual engine condition and satutory/classification requirements.*

Together with the fact that the MPS also considered which components benefited from group maintenance and even which parts are more economic to maintain at the same time the system is very progressive for its time. The maintenance planning system was able to interpret, plan and monitor on its own and therefore deleted the operator from the diagnosing and prognosing phase. This seems desirable because of the facts mentioned in section 1-2-2 but the pitfall is that not all the influencing factors are being considered in the software program of the system. When the output is studied by experienced operators these factors will probably not be overlooked. Since the CPMPS article only comments on design and software prototypes, of which no test results are presented, the assumption has to be made that the authors were

[28]Katsoulakos, P., Banisoleiman, K., Hornsby, C, Vekaria, A., Morgan, D., Ruxton, T. *Design and Development of CPMPS: A New Generation of Engine Management Systems.* CIMAC, 1988
[29]Katsoulakos, P., Banisoleiman, K., Hornsby, C, Vekaria, A., Morgan, D., Ruxton, T. *Design and Development of CPMPS: A New Generation of Engine Management Systems.* CIMAC, 1988

ahead of their time. Although they presented very good improvements the technical obstacles could not be tackled yet in that time. That is also why in the conclusion they state that *'any major future advancements in engine management could be only achieved through research into advanced engine sensors which need to become embodied in new engine designs'*. The authors also share the opinion that pressure signal monitoring will become more important in future systems.

Chapter 2

Faults in diesel engines

2-1 General faults

Many articles and books are dedicated to the subject of diesel engine faults. Some of them refer to one specific fault and others construct lists of possible faults. Most of the lists are composed from expert experiences. Besides mentioning the faults some authors also refer to causes, symptoms or consequences. The aim of this chapter is to collect all those lists and compose one complete list from all of them.

Table 2-1: List of industrial diesel engine defects and their occurrences

Class of defect	Occurrence (%)
Fuel-injection equipment and fuel supply	27.0
Water leakages	17.3
Valves and seatings	11.9
Bearings	7.0
Piston assemblies	6.6
Oil leakages and lubrication systems	5.2
Turbochargers (excluding damage by intruding foreign bodies)	4.4
Gearing and drives	3.9
Governor gear	3.9
Fuel leakages	3.5
Gas leakages	3.2
Breakages and fractures, other than mentioned	2.5
Miscellaneous	2.5
Foundations	0.9
Crankshafts	0.2
	100.0

Collacott composed such fault lists in his book for different types of mechanical systems including one dedicated to diesel engine faults. The list consists of defect classes and their occurences as reported from 410 stoppages in industrial diesel engines around 1970, see table 2-1. Since the table consists of classes instead of specific faults, the data dates back from 1970, and the type of engines in which these stoppages occurred this is not a very useful table.

Hountalas and Kouremenos used real life tests on a two stroke turbocharged marine diesel engine to validate their fault diagnosing model. Their goal is to develop a diagnosing tool which can detect a problem together with its origin. To test their tool they examined an operational diesel engine suffering from low combustion pressures and high exhaust gas temperatures. Analysis of the cylinder pressures in a pv diagram showed large deviations in maximum firing pressure, figure Figure 2-1 shows the measured firing pressures and the simulated compression pressure (non-firing) for two different engine speeds, per cylinder.

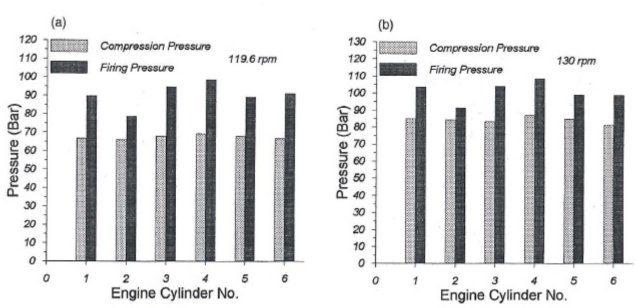


Figure 2-1: Simulated compression pressure and measured firing pressures per cylinder

Investigating these deviations the authors found out that the compression condition of especially cylinders 1, 2, and 6 is worse than the others. Cylinder 4 is in the best condition, showing the lowest amount of wear. The bad compression condition of three of the six cylinders is a cause of the low combustion pressures and the high exhaust temperatures. Furthermore the authors showed with measurements that the cylinders had varying injection timing. The effect of injection timing on the cylinder pressure diagram and heat release rate are shown in figure Figure 2-2. The pressure diagram shows the importance of accurate determination of the injection timing because of its influence on the shape and especially maximum of the pressure diagram. Earlier measurements showed that cylinder 3 and 4 are injected earlier than the other cylinders and the effect of this timing on the heat release rate is shown in the second part of the figure. Although it is hard to distinguish between the different lines in this diagram it can be seen that the heat release in cylinder 3 and 4 initiates earlier and terminates faster than cylinder 2 and 5. Also the fuel atomization of the injector nozzles is poor in some of the cylinders, causing low injection quality and influencing the combustion in a negative way.
In short, Hountalas and Kouremenos discovered with the help of their diagnosing tool that the fault symptoms low combustion pressures and high exhaust temperatures, were caused by:

- Uneven wear of the cylinders
- Unbalanced injection timing
- Poor fuel atomization in some cylinders

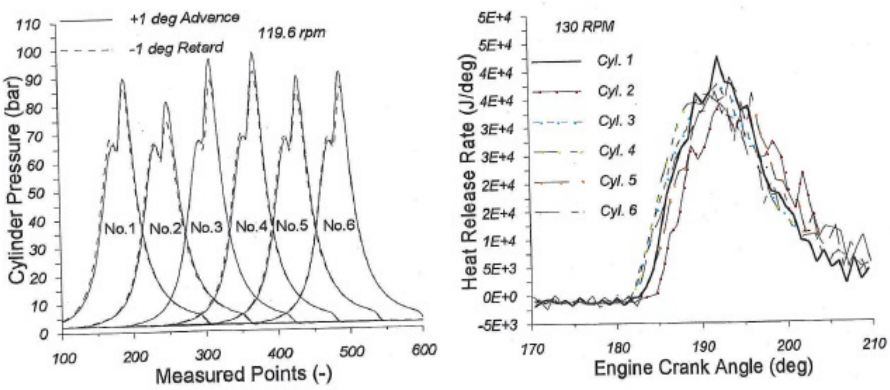


Figure 2-2: Measured effect of cylinder timing on pressure and heat release per cylinder

This example shows how investigating a faulty engine can unveil several causes. To discover the faults first the symptoms in the process parameters had to be sensed, in this case with an in-cylinder pressure and exhaust gas temperature measurement. During the investigation even more measurements were taken such as the brake power output per cylinder, the fuel flow rate, ignition timing, heat release rate and injector pressure to better pinpoint the origin of the problem. Solving this problem was therefore quite an intensive project and a lot of measurements were needed before the causes could be discovered.

In a later article, Hountalas predicts the process parameters of a marine diesel engine under faulty conditions based on a simulation model. Interesting about this article is that he accounts for off-design operational points; different load factors. The author simulates ten faults addressed by him as *'the most common ones'*.[1]

1. Compression fault, by applying variations in the compression ratio. Can be caused by deposits in the cylinder or replacement of parts.

2. Injector fault, by varying a constant called a_{mix} influencing the mixing of the fuel and air. Can be caused by for instance needle wear or hole blocking.

3. Injection timing error, by altering the crank angle. Can be caused by fuel cam wear or roller wear.

4. Air cooler efficiency fault, by reduction of air cooler effectiveness. Can be caused by corrosion or change of the heat exchange area.

5. Air cooler excessive pressure drop caused by deposits blocking the air cooler.

6. Turbine fault, by reduction of turbine isentropic efficiency. Can be caused by blade geometry variations due to wear or pollution.

7. Compressor fault, by reduction of compressor isentropic efficiency. Can be caused by changes in geometry.

[1] D.T. Hountalas, Prediction of Marine Diesel Engine Performance under Fault Conditions, Applied Thermal Engineering Vol. 20, 2000

8. Turbine inlet nozzle effective area change caused by pollution or wear.
9. Exhaust port fault, by reduction of exhaust port area. Can be caused by pollution.
10. Exhaust pipe fault caused by pollution.

He studied the effects of the faults on all of the engine's process parameters, the combination of parameter deviations should pinpoint the exact cause. The article states that in terms of combustion pressure all failures show a strong deviaton except for number 5 and 9 which means that these two faults can not be traced back with a pressure signal and other sensors are needed.

Three authors from the Ship Research Institute of Norway published their work on monitoring and diagnosing marine diesel engines in 1978.[2] They mention some disturbances in the combustion phase which can manifest themselves in the following characteristics:

1. Ignition delay
2. Lower rate of combustion
3. Combustion intensity
4. Incomplete combustion

With an increasing ignition delay a large part of the fuel combusts in an uncontrollable phase, which is undesirable especially in terms of performance monitoring. It can be recognized from an increase in the rate of pressure rise during ignition and a higher maximum pressure. Point two, the rate of combustion, is mentioned in this list because a longer combustion period can cause increased wear of liner and rings because of the enduring high temperature. A low rate of combustion leads to an increased duration of the combustion period. The combustion intensity is best characterised by measuring the temperature in the cylinder and depends on the rate and character of the combustion. This term combustion intensity is quite vague and not covered by any other theoretical paper. The fourth characteristic is undesirable because of the formation of environmental unfriendly products such as CO and soot. The result of incomplete combustion is a lower efficiency and thus is a part of perfomance monitoring rather than condition monitoring. As discussed before a crucial part of combustion monitoring is in-cylinder pressure measurement. For instance, the maximum pressure contains information about the length of the ignition delay and the rate of heat release in the initial combustion period. After burning and delayed combustion can be discovered by observing the cylinder pressure at a fixed crank angle during the expansion phase. Also the ignition timing can be used to specify the ignition delay. Furthermore, the compression pressure and the mean indicated pressure are measured to see if the cylinders are balanced in their timing and workload.

Jones and Li constructed a list of symptoms and the possible corresponding faults. The symptoms were:

- Power loss

[2] Fagerland, H., Rothaug, K., Tokle, P. *Monitoring and Diagnosing Process Deviations in Marine Diesel Engines.* Ship Research Institute of Norway, 1978

- Emission changes
- Lubrication system fault
- Noise and vibration
- Wear
- Thermal overload
- Leakages
- Other faults

The term symptoms is here used as the way in which faults can present themselves, directly but also indirectly. For instance a fault causing temperature rise can also present itself by a lower viscosity in the lubricant. Wear can also be a symptom considering that for instance a longer combustion period due to injector leakage can breakdown the oil film leading to increased wear. As seen, some of the symptoms can also be a fault or the other way around since the diesel engine is a whole network of subsystems with a lot of cause and effect relations. A symptom is considered to be *'a significant deviation from healthy behaviour'*[3] and is caused by the original fault, whether directly or indirectly.The mentioned fault symptoms can be measured with a condition monitoring system through different types of sensors. The change in in-cylinder pressure is not mentioned in this list altough it seems to be a good representation of the operational state of the engine. Only later on in the article pressure measurements are mentioned as a part of measurands but combustion monitoring should also be adapted in this list. The article also mentions the faults that could be causing the list of symptoms but since combustion monitoring is not one of them, they are not very useful for this survey.

Lin, Tan and Mathew wrote an article about condition monitoring and diagnosis of injector faults using in-cylinder pressure together with acoustic emission techniques. They state that faults in a diesel engine can be roughly devided in two groups: combustion related faults, concerning the fuel injection system, inlet/exhaust valve system, and cylinder/piston system, and non combustion related faults, including faults in all auxiliary devices such as the cooling system, gear, bearing, and turbocharger. This classification is based on the origin of the fault and therefore this does not mean that non combustion related faults can not be found with combustion monitoring. For instance, if the turbocharger has a serious malfunction this will influence the combustion in such a way that the pressure rise will be smaller. The article listed some of the most common fault symptoms of diesel engines:

- Misfire
- Knocking
- Insufficient power
- Overheating
- Poor fuel efficiency

[3]Grimmelius, H.T. *Condition Monitoring for Marine Refrigeration Plants.* TU Delft, 2005

- Excessive noise and vibration
- Excessive exhaust smoke
- Engine not starting

The authors stress the importance of knowledge about these symptoms and their related signal patterns, even by using simulation models, to be able to trace back to the origin of the fault.

In the research of Charchalis and Pawletko a fault database has been built by interviewing experienced diesel engineers. The questionnaire included a list of malfunctions of the system, created from 'professional literature', asking the 36 engineers to describe the symptoms of each malfunction. From these symptoms the authors constructed 35 diagnostic rules, linking them to the described malfunction. An example of such a rule concerning the injector is given below.

Damage: injector nozzle seizing (injector open)
Symptoms:

1. *Mean effective pressure - drop*
2. *Max. combustion pressure - drop*
3. *Fumes colour change - smoking*
4. *Combustion gases temperature in remaining cylinders - growing*
5. *Max. injection pressure - drop*

This type of malfunction-symptom rules are very relevant for this study but the authors did not want to share their knowledge because this example is the only out of the 35 rules which is described.

In an article from Ker-Wei Yu a similiar type of malfunction-symptom list is constructed and also published. He assembled a list from *'operator's experience and user manual from dealer'*[4]. Unfortunately Yu focussed mainly on subsystems: lubrication and cooling. This means that when searching for symptoms, only the subsystem parameters are addressed. Examples of these parameters are fresh water, sea water, and lube oil inlet and outlet temperature. A small part of the malfunction-symptom table is shown in table 2-2

2-2 Blowby

One of the before mentioned fault behaviors is diesel engine blowby or gas leakages. When blowby occurs, combustion gas can escape the combustion chamber by passing between the piston and the cylinder. Assuming the inlet port has been closed already, this loss of mass

[4]Yu, K.W. *An Intelligent Fault Diagnostic Tool for Marine Diesel Engine System by Neural Network with Fuzzy Modification.* National Kaohsiung Institute of Marine Technology, 1998

Table 2-2: List of industrial diesel engine defects and their occurrences

Fault condition	Symptoms	
Exhaust valves with burnt seat	Exhaust gas temperature	mid-high
	Engine speed	mid-low
Overloaded engine	Fresh water outlet temperature	mid-high
	Fresh water delivery pressure	high
	Sea water outlet temperature	mid-high
	Lube oil inlet temperature	mid-high
	Lube oil outlet temperature	high
	Exhaust gas temperature	high
Uncalibrated fuel injectors	Exhaust gas temperature	mid-low
	Engine speed	mid-low
Contaminated lube oil	Fresh water outlet temperature	mid-high
	Lube oil outlet temperature	high
	Lube oil delivery pressure	mid-low
	Exhaust gas temperature	mid-high

and enthalpy causes the pressure inside the combustion chamber to decrease and effectively the combustion pressure is being reduced. A decrease in the combustion pressure results not only in a performance reduction but it also affects the exhaust emissions. That is why blowby is a concern from both an economical and environmental point of view.

To prevent the air from leaving the combustion chamber, a number of piston rings are assembled around the piston. They seal the clearance between the piston and the cylinder in order to prevent blowby and consequently retain the gas pressure during compression and combustion. Due to its oscillating movement the piston exerts a lot of force on the piston rings which can cause a decrease in contact pressure and wear on the cylinder. These phenomena in combination with the pressure gradient can eventually lead to blowby. Once the hot and contaminated combustion gas passes through the developed gap it can cause a severe ring temperature rise, carbon deposit, and possible wear, increasing the gap even more.

In most literature, the passage between the rings is considered to be a labyrinth passage. A representation of this passage is shown in Figure 2-3[5].

The number of rings and their purpose depends on the type of engine. Figure 2-3b shows that there are two different ways in which the gas can pass a ring, on the piston side through a small clearance between the ring and its groove or on the cylinder side through an orifice. This model used by K. Wannatong et al suggests that blowby can be mathematically modelled by a one-dimenstion Reynold's equation for the small clearance and an isentropic orifice flow for the piston ring gap. In the model used for this thesis the same assumption as Aghdam and Kabi is made: the flow goes through the piston ring gap. In their simulation model they only accounted for the isentropic orifice flow and compared it with experimental results. This means that the we assume that the gas will pass between the ring and the cylinder and not

[5]Wannatong, K., Chancaona, S., Sanitjai, S. *Simulation Algorithm for Piston Ring Dynamics.* Simulation Modelling Practice and Theory Vol. 16, 2008

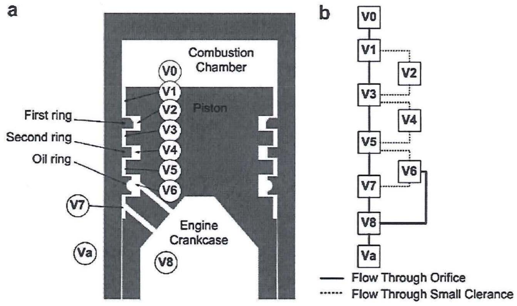


Figure 2-3: Labyrinth passage: a) cutaway model and b) block diagram flow model

through a small clearance between the ring and its groove. This comparison is showed in Figure 2-4[6].

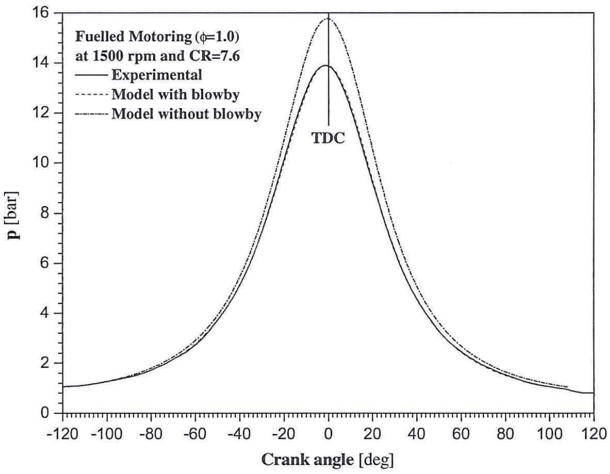


Figure 2-4: Experimental results versus model output of Aghdam and Kabir

The figure shows that the modelled blowby line coincides with the experimental blowby results. The authors tested at several speed levels and compression ratios and the maximum deviation from the experimental results was only 5%. Therefore it can be stated that their assumption of an isentropic orifice flow is a founded one.
Another assumption made is that the gaps of the different piston rings are equal and thus the gaps can be modelled as one gap. In this assumption there is no storage volume for the gas between two rings and consequently the gas passing the first ring will immediately pass the other rings to. This is stated because the area of the gap will be a model input variable and it is not possible to measure the size of the gap of each ring specifically, therefore this simplification will be sufficient for this model.
All literature about the blowby process uses the same foundation: orifice mass flow due to a pressure gradient and consequently a pressure change in the volume. This means that first the gas flow out of the combustion chamber must be determined and when the mass change

[6] Aghdam, E.A., Kabir, M.M. *Validation of a Blowby Model using Experimental Results in Motoring Condition with the Change of Compression Ratio and Engine Speed.* Experimental Thermal and d Science Vol. 34, 2010

is known the pressure change inside the combustion chamber can be computed.
To calculate the mass flow out of the combustion chamber we assume, like mentioned above, that the gas flow through the ring gaps results in an isentropic orifice incompressible flow. Shapiro mentioned this type flow in his book *The Dynamics and Thermodynamics of Compressible Fluid* and the same equation is also derived in Staperma's *Diesel Engines Vol. 2 Turbocharging.* Both describe the mass flow as seen below.

$$\dot{m}_{gap} = \frac{C_D A_{gap} p_U}{\sqrt{R T_U}} f_m \tag{2-1}$$

where

$$f_m = \begin{cases} \gamma^{\frac{1}{2}} \left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{2(\gamma-1)}} & \text{if} \quad \frac{p_D}{p_U} \leq \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \\ \left(\frac{p_D}{p_U}\right)^{\frac{1}{\gamma}} \left[\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_D}{p_U}\right)^{\frac{\gamma-1}{\gamma}}\right]\right]^{\frac{1}{2}} & \text{if} \quad \frac{p_D}{p_U} > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \end{cases} \tag{2-2}$$

and

$$C_D = 0.85 - 0.25\left(\frac{p_D}{p_U}\right)^2 \tag{2-3}$$

Equation 2-3 is obtained by fitting experimental measurements.[7] In the equations p_U, T_U and p_D represent the upstream pressure and temperature and downstream pressure. Some authors also include blowback in their simulation[8] but since it is not included in this model the upstream indicates the values inside the combustion chamber and the downstream represents the surroundings.
Once the amount of air flowing out of the combustion chamber $\dot{m}_{gap}$ is known the pressure can be calculated for the new situation. The best way to do this is to insert the new, decreased mass in the ideal gas law.

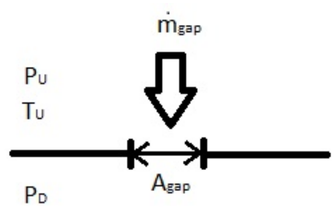


Figure 2-5: Schematic representation of the modelled orifice flow

2-3 Fuel injection faults

This type of fault occurs quite often compared to other types of failures, as can be seen in Figure 2-1 and confirmed by Lin et al. This statement has also been confirmed by the Marinebedrijf since it is their most common diagnose in case of a fault. Injection faults is a

[7]Tian, T., Noordzij, L.B., Wong, V.W., Heywood, J.B. *Modelling Piston-Ring Dynamics, Blowby, and Ring-Twist Effects.* Journal of Engineering for Gas Turbines and Power Vol. 120, 1998
[8]Wannatong, K., Chancaona, S., Sanitjai, S. *Simulation Algorithm for Piston Ring Dynamics.* Simulation Modelling Practice and Theory Vol. 16, 2008

set of different problems concerning the injection of fuel in the cylinder. The timing can be off, the injector holes can be eroded or clogged or fuel may leak due to a decreased tension in the spring. The difference between fuel leakage and injection timing is that during leakage the fuel is released in an uncontrollable way while the problem with injector timing faults is purely the start of injection. Another type of injection faults includes the fuel pump; if the fuel pressure changes so does the dispersion and atomization inside the cylinder causing deviations in the combustion process.

Lin et al use a diesel engine test rig to experiment with a faulty injector and compare this situation with a reference state for both the in-cylinder pressure and the acoustic emission. The authors state that injector faults can have a severe effect on the operating of a diesel engine, it can cause misfire, knocking, insufficient power output or even complete engine breakdown. In their article they implement the faulty state by partly grounding off the injector pintle head in order to simulate a defect in the fuel spreading pattern. They state that the fault could not be detected by comparing the pressure-time signal of the reference and the simulated injector fault contrary to the acoustic emissions. This is said to be caused by the fact that the fault only influences the spreading pattern and atomization of the fuel, not the amount of fuel or the injection timing. The figures that should defend the first part of this conclusion show a full cycle of compression, combustion and expansion and are not zoomed in at all, see Figure 2-6[9] Maybe if they showed a more detailed figure around TDC and the maximum pressure the difference would be better visible. The authors also states that the pressure signal is not completely useless when it comes to detecting a faulty injector because the lower orders of a post processing envelope analysis technique show significant deviations between the reference condition and simulated fault.

The effects of an injector problem on the performance of a diesel engine has been studied with a simulation model by Hountalas and Kourmenos. To simulate a faulty injector they reduced the fuel dispersion quality and expected that especially the rate of combustion would be influenced. The simulation showed that the power output and maximum combustion pressure decreased and the specific fuel consumption greatly increased. Injection timing can deviate in two directions, increasing the injection timing will result in an increase of efficiency and maximum combustion pressure and a decrease in exhaust gas temperature. But an increase of injection timing may also result in diesel knock, seriously damaging the cylinder. A decrease in injection timing will have the opposite effect.

[9] Lin, T.R., Tan, A.C.C., Mathew, J. *Condition Monitoring and Diagnosis of Injector Faults in a Diesel Engine using In-Cylinder Pressure and Acoustic Emission Techniques.* 14^{th} Asia Pacific Vibration Conference Hong Kong, 2011

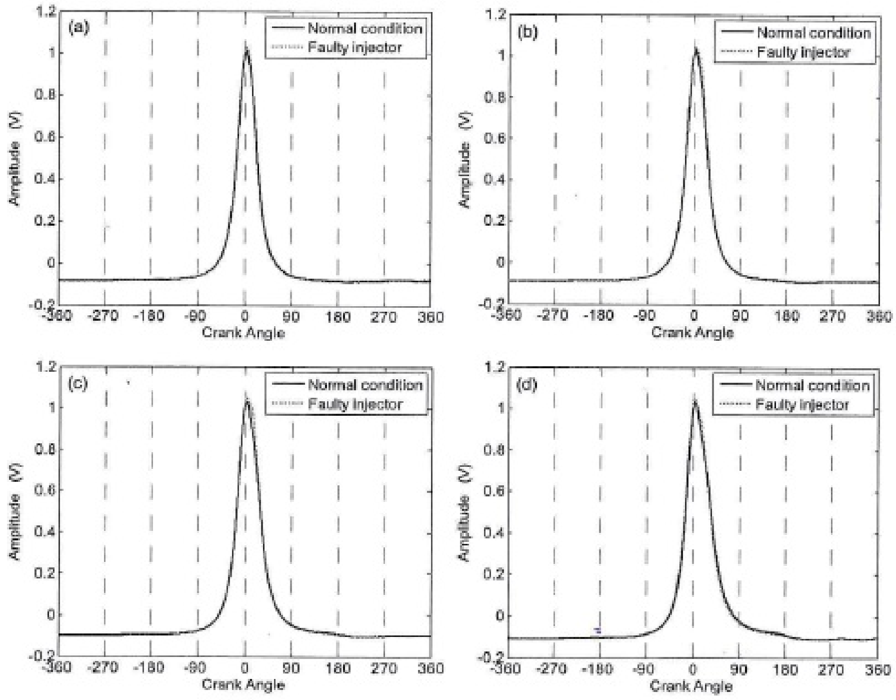


Figure 2-6: Averaged output of the in-cylinder pressure sensor at normal and injector fault conditions at a) unload, b)1/3 load, c) 2/3 load, and d) full load conditions

Chapter 3

Heat release

Heat release theory is an important aspect of this thesis and therefore the relevant parts will be discussed below. Most information is extracted from Stapersma's *Diesel Engines Vol. 3 Combustion*.

The heat release, as the name suggests, contains information about how the heat of the fuel is being released during a combustion process; it states the release of the fuel's chemical energy caused by the combustion process. Since it contains a lot of information about the combustion, analysing it is an important tool in the research of diesel engine processes. The whole functioning of a diesel engine is some sort of chain reaction with a lot of subsystems, all contributing to the combustion. Therefore subsystem problems can theoretically be found in the combustion characteristics. One of these characteristics is the heat release and that is why in theory it is perfectly suitable for fault diagnosis. This theory will be investigated in the thesis.

