MTZ

MOTORTECHNISCHE ZEITSCHRIFT

Measures to Limit the Latent Operational Danger of Large Marine Diesel Engines (above 2.25 MW)

Offprint for

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Measures to Limit the Latent Operational Danger of Large Marine Diesel Engines (above 2.25 MW) Part 1

Part 1 of this article by Schaller Automation examines the international issues involved in establishing and complying with safety regulations and the necessary technical measures to ensure the safe operation of large diesel engines.

1 Introduction

Large marine diesel engines, which in this context means all those diesel engines that are subject to monitoring in accordance with the SOLAS safety regulations for "fire precautions", can be a source of considerable danger during their operation. Therefore, continuous safety monitoring of the operating conditions is required in order to avoid both primary and secondary damage. The operational danger of large diesel engines can lead to the development of serious fires or to secondary damage, with the consequence that the ship is no longer manoeuvrable.

2 Latent Operational Danger

Two main areas of danger can be determined:

– breakage of machine components as a result of unexpected, sporadic mechanical overstress
– lack of lubrication on journal bearings and sliding surfaces.

2.1 Sporadic Mechanical Overstress

A particularly dangerous situation occurs when the engine over-revs as a result of insufficient speed control, for example if the main drive coupling breaks. Instant cut-off of the fuel injection within a fraction of a second can prevent excess speed and therefore limit or avoid destructive acceleration forces of the moving masses. State-of-the-art monitoring systems can be made sufficiently sensitive and quick to react, and with added redundancy their use becomes particularly reliable.

2.2 Lack of Lubrication

Contrary to the method of resolving problems of mechanical strength in machine parts, which, with the aid of modern structural analysis and computation methods, results in a high level of component reliability, determining the tribological characteristics of lubrication oils relies to a great degree on empirical studies. A clear definition of when the lubrication is starting to fail or when a lack of lubrication is evident is not yet generally available, in contrast to the application methods for determining the strength of materials as mentioned in Section 2.1.

The state-of-the-art monitoring systems available today are limited to monitoring the physical "after-effects" of failed lubrication, as manifested in the rise in temperature of a particular sliding surface as a result of friction. A very promising method for monitoring bearings is the recording of thermo-currents generated by the different metals of the sliding surfaces (e.g. shaft/bearing). The system developed by Schaller Automation (BEAROMOS = Bearing Overheating Monitoring System) is now being perfected for application in practical test cases.

Deficient lubrication results in friction that generates heat, which manifests itself in an increase in temperature on the sliding surfaces. Lubricating oil evaporating from an overheated part re-condenses again and produces a very dangerous phenomenon: the generation of explosive oil mist. Large engines with substantial crankcase spaces are susceptible to this latent operational hazard. The following will describe the dangerous phenomenon of a crankcase explosion as the result of lack of lubrication and oil mist formation, **Figure 1**.

Figure 1:A crankcase explosion can destroy an engine down to scrap

3 Oil Mist as a Dangerous Element during the Operation of Large Diesel Engines

3.1 History

3.1.1

In 1947, the occurrence of a dramatic crankcase explosion in a ship [1] led British institutes to conduct scientific investigations into the phenomenon. The findings, published in the mid 1950's [2, 3, 4], still represent the most important scientific study of the operational hazard involving crankcase explosion, especially in large diesel engines.

The international safety regulatory body, the "International Maritime Organisation" (IMO), with 156 member states, is an sub-organisation of the UN and has its headquarters in London. It was established in 1982 by the Inter-Governmental Maritime Consultative Organisation (IMCO), which assumed its duties in 1948.

Through the IMO, the SOLAS (Safety of Life at Sea) Regulations were launched with reference to "fire precautions". Chapter II-1 Construction Part E "Additional requirements for periodically unattended machinery spaces, Regulation 47" correlates to the fire hazard developing from crankcase explosions.

3.1.2

The intention of these regulations, which were introduced in the 1960's, was to improve the safety of marine engines and require monitoring by means of oil mist detection as a means of avoiding crankcase explosions. The regulation refers in particular to all internal combustion engines with an output of more than 2.25 MW or those with a cylinder greater than 300 mm. Further protective measures mentioned in the relevant SOLAS regulations for the prevention of crankcase explosions are not clearly defined (for example: "engine bearing temperature monitors or equivalent devices"), and a superficial, merely cost-oriented interpretation is not a safe means of preventing fire caused by crankcase explosion.

The supervision and implementation of the SOLAS regulations is largely the responsibility of national classification societies. Of these, the major ones formed an association in 1969 called IACS (International Association of Classification Societies). IMO and IACS (as an intermediary), **Figure 2**, compile and control the international regulations for ship safety in a defined cooperation [5].

3.1.13

In recent years, as a consequence of dramatic shipping catastrophes involving significant and costly environmental damage as well as the loss of material and unprecedented loss of human life, more effective safety regulations were agreed upon on an international level, with the intention of avoiding further catastrophes.

3.1.4

These include two agreements in particular:

– The Marpol Agreement (PSC = Port States Control, Internet: Equasis.org), in which the port member states are obliged to inspect the docking ships and verify that they comply with the valid safety regulations. If deficiencies are discovered, the ships are to be prevented from embarking until they comply with the safety regulations
– The ISM Code (International Safety Management Code), which has the primary objective of maintaining safe shipping operation and the prevention of marine pollution by ensuring that operators of ships fulfil the obligations and responsibilities determined by the Code.

The Code establishes safety management objectives and requires a safety management system (SMS) to be established by "the Company", which is defined as the ship owner or any person, such as the manager or chartering agent, who has assumed responsibility for operating the ship. The Company is then required to establish and implement a policy for achieving these objectives. This includes providing the necessary resources and shore-based support. Every company is expected "to designate a person or persons ashore having direct access to the highest level of management". The procedures required by the Code must be documented and compiled in a Safety Management Manual, a copy of which is to be kept on board.

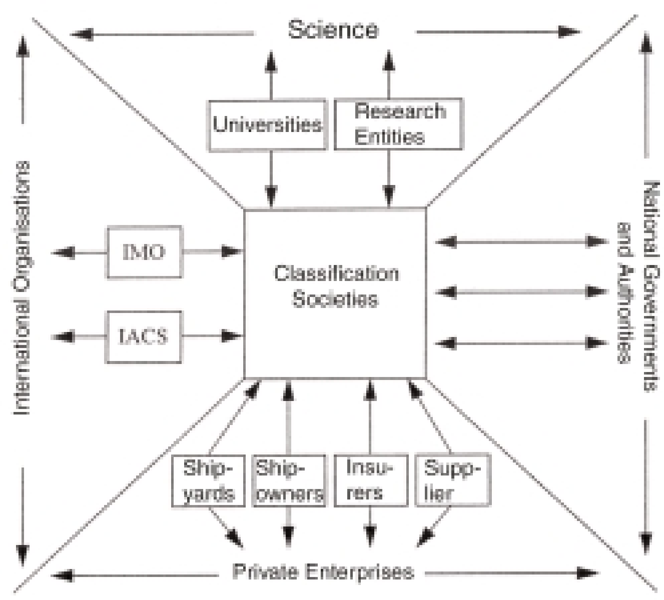
4 Technical Measures for Ensufing Safe Ship Operation

Apart from measures that guarantee the stability of the ship's hull, all equipment that is necessary for the safe operation of the ship must be fully functional.