Heat release can be expressed in different ways, equation 3-1, 3-2 and 3-3 represent the Net Apparent Heat Release Rate, Gross Apparent Heat Release Rate and Combustion Reaction Rate.

$$NAHRR = \dot{Q}_{comb} - \dot{Q}_{loss} = mc_v \frac{dT}{dt} + p\frac{dV}{dt} \tag{3-1}$$

$$GAHRR = \dot{Q}_{comb} = mc_v \frac{dT}{dt} + p\frac{dV}{dt} + \dot{Q}_{loss} \tag{3-2}$$

$$CRR = \xi = \frac{mc_v \frac{dT}{dt} + p\frac{dV}{dt} + \dot{Q}_{loss}}{u_{comb}^{ref} - \Delta u_{comb}^{ref}} \tag{3-3}$$

The heat release cannot be measured directly in the engine during combustion. It has to be calculated from in-cylinder pressure measurements combined with the engine parameters based on physical principles, such as the gas law and mass balance. This is exactly what will be done in the thesis simuations, as can be seen in the model explanations. The use of these physical principles includes a lot of assumptions, discussed in Chapter 5.

In this thesis the Vibe model will be used to quantify the heat release, one of the more successful and widely applied combustion theories. The basis for this model is the rate in which fuel molecules are broken up into so called 'active radicals' by 'attacking' oxygen molecules. To quantify this reaction rate, the normalised rate of combustion Z and normalised combustion progression X are introduced. They are stated as follows:

$$X = \frac{m_f^{comb}(t)}{m_{f,0}^{comb}} = \frac{\text{nr of fuel molecules broken up}}{\text{initial nr of fuel molecules}} \tag{3-4}$$

$$Z = \xi \frac{\Delta t_{comb}}{m_{f,0}^{comb}} \tag{3-5}$$

Where ξ, or combustion reaction rate (CRR), represents the time derivative of the burnt fuel. This value is produced by both simulation models.

$$\xi = \frac{m_{f,0}^{comb}}{dt} \tag{3-6}$$

When X and Z are expressed in non-dimensional time τ, which has the value 0 at SOC and 1 at EOC, the following mathematical simplifications result

$$X = 1 - e^{-a \cdot \tau} \tag{3-7}$$

with

$$Z = \frac{dX}{d\tau} \tag{3-8}$$

$$Z = a \cdot e^{-a \cdot \tau} \tag{3-9}$$

These normalised reaction progression and normalised reaction rate represent the linear Vibe model with parameter a. This model offers too little freedom to shape the heat release of a diesel engine combustion process. Therefore the non-linear Vibe model with added form factors is introduced.

The non-linear Vibe function adds more assumptions to be able to introduce more form factors. These assumptions are that the reaction rate is dependent on time and the reaction rate has to start off at zero and ends at zero. This results in the next equations for X and Z.

$$X = 1 - e^{-a \cdot \tau^{m+1}} \tag{3-10}$$

$$Z = a \cdot (m+1)\tau^m e^{-a \cdot \tau^{m+1}} \tag{3-11}$$

Parameter a is related to the combustion efficiency and the new parameter m is called the form parameter, shaping the Vibe function. A low value results in an early, peaky combustion while a higher value corresponds with a later, flatter combustion.As the equations show, this non-linear Vibe function is not capable of producing multiple combustion phases, which is needed to realistically describe the diesel engine's combustion.

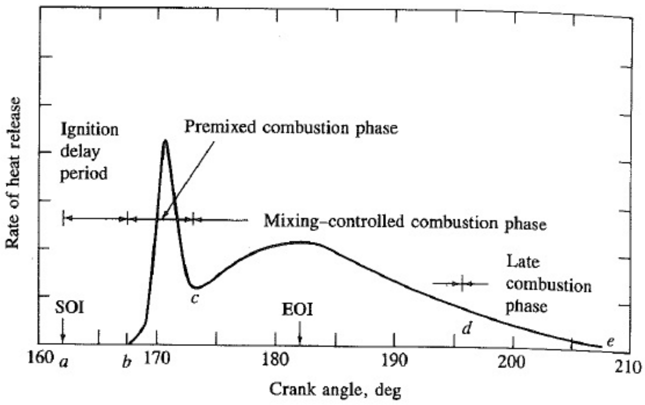


Figure 3-1: Example of a heat release rate diagram

An example of such a double phased combustion is shown in Figure 3-1[1]. During the first, premixed combustion phase the fuel that has mixed with the air between start of injection (SOI) and start of combustion (SOC) ignites rapidly in a few crank angle degrees. Because the fuel has had some time to build up and evenly mix with the air inside the cylinder, this combustion phase is often very peaky, described by a low m value. During the diffusive, or mixing-controlled, combustion phase, the heat release rate is controlled by the availability of fuel in the cylinder. This availability depends on the injection rate, atomization, vaporization, and preflame chemical reactions but is controlled by the slowest process, which is the fuel vapor-air mixing. The flattened shape of this combustion phase can be characterised by a larger shape factor.

Because of these different shape factors, multiple non-linear Vibe functions are often used in combustion reconstruction. It is formed by two or more Vibe functions on a common time base, all with their own weighting factor b. In this thesis only the double Vibe function will be used resulting in:

$$Z = b\left(a \cdot (m_1+1)x^{m_1} e^{-a \cdot x^{(m_1+1)}}\right) + (1-b)\left(a \cdot (m_2+1)x^{m_2} e^{-a \cdot x^{(m_2+1)}}\right) \tag{3-12}$$

$$X = b\left(1 - e^{-a \cdot x^{m_1+1}}\right) + (1-b)\left(1 - e^{-a \cdot x^{m_1+1}}\right) \tag{3-13}$$

Although each part has its own weighting and form factor, the parameter a will be the same for both phases.

[1]Heywood, J.B. *Internal Combustion Engine Fundamentals.* McGraw Hill, 1988

Chapter 4

Conclusions

This literature survey showed that the different maintenance strategies can be applied on different types of systems by combining their benefits and downsides with the demands of the system. Determining which program is best for a system can be tricky but it is very important and can eventually be profitable in terms of costs, performance, and reliability.
In the thesis a diesel generator from one of the Royal Netherlands Navy vessels will be considered. The most important factor when determining a maintenance strategy for this system is reliability: breakdown of the system should be avoided and therefore condition monitoring sounds as the best option. Another reason why condition monitoring is most suitable for this system is because the Netherlands Defense Organisation has its own maintenance and overhaul department, called the Marinebedrijf, with their own revising department and a wide variety of spare parts on the shelf. This makes the implementation of preventive maintenance relatively easy to implement
The condition of these specific diesel engines is being monitored by periodical vibration monitoring, tribology and in-cylinder pressure measurements. These three methods have to support eachother in determining the engines condition, in which they all have their own share. Pressure signal analysis is particularly interesting because it is measured during the core process of the engine; the combustion. In theory, most problems that arrise can be detected during the combustion phase since that is the moment that all the different elements come together.
Although the in-cylinder pressure signal contains a lot of information, the presentation determines what is visible and what is not. Currently the pressure-crank angle curve is being analysed but the previous chapters have shown that faults can be overlooked. In an attempt to improve the diagnostics of diesel engine condition monitoring and extract more information from the pressure signal, the heat release may be a candidate.
The literature survey showed that the heat release can potentially reveal more information about the combustion. Another benefit of the heat release compared to the pressure signal is that it can be quantified with the Vibe function parameters. The second discussed representation method of the pressure measurements is the temperature-specific entropy, Ts, diagram. Although not quantitative, Ts possibly simplifies the detection of faults.

In the thesis this small segment of the big picture of condition monitoring will be investigated in an attempt to improve the diagnostics.

Part II

Thesis

Introduction

Part I explained the theory as a foundation of this research. In the next part the theory will be used to search for a better way of presenting the obtained pressure measurement data in the scope of condition monitoring. As mentioned in the end of part I, three different represenations are being discussed

- pressure versus crank angle
- heat release in terms of Vibe parameters
- temperature versus specific entropy

The first one is nowadays the most common way of analysing the pressure signal and is a purely qualitative technique. The second and third representation are being investigated and compared to the first one. Of these three, Vibe is the only quantitative technique. The goal is to see if the pressure signal can be presented in such a way that analysis can be simplified and thus faults can be detected more easily and no unneeded overhaul is executed.

The next chapter will cover the simulation models being used to test the hypothesis. Although they are pre-existing, their purpose and functioning will be explained. Furthermore the determination of a benchmark engine will be discussed.
In chapter 6 the simulations run with the described models will be examined: which simulations were done, why and how. And to analyse the accuracy of the simulation the output is being verified.
After the simulations are run the outcome has to be analysed and validated, which is being done in chapter 7. In the analysis the simulations will be examined by the three different representations mentioned above.
Following from these chapters, conclusions will be drawn and further recommendations will be made in chapter 8 and 9.

Chapter 5

Modelling

To support the theoretical part of this survey some of the faults will be tested in practice. The optimal situation would be a real life test on a testbed. In that case the healthy condition, serving as a reference, could be measured and compared to the in-cylinder pressure measurements when one or several faults have been introduced. These tests would surely reveal the potential of the discussed condition monitoring methods. Unfortunately, within the available time frame of the thesis, this optimal testing condition was not available. Therefore existing simulation models, combined with measurement data from the diesel engines onboard the naval ships, are used to test the theoretical hypothesis that heat release and Ts diagram analysis can improve condition monitoring diagnostics.

The following chapter explains the background of the two existing MatLab models used to test the theoretical thesis. These models have been expanded in the scope of this thesis to artificially introduce blowby. Both of the models needed parameter adjustments to function as the selected benchmark engine. Also the chosen benchmark engine and its relevant (combustion)parameters are being considered in chapter 5-3.
All together this chapter will explain the tools used to simulate an existing engine and to serve as practical support of the theoretical foundation of this thesis.

5-1 Cylinder process model

One of the MatLab models used for the simulations is the cylinder process model. This model, as the name already indicates, simulates the process inside the cylinder and since the research considers in-cylinder pressure measurements this simulation model is very useful. A schematic representation of the model is given in Figure 5-1[1]. The model has been previously built in a modular way based on the readers *Diesel Engines* from Stapersma and the thesis of Ding.

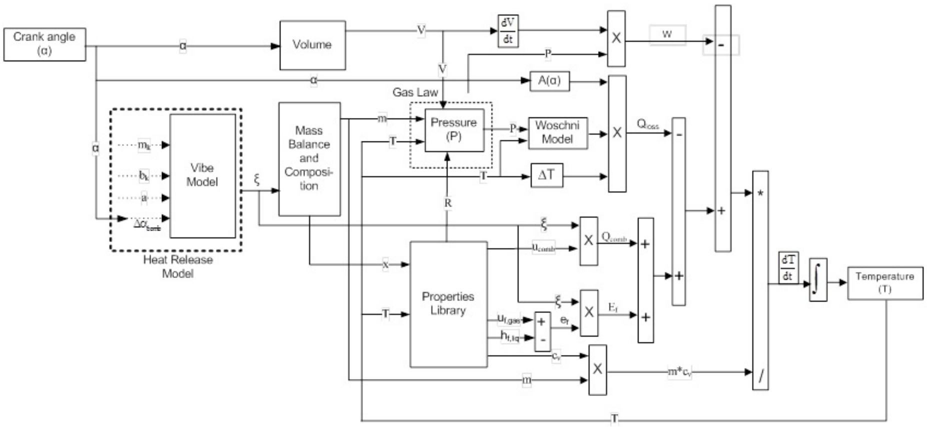


Figure 5-1: The cylinder process model

The basis of this model is a derived version of the energy balance as described in Equation 5-1. To solve this equation the simulation model contains different parts, all substituting to the process.

$$\frac{dT}{dt} = \frac{(u_{comb}^{ref} - \Delta u_{comb}^{ref})\xi - \dot{Q}_{loss} - p\frac{dV}{dt}}{m \cdot c_v} \tag{5-1}$$

First an empirical model is used to determine the heat release in terms of Vibe parameters. This heat release shape is then used to find the instantaneous mass and composition inside the cylinder with the mass balance.
Combining this mass, composition and the volume determined by the engine's geometrical information together with the temperature, the pressure can be calculated with the ideal gas law. As the flow diagram shows, the temperature comes from the output of the model. To prevent an algebraic loop, the first value of T, T_1 , is given as input parameter. The calulated pressure and temperature are used to determine the heat loss to the exposed cylinder area in terms of the Woschni heat loss coefficient.
The produced heat is determined by the output of the heat release model combined with the heating value of the fuel.
Finally the first law of thermodynamics combines the produced heat, lost heat and work, the area under the pV diagram, to obtain the nominator of Equation 5-1. The denominator can be calculated from earlier mentioned values.

[1]Campero, B.C. *Characterization of Combustion Profiles of Diesel Engines.* TU Delft, 2012

The equations and models used in the cylinder process model all have their own assumptions. One of these assumptions is that between the closing of the inlet valve and the opening of the outlet valve, the cylinder is a closed system. This means that nothing enters or exits the system in that time range. Obviously this assumption causes problems when blowby is being simulated. But apart from blowby, this assumption may be wrong since there is always some amount of mass leaking, which makes the cylinder a more open than closed system. Also the temperature of the cylinder area, devided in the wall, piston crown, and cylinder head, is assumed to be a constant during the combustion cycle. During injection the model assumes perfect atomization and direct combustion: the injection rate, evaporation rate and combustion rate are considered to be equal. This so called 'single zone model' is a simplified case of the more refined 'multiple zone models'. Simulation of atomization faults, like when the injector holes are eroded or the injection pressure is lowered, conflict with this assumption. Also, since the ideal gas law is implemented, the combustion gases are modelled as an ideal gas.

When the standard model parameters are set correctly, according to a predetermined benchmark engine, the most important input of the model are the Vibe parameters a, b and m. Although other variations are possible, the model standardly contains a double Vibe function. The Vibe model and its parameters have been previously discussed in the heat release part of the literature survey, chapter 3. Based on these parameters the combustion reaction rate is determined resulting in the pressures and temperatures that can be assigned to the corresponding crank angles.
In short, this model links the shape of the heat release, according to the Vibe parameters, to the pressure signal in the cylinder. Although it can be used for a lot of different simulating purposes and it offers many input parameters which can be altered, most values will be kept constant in this application. For instance the type of fuel that is used or the scavenging efficiency.

The model serves different purposes in this survey, depending on the combustion information available. In case the pressure trace is known, the cylinder process model is used to validate the produced Vibe parameters from the heat release model by comparing the output pressure signal with the original one. Its second function is to visualize the effects of blowby on a healthy pressure signal. For this purpose a blowby subsystem had to be created and implemented in the existing cylinder process model. How this is done is presented in chapter 5-1-1. The model has been build to investigate the different combustion parameters and has not yet been used to visualize the effects of faults in diesel engines. That is why a secondary goal of this thesis is to explore the model's possibilities in fault simulation applications.

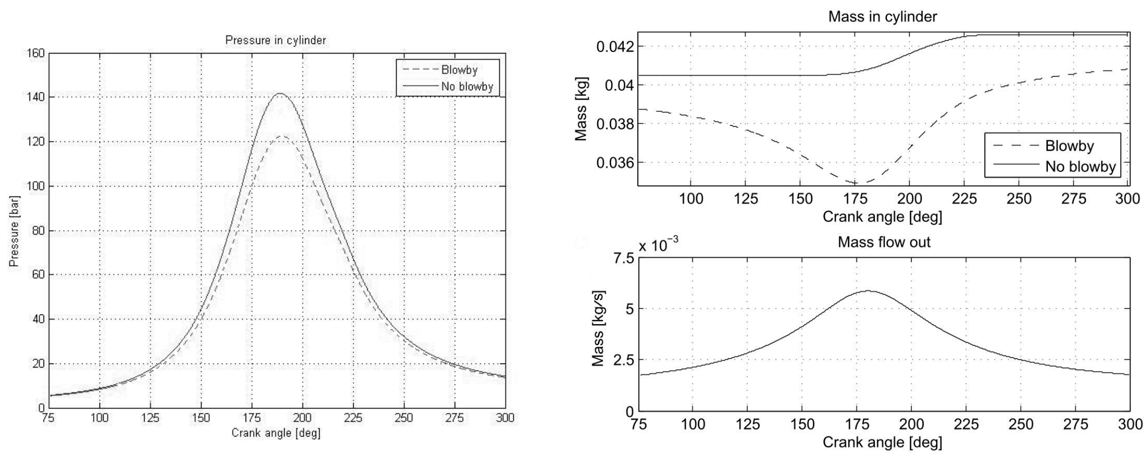
5-1-1 Blowby implementation

To implement the blowby theory from chapter 2-2 in the existing MatLab cylinder process model, a subsystem is added in simulink. The subsystem is added to the block where the pressure is calculated, see Figure A-1 in appendix A. This pressure is used as an input for the blowby system. All the inputs and their source are addressed in Table 5-1. With this input, the mass loss, new mass, and new pressure are being calculated for each time step in the simulation. The total subsystem as it is implemented in simulink is shown in appendix

Table 5-1: Input blowby subsystem

Parameter		Source
Downstream pressure	p_D	Manual input, standard 1 bar
Upstream pressure	p_U	Output from simulink
Upstream temperature	T_U	Output from simulink
Discharge coefficient	C_D	Computed from equation 2-3
Gas constant	R	Output from simulink
Volume combustion chamber	V_p	Output from simulink
Specific heats	c_p, c_v	First value: manual input and calculated from R, other values: output from simulink
Area of the gap	A_{gap}	Manual
Mass inside combustion chamber	m	Output from simulink
Blowby	-	Manual: 1 if blowby, 0 if no blowby

A Figure A-2 and Figure A-3. The blowby subsystem assumes that the leaking mass does not contain unburned fuel that has just been injected. This assumption is according to the model's single zone assumption, discussed earlier in this chapter. An example of the influence of this blowby subsystem on the simulation is shown in Figure 5-2. The graph corresponds with the images found in literature, as shown in Figure 2-4.



(a) *Pressure* **(b)** *Mass*

Figure 5-2: Example of blowby influence on simulated pressure and mass

The full lines in Figure 5-2a and Figure 5-2b I represent respectively the pressure and the mass inside the cylinder with no blowby, while the dashed lines represent the same input but with the simulated blowby. The line in Figure 5-2b II shows the mass flow exiting the cylinder due to the blowby process. Because of the dependancy of $\dot{m}_{gap}$ on the difference between p_D and p_U, of which p_D is assumed to remain constant, it has the same shape as the pressure trace.

Due to the lack of real blowby cases, the size of the ring gap had to be estimated. The magnitude was derived from Wannatong et al and Aghdam et al who mentioned the gap area used in their blowby simulation. These values ranged between 0.99 mm^2 and 1.81 mm^2.

Assuming that the size of the engine and specifically the circumference of the piston head is an influencing factor on the gap area, the type of engine considered in the articles had to be compared to the benchmark engine. In Wannatong et al the engine bore is given to be 80.26 mm, which is almost 3.5 times smaller than the benchmark engine with a bore of 280 mm. That is why the range of gap area of the benchmark engine is estimated to be between 2 mm^2 and 3.5 mm^2. In the simulations the area of the gap was set to 3 mm^2.

5-2 Heat release calculation model

The second model is called the heat release calculation model. Besides the standard input parameters it loads a pressure trace and the accompanying crank angles from an excel database and produces the corresponding temperature, heat release, and burnt fuel. The combustion reaction rate can then be fitted with a Vibe function to produce the matching parameters.
Most of the formula's used in this model are also implemented in the previously discussed cylinder process model, only in a different order, with this model being an "anti-causal" simulation. This means that the models can be used interchangeably to validate one system's output by reproducing its input with the second model.
The uploaded crank angle, together with the geometrical input data and rotational speed produces the instantaneous volume. Combined with the pressure signal this results in the work done by the piston. Furthermore the ideal gas law is used to determine the temperature and the feedback of the combustion reaction rate determines the composition of the content of the cylinder. Just like in the cylinder process model, Woschni is used to determine the heat loss. The Net Apparent Heat Release Rate excludes the heat loss while for the Gross Apparent Heat Release Rate this heat loss is being added. The schematic representation of the heat release model is shown in Figure 5-3[2]. The model has been previously built in a modular way based on the readers Diesel Engines from Stapersma and the thesis of Ding.

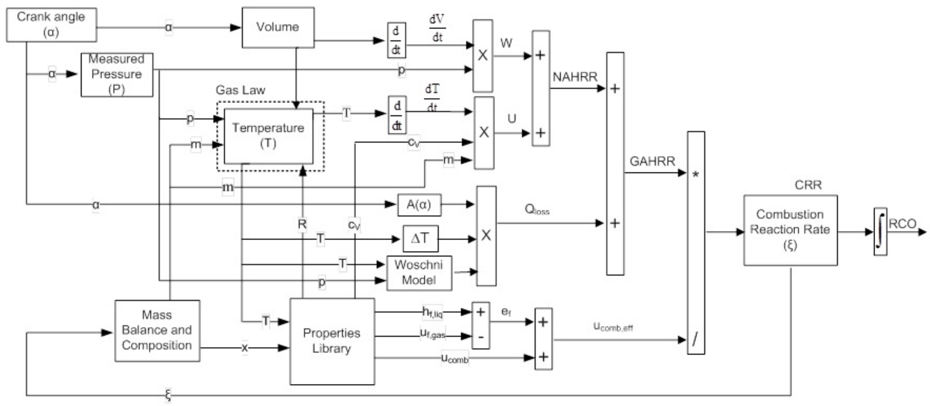


Figure 5-3: The heat release calculation model

When the standard model parameters are set correctly according to the predetermined benchmark engine, the most important input of the model are the pressure trace and crank angles. These are uploaded from actual measurements taken from the benchmark engine and supplied by the Marinebedrijf. This department of the Netherlands Defense Organisation manages, among other types of data, all the pressure measurements taken from the pressure measurement-compatible diesel engines on board the navy vessels.
The heat release model is used to produce the combustion reaction rate of a pressure measurement and fits this according to the double Vibe function. The fit will result from either the normalised rate of combustion Z or the normalised combustion progression X. These are derived by the model from the produced ξ according to the following equations:

[2]Campero, B.C. *Characterization of Combustion Profiles of Diesel Engines.* TU Delft, 2012

$$Z = \xi \frac{\Delta t_{comb}}{m_{f,0}^{comb}} \tag{5-2}$$

and

$$Z = \frac{dX}{d\tau} \tag{5-3}$$

The loaded pressure measurement can originate from the before mentioned database but it can also be produced by the cylinder proces model. This second possibility is used in the blowby simulations.

5-2-1 Blowby implementation

When blowby is simulated with the cylinder process model, it generates a set of pressures and corresponding crank angles which can be uploaded in the heat release model to fit this according to Vibe. The only adjustment that has to be made in the heat release calculation model in order to realistically simulate the heat release is the mass change. Therefore the blowby subsystem from the cylinder process model is implemented in the mass balance.

5-3 Benchmark engine

Because the simulations are meant to replace real life engine tests the model needs to be as close to a real engine as possible. This means that its input must be set to an existing engine, a benchmark engine. Choosing a suitable benchmark engine means it will have to meet some requirements.

- The engine needs to be fitted for in-cylinder pressure measurements
- There needs to be a database of previously measured pressure traces
- At least one of these traces should be suitable to serve as reference condition
- The database preferably contains pressure measurements of known faulty conditions
- Basic information of the engine needs to be easily retrievable
- The engine load needs to be as constant as possible

It is obvious that the search for a benchmark engine started at the non destructive research department (NDO) of the Marinebedrijf since they administer the measurement data of all the diesel engines used in the Royal Netherlands Navy. Although non of the engines is fitted with online, continuous pressure measurement, some are fitted for temporary pressure measurements obtained with a system called Premet. These measurements are obtained regularly and are used to monitor the engine's condition by qualitatively analysing the shape of the pressure trace versus crank angle. Since pressure traces are required for the benchmark engine, the ones not suitable for pressure measurements can already be discarded.

With the requirements in mind the benchmark engine choosen is the 12SW28 diesel engine, or more specifically the four engines installed on board the Zr. Ms. Rotterdam. The reason this engine has been selected is because it is a diesel generator, meaning that it runs at relatively constant load, easing the comparison of the measurements. Besides that there is a lot of data in the form of engine parameters and pressure measurements available from the year 2002 to 2013.

The data available has been retrieved from the NDO department, the engine producer Wartsila, and the ship Zr. Ms. Rotterdam. When studying the gathered material, a few differences became clear right away.
First of all, the data supplied by Wartsila mentioned a SW280 instead of a SW28 engine. They mentioned that a lot of different editions of this engine are available depending on the application and release date. Differences can be found in valve timing, injection timing, type of injectors etcetera which influences the pressure signal.
The data from the ship consisted of a so called 'afnameverslag,' or delivery report, dating back to 1995 when the engines were bought. Since then, has received modifications because the Marinebedrijf reported another valve timing than the delivery report. According to them the valve timing has been changed because of 'occasional starting problems'.
Since the Marinebedrijf seems to be the most up to date source, their information is applied and where possible the delivery report is used.

The relevant technical specifications received from the different parties are listed in Table 5-2. It shows that the difference between some parameters is quiet large, especially the pressure of the injected fuel. Apparently the values from Wartsila are based on a configuration with fuel pumps producing a much higher fuel injection pressure. The differences are probably caused by the age of the Rotterdam engines compared to the state of the art configurations Wartsila delivers nowadays.

Besides the engine parameters, the NDO department also handed over the database containing all of the SW28 in-cylinder pressure measurements obtained with the PREMET system since 2002. The database consists of 25 folders from different dates. Some of these folders contained PREMET files, which can only be viewed with the PREMET software program, some only included the excel spreadsheets with the pressure values, and other folders had both. Not all folders included all of the four engines and in most cases the load in terms of percentages was not mentioned. Most of the folders containing excel spreadsheets had several versions of it, all with small shifts of the TDC position. The way in which this TDC is determined can be found in appendix C. The NDO department told that when other operators use the post processing TDC detection, they sometimes adjust it because it seems to be off. The adjusted versions, together with the original version, are all saved in the same folder with different additions like 'manTDC', 'AUTOTDC', 'NDO' and 'corrected'. Some of the folder names had additions too, like 'measured by the Marinebedrijf', 'modified by Rotterdam' or 'BNO'.

The excel spreadsheets format leaves some room for additional information about the measurement, such as the number of cylinders, the bore, and the firing order. Although these values are considered to be constant, they are not the same in all of the excel spreadsheets. For instance, the length of the connecting rod is 630mm, as reported by the Marinebedrijf and the excel spreadsheets from 2002 till roughly 2009. Then suddenly the length of the connecting rod is said to be 1015mm in the excel sheets from 2010 and later. All of these factors introduced uncertainties of which dataset was a good representation and which was not.

There was also a difference in the number of measured datapoints: most of the spreadsheets consisted of 360 datapoints per cylinder for one revolution while others contained four times this amount, without any clear reason. Stapersma mentiones that a cylinder pressure signal related to the crank angle should contain at least 500 data points for every revolution.[3] If all the measurements consisted of 1440 datapoints, the curve would be more accurate.

In all the gathered data, the search was for a good reference value and datasets containing proven faults. For the reference value, the data from Wartsila and the delivery report were discarded because of the modifications. In the database from the Marinebedrijf one folder is named '190802 BNO', representing measurements after overhaul on the 19th of August 2002. When the assumption is being made that 'measurements after overhaul' means that the engines are all restored in their optimal running condition, this measurement seems to be a good reference value. Although they have not been taken recently, it is the best option available in the database. The folder contains the excel spreadsheets of the engines, except

[3] Stapersma, D. Lecture notes TU Delft, *Diesel Engines Vol. 3 Combustion*. RNLNC, 2010

for diesel engine four. A reason for this could be that this engine has not been overhauled due to less running hours.

Finding a dataset with a known fault is difficult since the diagnostic reports are not included and above that no feedback is incorporated in the diagnostic process. One folder, dating from the 28th of March 2012, contains, besides the excel spreadsheets, four text files describing for each engine which cylinder is diagnosed with leaking injectors. Ofcourse, this diagnosis has not been validated from the overhaul department with the lack of feedback but still, the dataset is a good candidate for fault analysis.

Unfortunately no other datasets containing other types of faults have been found. This means that from the database, two datasets will be analysed with the simulation: one after overhaul, functioning as a reference condition, and one with diagnosed leaking injectors.

Table 5-2: Specifications benchmark engine

Parameter		Value	Source	Model input
Manufacturer	-	Stork Wartsila	Afnameverslag	
Engine type	-	12 SW 28	Afnameverslag	
Brake power	P_b	3780 kW	Afnameverslag (100%)	
Rotational speed	N	900 rpm	Afnameverslag (100%)	X
Mean effective pressure	P_{me}	22.7 bar	Afnameverslag (100%)	
Number of cylinders	i	12	Afnameverslag	X
Bore	D_b	280 mm	Afnameverslag	X
Stroke	L_s	300 mm	Afnameverslag	X
Stroke volume	V_S	0.0185 m^3	Calculation	X
Length connecting rod	L_{cr}	630 mm	Metingen Marinebedrijf	X
Inletvalve opened	-	61^o btdc	Afnameverslag	
		51^o btdc	Marinebedrijf	
Inletvalve closed	-	66^o abdc	Afnameverslag	
		76^o abdc	Marinebedrijf	X
Exhaustvalve opened	-	70^o bbdc	Afnameverslag	
		60^o bbdc	Marinebedrijf	X
Exhaustvalve closed	-	45^o atdc	Afnameverslag	
		55^o atdc	Marinebedrijf	
Moment of injection	-	16^o btdc	Marinebedrijf	
Fuel consumption	-	793.14 kg/h	Afnameverslag	
Specific fuel consumption	sfc	209.94 g/kWh	Afnameverslag	
Inlet air temperature	T_1	325 K	Afnameverslag	X
Inlet air pressure	P_1	2.70 bar	Afnameverslag	X
Geometric compression	ϵ	13	Marinebedrijf	X
ratio		12.7	Wartsila	
Volume top dead centre	V_{TDC}	0.0015 m^3	Calculation	
Air fuel ratio	afr	16.5	Calculation	
Air excess ratio	λ	1.129	Calculation	X
Fuel injection pressure	$P_{fuel,inj}$	1425 bar	Wartsila (MDO)	
		340 bar	Marinebedrijf	X
Fuel injection temp	$T_{fuel,inj}$	314 K	Estimation	X
Cylinder wall temp	T_{wall}	500 K	Estimation	X
Piston crown temp	T_{piston}	700 K	Estimation	X
Cylinder head temp	T_{head}	680 K	Estimation	X
Swirl factor	$\frac{w_t}{c_m}$	5	Estimation	X
Woschni constant	C_{hl}	130	Estimation	X

Chapter 6

Simulation and verification

Since reallife tests with self-induced faults were not feasible, this chapter will deal with the executed simulations. Verification of the results is done by reproducing the original input with the cylinder process MatLab simulation model as will be explained in this chapter.

Three types of simulations were run, forming the three parts of this chapter. First, the reference condition will be analysed by running the heat release model with a data set obtained directly after maintenance. Secondly, the same dataset will be run but blowby will be introduced with the cylinder process model. Finally, a seperate dataset is loaded which is marked to contain leaking injectors, according to NDO diagnosis.

6-1 Reference condition

The best way to establish a reference condition for the benchmark engine would be to use the pressure trace from the so called 'afnameverslag'. Unfortunately, this pressure signal is not representative as a reference, since the engine has been modified after purchase. This is also shown in Table 5-2, where the valve timing reported by the Marinebedrijf differs from the afnameverslag. To obtain a realistic reference value, another dataset has been used. In the data provided by the Marinebedrijf one dataset is named 'BNO', which represents the tests after overhaul. This dataset originates from the nineteenth of August 2002 and contains the pressure measurements of one cycle of all the cylinders, except diesel engine four. The reason this engine is missing in the dataset could be that it did not need maintenance and therefore was not tested afterwards. The pressure signal is normally displayed with the PREMET software program, supplied with the measuring gear, but the values can also be presented in an excel spreadsheet. This sheet contains some basic information about the measurements and twelve columns of 360 pressure values, one column for every cylinder and one row for every crank angle from 1 to 360 degrees. When these pressures and their corresponding angles are uploaded in the heat release model, it produces information of the combustion process.

As mentioned before, the dataset is used to determine the healthy condition of the diesel engine so it can be compared to other, faulty conditions later on. To establish a founded image of the healthy condition, six cylinder measurements will be run from two different diesel engines resulting in twelve cylinders in total. First, one of these simulations will be presented below, serving as an example, and then the other results will be shortly presented.

6-1-1 Example

The heat release model will be adjusted in such a way that the basic settings are corresponding with the benchmark engine data and that it will load the right pressures and crank angles from excel. When the model is done with the simulation the outcome is checked, for instance the value of T_1, p_1, m_{fr} and the exact SOC and EOC, in a second run some of these values will be corrected.
Because m_{fr} is not known for the benchmark engine it has been adjusted every simulation to obtain a combustion efficiency η_{comb} of about 1 at the end of combustion, with $\eta_{comb} = X_{end}$. The result is shown in Figure 6-1.

This adjustment was also needed in the work of Ding, he choose to alter the swirl factor to obtain the same results. The adjustment of m_{fr} ranges between $0.78 < m_{fr} < 0.9$. The range is quite big and no single value can be choosen to represent all of the cylinders when the assumption is being made that all cylinders are perfectly healthy and thus have a combustion efficiency of about 1.
From the second run, the normalised combustion reaction rate (Z) and the normalised fuel burnt (X) versus the dimensionless combustion time τ is fitted by a custom equation in the curve fitting application. These custom equations are based on Vibe parameters and given in equation 6-1 and 6-2. In this figure only the combustion phase is fitted and therefor the values before SOC or $\tau = 0$ and after EOC or $\tau = 1$ are excluded from the fitting.

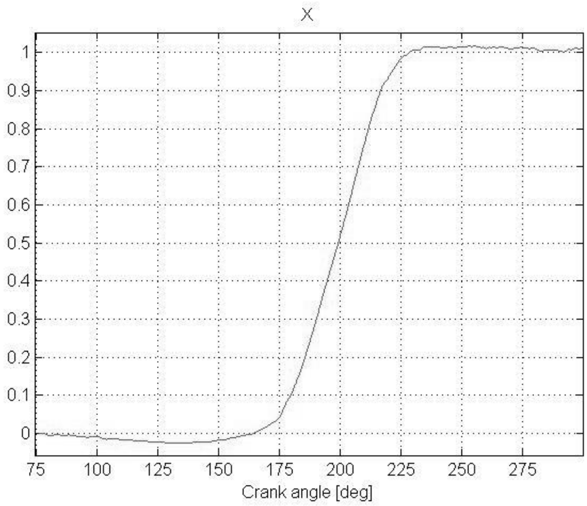


Figure 6-1: Heat release of a reference cylinder

$$Z = b\left(a(m_1+1)x^{m_1}e^{-ax^{(m_1+1)}}\right) + (1-b)\left(a(m_2+1)x^{m_2}e^{-ax^{(m_2+1)}}\right) \tag{6-1}$$

$$X = b\left(1-e^{-ax^{m_1+1}}\right) + (1-b)\left(1-e^{-ax^{m_1+1}}\right) \tag{6-2}$$

This fitting will produce the Vibe parameters a, b_2, m_1 and m_2, b_1 can be calculated from b_1+b_2=1 and because of this dependance only one value for b will be discussed. A double Vibe model is choosen because Ding experimentally proved that a double Vibe model produced a better fit than the single Vibe model but the triple Vibe model did not provide further significant improvement.[1] Ding also assumed a constant value for a of 6.9, to simplify the fitting procedure. Also he showed that a change in m and a change in a almost has the same results. This means that a change in m can be compensated by a change in a. Since the fitting procedure in this thesis did not experience any difficulty, both values are free to choose by the curve fitting application. Such a double Vibe fit results in Figure 6-2a and Figure 6-2b, being screenshots from the curve fitting application, and the corresponding parameters are listed in the table in 6-2.
The parts before SOC and after EOC of Figure 6-2a show a clear striped pattern, which probably results from interference of the signal and the sampling rate. Together with the Vibe parameters, also R$_{square}$ is tabulated. This parameter contains information about the goodness of fit; when its value is 1 the fit is a perfect replica of the original line. Compared to other examples of Vibe quantified heat releases[2] the values for m are very high. Usually the premixed combustion has an m lower than 1 and the diffusive phase about the size of the premixed phase in Table 6-2. This means that the combustion phases are less peaky and appear much later. A reason for this could be that the value for SOC is too low, resulting in an early start of τ, but when looking at the heat release flow this does not seem to be the case. Another cause could be a systematic fault in the input data. Some possible examples can be found in appendix B.

[1]Ding, Y. *Characterising Combustion in Diesel Engines.* VSSD TU Delft, 2011
[2]Stapersma, D. Lecture notes TU Delft, *Diesel Engines Vol. 3 Combustion.* RNLNC, 2010

Although, according to the R_{square} values, both fits are reasonably good, the parameter values are far from identical. To check which set of parameters match the original dataset the best, each set is checked with the cylinder process model and the resulting pressure signal is compared to the original one. This comparison is shown in Figure 6-3a and Figure 6-3b. In these figures, the dashed line represents the original pressure signal and the normal one shows the reproduced pressure trace from the cylinder process model based on the Vibe parameters obtained from the Z and X fit respectively. Both lines are reasonably suitable as combustion representation, but obviously the Vibe parameters obtained from the fitting of the normalised burnt fuel produce the best representation of the original pressure signal.

Besides the Vibe parameters, also the Ts diagram will be analysed in the scope of condition monitoring. In Figure 6-4 this diagram is shown, again with the dashed line being the calculated temperature-entropy from the original pressure trace and the normal one is simulated according to the Vibe parameters from the X fit. The dashed line, produced by the heat release model shows a gap in the compression phase. This missing data is found in most of the Ts diagrams from the heat release model. Although the cause was not found, it is not a problem while analysing, since the starting point is shown and a small reconstruction can show where the line would have been.

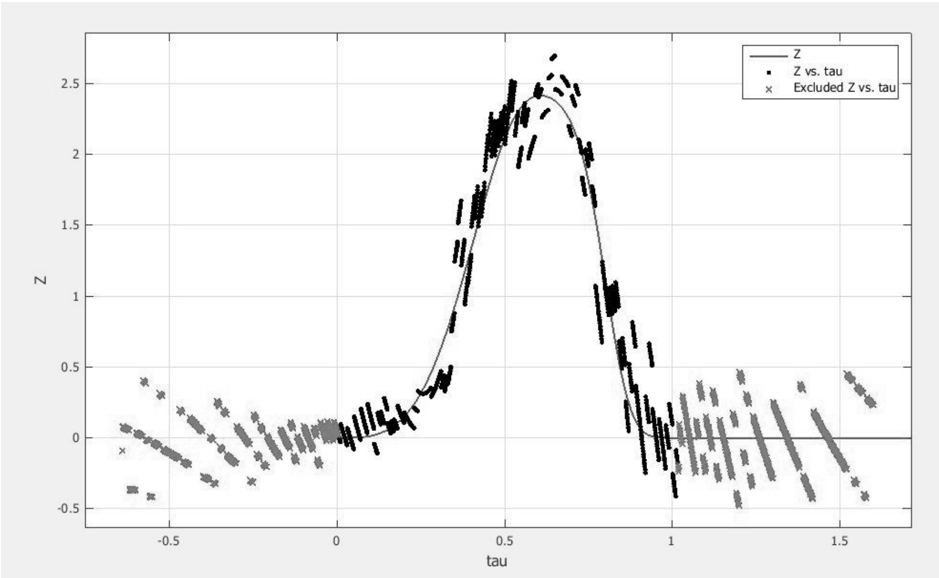
6-1-2 Simulations

As mentioned before, to establish a good image of the healthy condition, twelve cylinders were simulated in the way described above. In all cases, the X fit was proven to give a better combustion reconstruction than the Z fit. This is caused by the smoothing of the signal when Z is integrated to obtain X, which is also visible in the dispersion of the datapoints in Figure 6-10a. The best fit was easily found by MatLab and the accuracy of the fit, R_{square}, was always above 0.99. The obtained Vibe parameters are depicted in table 6-1. In these simulations the SOC and EOC are kept constant at respectively 140^o and 240^o.

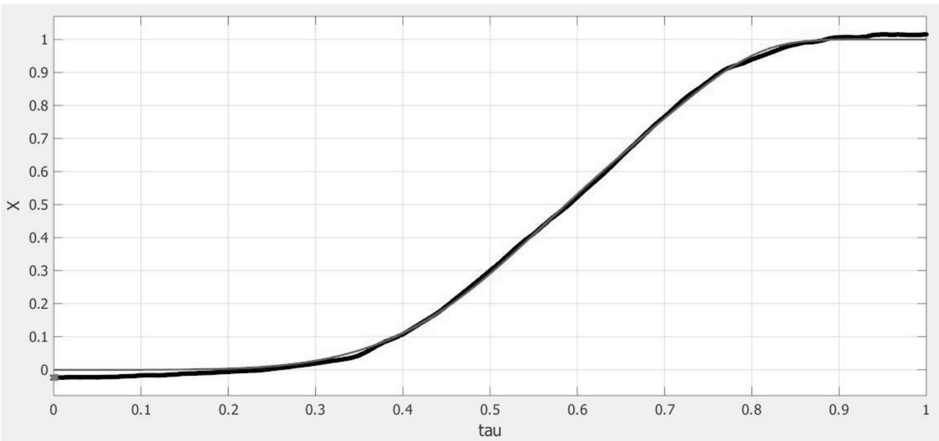
Table 6-1: Vibe parameters all the reference cylinders

	cyl 1	cyl 2	cyl 3	cyl 4	cyl 5	cyl 6	cyl 7	cyl 8	cyl 9	cyl 10	cyl 11	cyl 12
a	10.95	10.04	16.16	13.28	16.9	13.11	17.77	17.53	15.45	21.66	19.97	20.09
b_1	0.777	0.779	0.603	0.757	0.657	0.788	0.714	0.669	0.745	0.741	0.687	0.669
b_2	0.223	0.221	0.397	0.243	0.343	0.212	0.286	0.331	0.255	0.259	0.313	0.331
m_1	3.431	3.463	3.511	3.646	3.645	3.748	3.968	3.995	4.043	4.388	4.104	4.028
m_2	9.369	7.279	9.275	10.53	10.57	11.99	13	9.156	10.82	12.15	11.08	10.19
m_{fr}	0.86	0.87	0.78	0.78	0.78	0.85	0.83	0.87	0.9	0.81	0.87	0.88

An extensive analysis of the results can be found in chapter 7.



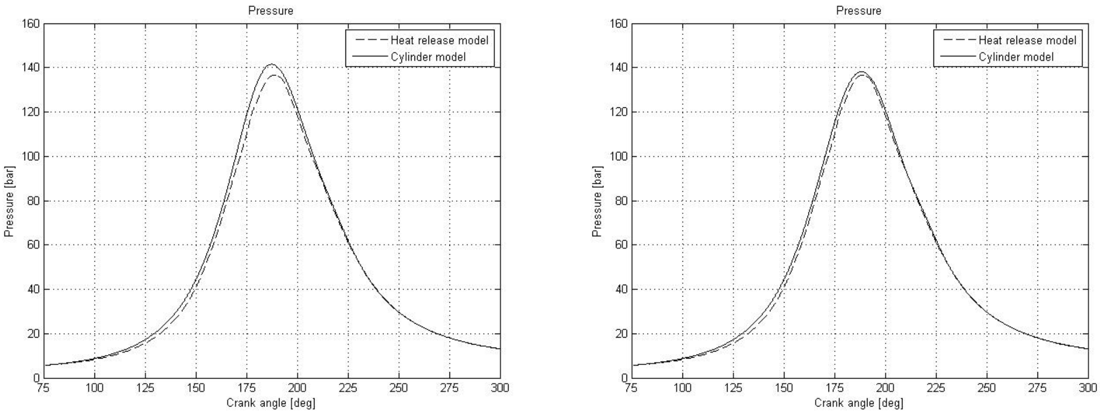
(a) Z fit



(b) X fit

Parameters	Z fit	X fit
a	13.33	17.53
b_1	0.6336	0.6689
b_2	0.3664	0.3311
m_1	3.426	3.995
m_2	7.338	9.156
m_{fr}	0.83	0.83
SOC	140^o	140^o
EOC	240^o	240^o
R_{square}	0.9501	0.9993

Figure 6-2: Fitting the heat release of the reference condition



(a) According to Z fit parameters

(b) According to X fit parameters

Figure 6-3: Reproduced pressure trace by the cylinder process model compared to the original one

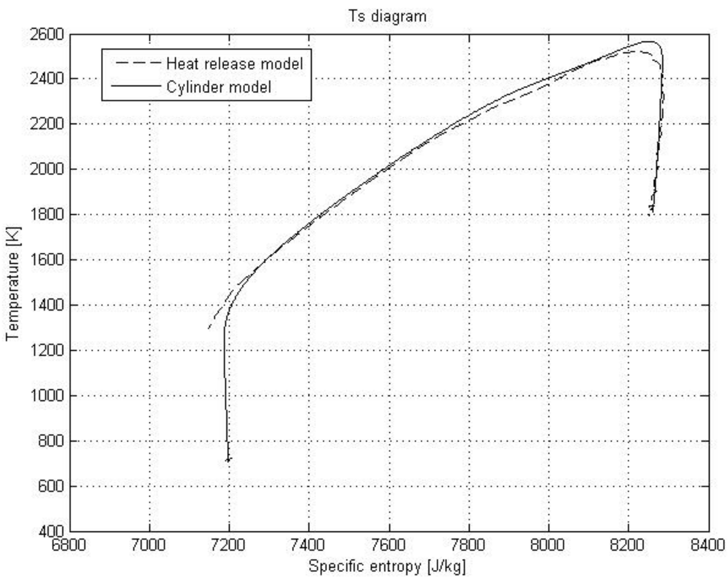


Figure 6-4: Original and simulated temperature-specific entropy diagram

6-2 Blowby

In chapter 5, the blowby subsystem of the cylinder process model and heat release calculation model have been discussed. Because of this simulated fault behaviour it is possible to examine the effects of blowby on the pressure and heat release profile without the need of a dataset containing this fault. To be sure that the simulated output contains only blowby and no other influencing faults, the reference condition is used as input. The cylinder model uses the Vibe parameters of the reference cylinders found in the previous chapter and applies a blowby process on it. The produced pressure signal is then loaded in the heat release model to simulate the blowby heat release. First the more realistic case of a pressure signal containing an unknown blowby fault will be discussed. In that case, the mass in the heat release model will not be altered by the blowby. If the presence of blowby in the pressure signal would be known, the mass in the heat release model can be adjusted, which will be done later on.

The standard settings of the blowby process are a gap area of 3mm^2 and a downstream pressure of 1 atm, according to the literature survey and assumptions made in these chapters. A severe gap was choosen to be sure that the output will give a clear image of the effects of blowby on the pressure, heat release and Ts diagram. The downstream pressure, or pressure inside the carter, is assumed to be equal to the atmospheric pressure and stay constant.

To investigate the effects of blowby, the Vibe parameters of eight reference cylinders are used. These cylinders are randomly choosen from the twelve which were already simulated as a reference. Just like in the previous chapter an example will be examined first and after that the other measurements will be depicted. Also the example will be compared with the outcome without blowby.

6-2-1 Example

One of the reference cylinders will be subjected to blowby in the cylinder process model. To do so, blowby is activated and the Vibe parameters and settings for T_1, p_1 and m_{fr} are applied. These parameters are the same as the ones used in the overhaul simulations. The output of the simulation, the faulty pressure at different crank angles, will be written to an excel sheet. This pressure is then uploaded in the heat release model with the same parameter settings but without blowby mass change activated. Next the produced heat release profile will be fitted. Again, both Z and X are fitted with the functions mentioned in the previous chapter resulting in Figure 6-5. The reason that blowby mass decrease is switched off in the heat release model is because in reality you would not know before hand that blowby is occuring, let alone that you know how big the gap is. For this reason the pressure signal will contain the blowby effects, just as is produced by the cylinder process model, but the heat release model will assume normal mass change according to the geometry. Later on in this chapter the situation with activated mass change in the heat release model will be discussed.

Just like in the preceding simulations, the X fit gave better results in reproducing the pressure signal but still they were not acceptable. This was to be expected because the fit line does not correspond to the black line for more than a third of the combustion cycle because of the negative values in the first part.

To find the cause of this, various input parameters were checked. Two of these parameters are the start of combustion (SOC) and end of combustion (EOC), these are specifically important because they decide the time frame of the non dimensional combustion time τ. Combustion starts when there is positive heat release for the first time in the cycle and ends when this heat release becomes zero again. Checking the SOC and EOC is therefore done with the heat release flow diagram produced by the heat release model, of which a zoomed in image is shown in Figure 6-6.

Until then, these two parameters never needed any adjustment and the combustion phase was set from 140^o to 240^o but clearly in case of blowby these parameters needed some adjustments. The image evidently shows that SOC is at 160^o and EOC can be roughly stated at 260^o which means a shift of 20^o. This means that $\tau = 0$ will be shifted to the right and the heat release during the combustion phase will consequently contain less negative values.

Still, some values remain negative at the beginning of the combustion phase but this is also the case with the overhauled cylinders in Figure 6-2. Fitting this adjusted function according to the Vibe model was simplified because less parameter boundaries had to be set and the R_{square} also increased. The produced parameters are presented in Table 6-2, together with the found Vibe parameters when no blowby was applied.

Table 6-2: Vibe parameters of blowby

Parameters	Blowby	Reference
a	10.69	10.95
b_1	0.7349	0.7767
b_2	0.2651	0.2233
m_1	2.336	3.431
m_2	7.071	9.369
m_{fr}	0.86	0.86
SOC	160^o	140^o
EOC	260^o	240^o

This single example shows an increase of b_2, and therefor a decrease in b_1, and decreasing a and m values. Looking at the theory of the Vibe model, this would mean that the blowby makes the combustion more peaky and although the premixed phase stays dominant, it looses some of its share to the diffusive combustion. Also, the slightly lower a value shows a lower combustion efficiency.

Interpreting the results of the heat release is tricky since it shows the results of the heat release model when a pressure signal influenced by the leaking mass is loaded while the model assumes a constant mass. Therefor, the shown heat release is incorrect and does not represent what is happening in the cylinder. If a measurement would contain blowby without knowing about it, this incorrect heat release shape together with the lower peak pressure would indicate a possible blowby situation.

In Figure 6-8 the temperature-specific entropy diagram is depicted. The lines are produced by the cylinder process model and heat release model.

As mentioned in the beginning of this chapter, the most realistic monitoring situation has been treated so far; a considered healthy heat release shape is subjected to blowby and the altered pressure signal is fed into the heat release calculation model assuming no mass changes. In the next part the assumption is being made that the blowby fault is known, including the size of the gap, and therefore the mass change is also simulated by the heat release model.

As expected, the pressure signal stays the same since the pressure signal produced by the cylinder process model remains unchanged. The heat release however changes a little, this can be seen in the comparison between the heat release in the reference condition and the second blowby condition in Figure 6-9. This difference, although small, was not to be expected and is probably caused by a double numerical deviation due to the mathematical operations in both models. Figure 6-10 shows the X and Z fit sessions together and the parameters found are depicted in Table 6-3. Here the difference between the reference fit parameters and blowby 2, although small compared to blowby 1, is shown. Compared to Figure 6-7 the X fit no longer has the dip around $\tau = 0$ and it no longer increases after $\tau = 1$. X=1 is not reached since the same m_{fr} as in the reference condition is being used and apparently less fuel is burnt due to the blowby.

The Z fit shows more distinguishable combustion phases which is also visible in the Vibe parameters in Table 6-3. The reference value is the fit determined from the BNO pressure files, blowby 1 represents the fit earlier this chapter without mass change in the heat release model and blowby 2 corresponds with the fit in Figure 6-10. Compared to blowby 1, blowby 2 shows a later diffusive combustion phase and the difference between the two phases also becomes bigger, confirming the earlier conclusion that the combustion phases were more distinguishable.