4.1

The ship can only manoeuvre if the ship's propulsion system and the rudder system are in working order. For the majority of modern ships built in the last few decades, diesel engines were installed to produce mechanical power for propulsion, as well as to provide electrical power to drive auxiliary equipment. Auxiliary equipment includes such things as the hydraulics for the rudder activation or in some cases the diesel-electric propulsion of the ship.
A very important measure for the safe operation of the ship is the preservation of the diesel engine's operation. For this reason, the diesel engine must not be allowed to suffer severe damage and anomalies should be reduced to a minimum by means of early recognition. This would allow a simple repair to be carried out on board or would facilitate assistance from land to sea.

Figure 2: Intermediary model of the classification societies [5]



4.2

The classification societies are currently establishing rules for redundant diesel engine power units, especially to secure the function of the ship's propulsion system and the function of the rudder.

5 Oil Mist as a Damage Indicator

Oil mist is a dangerous element but, if recognised early, it can also serve as a suitable indicator that measures are required to prevent the marine diesel engine from suffering damage.

Today's oil mist detectors, **Figure 3**, **Figure 4** and **Figure 5**, utilize a light path for the recognition of the passing oil mist. The oil mist itself causes clouding in the light path [6]. Highly concentrated and explosive oil mist (air/oil droplet mixture) produces a very strong cloudiness (light absorption). For the early detection of oil mist, such as that generated by frictional damage as a result of failed lubrication, the light path measuring system has to react with high sensitivity. This results in a discrepancy due to the fact that, during normal engine operation, oil mist of a lesser concentration also develops in areas in which the evaporation temperature of the oil is reached (above 230°C). This condition leads to "false alarms", which trigger unnecessary automatic engine shut-downs. However, this depends on how the oil mist detection has been integrated into the engine's safety system.

It is obvious that only an immediate engine stop or at least a reduction in power (slow-down) to reduce the ongoing friction will limit the damage efficiently. At present, no solution to this problem can be proposed, since there is still a lack of fundamental studies.

5.1 System Configuration for Efficient Safety Equipment

An additional question with regard to the application of oil mist detectors for engine protection is that of the right system configuration for efficient engine safety equipment based on oil mist detection (OMD). As yet, the classification societies (Section 4) have not established the rules within the framework of IACS,.

Due to the pressure of cost reduction in the supply industry for ships and marine equipment, the lack of unequivocal regulations leads to inadequate solutions for safety related to oil mist detection. It is clear that, during normal trouble-free operation, safety equipment is irrelevant and only becomes necessary at the moment when the emergency occurs.

In addition, a number of other non-lubrication-related anomalies in the diesel engine can be recognized, for example when the cooling of pistons is failing and the temperature increase causes an exceptional oil mist generation that is ultimately detected.

6 OMDEA, Oil Mist Detection Efficiency Approval

Following a meeting attended by representatives from classification societies, OMD manufacturers and scientists, Schaller Automation established the project "OMDEA" with the aim of developing improved fundamentals for controlled engine safety. Within the framework of stringent safety regulations for ships, engines are also required to have certification known as the "Type Approval Certification" (TAC). Included in the TAC are tests for safety equipment, such as measures against crankcase explosions.

6.1 OMDEA Certificate

Schaller Automation is currently developing the fundamentals for making the corresponding certification applications to the classification societies. For an OMDEA certificate to be issued, the scientifically based principles of oil mist generation resulting from lack of lubrication must be presented.

Schaller Automation commissioned the Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau (mkl) at the University of Karlsruhe, Germany, under the direction of Prof. A. Albers, to scientifically formulate these basic principles. The findings from the experiments carried out were so encouraging that a second series of tests has been added to the program.

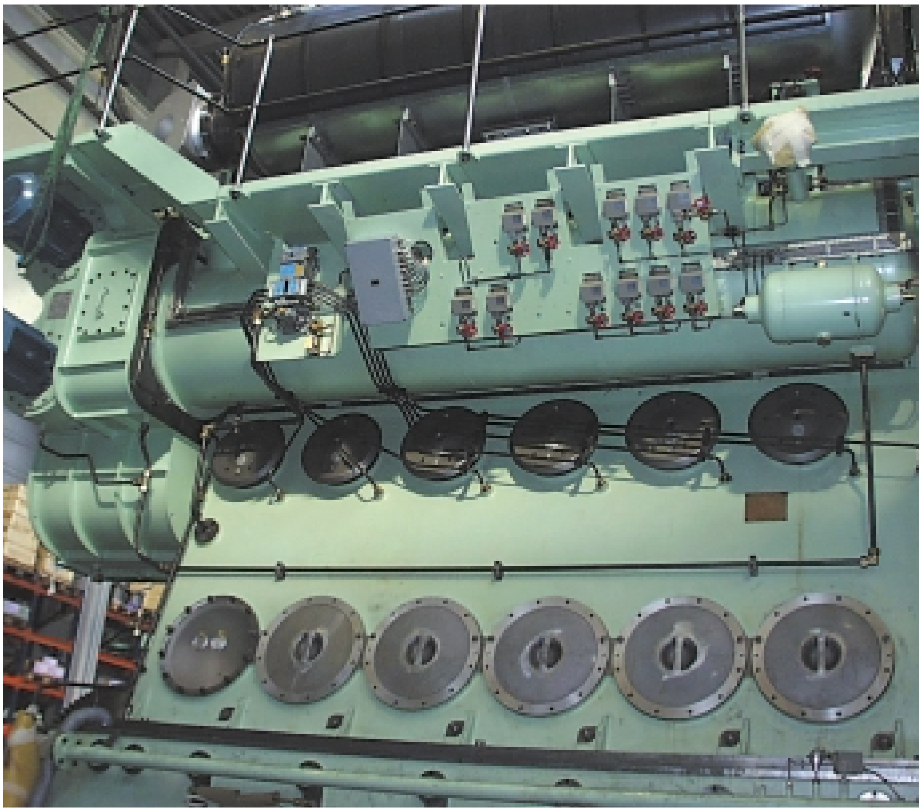


Figure 3: Oil mist detector installed on a crosshead two-stroke engine. Power output 9 MW (output up to 70 MW per unit can be realized)

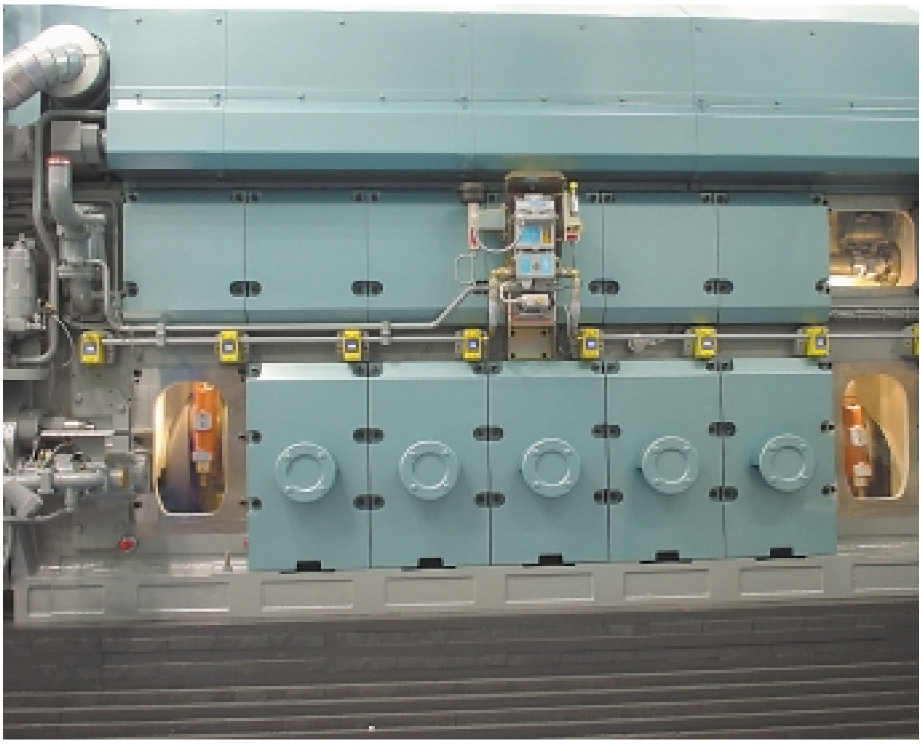


Figure 4: Oil mist detector installed on a four-stroke diesel engine, 2,4 MW, up to 50 MW per unit can be realized

Figure 5: Classic oil mist detector provided with siphon block suction system for each crankcase compartment

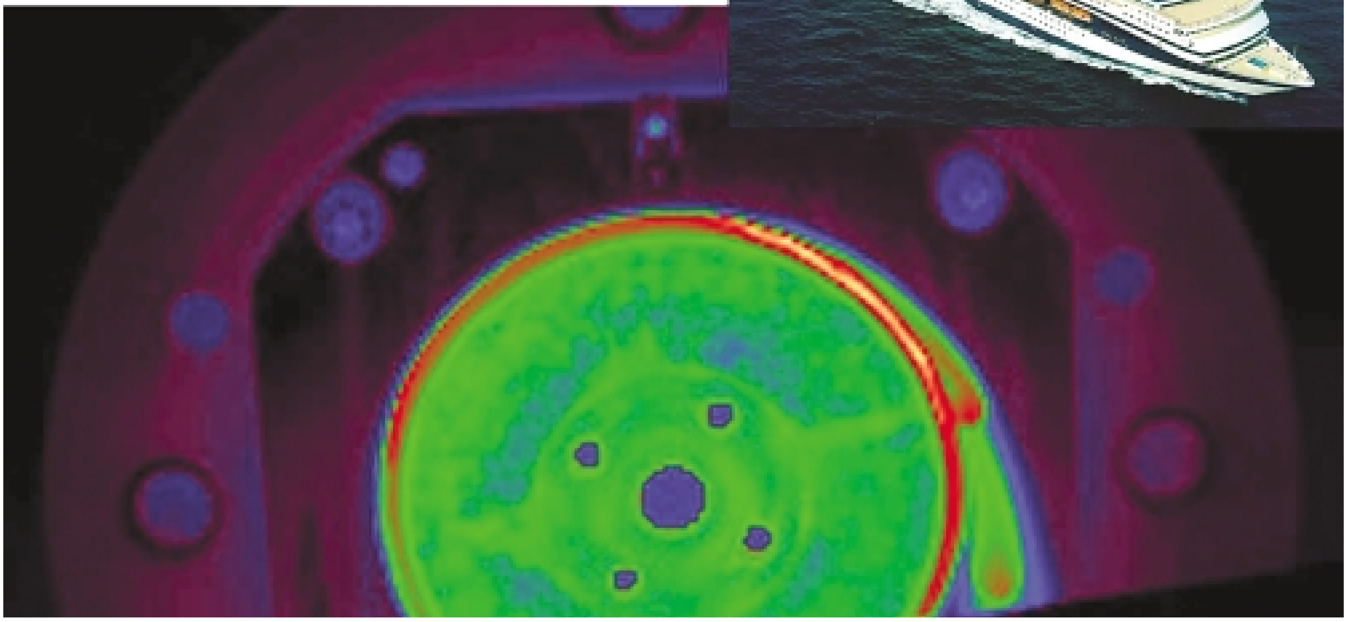
The findings of the research will be presented in Part 2 of this article. The results of test series conducted by the company FMC, Fiedler Motoren Consulting Kiel GmbH, Germany, will also be published in Part 2.

7 Concluding Remarks

In an internet search to find information on marine accidents caused by diesel engines, the term "Crankcase Explosion" appeared more than one thousand times. At present, the information is being scrutinized within the OMDEA project.

Schaller Automation has sponsored a neutral Internet Forum, www.dieselsecurity.org, with the aim of raising the awareness of diesel engine safety problems on a global scale among those involved. Furthermore, it aims to encourage the exchange of experience relevant to the improvement of safety measures. This also applies by analogy to land-based diesel power plants.

In Part 2 (planned in MTZ 12/2001), a report will present scientifically attained results of tests carried out to enable a better assessment of the physical phenomena of sliding surfaces and journal bearings running under poor lubrication conditions.