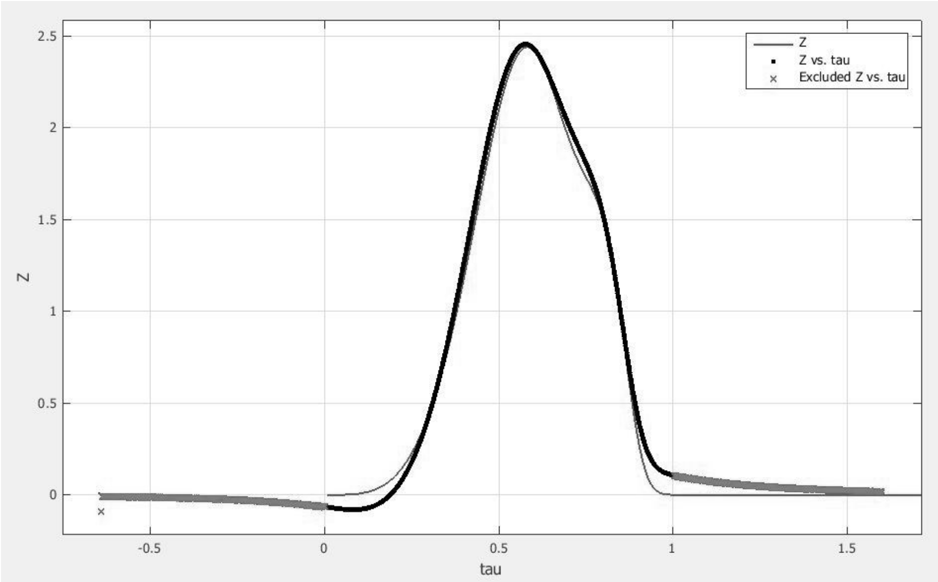
Table 6-3: Vibe parameters of blowby

Parameters	Reference	Blowby 1	Blowby 2
a	10.95	10.69	10.42
b_1	0.7767	0.7349	0.7846
b_2	0.2233	0.2651	0.2154
m_1	3.431	2.336	3.395
m_2	9.369	7.071	9.404
m_{fr}	0.86	0.86	0.86
SOC	140^o	160^o	140^o
EOC	240^o	260^o	240^o

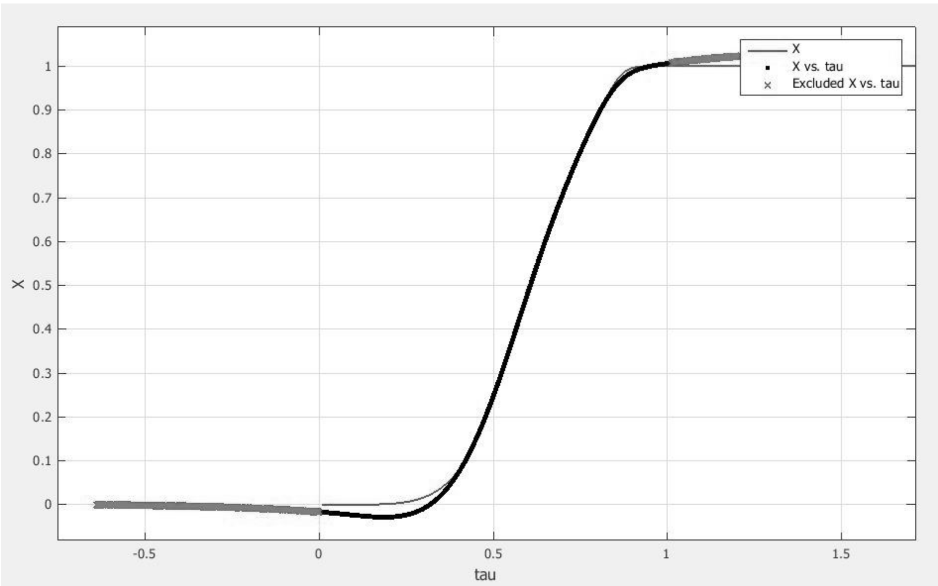
The Ts diagram is depicted in Figure 6-11 with, again, blowby 1 representing the earlier mentioned situation and blowby 2 the new situation with changing mass. The figure shows that in the new situation the compression part is almost identical with the reference condition but especially the end of the combustion shows an elevated temperature and specific entropy. The shape of the polytropic expansion stays the same but at a higher value.

6-2-2 Simulations

The results of the remaining blowby simulations were obtained in the same way as situation 1 since this is the most realistic way in which the condition would be monitored. The simulation of seven other arbitrary choosen reference cylinders resulted in comparable results as mentioned in the example: all the parameters altered in the same way as the first cylinder. For all seven of these simulations the combustion phase was shifted to 160^o-260^o, the X gave a better fit than Z, and the R_{square} was larger than 0.99. The complete comparison of the reference and blowby parameters will be discussed in the next chapter. Also in the next chapter the Ts-diagram will be directly compared with the healthy one.



(a) Z fit



(b) X fit

Figure 6-5: Fitting the heat release of simulated blowby

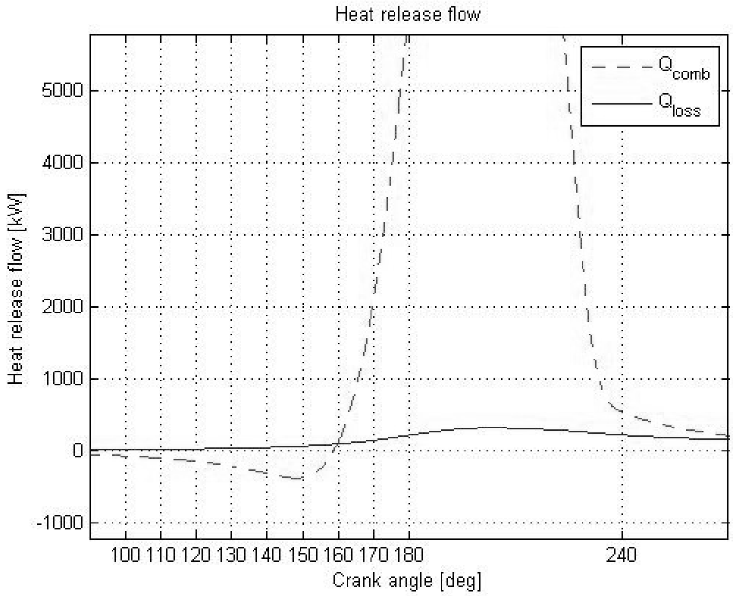


Figure 6-6: Zoomed in heat release flow diagram of simulated blowby

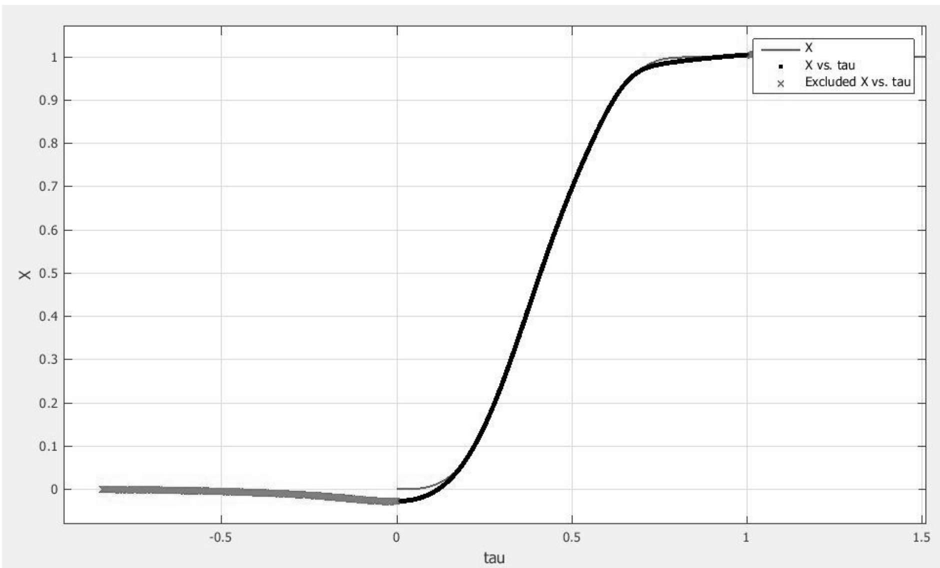


Figure 6-7: Fitting heat release of simulated blowby with adjusted SOC and EOC

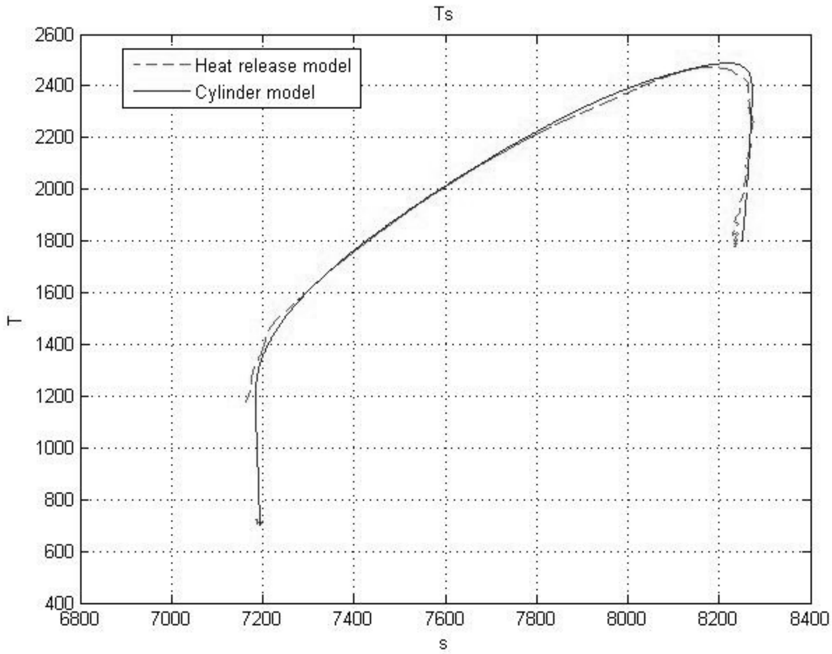


Figure 6-8: Fitting the heat release of simulated blowby with adjusted SOC and EOC

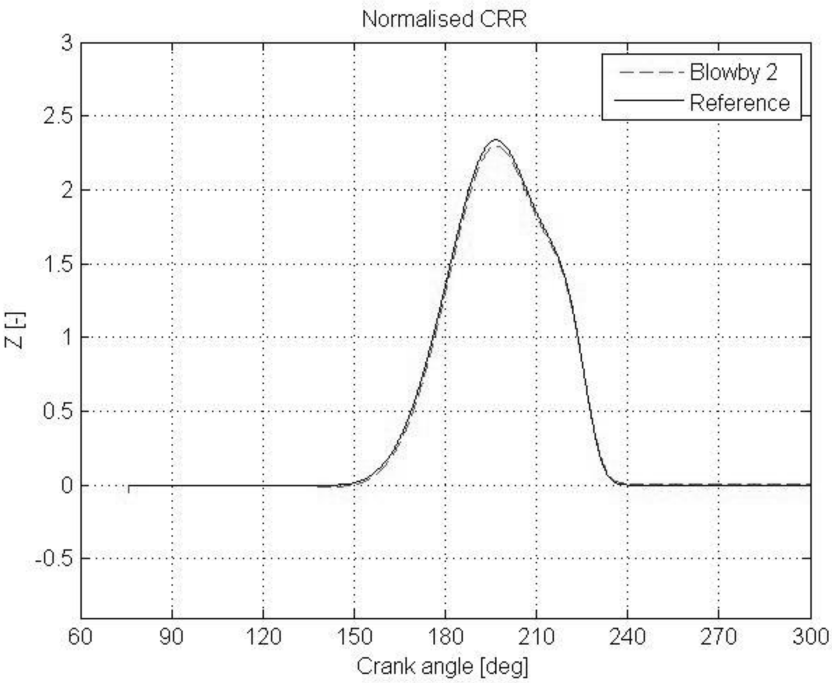
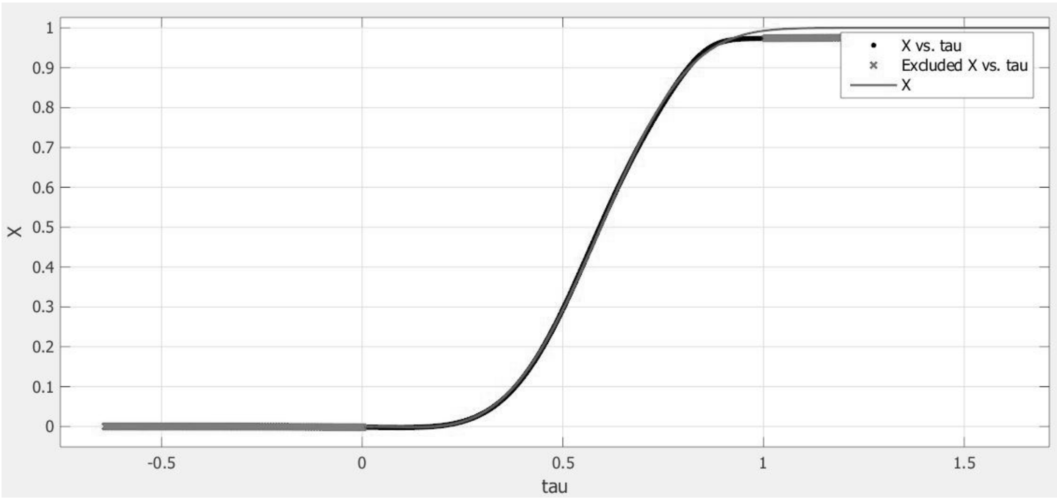
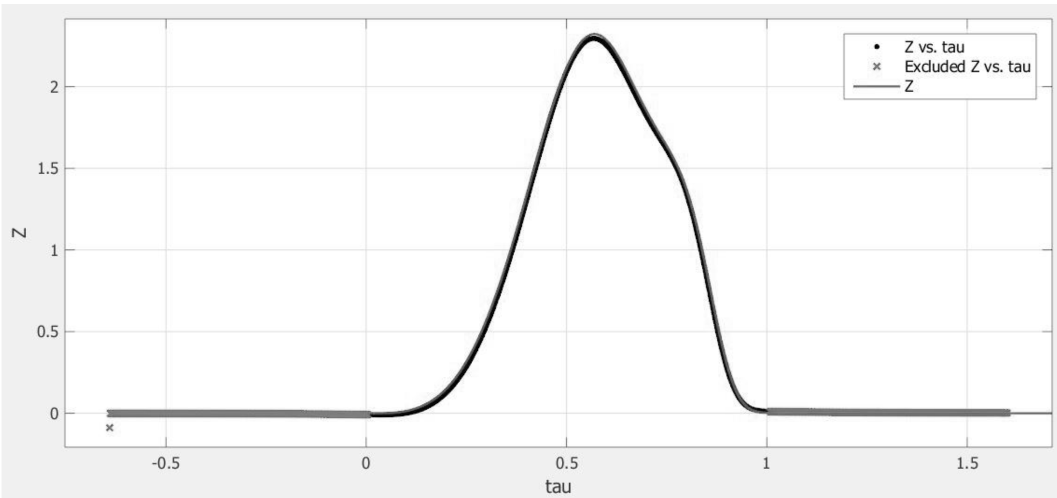


Figure 6-9: Heat release of reference condition compared to blowby situation 2



(a) Z fit



(b) X fit

Figure 6-10: Fitting the heat release of simulated blowby with changing mass

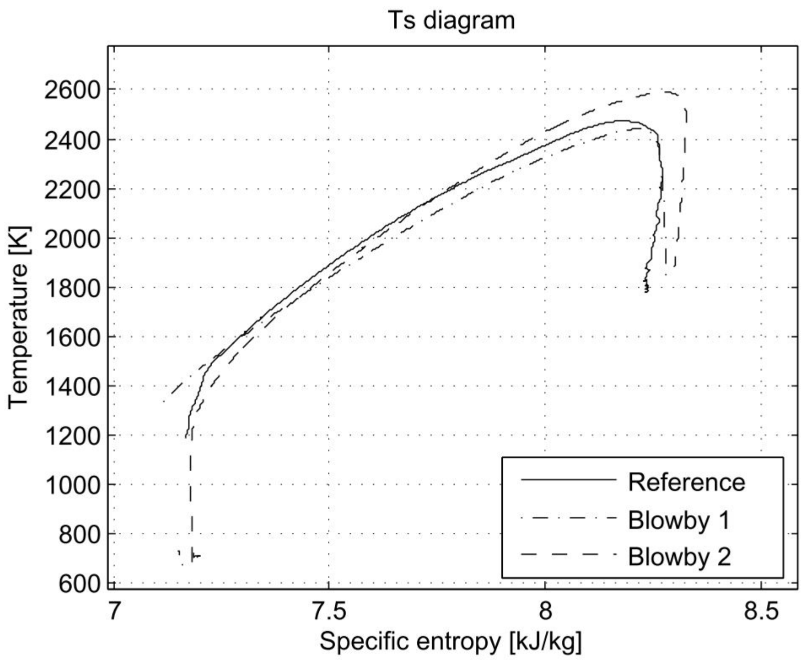


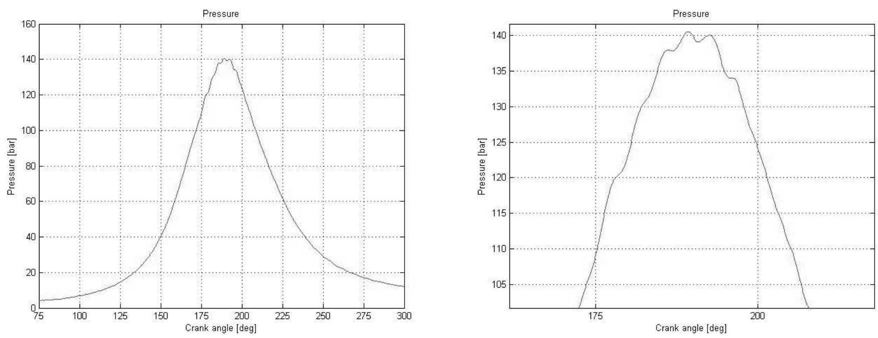
Figure 6-11: Comparing the Ts diagram of the reference condition, blowby 1, and blowby 2

6-3 Leaking injectors

In this last set of simulations a dataset labelled as containing leaking injectors is considered. This diagnosis has been carried out by te NDO department according to deviations in the pressure versus crank angle diagram. The report shows small vibrations in the pressure trace and therefore some cylinders are classified as having leaking injectors. Although all of the four diesel engines contained some leaking injectors, most of them also had cylinders labelled as healthy.

The purpose of these simulations is to see whether the cylinders diagnosed with leaking injectors, based on the pressure trace by the Marinebedrijf, will also show deviations in the heat release analysis and Ts diagram. Comparisons can be made with the reference cylinders but also with the labelled healthy cylinders in the same engine.

The dataset dates from the 28^{th} of March 2012 and involves all four of the diesel engines. The simulations start with diesel engine number three since this dataset contains 1440 datapoints per cylinder for a full revolution while the others only have one datapoint for every crank angle degree. The reason why these datasets contain less information is not clear from the files. The only difference is in the name of the excel file of the third engine, containing 'TDC' as addition. All twelve of the cylinders will be simulated and three of them were diagnosed with leaking injectors, according to the report.



(a) **(b)** Zoomed in

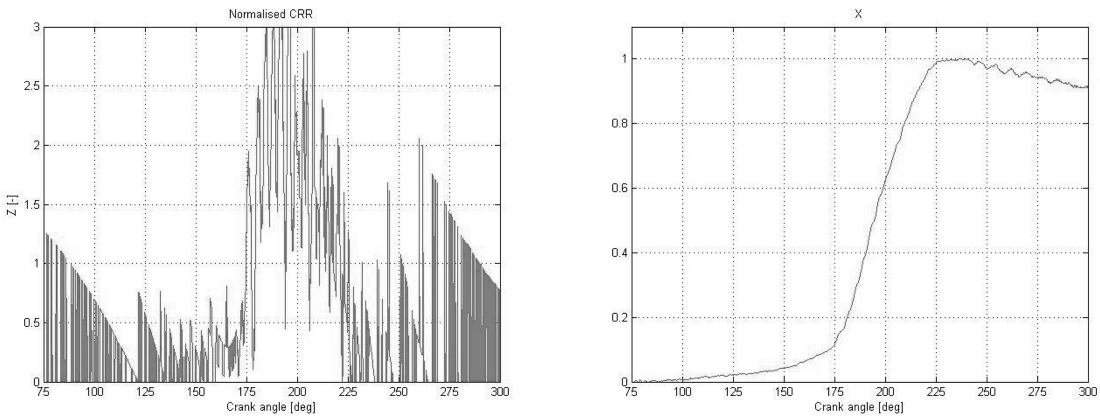
Figure 6-12: Pressure signal of a diagnosed leaking injector

Twelve cylinders, of which three containing a diagnosed fault, seems enough to get a good impression of the difference between the three diagnosing methods in case of leaking injectors. For the sake of completeness, a second diesel engine will also be simulated, containing six assumed faulty injectors. Additional value is that the difference between an input of 1440 and 360 datapoints can be investigated.

6-3-1 Example

Simulation and validation of this dataset is done in the same way as the BNO cylinders: the pressure trace with corresponding crank angles is loaded in the heat release simulation program, modelled with Vibe parameters, and the parameters are validated using the cylinder process model. To illustrate this, the simulation of one cylinder labelled as containing a leaking injector is shown below.

Based on the pressure signal shown in Figure 6-12a, the condition of this cylinder has been diagnosed as faulty and needing injector overhaul or replacement. When this pressure signal is compared to the healthy ones in Figure 6-3 especially the top part has an unusual, vibrating shape. This can be caused by the disturbed injection, troubling the atomization. The injection, and therefore also the combustion, may be jerky, causing the pressure rise to fluctuate because of all the little 'explosions'. Also the size of the droplets may be too big, first taking up heat to break up, an endothermic process, and subsequently causing these sudden combustions, an exothermic process. Another explanation could be that the fluctuations originate from the measuring, for instance due to pollution in the measuring channel.



(a) Normalised combustion reaction rate (Z) **(b)** Normalised fuel burnt (X)

Figure 6-13: Heat release of a diagnosed leaking injector

The corresponding normalised combustion reaction rate and burnt fuel are depicted in Figure 6-13. Notable is that the combustion reaction rate is extremely fluctuating, this will trouble a good Vibe fit for the value Z. Also the interference in the beginning and end part of the signal can be seen.

Also the normalised burnt fuel shows some irregularities: although injection timing is set to a crank angle of 164^o, the line shows that fuel is already burnt from about 100^o. This sounds reasonable, taking into account that a leaking injector means that already before injection, fuel is leaking into the cylinder. If the pressure and temperature in the cylinder are sufficiently high, this fuel can partly burn before actual injection has started. The chance that this will occur so early in the cycle is extremely small and therefore other possible causes are tested in appendix B. Also, this theory of early combustion does not meet up with the slow starting heat release in the reference condition, shown in Figure 6-1. In this case, the shape of X

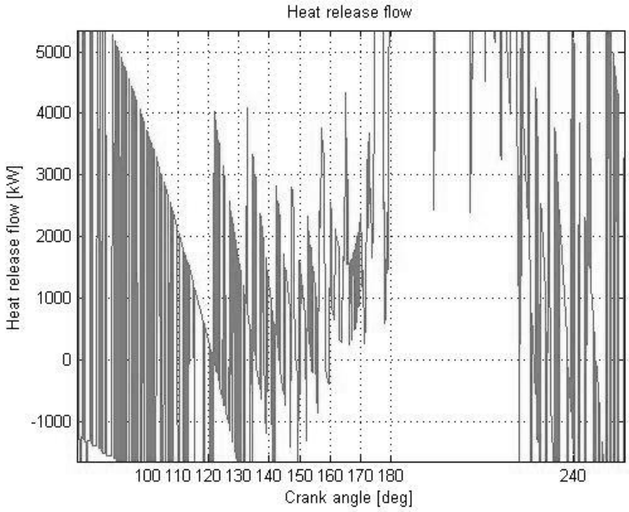


Figure 6-14: Heat release flow of a diagnosed leaking injector

could be caused by a TDC shift, a p_1 that is too low, or the presence of a signal filter in the pressure sensor. Although this will be a problem in the fitting since Vibe assumes that X stays zero untill SOC. A solution would be if the SOC is set earlier but in this case, according to Figure 6-14, the choosen 150^o does not need any adjustments. The only way for Vibe to follow this part of the function is to allow negative values for parameter m.

Another abnormality is the declining nature at the end. This can not be explained with the theory but it will not bother the fitting because the combustion phase ends just before the decline at 240^o.
Figure 6-15 displays the two functions and their best fit with the corresponding parameters.

The Z function is very scattered and not surprisingly the fit does not have a high accuracy. But besides the accuracy, the line seems to follow a good patern between the extremes and the parameters have a credible magnitude, compared to the reference.

The X fit on the other hand, has a close to perfect accuracy but unusual values for $b(_2)$ and m_2. The small positive b and corresponding large negative m show there is a very small, very late combustion at the end of the combustion phase but also it makes the normalised burnt fuel start at X<0. A negative m value causes an infinite heat release at X=0, which is needed to meet up with the early increasing X. In Figure 6-13b it seems like the Vibe fit does not start at 0 but since the slope is infinite due to the negative m, the curve fitting application was not able to depict that part. Although the last quality is needed to get a good representation when fitting X, the first part seems physically impossible.

When verificating the two sets of produced Vibe parameters with the reproduced pressure signal of the cylinder process model, Figure 6-16 results. The image shows that unfortunatly Vibe is not able to reproduce the pressure trace of a leaking injector; especially the first half does not correspond with the original and also it does not contain any vibrations near the maximum pressure. Another conclusion that can be drawn from this figure is that although both Vibe fits do not give a satisfying output, the Z fit seems to be better than the X fit since the maximum pressure is a little higher. This means that the negative value for m_2 together with a higher goodness of fit do not produce a better representation.