Measures to Limit the Latent Operational Danger of Large Marine Diesel Engines (above 2.25 MW) Part 2

Part 1 [7] of this article by Schaller Automation pointed out that there are internationally controlled safety regulations on this subject. However, these regulations are not specific and their implementation is difficult, since there is a lack of precise technical and verifiable definitions. Part 2 describes the efforts of Schaller Automation to make the fundamental safety measures achievable in a practicable manner and to allow the efficiency of these measures to be confirmed without the need for such compromising concessions as "where practicable" [8]. In order to create the basis for achieving this aim, tests and extensive measurements were performed at the Institute for Machine Design and Vehicle Construction of the University of Karlsruhe (TH). The findings of this research show that a definite improvement in engine protection measures is possible, and positive results can be achieved by the controlled application of these measures.

9 Introduction

Part 2 of this article described how Schaller Automation is pursuing efforts to obtain more tangible information on the extent of damage to large diesel engines on a worldwide scale.

In spite of the support provided by Classification Societies, these efforts have unfortunately not been very successful. Therefore, consideration of this subject depends more or less on calculated speculation supported by personal practical experience and empirical evaluations. From information and stored data currently available, it was possible to derive that, related to the service life of all engines, the occurrence of crankcase explosions lies in the lower single percentage range.

Without the mandatory monitoring regulation for large marine diesel engines, the percentage of crankcase explosions would certainly be higher. However, a significant number of these safety-enhancing installations must be discredited, **Figure 7** [9].

This example of an installation for which the client did not utilize the urgently needed design support reveals deficiencies that make the correct functioning of the OMD system (Oil Mist Detection) impossible. The sampling pipes were fitted horizontally and parallel to the engine and will therefore fill up with the fallout oil of the oil mist. What is even more disturbing is the sagging of the pipe that is formed by the hose connection (Figure 7), which will certainly fill up with oil and impede the extraction at that point. In addition, the likelihood of condensed water being trapped within the sagging pipe will make the safety-relevant function unworkable and cause long-term damage to the system (rust deposits).

The example shows that only a complete OMD system adapted for a specific type of engine should be designed, delivered and commissioned by one and the same organization, the manufacturer. In order to improve the OMD protection measures for large diesel engines, Schaller Automation initiated the OMDEA (Oil Mist Detection Efficiency Approval) Project. Part I, Sections 6 and 6.1 [7] contains basic tests relevant to oil mist formation.

10 Proposal for the Structure of OMDEA Certification and Requirements for the Derived Experiments

10.1 Efficiency of an OMD System

Three efficiency categories are recommended:

10.1.1 Protection Category 1

The minimum efficiency required for a protection system encompasses only the prevention of explosions. It fulfils the requirements of SOLAS Regulations for "fire precautions" (Part 1 [7], Section 3.1, Paragraphs 3 and 4)

10.1.2 Protection Category 2

Evaluation of oil mist development in the crankcase by the OMD system to prevent severe frictional damage by means of differentiated automatic intervention in the engine operation. It by far surpasses the minimum SOLAS requirements.

10.1.3 Protection Category 3

Damage localization based on Protection Category 2. This enables the quick location of the affected compartment and recognition of the damage. Damage that has not been located successfully can result in the affected engine being restarted by the personnel, thus severely aggravating the condition.

10.2 Assessment Criteria for the Effectiveness of an OMD system

Three criteria are paramount for assessing the effectiveness of an OMD system:

10.2.1 Criterion 1: Sensors and Evaluation

In the case of developing damage, sufficient sensor sensitivity must be available in relation to the generated oil mist concentration (opacity, %OP), and a reliable software evaluation for the indicator function of the oil mist must be ensured.

10.2.2 Criterion 2: Immunity to false alarms

An oil mist warning signal should not be triggered if no frictional damage is devel-

9 Introduction

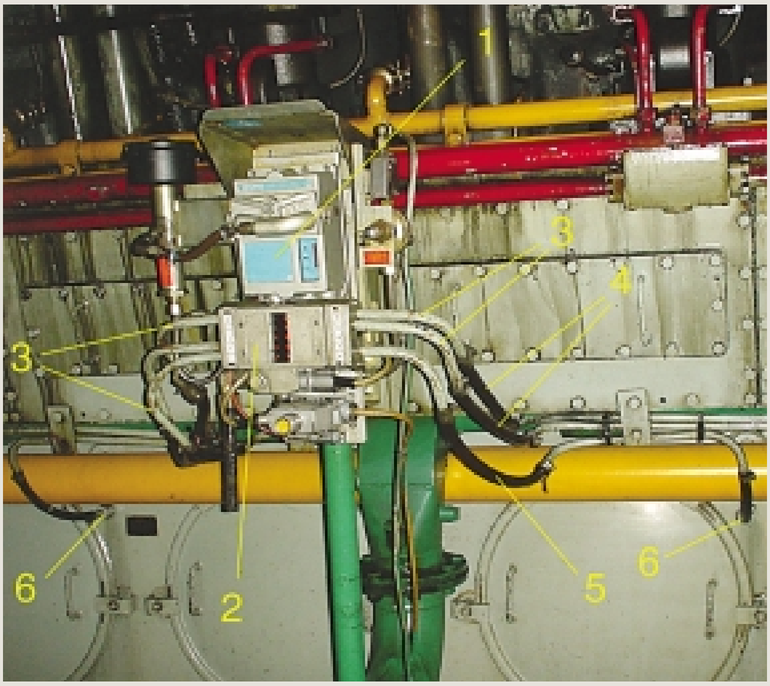


Figure 7: Incorrect installation of an oil mist detector VISATRON® VN215 with individual suction pipe connected to each compartment for localization of damage
1. VISATRON VN 215
2. Valve box with reed valves for selection of suction pipes according to a search-run algorithm. Indication of damage compartment (red dots in display window)
3. Individual suction pipes
4. Hose connection between the suction pipes and pipe elbows inserted in valve box 2
5. Sagging hose in the sampling system
6. Connection to the matching compartment

11.2.1 Test Bench and Measurement Method

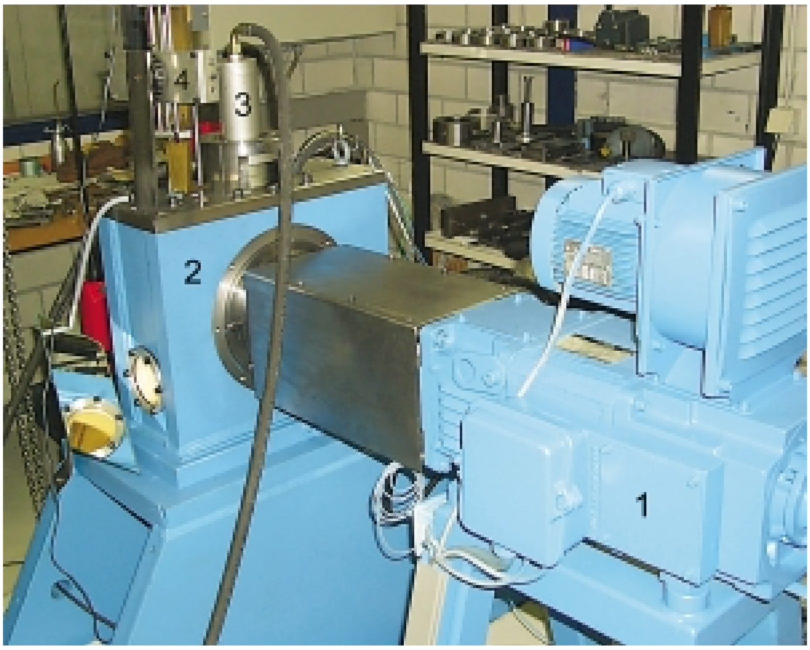


Figure 8: Small bearing test bench
1: Motor; 2: Test bench housing; 3: Hydraulic cylinder; 4: Endoscope-camera

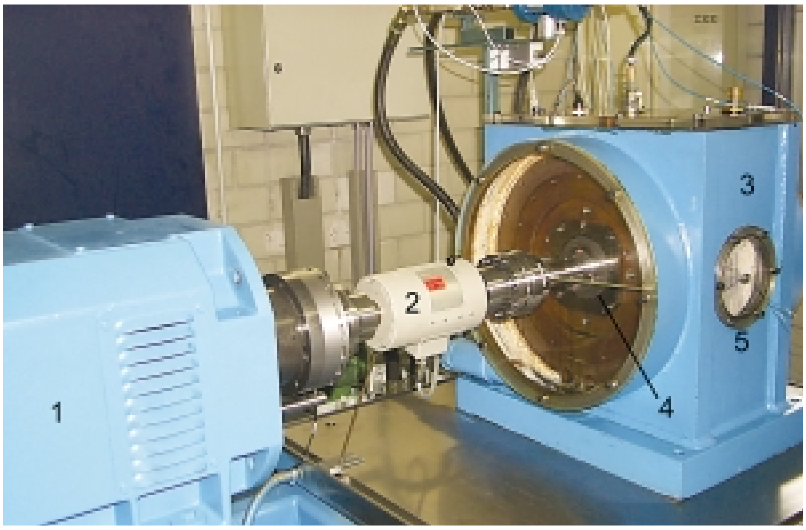


Figure 9: Large bearing test bench
1: Motor; 2: torque measuring shaft; 3: Test bench housing; 4: Support bearing; 5: Window for opacity observation

oping. This criterion is even more important for the acceptance of an OMD system than Criterion 1.

10.2.3 Criterion 3: Availability of the protection system

The reliability of the OMD system must be proven, taking into consideration marine environment conditions, the direct installation on the engine and the obligatory tests (vibration, temperature, resistance to humidity, high EMC).

10.2.4 The Levels of Operational Safety

– System Safety Level 1: The system controls itself and a special alarm signal is activated when the protection function for ascertaining oil mist is malfunctioning (low-cost version)
– System Safety Level 2: In addition to System Safety Level 1, a second system provides redundancy. For both safety levels, a dedicated worldwide maintenance service must guarantee the availability of the systems.

10.2.5 Influence of an OMD System on Engine Operation

At present, there is no clear decision on whether an OMD should react by activating STOP or SLOW DOWN of the engine in the event of a lack of lubrication. A solution to this point must be found, especially in the case of nautical emergency situations. The ship's master should be supported by sensitive software to provide an aid to decision-making.

11 Experimental Investigations

11.1 Tribological Tests on Lubricated Sliding Surfaces and Oil Mist Simulation Tests in Large Engines

Extensive tests were conducted in order to find out more about the oil mist resulting from frictional damage caused by insufficient lubrication. For the OMDEA project, the aim is to study which methods are required for the purpose of simulating oil mist development and oil mist behaviour in the crankcase.

In order to obtain meaningful knowledge about oil mist formation, two different experimental rigs for sliding bearings were utilized:

- A specially designed test rig for a radial sliding bearing
- A linear sliding guide for the simulation of the piston/cylinder function, in the form of a rotating disc with a lubricated guide block

11.2 Examination of Radial Bearings

11.2.1 Test Bench and Measurement Method

The experiments were conducted on the small, **Figure 8**, and the large, **Figure 9**, radial bearing test bench of the Institute for Machine Design and Vehicle Construction of the University of Karlsruhe (TH) by Prof. Dr. A. Albers. The set-up of the small bearing test bench is shown in **Figure 10**. The test bearing on which the loading force is applied by means of a hydraulic cylinder is located between the two support bearings, which hold the shaft radially.

The small bearing test bench enables experiments with 180° half plain bearing shells to be carried out. A triple layer bearing of lead, copper and tin (Glyco 40), together with a bronze bearing with a diameter of 61.5 mm and width of 9.5 mm were employed. On the large bearing test bench with the same basic set-up, only complete plain bearing shells with a diameter of 118 mm and a width of 18 mm were used. Apart from the measuring variables required for describing the operating conditions, such as rotational speed, driving torque, loading force, bearing temperature and oil intake temperature, the opacity was used as a measure of the oil mist formation.

Based on the test bench volume containing the oil mist, the opacity measured in %OP [10] facilitates a calculation of the vaporized oil quantity.

Furthermore, the BEAROMOS signal was measured on the test bench. BEAROMOS is a monitoring system developed by Schaller Automation for bearings and sliding surfaces, and is based on the thermocouple effect. The shaft and bearing are thus used as a thermocouple pair. In the case of dry friction within a bearing, the thermoelectric voltage that is generated drives a signal current through the circuit, which is closed by means of a collector [11].

The position of the temperature sensors on the back of the bearing can be seen in Figure 10. During the experiments, thermographic, **Title Figure**, and video recordings were made in order to document the oil mist formation.