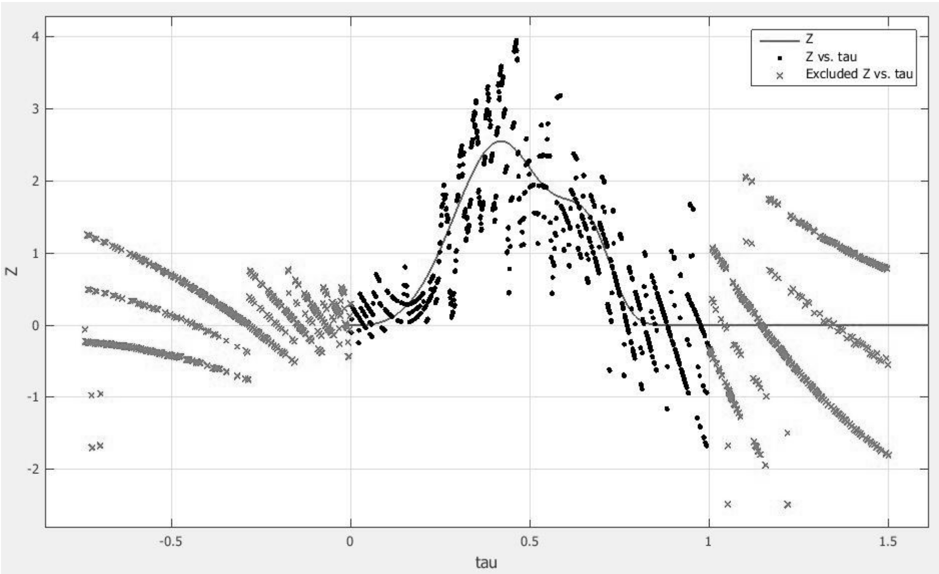
Figure 6-17 shows the Ts diagram for this cylinder with leaking injector. A notable deviation from the healthy case is that the specific entropy increases very early: normally the first part of the line, corresponding with the polytropic compression phase, is almost vertical with a slight decrease in specific entropy. This phenomenon could be caused by a shift in TDC position, as discussed in appendix B. The middle part seems to be corresponding with the healthy curve but the last part, corresponding with the polytropic expansion, is dissimilar because of the fast decreasing entropy, this is supposed to only decrease a little during the temperature decrease. This effect is also seen when a signal filter is applied on the data, as discussed in appendix B. The early entropy increase matches the early rising X and the decreasing s corresponds with the decreasing X after $\tau = 1$.

6-3-2 Simulations

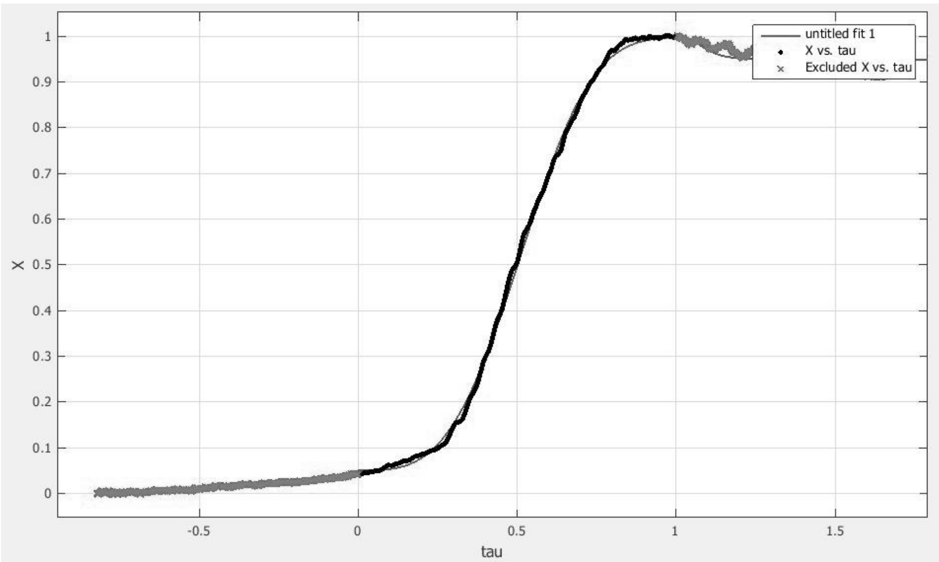
The other eleven cylinders of this diesel engine were also simulated. Two of these were diagnosed with leaking injectors and the others were considered healthy, based on the pressure signal. But when the healthy cylinders were simulated, their heat release contained the same deviations from the healthy engine discussed in the previous chapter as the leaking one. This could also be a confirmation that these measurements contain a structural fault, as mentioned in appendix B. To validate these findings, another six cylinders of a second diesel engine have been simulated. Marginal note here is that the data from this second diesel engine contains about a quarter of the datapoints of the first simulated diesel engine. Since in theory the second engine does not reach the mentioned minimum of 500 datapoints per revolution[3] this could give distorted results.

The question during the simulation was whether the X or Z fit was leading. Benefits of the Z fit is that it contains realistic values and seems to give better results in the validation (Figure 6-16). On the other side, it did not give a good fit according to the R_{square} value because the signal is very scattered. The X fit did have high R_{square} values and did not differ as much from the Z fit in the verification that it has to be discarded. Besides, in the previous analysis the X fit was leading so for fair comparison this pattern should be followed. On the other side the X fit produced strange values for some of the Vibe parameters which seems to be physically impossible. Ding also encountered negative Vibe parameter values in his thesis. His explanation was that they were caused by the partial load of the engine. In this case the negative values seem to be a result of the defects, which is the purpose of this quantitative monitoring technique. Weighing the above benefits and downsides, the X fit is choosen.

[3]Stapersma, D. Lecture notes TU Delft, *Diesel Engines Vol. 3 Combustion.* RNLNC, 2010



(a) Z fit



(b) X fit

Parameters	Z fit	X fit
a	30.85	6.532
b_1	0.6662	0.9494
b_2	0.3338	0.0506
m_1	3.08	2.363
m_2	6.984	-27.39
m_{fr}	0.96	0.96
SOC	140^o	140^o
EOC	240^o	240^o
R_{square}	0.7075	0.9992

Figure 6-15: Fitting the heat release according to Vibe

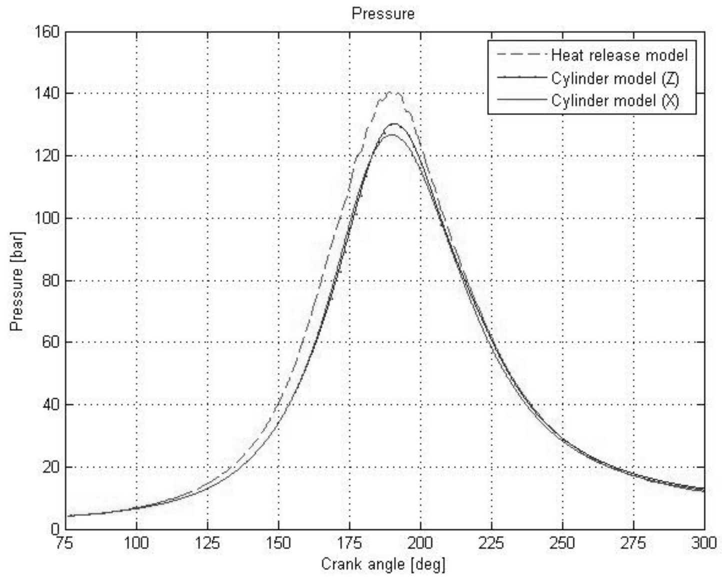


Figure 6-16: Pressure according to the two sets of Vibe parameters versus the original pressure signal

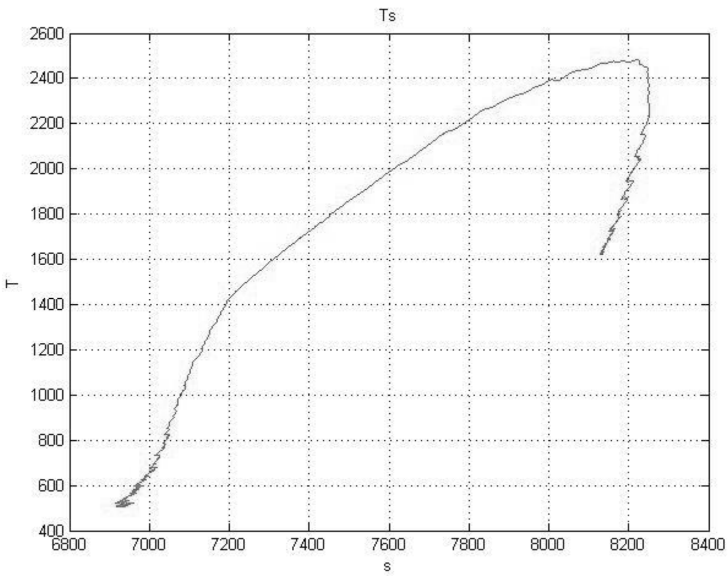


Figure 6-17: Temperature versus entropy of the cylinder containing a leaking injector

Chapter 7

Analysis and validation

The results of the previously discussed simulations will be studied in this part. All of the results will be presented, compared and analysed. Also the outcome will be validated on the basis of the heat release theory.
Because the aim of the thesis is to find a better, or even quantative way of condition monitoring, the results will be discussed for all the three analysis methods, namely the pressure curve, Vibe parameters and temperature-specific entropy diagram.
The three situations that are being considered have also been discussed in the previous chapter: reference, blowby, and leaking injectors. To make a good analysis possible, a few assumptions have to be made. First of all the reference condition is assumed to be a healthy condition for all of the simulated cylinders. In this way it can serve as a baseline to which the other simulations can be compared.
The second assumption is that the dataset with some cylinders diagnosed with leaking injectors, only contain that type of fault. This is an extremely simplifying assumption but since there is no feedback in the monitoring and overhauling process, there is no confirmation. That is why the label 'containing leaking injectors' of the dataset is in this thesis being considered as the feedback. If this assumption is not made, the outcome can not be analysed because in theory it can contain hundreds of faults, all influencing eachother. This is why the only way of establishing a good condition monitoring program requires feedback from the ship and from the overhaul department. Only then reliable criteria can be developed.
For the blowby the assumption is made that during the analysis of the faulty pressure signal, produced by the cylinder process model, with the heat release model, the presence of blowby is not known. This means that the mass flow out of the cylinder is not simulated in the heat release model.

7-1 Pressure

In this first part of the analysis and validation the aim is to clarify the way in which diesel engine condition monitoring is being executed on board and at the Marinebedrijf. What are the images they use to diagnose the condition and how do they look at it? But also which problems seem to be detectable in these images and which not.

The measurements can be anaylised on board of the ship, where the measurement are taken or at the NDO department of the Marinebedrijf. Sometimes both parties check the PREMET measurements as a form of double checking. For a good representation of the pressure diagram the top dead center (TDC) has to be determined with the software since the PREMET measuring system does not have its own TDC detection. The detection requires manual operation and therefore contains subjectiveness. This subjectiveness can have consequences for the timing of p_{max}; although it will not alter the shape of the pressure curve it can cause a horizontal shift.

When the TDC has been determined for every set of twelve cylinders separate, the pressure is displayed versus crank angle. Diagnosing this diagram revolves around the comparison of the individual cylinders of an engine; the operator checks for significant deviations between the twelve cylinders. Again, this is a very subjective technique because what some may label as a deviation can be ignored by others and the other way around. Also this means that no trend in time is being monitored although a database from over 10 years of measurements is available.

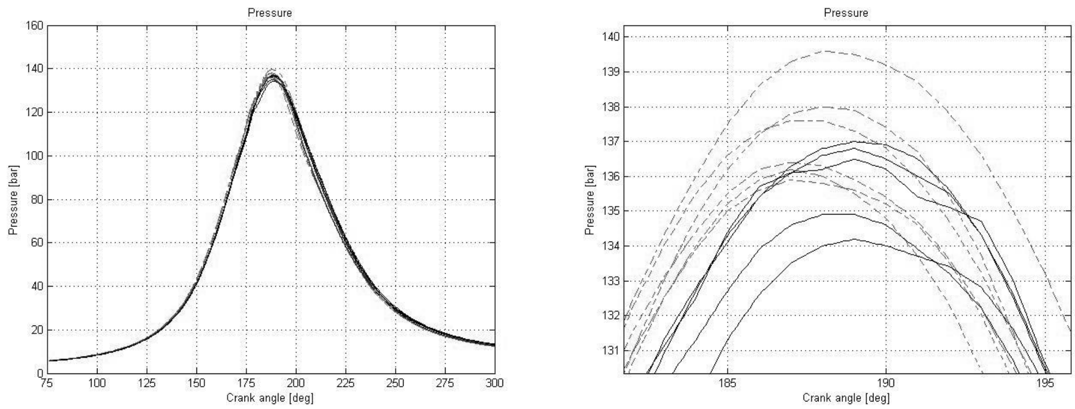
According to the NDO department, traces that contain imperfections are most likely to contain an injector fault. This straightforward diagnosis is the result of different developments. First of all, injector problems are a likely cause of deviations as can be seen in Table 2-1. Secondly, injector replacement is a relatively easy operation since revised injectors are on the shelf. And finally, the pressure measurement is difficult to analyse and pinpointing the type of fault is even more intricate. This problem in analysing the pressure curve also results from the lack of theoretical knowledge and changing operators.

When the deviations have been diagnosed, the injectors are removed and sent for overhaul while an overhauled one is installed. Regrettably there is no feedback from the overhaul department informing the NDO department or the ship what the actual condition of the removed injector was. That is why reports containing an alleged fault are never confirmed nor invalidated. It is possible that the irregularity in the pressure trace is caused by another, less common fault and the injector is in perfect shape. The lack of this feedback may cause the existing fault to develop and cause damage inside the engine. Another possibility is that the deviation in the pressure signal is caused by pollution or poorly calibrated hardware.

In this thesis the condition is assesed by comparison to a reference, considered healthy condition. This approach is not being applied in current condition monitoring. Currently the condition is solely determined by relating the twelve individual measurements to eachother and no other comparison is being made. In this way, the balance inside the engine is determined, which is very important, but trends in time are being ignored.

7-1-1 Reference condition

In Figure 7-1 the pressure measurements of the simulated twelve cylinders which were recently overhauled are being displayed. Every line represents the measurement of one cylinder and the two different types of lines represent the two diesel engines the cylinders originate from.



(a) **(b)** Zoomed in on p_{max}

Figure 7-1: Pressure measurements of the recently overhauled engine

Figure 7-1a shows that the cylinder measurements are quite alike and therefore the assumption of a healthy engine is well-founded. In Figure 7-1b the problem of the manual TDC selection becomes clear; the two types of lines are about 1^o to 2^o off for every single cylinder. This sounds reasonable since the TDC selection is established for every engine separately. Also the normal lines on an average reach a lower p_{max} than the dashed lines which may indicate that the measurements have been taken by another protocol. This could mean different operators, measuring devices, loading conditions or simply at two different times with changing environmental conditions. Whether these differences have occured during these measurements can not be traced back since the files in the database do not contain any of this information. The presence of a systematic fault could also cause this difference. The effect of some of these faults are shown in appendix B. In this case it seems that the cylinders presented by normal lines are measured with a signal filter. In this case the differences are very small but can cause errors in the heat release diagnosis. The measurement conditions should be monitored and logged to prevent possible bigger deviations to be wrongly interpreted.

7-1-2 Blowby

The effects of blowby presented by the simulations are quiet straight forward, in all cases the timing of p_{max} stayed the same but the magnitude decreased significantly. An example of this is shown in Figure 7-2. The figure shows that the first part of the curve stays the same but when volume is further decreasing the pressure increase becomes less steep compared to the original curve, resulting in a reduction of the maximum pressure of about 19 bar. It almost looks like the curve has been compressed in a vertical direction. Besides that there are no visible deviations in the shape of the pressure curve. This is according to the expectations following from chapter 2-2.

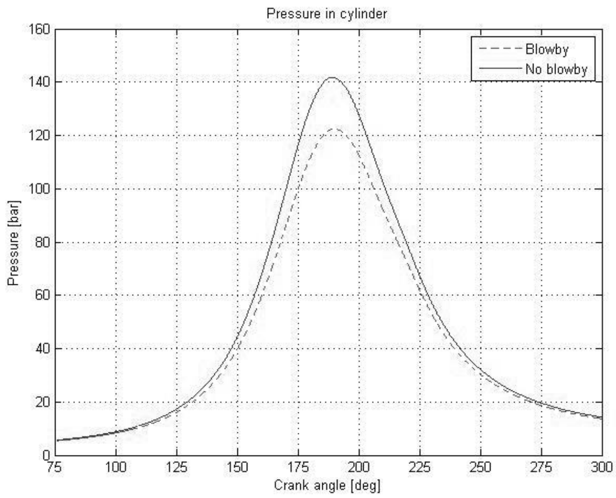


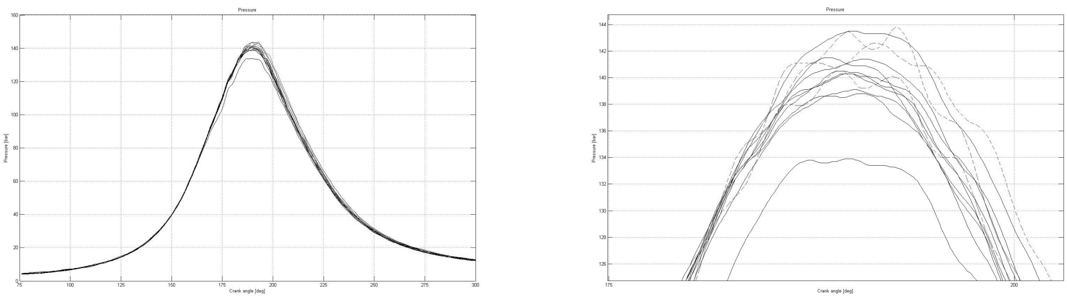
Figure 7-2: Pressure curve of simulated blowby versus original overhauled condition

The size of the cutback in p_{max} is mainly determined by the preset gap area. In this case only one, quiet large area is tested, causing the considerable pressure decrease. When the gap area is decreased, the maximum pressure will increase with it. In Equation 2-1 most of the coefficients can be considered as constants except for the gap area. When blowby starts to occur, the gap area will be small but if operation continues and no countermeasures are taken it will enlarge, causing a proportional increase of the massflow exiting the cylinder. This decrasing mass in the cylinder will lead to a proportional decrease of the pressure, based on the ideal gas law. Therefore changes of the gap area will have an inverse proportional effect on the pressure.

In this case the fault is easy to diagnose from the pressure curve. But as mentioned above, blowby is a developing fault meaning that a small gap may not be traceable until it has grown to a considerable size. For instance, if one looks at Figure 7-1b, the difference between the maximum pressure is about 5.5 bar although all of the cylinders individually are considered to be healthy. When these differences between p_{max} are considered to be normal, it becomes harder to detect the beginning of blowby. The question is, when is the gap big enough and thus the pressure decrease large enough for the operator to determine there is a fault? The subjective nature of this task plays an important role in this question; what one may find unusual can be considered healthy by another individual. Another possible problem in diagnosing blowby is the method of comparison: if all cylinders would suffer from some amount of blowby it is harder to detect when they are only compared to each other. Ofcourse, the chance that this will happen is extremely small but the actual condition would become more clear by comparison with a known healthy condition.

7-1-3 Leaking injectors

This part of the pressure signal analysis is the most interesting one, since it gives a good view on the current diagnose process. Figure 7-3 shows exactly what the operators saw when they rejected the cylinders represented by the dashed lines and approved the normal ones. The conclusion was that the three disapproved cylinders contained leaking injectors.



(a) **(b)** Zoomed in on p_{max}

Figure 7-3: Pressure measurements of an engine with three diagnosed leaking injectors

Figure 7-3b shows that the dashed lines have a more fluctuating shape around p_{max} than the black ones. The conclusion drawn by the operators is purely based on this deviation and when studying the comparison of all the cylinders it is understandable. On the other hand, the normal lines also show some fluctuations but they become less visible due to the three extreme ones. If the approved cylinders are compared with the lines in Figure 7-1b they would almost all show a deviation. This means that if the cylinders were all individually compared with their own baseline pressure signal, the outcome most likely would have been that all injectors were leaking in some amount.

The conclusion that the vibration in the signal is caused by a leaking injector sounds reasonable since leaking fuel will likely cause a fluctuation in combustion and therefore also in the pressure signal. The only question is if there is a possibility that some sort of pollution could have caused the strange shape.

Remarkable fact is that the cylinder with a notable lower maximum pressure than the others is approved without any further investigation. Especially since the cylinders are compared to eachother, this one really stands out because of its low maximum pressure and flattened upper side. Unfortunately the motive of the operator can not be traced back. Based on what has been found in the previous section it could be a case of blowby.

7-1-4 Conclusions

The current way of taking measurements, representing the outcome, and diagnosing the engine's condition leaves a lot of room for subjectiveness, causing possible errors in every stage.

A different operator or environmental condition can seriously mess with the results.
Currently the diagnostics are based only on the comparison of the twelve cylinders. Although this gives a good view on how the engine is balanced, it can also hide faults. An extra comparison of every cylinder with its own predetermined baseline, corresponding with a healthy condition, could potentially reveal more faults. The database could facilitate this trend monitoring but unfortunately it lacks in uniformity. Besides, in the current condition monitoring process no feedback is implemented from either the ship or the overhaul department.

The results in this chapter have shown that both blowby and leaking injectors can be traced with the pressure curve, but that these deviatons could also be caused by pollution or a systematic fault.
Blowby shrinks the pressure signal in a vertical direction resulting in a lower p_{max} at the same crank angle. Since this is a developping fault, of which the effects may not be very clear in the first stage, comparison with a healthy condition of every individual cylinder could reveal the fault more quickly. Due to the deviation in healthy pressure curves, blowby may be hard to discover from the standard comparison.
Leaking injectors seem to result in vibrations of the pressure signal around p_{max} caused by atomization problems. Currently no threshold is used to determine how big the vibrations have to be to discard the injector and that is why in mutual comparison only the worst ones are diagnosed as faulty. In this case there are to possible explanations: or all cylinders have injector problem or all of the measurements are invalid, due to a systematic fault.

7-2 Vibe parameters

After the pressure diagram analysis, which is currently used in the Navy diesel engine condition monitoring program, the first aim for improvement is through the Vibe parameters. The reason this is investigated is because the heat release potentially contains a lot of information about the combustion process, and all its influencing factors, and thus the current state of the engine. Analysing the heat release could be done by studying the combustion reaction rate curve but this would involve much of the problems also occuring in the current method of curve analysis. The aim is to exclude this subjectiveness and therefore the value of the Vibe fit parameters of the curve will be analysed.

Just like in the pressure part, the reference condition will be discussed first to build a range of parameters in which the engine is considered healthy. This range is then being compared to the outcome of the simulations of blowby and leaking injectors.

7-2-1 Parameter *a*

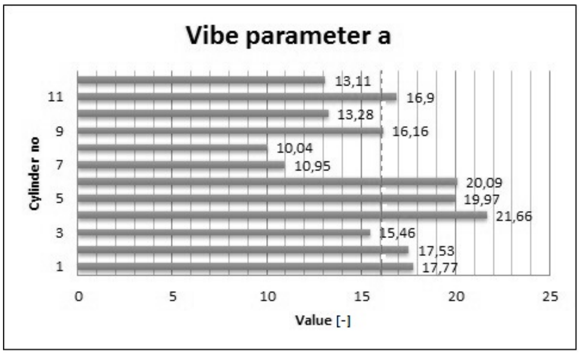
Parameter a is related to the combustion efficiency by[1]:

$$a = -ln\,(1 - \eta_{comb}) \tag{7-1}$$

and has been discussed in the literature survey. Although it is not a very influencing factor on the shape of the heat release, it will be analysed below.

Overhauled

In Figure 7-4a the resulting values of a for all the simulated cylinders are shown. The dashed line represents the average value and the range of the values are given in Figure 7-6b.



(a) Value per cylinder

Minimum	10.04
Average	16.08
Maximum	21.66

(b) Range

Figure 7-4: Parameter *a* of overhauled engine

The established range states that the combustion efficiency η_{comb} lays between 0.99996 and 0.999999996.

[1] Stapersma, D. Lecture notes TU Delft, *Diesel Engines Vol. 3 Combustion*. RNLNC, 2010

Because the outcome of a is influenced by the adjusted m_{fr} it is, in this application, not a reliable condition monitoring parameter. This is because m_{fr} is used to make sure that X_{end} reaches 1. Since $X_{end}=\eta_{comb}$ and a according to equation 7-1, these values are related to eachother.[2] If in practice a specific cylinder would be diagnosed by comparing it to the overhauled state, it could be possible to use the parameter a in terms of condition monitoring. In that case the overhauled engine should be considered as new and its m_{fr} can be adjusted to match a combustion efficiency as close as possible to 1 at EOC or τ=1. This rate of nominal injected fuel can then be used to obtain a comparable value for a for the next measurement of the specific cylinder by choosing the same value.

This type of comparison works perfectly for six of the above cylinders that were also used to simulate the blowby process. For the leaking injectors, unfortunately, another diesel engine has been simulated because the set contained more datapoints. But even if the same cylinders were simulated, the comparison would still not give the desired results since the measurements with the leaking injectors were taken in 2012 while the reference dataset date back from 2002. The timespan of 10 years is too big for the reference condition to serve as a good comparison since a lot of aspects of the engine could have been altered since then and the value for m_{fr} is probably not representative anymore. Consequently, for good comparison results the standard should be obtained regularly, for instance after every overhaul.

Blowby

Since the value of m_{fr} used in the overhaul simulations is also adapted for blowby, it is possible to compare the blowby results of parameter a with the reference condition.

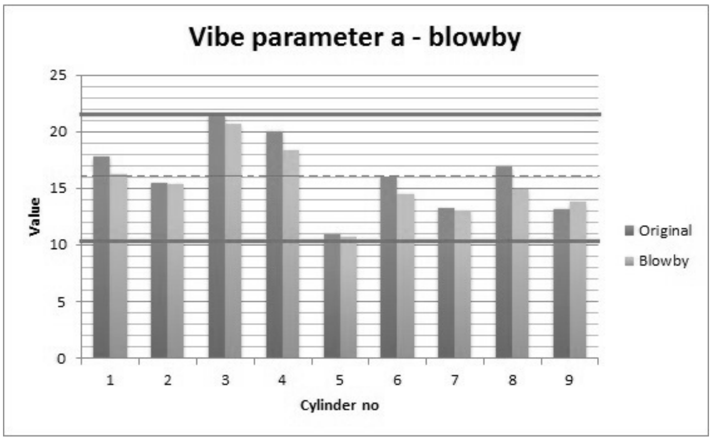


Figure 7-5: Parameter a: comparison between overhauled and blowby

Figure 7-5 shows that on average, parameter a becomes smaller due to the blowby process, only cylinder number 9 shows a slight increase. A lower a value results in a decrease of combustion efficiency. This sounds reasonable for the case of blowby; since the pressure build up is slowed down and the maximum pressure is lower, the time frame in which the pressure is high enough for fuel to burn becomes smaller. In this smaller timespan, which is also

[2]Stapersma, D. Lecture notes TU Delft, *Diesel Engines Vol. 3 Combustion*. RNLNC, 2010

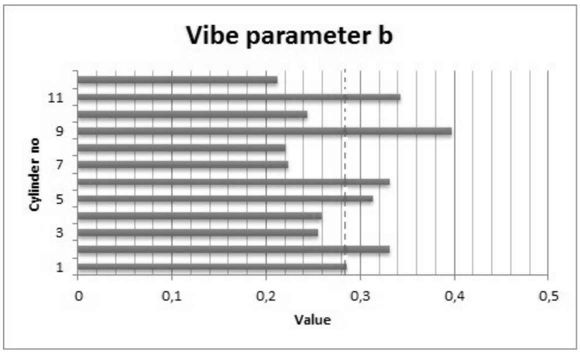
mentioned in the previous chapter, and with the lower pressures, it is impossible to maintain the same combustion efficiency and therefore it will decrease.
Although the decrease is visible in most cases, the new values of a are still well inside the established range, presented by the thick lines. Apparently it is better to set up a range around every cylinder individually, since the fluctuation between the cylinders is too large to obtain a universal range for the value of a. As shown, if measurements of all cylinders individually would be compared to its own reference, healthy state, the decrease in a due to blowby would become visible because the same image as Figure 7-5 would be presented. In practice, this might not work so well since the image is a simplified version of what the reality would show because of the artificially introduced blowby on a 'clean' heat release signal. Also the cange in a is rather small, even with this relatively large gap area, and is easily overlooked.