11.2.1 Test Bench and Measurement Method

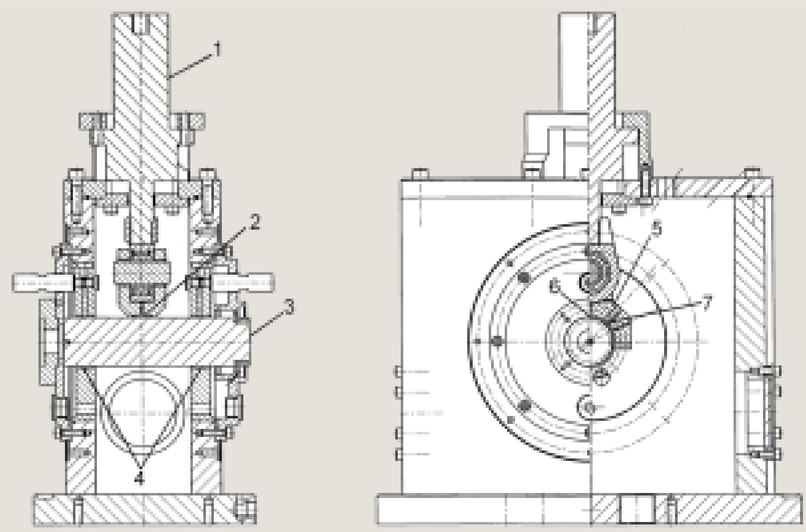


Figure 10: Section drawing of the small bearing test bench

1: Hydraulic cylinder;
2: Test bearing;
3: Shaft;
4: Support bearing;
5: Test bearing carrier;
6: Temperature test point T1 on the bearing rear in direction of force application;
7: Temperature test point T2 in highly loaded area

11.2.2 Tests on the Small Bearing Test Bench

The formation of the oil mist was demonstrated using half plain bearing shells and complete plain bearing shells. The test bench was driven at a speed of 3000 rpm in order to simulate the performance of large diesel engines as far as possible. The sliding speed is then of the same order as that found in actual large engines. The diagram in **Figure 11** shows the measurement results of a test with a statically loaded bronze half shell. The start of the seizure is clearly concluded from the rapid rise at 65 s of the measurement time. The bearing temperature increased within a short time from 63 °C to almost 300 °C. The oil mist formation could be observed from a bearing temperature of 200 °C onwards. The opacity therefore increased from approximately 2 % to 75 %.

The oil mist formation began almost 7 seconds after the beginning of the bearing seizure. BEAROMOS, on the other hand, showed a signal increase even before the torque increase, which indicated the developing bearing damage. As the seizure began, the BEAROMOS signal once again increased notably. During the evaluation conducted after the test, the bearing showed clear traces of seizure and could have been classified as damaged.

A total of about 60 seizure tests were performed on the small bearing test bench. The test results showed that the formation of oil mist could be strongly promoted by an increase in the oil temperature. This already proves that the formation of oil mist is very dependent on the thermal boundary conditions. The average value of the bearing temperature at which oil mist formation could be observed is around 170 °C with a large standard deviation of 40 %.

The diagram in **Figure 12** shows the values of the gradient of opacity related to the friction determined in the test bearing. The almost linear relationship observed between the two quantities is indicated by the interpolation line. This means that a stronger oil mist formation can be expected at a higher friction value in the bearing. If one forms the quotient of the opacity gradient and the friction, which is a measure of the gradient of the line in Figure 12, one gets an average value of 0.24 %/(kWs) with a standard deviation of 0.08 %/(kWs). It appears therefore that it is possible to relate the opacity gradient to the friction, and thus to the occurrence of bearing damage. It can be further concluded from Figure 12 that a minimum amount of friction needs to be induced into the system for oil mist to form. Up to a certain limit, the developing frictional heat can be dissipated completely by heat conduction in the bearing, housing and shaft, as well as by radiation and by the lubricating oil. Only when these possibilities for heat dissipation are no longer sufficient does the oil heat up strongly and is consequently subjected to vaporization, thus resulting in oil mist formation due to drop condensation. An analogue relationship between the friction and temperature gradient is evident. This is comprehensible, since a higher amount of friction induces more thermal energy into the system over time (heat flow), and therefore the temperature increase is also greater. In the test with complete plain bearing shells, the average opacity gradients were distinctly lower. The average opacity was 0.8 %/s in the half bearing shells, while the gradients for complete bearing shells were between 0.01 and 0.25 %/s. The average value for all the measurements was 0.1

11.2.2 Tests on the Small Bearing Test Bench

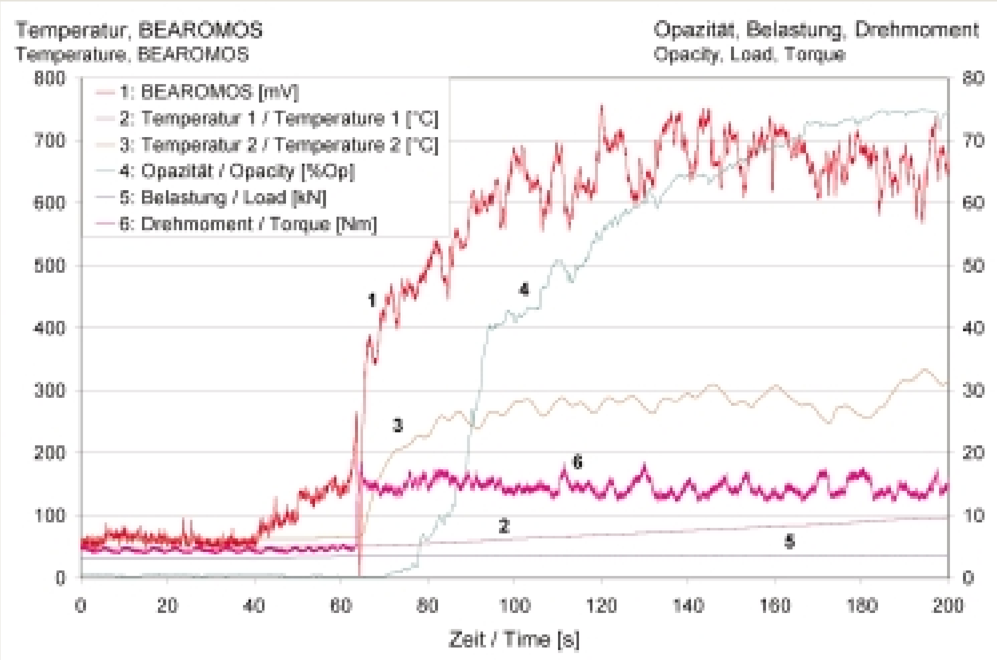


Figure 11: Measurement on the small test bench under static loading with a bronze-half plain-bearing shell loading force 3,7 kN, average bearing pressure 6,3 N/mm2, Oil inlet temperature 40° C