7-2-2 Parameter b_2

The value b adds a weight factor to the two parts of the double Vibe function, it states the relative importance of the combustion phase in terms of b_1 and b_2. In this part only the value of b_2 will be discussed because in the fit function the weight factors are stated as b and (1-b) since $b_1+b_2=1$. To prevent mixing them up, b is always assigned to the diffusive combustion phase, b_2.

Overhauled

The values obtained from the simulation of the overhauled engine together with the resulting parameter range are shown in Figure 7-6.



(a) Value per cylinder

Minimum	0.212
Average	0.285
Maximum	0.3969

(b) Range

Figure 7-6: Parameter b_2 of overhauled engine

Figure 7-6a shows that especially cylinder number 2, 6, 9, and 11 are influencing the average value since they are considerably larger compared to the other ones. Half of the cylinders have a b between 0.2 and 0.26, all lower than average. But since all the cylinders from the reference dataset are considered to contain no fault, they should all be included in the range.

Blowby

In Figure 7-7 the values of b_2 in case of blowby are directly compared to the overhauled condition. It shows that in all individual cases b_2 is higher with blowby. This increase varies between 3.5% and 24% but on average b_2 increases for about 10% per cylinder.

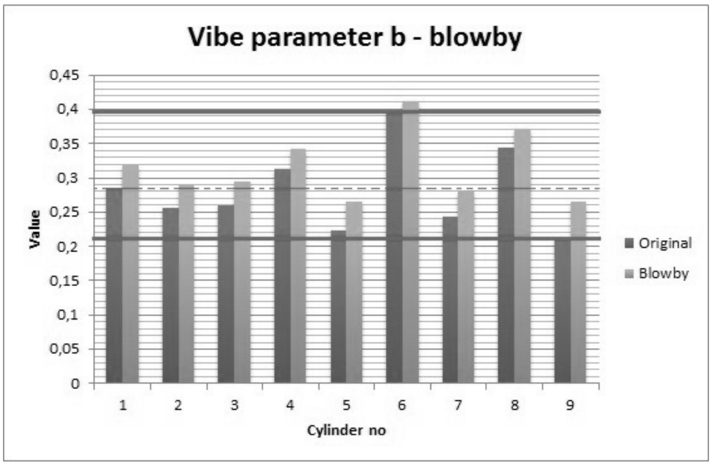


Figure 7-7: Parameter b_2: comparison between overhauled and blowby

Even though this is a significant difference which is well detectable for each cylinder, the blowby values are still inside the established range of healthy parameters. Corresponding with parameter a it seems to be best if ranges are determined for every individual cylinder around the baseline condition. For instance, a 5% margin around the reference condition would reveal eight of the nine cases of blowby in this situation.
The increase of b_2 shows that diffusive combustion gains a bigger share of the total combustion phase. Consequently, the weight factor assigned to the premixed phase becomes smaller. It already has been mentioned that since the pressure rise is slowed down due to the mass loss, more fuel is combusted later on in the combustion phase.

Leaking injectors

In theory, leaking injectors would cause a decrease in parameter b_2 because the fuel is already partly injected before the preset start of injection. The early released fuel can already mix with the compressed air inside the cylinder and contribute to the premixed phase. Consequently less fuel will be left to form a decent diffusive combustion phase, causing b_2 to decrease.

To check if this theory corresponds with the reality, the simulation results are shown in Figure 7-8. In this figure the light bars represent cylinders that were considered healthy and the darker coloured ones are labelled as containing leaking injectors, following from the report. The lines representing the previously discussed range are not visible since even the minimum is too high to fit in the scope of this diagram.

Notable difference can be seen between the first twelve cylinders, all from one engine, and the last six from another engine. The first twelve are all extremely small compared to Figure 7-6a and the corresponding range. Also, the three faulty cylinders do not seem to have a striking different value of b_2. What does seem to correspond with theory is that the leaking injectors cause a decrease of b_2. But still the reason why all of the values, also the considered healthy ones, are that much lower is not clear. If the assumption of a decreasing b_2 is true, and another assumption is that the darker bars are a good representation of this phenomenon, the only conclusion can be that all of the cylinders contain leaking injectors. This could be plausible when looking at Figure 7-3b compared to Figure 7-1b. Another possibility is that a mistake has been made while taking the measurements of all twelve cylinders but since this can not be proven or redressed this will not be assumed. A simulation fault is also unlikely since reruns were done to confirm the outcome and the exact same procedure as in Figure 7-6a has been followed. A last cause could be a systematic fault as discussed in appendix B. This possibility for this dataset has already been addressed in chapter 6-3.

For extra reasssurance, the heat release of six cylinders of another engine have been simulated, they are labelled cylinder 13 till 18. As mentioned in one of the previous chapters, this dataset contains four times less datapoints for the same interval. Out of the six simulated cylinders, three were labelled as faulty. When looking at Figure 7-8, the cylinders all have a higher b_2 value than the first simulated engine but they are still far beneath the range. Another striking feature of these six cylinders is that the three diagnosed faulty ones do not stand out between the others. If more leakage would mean lower values of b_2, it would mean that cylinder 14, which is considered to be healthy by the report, is the most faulty one. For the same reason as the first engine, all of these six cylinders can be considered, on the basis of parameter b_2, to contain leaking injectors. This assessment is based on the assumption that a leaking injector is the only possible fault in this dataset, as described earlier in this chapter. A systematic fault can not be excluded.

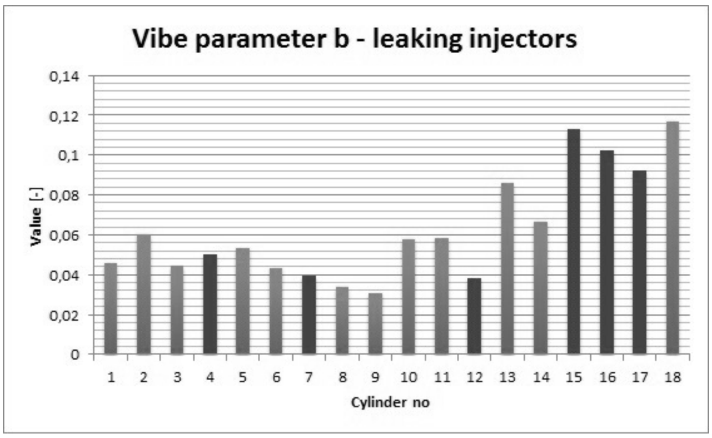


Figure 7-8: Parameter b_2 of two engines containing leaking injectors

The comparison between the first twelve and last six cylinders is difficult since there seems to be a fundamental difference in the size of b_2. An explanation could be that the amount of datapoints are an influencing factor or that the measurements of the two engines have been taken differently.

7-2-3 Parameter m_1 and m_2

In this section parameters m_1 and m_2 will be analysed for the three different simulation results. This Vibe parameter is called the form or shape factor because it determines the shape of the heatrelease and both combustion phases have their own value. In general the form factor of the diffusive combustion phase, m_2, has a higher value than m_1, for the premixed phase. The effect of a changing form factor on for instance the pressure and temperature depend on the value of the assigned weightfactor b.

Reference condition

In Figure 7-9 the values of m for the twelve simulated, assumed healthy cylinders are shown. The different shapes of the diffusive phase and premixed phase are visible in this graph. The blue lines in the graph represent the average value of both parameters. m_1 seems to be pretty stable around the value 4 but m_2 fluctuates between 7.3 and 13.

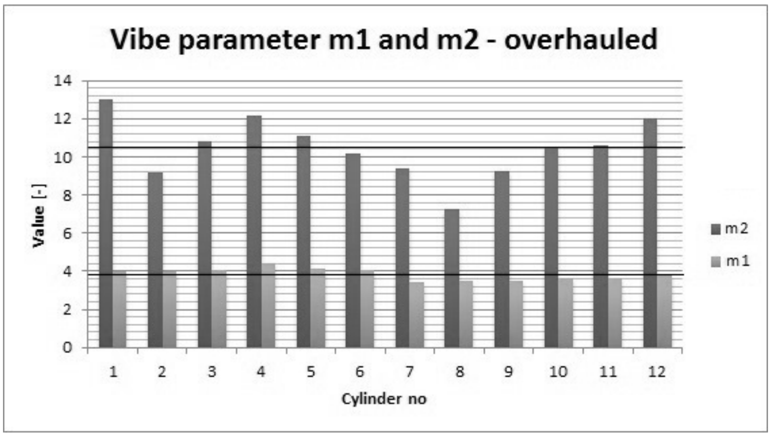


Figure 7-9: Parameters m_1 and m_2 of the overhauled engine

Blowby

For a good comparison, the values of m_1 and m_2 are depicted for both the reference dataset and the simulated blowby in Figure 7-10. The graph shows that both of the parameters decrease due to the blowby process. In theory this means that the heat release decreases in both the premixed and diffusive phase. The previous section showed that the blowby causes an increase of b_2 but still the diffusive phase will maintain a lower weightfactor than the premixed phase. This means that although the absolute change in m_1 is smaller, its effect on the heat release is increased due to the blowby.

The lower heat release due to the blowby is obvious since the optimal situation of pressure build up is being disrupted by the mass leaking from the cylinder. If a certain threshold pressure value is needed for the fuel to combust, the vertically compressed pressure curve will lead to a shorter combustion period. This shorter period will lead to a lower heat release and thus less efficient operation.

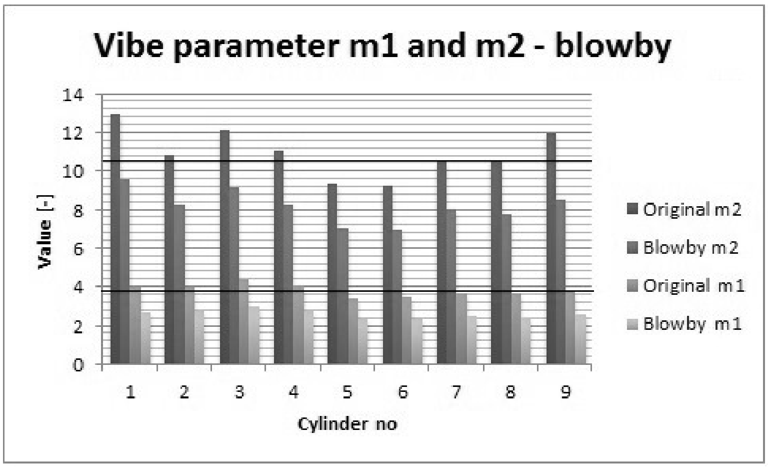


Figure 7-10: Parameters m_1 and m_2: comparison between overhauled and blowby

The difference between overhauled and blowby is evident in the graph but ofcourse the situation is simplified compared to the reality since the blowby has been simulated by the model and no other influences play a role. On the other side, the assumption is that the blowby fault is unknown and therefore the mass in the heat release model is not adjusted. This means that although this is a more realistic view, not all effects of blowby are clearly visible.

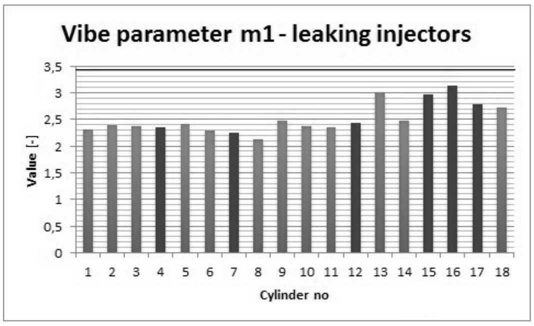
This graph again shows the importance of having a standard for every cylinder for comparison reasons instead of only comparing the cylinders mutually. For instance, if cylinder 1 is having blowby problems but the other cylinders are healthy, the change in m_2 completely blends in with the healthy values of cylinder 5 and 6. Also the little change in m_1 will be hard to see, causing a possible faulty diagnose.

Leaking injectors

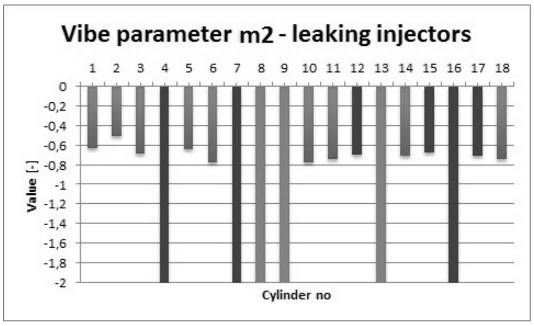
Since the dimension of the values of m_1 and m_2 were too different, the parameters are seperately depicted in Figure 7-11. Again the darker bars correspond with the cylinders that are diagnosed with leaking injectors.

In Figure 7-11b all values are well beneath the minimum of the healthy range but the 18 values do not show irregularities when compared with each other. Again, the difference between the first twelve and the last six cylinders is clearly visible.

The most striking are the negative values in Figure 7-11a. In the theory of Vibe, negative m values are not common since they would cause the speed of the reaction to be infinite at $\tau = 0$, which is physically not possible. The reason why the fit produces these negative values is because the normalised burnt fuel does not start at zero at the start of combustion, as can be seen in Figure 6-13b, and therefore needs an inifinite speed at the start to be able to meet the first part of the graph.



(a) m_1 per cylinder



(b) m_2 per cylinder

Figure 7-11: Parameter m_1 and m_2 of engines containing leaking injectors

The theoretical reason why the normalised fuel burnt does not start at 0 when $\tau = 0$ has been discussed in the previous chapter. It looks like the leaking fuel combusts before actual injection. The chance that the conditions inside the cylinder are already suitable for combustion is very small and therefore a systematic fault is plausible.

The value of m_2 however shows large variations between the cylinders, number 8 even had an m_2 of -590. The smaller negative values would disappear compared to this and that is why some of the bars are continuing outside the graph. In theory the cylinders that had the most fuel leaking before SOC would have the biggest absolute m_2 values. This would mean that especially cylinder 4, 7, 8, 9, 13 and 16 are faulty. Three of these have been diagnosed with leaking injectors but the other three have been approved by the operators. Also, cylinder 12, 15 and 17, who had their injectors removed based on the report, do not show extreme values for m_2. This information combined results in the conclusion that or, all cylinders contain injectors that are leaking fuel, although some more than others, or a systematic fault is occuring from the input parameters.

Ding also used negative m values in his thesis[3]. He states that although the infinite reaction rate at the start of combustion is physically unrealistic, negative values are needed for the fit because in part load the reaction coordinate is relatively steep. The magnitude of his m in the double Vibe function is -0.234, which is less negative than the maximum of Figure 7-11a of -0.5. This means that there is a possibility that Ding has been experimenting with an engine containing a leaking injector. If so, the leakage was not that bad compared to the findings in this thesis but it certainly played a role in his results.

7-2-4 Conclusions

Parameter a does not seem to be a good parameter in terms of condition monitoring because of its dependance on m_{fr}. When simulating the overhauled cylinders, the value for m_{fr} turned out not to be constant. Its base value should be determined for every cylinder individually to be used in later analysis and obtain comparable results for a. Since it says something about the combustion efficiency, in general a will decrease for all alterations since the reference is

[3]Ding, Y. *Characterising Combustion in Diesel Engines.* VSSD TU Delft, 2011

assumed to be the optimal running condition. a can at the most serve as an efficiency monitor rather than a way to detect a fault and therefore it might be more suitable for a performance monitoring program.

Parameter b_2 shows big fluctuations between the overhauled cylinders. In case of blowby this parameter increases with about 10%, which can easily be detected by trend monitoring. When leaking injectors are introduced, b shows a significant decrease. Since not only the labelled leaking injectors but also the ' healthy' cylinders have b values well beneath the minimum of the reference cylinders, the statement that all of them contain leaking injectors is a possibility. But considering the information in appendix B it is probably caused by a systematic fault that can not be proven or easily restored. The difference between the two engines is most probably caused by the shortage of datapoints of the second dataset.

Vibe parameter m_2 has fluctuating values in the overhauled cylinders, while m_1 is quiet stable. In the case of blowby, both of the m values decrease. Especially m_2 shows a significant change, which can easily be detected when trend monitoring is used. The leaking injector also causes both parameters to decrease but the striking difference is that m_2 becomes negative for all cylinders. This can also be seen graphically when looking at the start of the normalised burnt fuel X versus normalised time τ. Again, this could confirm that all of the injectors are leaking fuel to some amount. Ding also incorporated negative values for m_2 in his thesis and although he found his own explanation for this, there is a possiblity that he has been experimenting with leaking injectors. The negative m_2 was to be expected looking at the normalised burnt fuel: the curve showed the deviation and the parameter quantified it. Unfortunately, since a systematic fault can not be excluded, this is probably the best explanation for the analysed deviations.

For all parameters has been proven that it is impossible to establish one healthy range as a reference. Even the overhauled condition contained so much deviations between the cylinders that a range can only be adapted if it is established individually for every cylinder.

7-3 Ts diagram

The last representation technique for diagnosing the condition of a diesel engine based on pressure measurements, is the temperature-specific entropy diagram. The reason that the Ts diagram is considered is because it potentially contains a lot of information about the combustion. In theory it can not only show possible faults but it can also show the location of the fault.
In literature, no other investigation in the possiblities of incorporating Ts in condition monitoring has been found. So just like the Vibe function, it is completely based on theory and the simulations are used as a practical example.

In the following sections, a comparison will be made between the three types of simulations in terms of the Ts diagram.

7-3-1 Reference condition

Figure 7-12 shows the Ts diagram of some of the reference cylinders. Again, there is notable difference between the cylinders but the assumption that all cylinders are healthy still counts. This means that some deviation in the Ts shape is possible without faults being introduced. Although the faulty Ts graphs have not yet been discussed, the variation in healthy cylinders recommends that the cylinders should be compared to their own baseline.

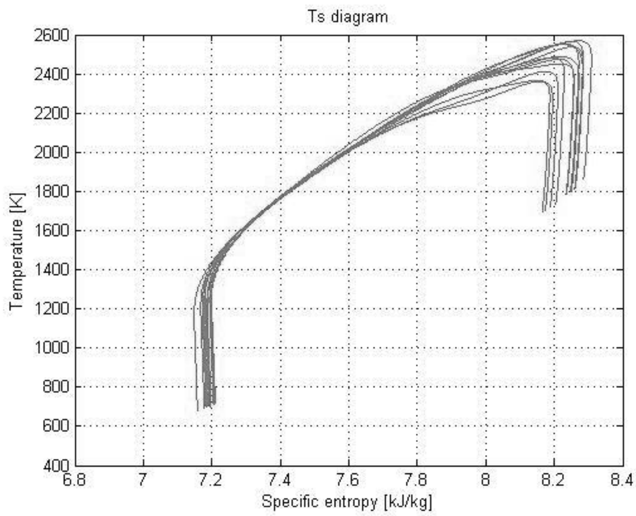


Figure 7-12: Temperature-specific entropy diagram of the reference condition

7-3-2 Blowby

Because the blowby is artificially introduced and the settings of the blowby process are the same for all the simulations, individual comparison for every cylinder will show the same results. One of these results in shown in Figure 7-13. The beginning is quiet similar but in the end, the blowby reaches a higher temperature and specific entropy. Since the area between the two lines in the first half of the graph is smaller than the second half, the area underneath the dashed line is larger. Meaning that in case of blowby more heat is developped and consequently the ability to do work decreases.

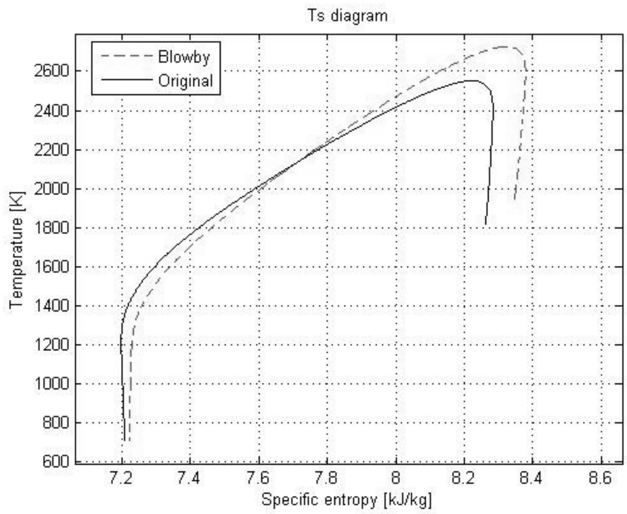


Figure 7-13: Temperature-specific entropy diagram: comparison between overhauled and blowby

The higher specific entropy is partly due to the leaking mass; since the unit of specific entropy is kJ/kg, a decrease in mass results in a higher value. The higher temperatures can be related to the ideal gas law, being pV=mRT. Due to the blowby, m decreases causing a reduction of p. Apparently not all mass loss is accounted for with the pressure but also the temperature changes with it.

To stress the importance of comparison to a baseline, besides the traditional comparison, Figure 7-14 has been constructed.

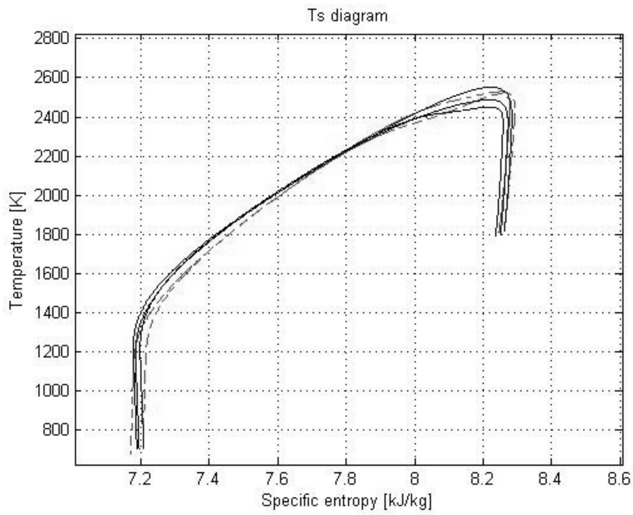


Figure 7-14: Temperature-specific entropy diagram: comparison between reference and blowby

The black lines correspond with the overhauled situation of three cylinders while the dashed lines represent two other cylinders in case of blowby. Considering this is a quiet realistic image, if the different line styles were not there, it would be hard to point out the two cylinders that are suffering from blowby. Ofcourse the lowest two Ts curves are used to simulate the blowby but that does not make it a less realistic image. The point is that comparison between the cylinders in one measurement is not enough to reveal faults.

7-3-3 Leaking injectors

Figure 7-15 shows the Ts curves of all cylinders in a diesel engine labelled to contain leaking injectors. Again, the dashed lines represent the diagnosed faulty cylinders while the black lines correspond with the healthy ones. The dashed lines completely blend in with the normal ones, which was to be expected because of the findings in the previous two chapters. Based on the pressure signal and the Vibe parameters the conclusion can been drawn that, or all of the cylinders contained an injector that was leaking to some amount, or a systematic fault is occuring. In this case, the shape of the expansion phase seems to correspond with a TDC shift or an applied signal filter. The first part however, can not be explained with the discussed faults in appendix B.

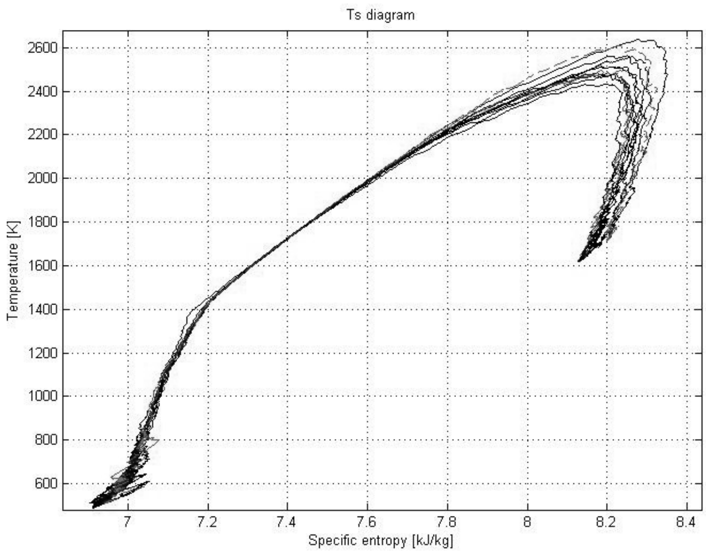


Figure 7-15: Ts diagram of engines containing leaking injectors

The shape of the Ts curve is different from the overhauled especially in the polytropic zones in the first and last part. Usually these parts form an almost vertical line, representing the polytropic compression and expansion. In general the compression shows a slight decrease in entropy but in this case the entropy only increases, which means that heat is already developing in this stage. This would correspond with the findings in the previous chapter because the leaking fuel seems to start to combust before the injection starts causing early heat release in the cylinder. Since the piston is still moving upwards, during this early combustion it is not delivering any work. This lost energy in the form of heat therefore makes the engine less efficient. But the possibility that the fuel starts to combust this early in the cycle is very small. The strongly decreasing entropy at the end of the combustion cycle shows that the air in the cylinder is more cooled down than in the healthy situation. This increased cooling effect, both in duration as in magnitude, is corresponding with the Vibe parameter b_2 found in the previous chapter. Parameter b_2 showed a cutback due to the leaking injectors, meaning that the share of the diffusive combustion phase has dropped. Consequently, less heat is being released at the end of the cycle, causing the early and quick cooling down.