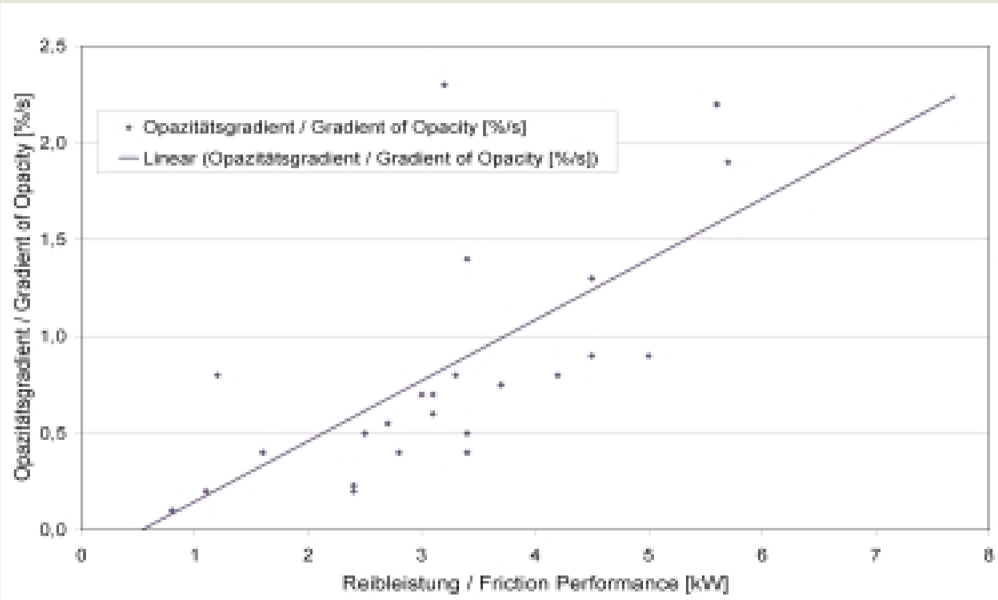


Figure 12: Gradient of opacity vs. friction performance for measurements on the small test bench

%/s. The oil mist formation in a complete shell was therefore slower by almost one order of magnitude than in the tests with half shells. This deviating behaviour can be explained by the better cooling of the shaft in the case of a complete shell. The lubricating oil in the complete shell is made to flow onto the lower bearing side, and, after circulation, some of the oil remains in the lubrication gap, unlike half bearing shells, in which the lubricating oil is thrown out. Thus, more heat energy can be dissipated from the complete bearing and the shaft. In this context, the significance of the energy balance in the bearing for the formation of the oil mist and for the time progression in the case of oil mist formation must be emphasized. As can be observed, changes in the thermal boundary conditions – in this case, heat dissipation – have a critical influence on the formation of oil mist.

11.2.3 Tests on the Large Test Bench

At present, tests are being conducted on the large bearing test bench with the aim of verifying the results obtained from the small bearing test bench for a larger shaft diameter. The results determined so far are presented in the following. Apart from the quantities such as loading, torque, bearing temperature and opacity described already, the splash-oil temperature, which is the temperature of the lubricating oil thrown out from the test bearing, is also measured. An example of a measurement is shown in **Figure 13**. A complete bronze bearing shell, which was loaded by a force of 3.8 kN, was used as a test bearing. The bearing seizure can again clearly be seen from the torque increase, as well as from the rise in the

11.2.3 Tests on the Large Test Bench

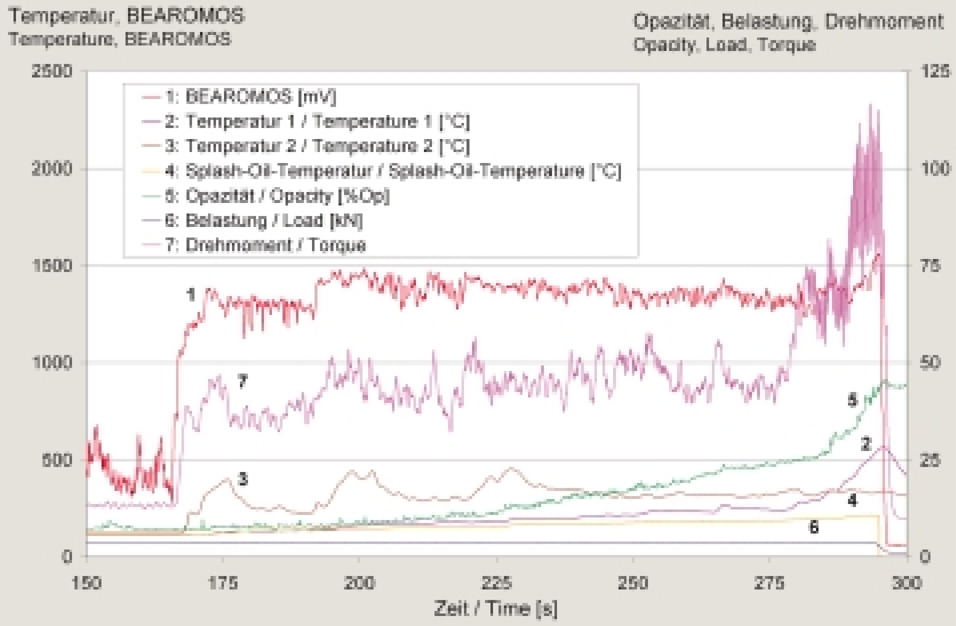


Figure 13: Measurement on the large test bench under static loading

BEAROMOS signal a short time before. The bearing temperature in the highly loaded area (T2) increases rapidly to over 400 °C. An increase in the splash-oil temperature can be observed at about 6 seconds after the start of the seizure. By the end of the measurement time, the value increases slowly from 115 °C to about 215 °C. Oil mist formation begins about 26 s after the start of the seizure. The average gradient of opacity, which initially was around 0.25 %/s, increases to 1.6 %/s after the second torque rise. During the measurement, the opacity increases from 7 % to a maximum of 45 %. This corresponds to about 1 g of vaporized oil quantity.

Figure 14 shows the relationship between the friction and the gradient of opacity, which is already known for the same bearing test bench from Figure 12. With the measurements available so far, this also yields a linear relationship between the two quantities. It is confirmed that oil mist is formed only after a minimum amount of friction. The value of about 6 kW, at which oil mist begins to form, is about one order of magnitude greater than the corresponding value of the small bearing test bench. It can be assumed that this is the result of the different thermal boundary conditions. The test bearing carrier of the large test bench clearly exhibits a larger thermal mass than that of the small test bench.

11.2.4 Conclusions from the Radial Bearing Tests

Oil mist formation in bearings was demonstrated on two test benches with different shaft diameters. An approximately linear relationship was found to exist between the induced friction and the gradient of opacity. It showed that the energy balance is of significant importance for the formation of oil mist in the bearing. The temperature of the supplied lubricating oil and other thermal boundary conditions therefore have a decisive influence. The heat energy induced into the system by the seizure is completely removed by the bearing carrier, shaft and oil. Only when these facilities for heat dissipation do not suffice does the oil in the gap heat up to such an extent that vaporization occurs. Due to the subsequent recondensation outside the bearing, oil mist is finally formed. Damage to the bearing occurred in all tests where oil mist was formed.