7-3-4 Conclusions

The Ts curves of the overhauled engine show a lot of deviations between the cylinders, as was to be expected from the previous representation techniques.

The blowby simulation, without mass change in the heat release model, causes an increase in both the temperature as the specific entropy. This would mean that more heat is being produced and the ability to perform work is being decreased. It has been shown that without a baseline, a cylinder suffering from blowby can be undetectable when compared to other healthy ones. Problem with these findings is that the presence of a systematic fault is very likely but since the precise nature and magnitude of the fault can not be traced back, it cannot be restored for these simulations.

Leaking injectors seem to cause a disturbance in the polytropic compression and expansion phase of the combustion cycle. This has to do with the premature combustion due to the leaking fuel together with the early cooling down. The Ts diagram again shows that no significant difference can be found between the diagnosed faulty and healthy cylinders. This could mean that all cylinders contain a leaking injector but because this is very unlikely, the deviations are probably caused by a systematic fault.

Chapter 8

Conclusions

This chapter contains conclusions that can be drawn from the theory and the simulation results. It answers the question on whether the two newly introduced representation techniques, both based on the pressure measurement, are suitable for condition monitoring purposes. Also the quantitative Vibe parameters and qualitative Ts diagram, are compared to the currently used pressure curve analysis.

First of all we can conclude that the existing condition monitoring process of naval diesel engines can and should be improved to optimize the maintenance program. Currently the measurement, implementation and analysation contains a lot of uncertainties and are dominated by subjectiveness. An important and relatively simple improvement would be implementing trend monitoring in time: the thesis showed that comparing measurements with a reference value can more easily reveal deviations. Only comparing cylinders with each other may hide faults since every cylinder shows a different curve, causing deviations even in the reference conditions. Also the feedback from the overhaul department or the ship should be incorporated in the CM program. Together with a more uniform database this could help to learn from possible errors.

Analysing faults with the MatLab models revealed some difficulties. In terms of Vibe, the assumptions forming the foundation of this heat release model can cause problems in case a fault is simulated since assumptions may not be met, making the outcome invalid. Also diagnosing blowby is tricky with the heat release model since one of its assumptions is the standard mass balance, which does not account for blowby mass flow. Ofcourse this can be modelled but if used for condition monitoring purposes, the presence of blowby is ofcourse not known beforehand.

The dataset and simulation results contain a lot of abnormalities which, in some cases, could be labelled as deviations due to faults. However, the consistency of these abnormalities suggest that the results are not very reliable and might contain one or more systematic faults.

The deviations can be caused by several errors, of which five are discussed in appendix B. Unfortunately, neither of these conclusions can be confirmed and therefore no clear final conclusion can be drawn. But when looking at all the questionable outputs, some of the input data must contain errors. These errors may not be a problem while analysing the raw pressure signal but are enlarged when they are post processed by the simulation model.

The unsatisfying but most important conclusion is that the useful or uselessness of heat release and Ts diagrams, as representation technique of the pressure signal, can not be proven, based on this thesis.

Chapter 9

Recommendations

The recommendations are divided into two parts: the first part will describe recommendations for the current maritime diesel engine condition monitoring process at the Netherlands Defense Organisation. The second part contains recommendations concerning the rest of the thesis.

Recommendations to increase the efficiency of the current condition monitoring process at the Netherlands Defense Organization are:

- Trend monitoring in time should be incorporated besides the current comparison method.
- For the sake of trend monitoring, a reference value should be determined for every cylinder individually and be renewed after every overhaul to function as comparison for new measurements.
- Feedback from the overhaul department and the ship should be incorporated in the condition monitoring program to obtain better results.
- The current way of TDC detection should be analysed, it contains too much subjectiveness while the position of TDC is a determining factor in the results.
- Completeness and uniformity is key in building a representative database: every measurement folder should contain one set of measurements, the report, and the feedback.
- Measurements should be accompanied by extra information such as the reason of measuring, the operator, and possible environmental conditions playing a role.
- Although the possible systematic faults hardly bother the pressure analysis, they should be traced and fixed before any other representation technique is implemented.

Further recommendations concerning the research are:

- Measurements obtained from a testbed could delete the systematic faults and simplify the research.

- The nature of the systematic faults should be investigated to improve the input of the models and therefore the simulations.
- The effect of different combinations of systematic faults should be tested.
- In this thesis only two types of faults have been discussed. Further investigation is needed in the effects of other faults, or even combinations of faults, on the pressure, heat release, and Ts diagram. For good identification, this could be established on a testbed or through simulations.
- Besides blowby, other fault implementations in the two MatLab models can contribute to the previous recommendation.
- When other types of faults are being investigated, special attention should be paid to the ability of Vibe to express these faults, considering its theoretical assumptions.
- A new reference value should be obtained to check whether the overhauled data used in this thesis can indeed be used as a reference, as is being assumed.
- The pragmatism of the gap area used in the blowby simulations should be ascertained. Also other gap areas should be simulated to provide insight on the development of blowby and how this can be detected in an early stage.
- A better way of determining a representative value for m_{fr} in simulations should be found.

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Part III

Appendices

Appendix A

Simulink blowby subsystem

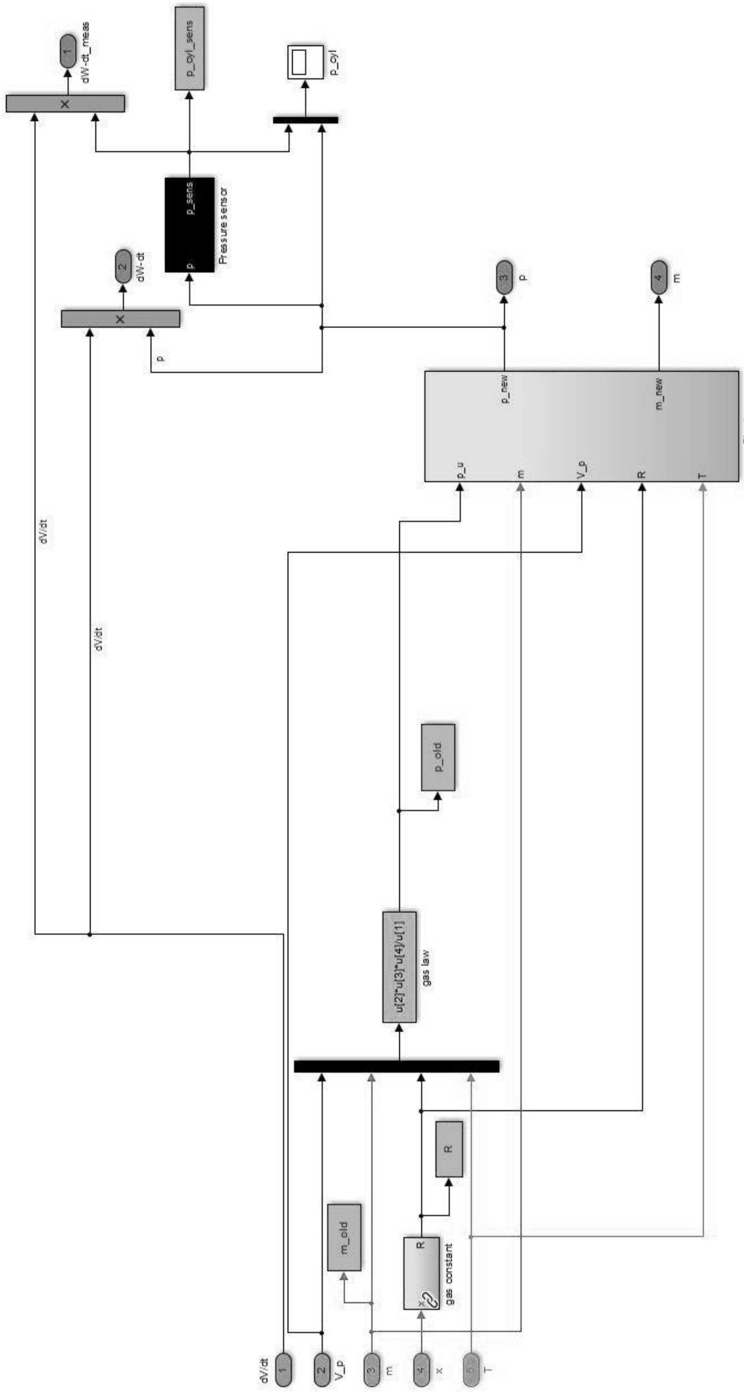


Figure A-1: Placing of blowby subsystem

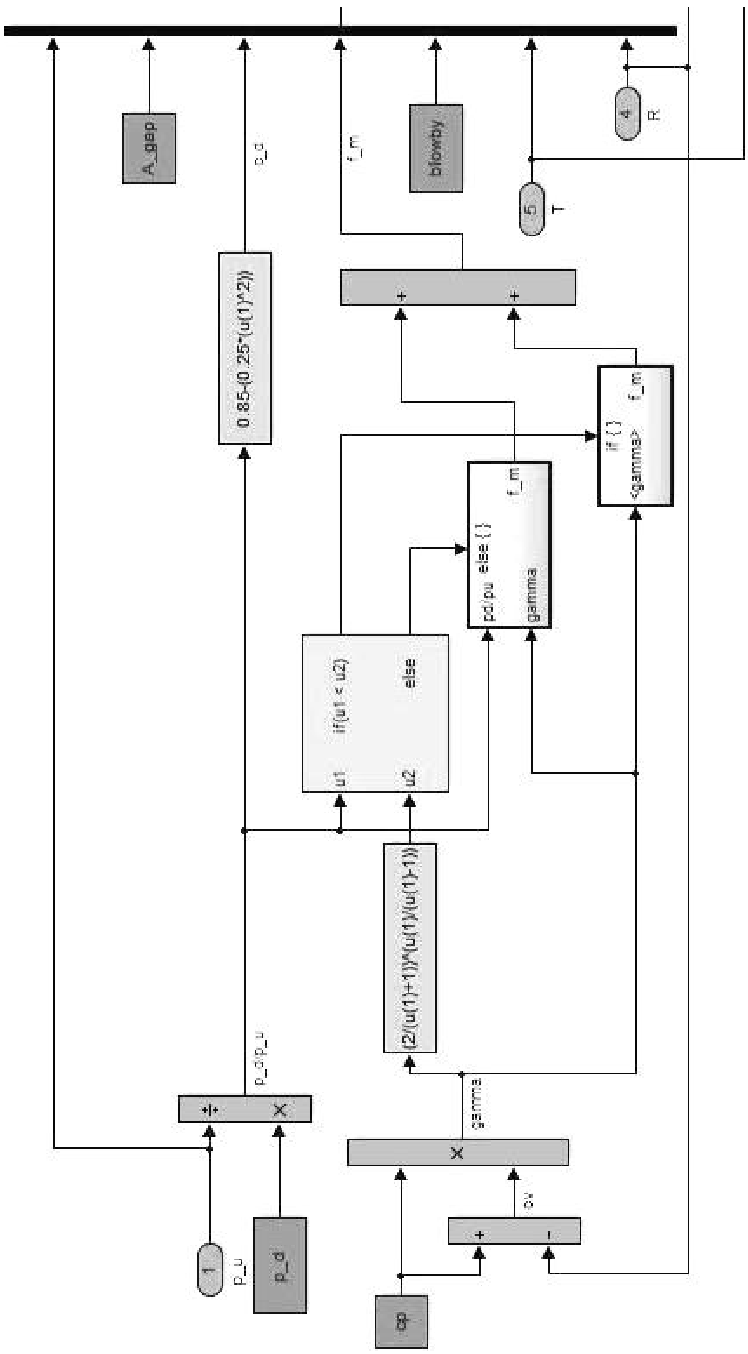


Figure A-2: Content of blowby subsystem part I

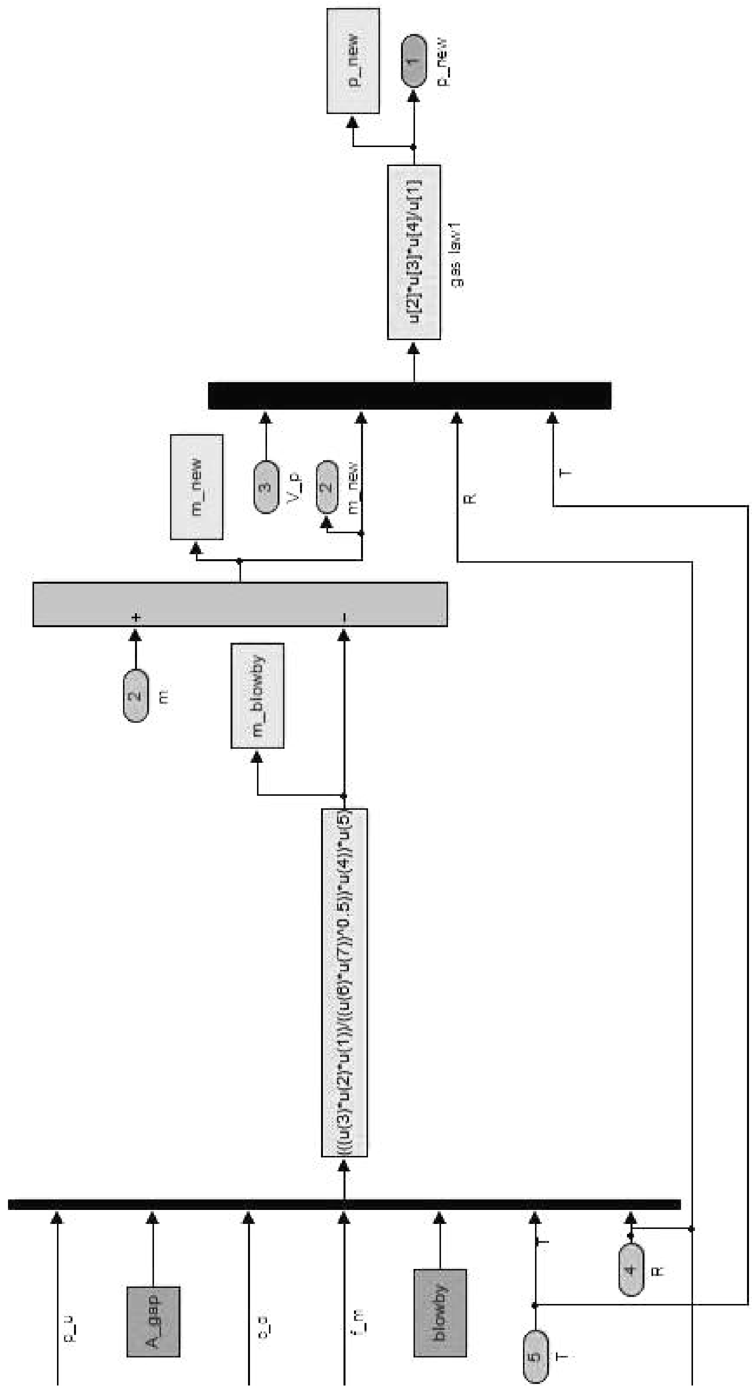


Figure A-3: Content of blowby subsystem part II

Appendix B

Systematic faults in pressure measurements

After analysing the pressure measurements and the simulation output following from it, there seems to be enough reason to question the quality of the measurements and accuracy of the simulation input. First of all, the maximum pressure seems to be quiet low compared to the reported maximum combustion pressure in the afnameverslag. Most datasets have a maximum of about 140 bar, while a p_{max} of about 153 bar is documented. Although the afnameverslag has been produced before the valve timing has been altered, still the difference of about 10 bar is quiet large. Another remarkable result are the m values of the fitted Vibe functions, in most cases they are extremely high, resulting in relatively late and flat heat release shapes of both the premixed and diffusive combustion phase. The mean indicated power of most simulations has a value of around 300 kW. In theory, when a 100% load is assumed, the mean indicated power is supposed to be the mentioned brake power, devided by the number of cylinders and the mechanical efficiency, resulting in about 350 kW. The reason for this lower value is not clear. A possible explanation could be that the assumed load of 100% is incorrect. Most excel files from the NDO database do not explicitly mention the load at which they were measured but the name of the file used as reference condition contains the description '100%'. The file containing the leaking injectors does not mention any load factor.

The last reason to doubt the pressure measurements is the way in which they are recorded, analysed, and saved. It seems there is no clear step by step manual for measuring and the post processed TDC detection is far from accurate, let alone the degree of subjectiveness. The detection method of the TDC is clarified in appendix C. Also the database is confusing, making it difficult to select the right measurement.

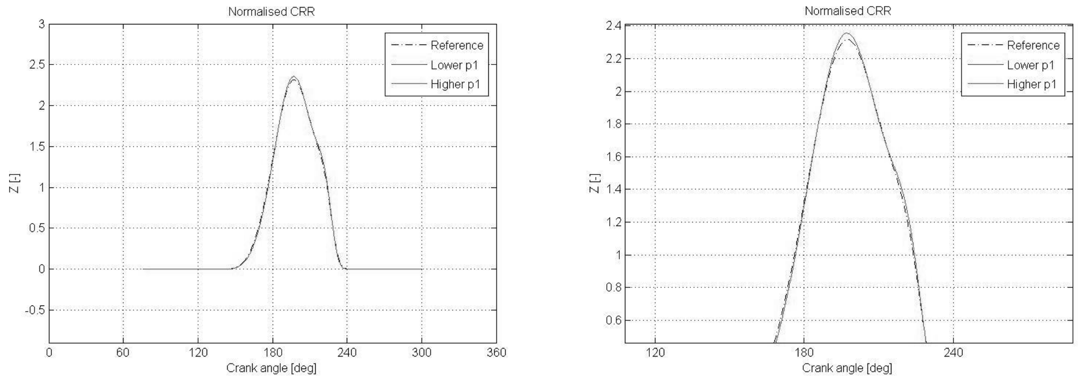
All these reasons together make it plausible that the pressure measurements contain some systematic fault. To see what type of fault could cause these deviations, this appendix simulates the effect of five possible faults:

- p_1 in the simulation program, both up and down
- T_1 in the simulation program, both up and down
- C_{hl} (constant in Woschni's heat loss formula) in the simulation program, both up and down
- TDC position in the measurements, both up and down
- The presence of a signal filter in the sensor

The systematic faults will all be introduced on the same reference cylinder and compared in terms of the normalised CRR, normalised burnt fuel, temperature-specific entropy diagram, and in some cases the pressure diagram.

B-1 p_1

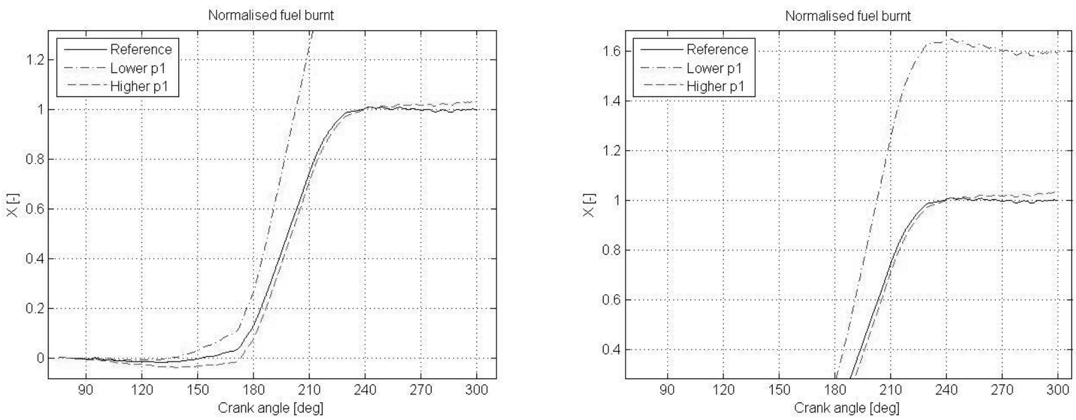
To test what the effect of a change in p_1 would be, the value has been increased by 2 bar and decreased by 1 bar.



(a) **(b)** Zoomed in

Figure B-1: Normalised CRR with increased and decreased p_1

The normalised CRR shows an increase of the maximum value for both an increase and a decrease which means that a wrong p_1 can not be the cause of the high values for m.



(a) First part **(b)** Last part

Figure B-2: Normalised burnt fuel with increased and decreased p_1

Figure B-2 shows that a lower p_1 results in early heat release and an extremely high mass of burnt fuel. Even with an adjusted $m_f r$ it can not reach 1 at EOC. The higher p_1 causes a dip around the start of combustion and a slight increase after EOC.
The difference in results of the CRR and the m_f may be caused by the fact that the first one is produced by the cylinder process model while the second one is produced by the heat release model, which normally assumes the p_1 as mentioned in the afnameverslag. Changing the value for p_1 in the cylinder model results in a shift of the pressure trace while in the heat release model it only influences the value for m_1.

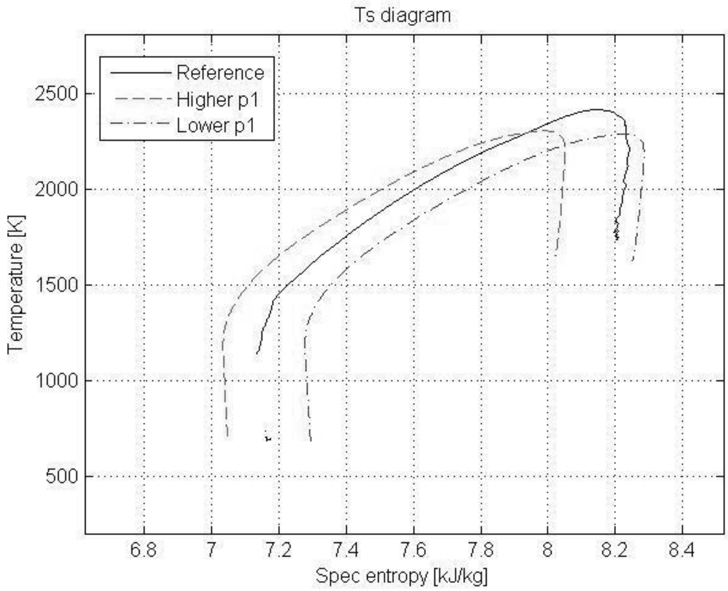


Figure B-3: Temperature-specific entropy diagram with increased and decreased p_1

The Ts diagram shows that a change in p_1 hardly changes the shape of the figure, the whole curve shifts down and left for the higher value and down and right for the lower value.

The mean indicated power in the reference condition of this specific cylinder is 264 kW. The pressure increase simulation produced a mean indicated power of 367 kW and the decrease a value of 154 kW. This shows that a more suitable value for $P_{i,mean}$ can be reached when the pressure is increased.

B-2 T_1

To test what the effect of a change in T_1 would be, the parameter has been increased and decreased by 25 K.

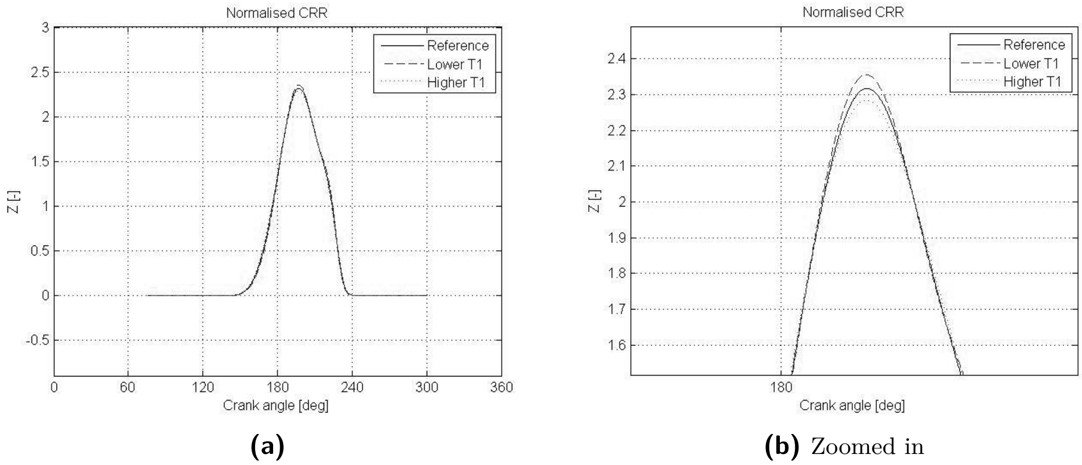


Figure B-4: Normalised CRR with increased and decreased T_1

Although Figure B-4a does not show big deviations, Figure B-4b shows that an increase of T_1 results in a lower heat release and the other way around. This is probably caused by the temperature gradient in terms of heat loss to the walls. Furthermore the shape is not altered.

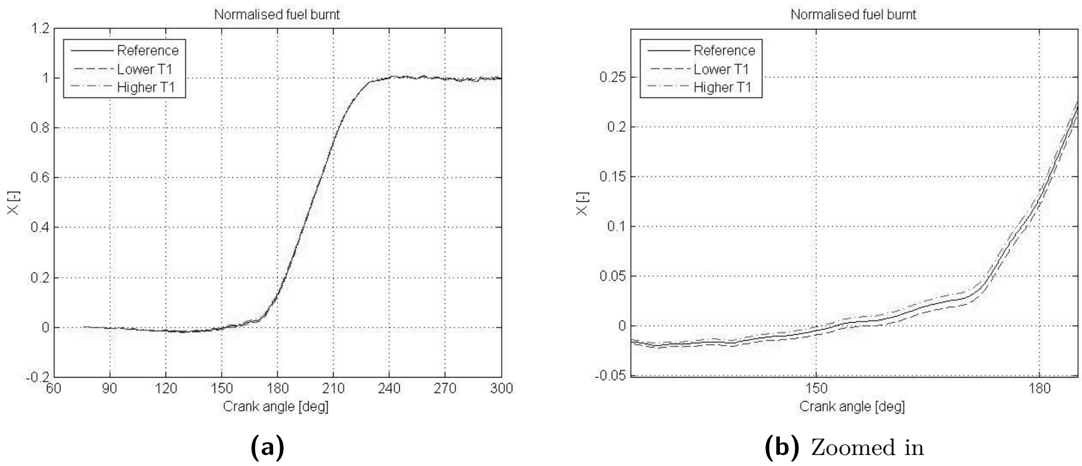


Figure B-5: Normalised burnt fuel with increased and decreased T_1

The burnt fuel does not show a lot of changes, only when zoomed in a small difference is detected; when temperature increases the line is shifted a bit upwards and the other way around. This results from the changing m_1, which is determined with the value of T_1.

The Ts diagram shifts upwards and right for an increasing value and downwards and left for a smaller T_1. T_1 has a direct impact on the temperature and indirect on the specific entropy.

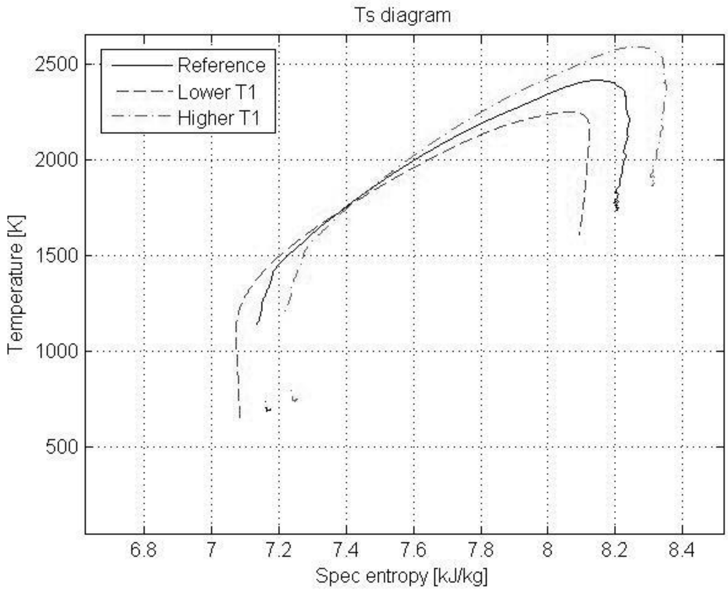


Figure B-6: Temperature-specific entropy diagram with increased and decreased T_1

In terms of mean indicated power, the higher T_1 resulted in a slightly increased $P_{i,mean}$ with 265 kW. Apparently the influence of the temperature is not very big but a decrease in T_1 is not desirable.

B-3 TDC shift

To test what the effect of a TDC shift in terms of crank angle would be, the TDC has shifted 2 degrees both sides.

The pressure signal will look like Figure B-7, as was to be expected.

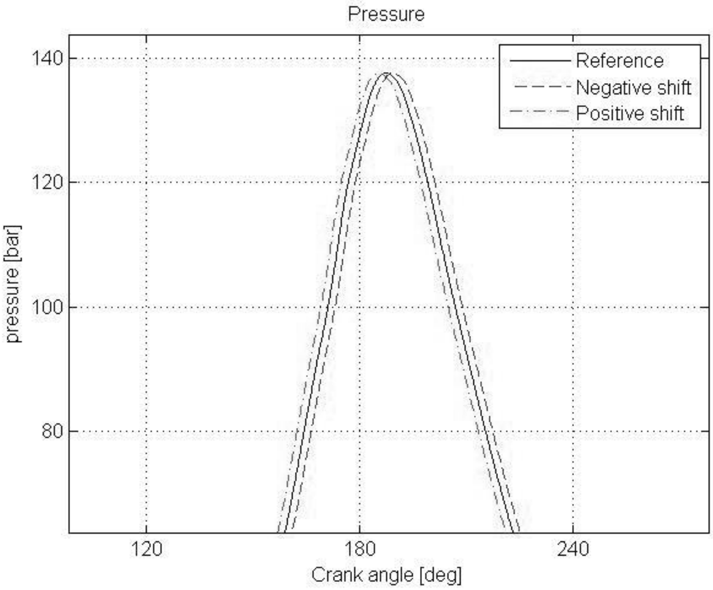
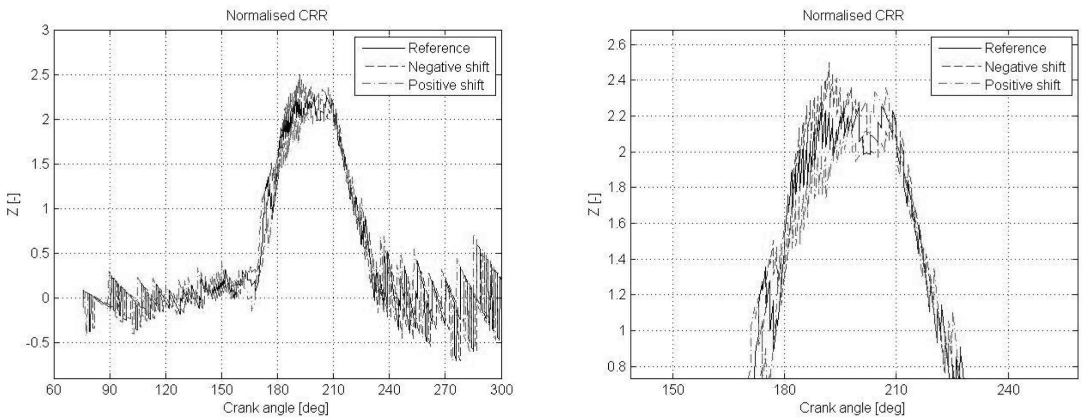


Figure B-7: Pressure signal for shifted crank angles



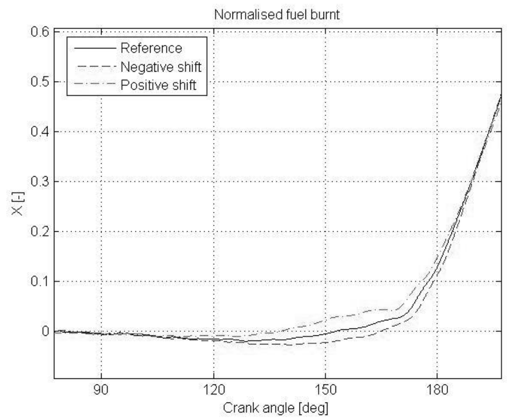
(a) **(b)** Zoomed in

Figure B-8: Normalised CRR with positive and negative crank angle shift

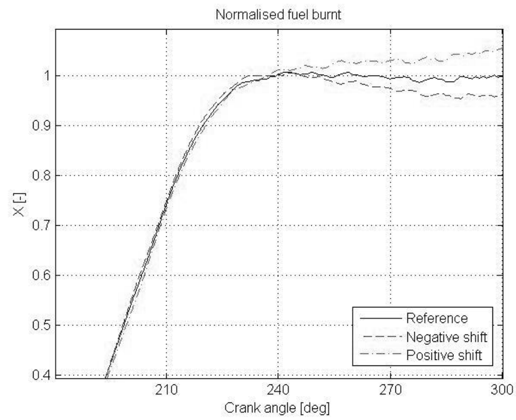
The normalised CRR is a bit harder to analyse since the raw graphs from the heat release model are displayed. They show that although the start and end are about the same, a positive shift causes a later peak in the heat release and the negative shift moves the peak forward. This means that a positive shift increases the diffusive combustion while in case the

TDC shift is negative the premixed phase increases. Although this will certainly effect the value of m, it will not create much more realistic values.

Figure B-9 shows that a positive shift will not produce a more realistic image since X increases before SOC and after EOC. A negative shift however seems possible since the dip before SOC is also seen in other engines, just like the small decrease after EOC.



(a) First part



(b) Last part

Figure B-9: Normalised burnt fuel with positive and negative crank angle shift

The Ts diagram shows that a positive shift causes a strange bump in the compression phase and a slight increase during expansion. More realistic is the negative shift, with its normal shape but an increase compared to the reference condition.

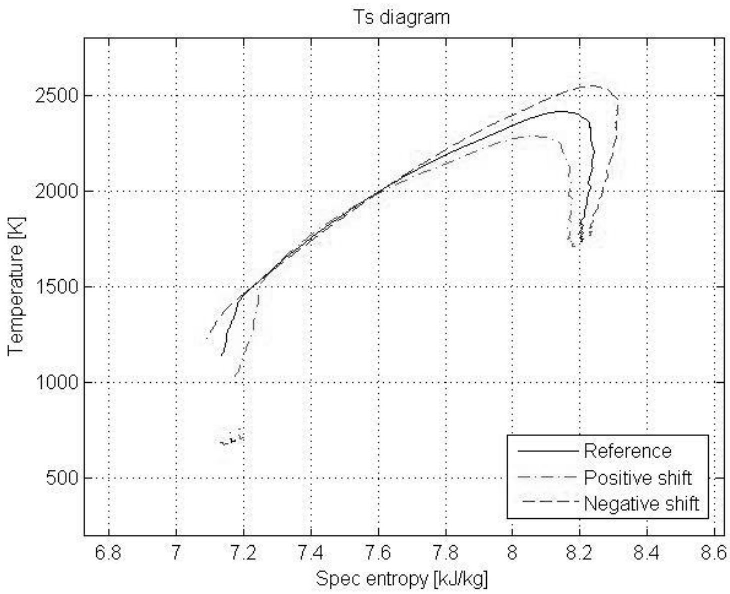
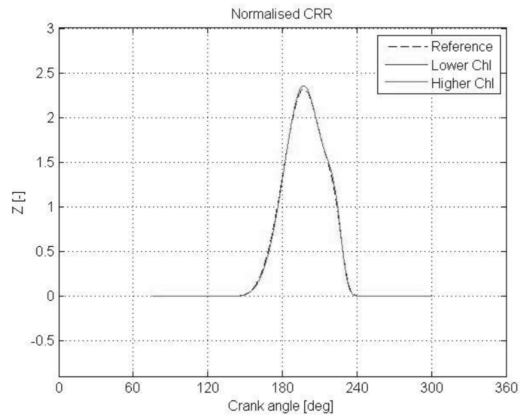


Figure B-10: Temperature-specific entropy diagram with positive and negative crank angle shift

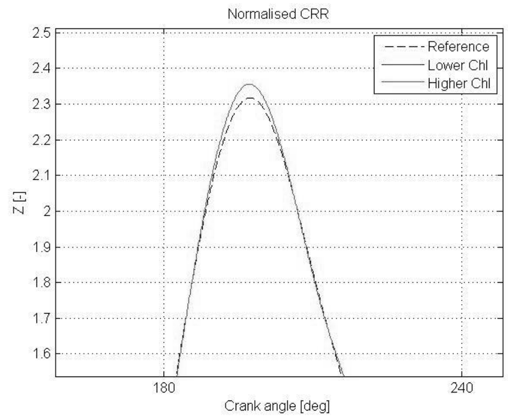
The negative shift increased the mean indicated power to 295 kW while the positive shift resulted in a $P_{i,mean}$ of 228 kW.

B-4 C_{hl}

This constant of the Woschni formula for determining the heat loss is not known for this engine and therefore estimated. Because of this estimation it is well possible that C_{hl} should be higher, 220, or lower, 80, of which the effects are depicted below.



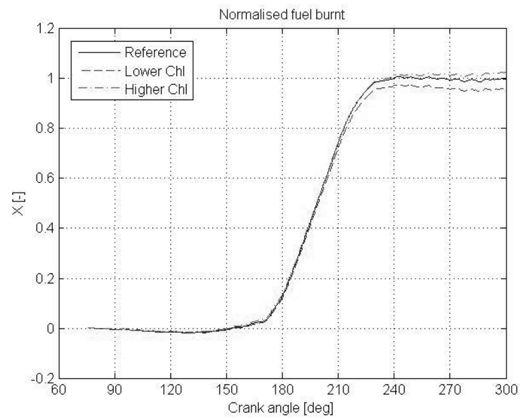
(a)



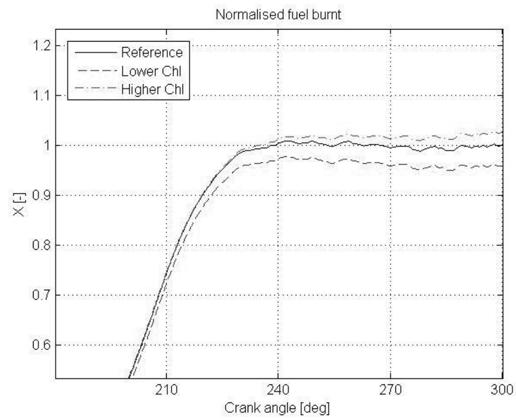
(b) Zoomed in

Figure B-11: Normalised CRR with increased and decreased C_{hl}

A change in this Woschni constant will cause an increase of heat release but a lower value will stop the burning of fuel in an earlier stage as can be seen in Figure B-12b. An increase will cause a slightly higher end value.



(a)



(b) Zoomed in

Figure B-12: Normalised burnt fuel with increased and decreased C_{hl}

Higher C_{hl} values cause a decrease in both specific entropy and temperature in the end part of the graph. This lower temperature is probably due to the higher heat loss value and vice versa. Both of them look reasonable.

The lower C_{hl} value increased the mean indicated power to 271 kW while the increase resulted in a $P_{i,mean}$ of 251 kW.

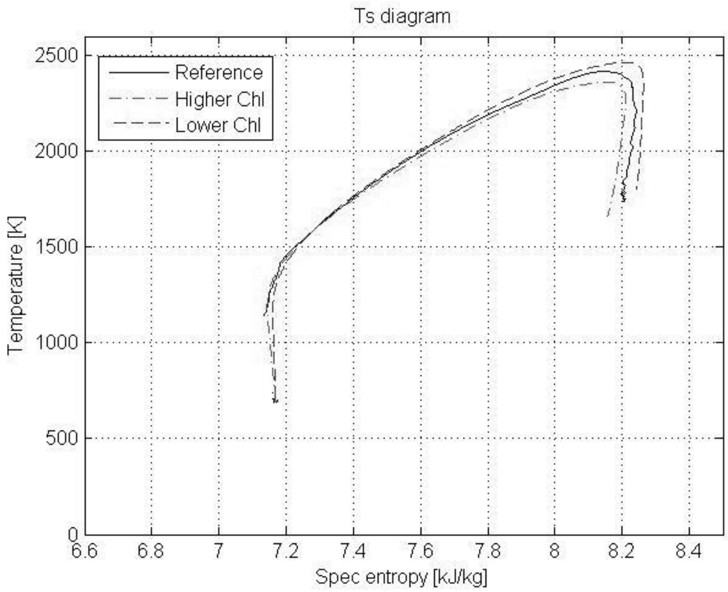


Figure B-13: Temperature-specific entropy diagram with increased and decreased C_{hl}

B-5 Signal filter

There is a possiblity that the pressure sensor contains some sort of filter, causing a change in the recorded pressure signal. To know what the effect of such a change would be, the original data is run with a simulated sensor containing a signal filter.

As can be seen in Figure B-14 it causes the pressure signal to shift to the right and decreases the maximum pressure. This sounds plausible for the used measurements since they have a relatively small p_{max}.

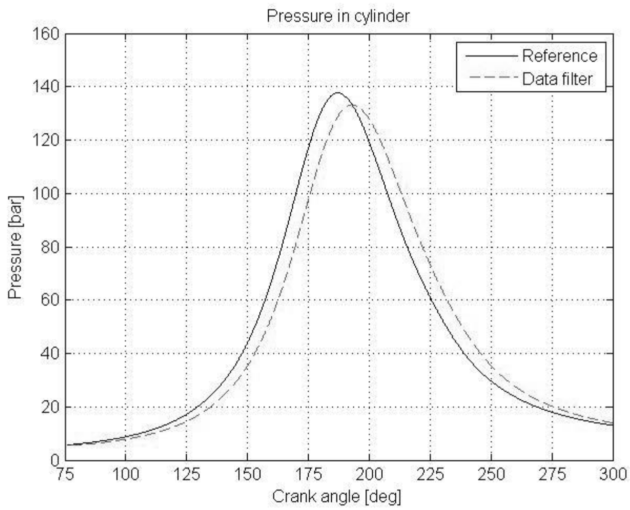


Figure B-14: Pressure signal with a signal filter

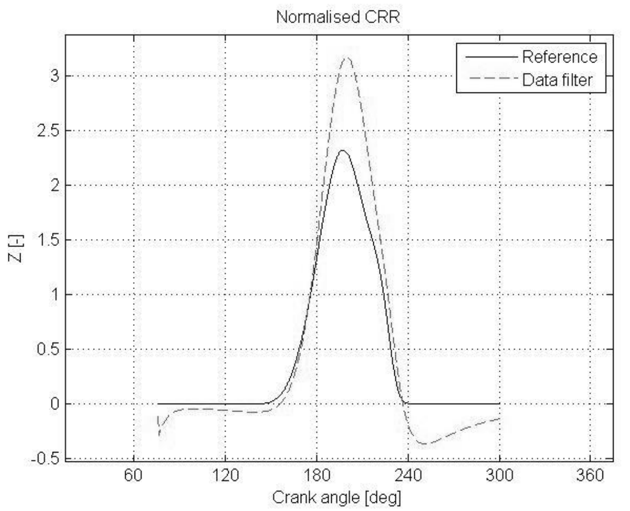


Figure B-15: Normalised CRR with a signal filter

The maximum of the normalised CRR increases a lot, just like the burnt fuel. Although the shape of the burnt fuel looks realistic, including the dip around SOC, the normalised CRR does not.

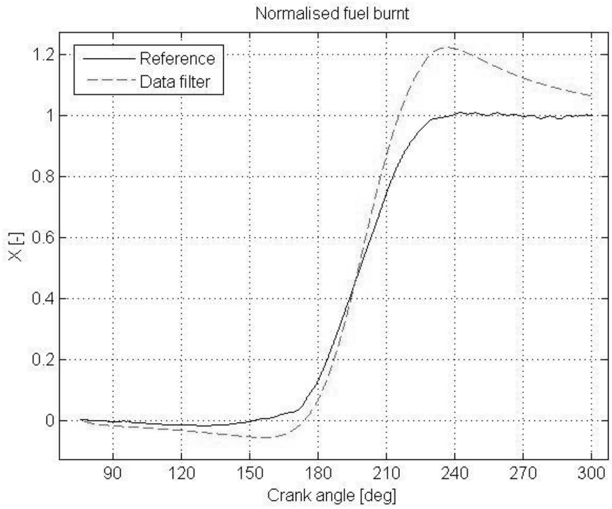


Figure B-16: Normalised burnt fuel with a signal filter

Strangely the Ts diagram not only misses a part of the compression phase but for the first time also the expansion phase is not completely determined. Again, the cause of this has not been found. But studying the shape, the Ts graph would probably show an extremely large cooling effect during expansion.

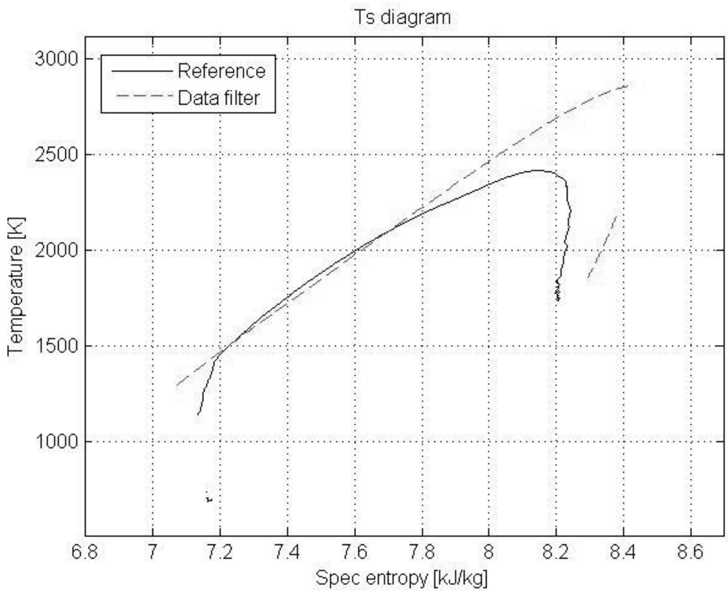


Figure B-17: Temperature-specific entropy diagram with signal filter

Adding a signal filter resulted in an increase of the mean indicated power to 363 kW.

B-6 Conclusion

Based on the received measurements and results of the simulation models, it is plausible to think that they might contain some systematic errors. The problem is that finding the cause is intricate, let alone restoring it. Therefore, this appendix has discussed five possible problems. As a result it seems possible that the p_1 should be a bit higher, this would increase the mean indicated power. Still this would not solve all of the problems found. The effect of a T_1 change is very small and is therefore unlikely causing the abnormalities. A TDC shift is probably needed since the TDC detection is very unreliable. Judging from the figures this should probably be a negative shift since a positive shifts only worsens some of the deviations. Changing C_{hl}, a Woschni constant, will not cause a lot of change and is therefore not needed. Finally, the pressence of a signal filter is a good possiblity but again this can not be confirmed nor can the signal be restored.

Appendix C

TDC detection

The goal of this appendix is to clarify the way in which the TDC is currently detected at the Marinebedrijf.

To have a good impression of what is happening inside the cylinder concerning the pressure, the position of the TDC needs to be known. In that way, the timing of the maximum pressure can be determined, which is an important condition monitoring parameter. Also the timing of the pressure rise or even the pressure at a set point can be used to diagnose the engine's condition.

The most used technique for TDC detection in pressure measurements is applying a marker on the flywheel. This is not the technique used in the PREMET measurements because in some engines the flywheel is not easily accesible. Therefor, another technique is used during the post processing of the measurements with the supplied PREMET software. In Figure C-1 a screenshot of such a TDC detection method in the PREMET program is shown.

It shows the pressure trace and a dashed line, representing $\frac{dp}{d\alpha}$. The TDC is determined by finding the first real decreasing part of this dashed line and matching its slope with the third line. The whole picture will then be shifted in such a way that this third line will be go through the origin.

The TDC can be determined for every cylinder separate or the technique can be applied on one cylinder and the program automatically applies this shift on the rest of the cylinders.

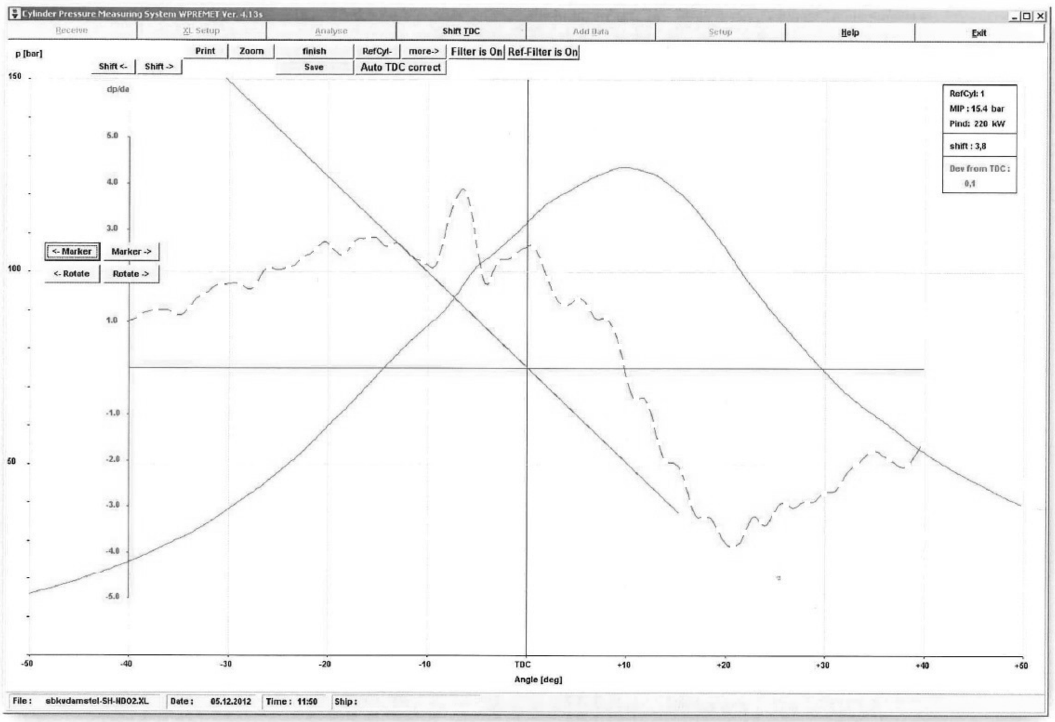


Figure C-1: TDC detection with the PREMET software

Appendix D

Research proposal

Project name: Optimizing diesel engine condition monitoring using a thermo dynamical approach

Background: Condition monitoring (CM) is associated to the relative new maintenance concept of Condition Based Maintenance (CBM) but is already widely applied in the current diesel engine maintenance programs. It is an important component of predictive maintenance and used to detect a developing failure via deviations of a measurable engine parameter. Although all gathered under the same name the approaches can be very diverse, varying from torsional vibration analysis to acoustic monitoring and exhaust gas temperature measurements. This thesis project will focus on analyzing the in-cylinder pressure measurements that are currently displayed and analyzed through an indicator diagram. Analyzing such a diagram for the purpose of CM can be very intricate, even for the trained eye. This can lead to unintended ignorance of developing failures and thus inadequacy of the predictive maintenance program. Therefore alternative visualization techniques and even quantitative methods, using the same measurements, are crucial in improving this maintenance concept. In this thesis project the thermodynamic approaches investigated are a heat release model to construct the corresponding Vibe function, a fitted Seiliger model and visualization trough a Ts-diagram. By analyzing the quantitative values of the first two methods the link to the current status of the in-cylinder process can be made. The third method is investigated to see if it contains more visual information than the currently used pV-diagram. The intent of these techniques is to simplify the analysis of the results, therefore faults can be detected and specified more easily and are not overlooked.

Objective: The main goal of this thesis project is to explore the possibilities of implementing Vibe and Seiliger models in an improved, quantitative diesel engine CM program. Furthermore the Ts-diagram is investigated to explore its possibilities as a visual CM technique, compared to the current visualization methods.

Specified tasks:

- First of all it is important to know more about the currently used diesel engine CM programs including their possibilities and shortcomings.
- Also a thorough knowledge of the heat release model and familiarization with the simulation program is needed to determine its applicability on CM.
- All the possible in-cylinder faults and their thermo dynamic symptoms have to be examined and mapped. During this analysis the question should be asked whether the faults are detectable via the in-cylinder process monitoring system.
- Another important part of this project is collecting operational engine data. By gathering measurement data and the faults engines suffer from, a database can be built on the thermodynamic symptoms of a specific fault.
- This database, in combination with a lot of simulations, should demonstrate whether Vibe and/or Seiliger models are suitable for CM. If they are, the so called 'new state' parameters must be determined to serve as a reference value.
- The choice has to be made whether these parameters have to be determined for every single point in the operation envelope or just for one single reference point. In the latest case specific running conditions have to be prescribed for the measurements or corrections need to be made to compensate for the offset on operating conditions.
- For every detectable pre-determined fault the deviation on the reference value need to be resolved.
- To test the results from the above mentioned points a case study is carried out.
- If time is available this theory can be implemented in a semi-automated CM program.