However, bearing damage was also observed in bearings where oil mist was not formed. In those tests, the resulting energy quantities did not suffice to increase the gap temperature to such an extent that the vaporization temperature range of the oil was attained. Outside the installed measurement devices for monitoring the bearing, the BEAROMOS signal always responded before an increase in bearing temperature or opacity. The increase in the splash-oil temperature followed that of the bearing temperature with little delay, though with a clearly lower increase rate.

With reference to the OMDEA project, it was only possible to outline a summary of the experimental results within this article. Further results can be found in [12].

11.3 Sliding Block Experiments

Several experiments were performed in which the sliding speed between the sliding block and the disc was altered in order to adapt to the mean piston speed and power output of relevant engine types for which OMD monitoring is considered.

11.3.1 Test Bench and Measuring Technique for Sliding Block Experiments

The sensor arrangement was basically identical to the one utilized for the radial bearing experiments (11.2). The oil mist opacity originating in the volume of the enclosed measuring chamber can also be converted into an evaporated oil quantity.

11.3.2 Conclusions from the Sliding Block Tests

The diagrams showing the curves of the measured values, temperatures, opacity and BEAROMOS signal are comparable with those resulting from the radial bear-

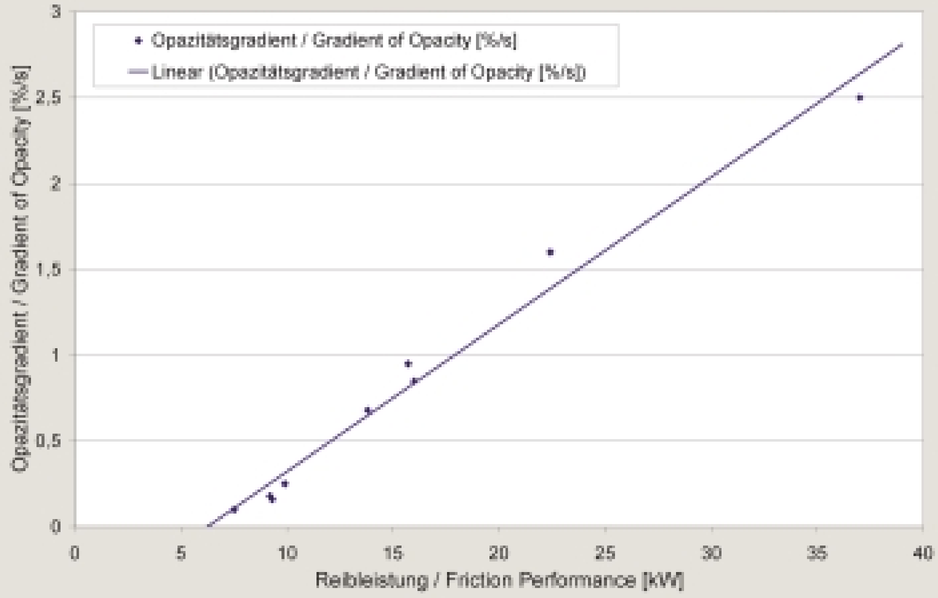


Figure 14: Gradient of opacity vs. friction performance for the measurements on the large test bench

ing tests. Therefore, a detailed description is not required here.

A significant point is the fact that, when a steel disc and a cast iron sliding block are paired under the same testing conditions, the oil mist formation is very much faster than with the combination of a steel disc and a sliding block of multi-layer material.

11.4 Oil Mist Expansion and Oil Mist Behaviour in Crankcases of Large Engines

Schaller Automation conducted experiments on this subject more than 35 years ago [13]. However, compared to the tests performed in the past, the experiments within the framework of the OMDEA project require an oil mist generator that permits the evaporation of an amount of oil and its re-condensation into oil mist (11.2.3), as in the case of real damage. Therefore, the tests represent an appropriate simulation of the damage that occurs in engine types monitored by OMD.

An additional target of the investigations is to collate the tribological experiments (11.2 and 11.3) and analyses from OMDEA and transform them into dimensions of real engine types, which are monitored in order to define "Standard Damage" in relation to oil mist formation. Moreover, the similarity observations [14] utilized by Prof. Groth can be of valuable assistance, and the relationships shown in Figure 12 and 14 are based on these.

11.4.1 The Oil Mist Generator

A controllable oil mist generator is essential for the production of the type of oil mist found in the case of damage. It is a prerequisite that the oil mist achieves a specific opacity as formed during real damage, depending on the engine crankcase size, expansion rate and wash-out effect caused by intensive lubricating oil splashing. In order to achieve this, a physical effect is applied, Title Figure. Lubricating oil under pressure is heated up and, as a result of the heat content (enthalpy), it vaporizes as it expands under atmospheric pressure. In this way, the equivalent oil mist for the simulation of "Standard Damage" can be generated.

11.4.2 Experiments on Oil Mist Simulation in Crankcases

Within the scope of preparing the OMDEA certificate, oil mist simulation experiments were conducted with a four-stroke trunk piston engine with a nominal output of approximately 7000 kW and a speed of 500 rpm , and a second four-stroke engine with a nominal output of approximately 8000 kW and a speed of 1200 rpm , utilizing a new oil mist generator.

Figure 16 shows the induction curves of the oil mist and its dispersion in the compartments of a newly developed four-stroke engine with a high power output. Analogue results were confirmed and described by Schaller Automation 25 years ago [13]. It should be noted that higher thermal loads in modern four-stroke engines also influence the wash-out effect of oil mist (curves B1 to B3), resulting from higher splash-oil quantities discharged from the piston cooling outlet. The wash-out effect caused by the intense amount of oil spray is also the reason why it takes longer to obtain measurable values of oil mist opacity in the compartments located further away from the one in which damage is being simulated. The curves A1 to A3 show the early phase of induction per time unit, containing relatively low amounts of oil mist. It can be seen that both the engine speed and the load have a clear influence on the dispersion of oil mist along the different compartments.

Curves B1 to B3 clearly display the wash-out effect caused by the oil spray, and the dissipation of oil mist moving in the compartments in the direction of the crankcase ventilation. The simulation experiments performed on the high-speed engine show analogous results. However, the characteristic values deduced from the B curves point to a slightly higher dissipation factor. It can be clearly deduced from both engine categories that efficient engine protection in the sense of OMDEA is worthwhile and possible to achieve.

12 Summary

The situations described in Parts 1 and 2 of this article, and the results from the

11.4.2 Experiments on Oil Mist Simulation in Crankcases

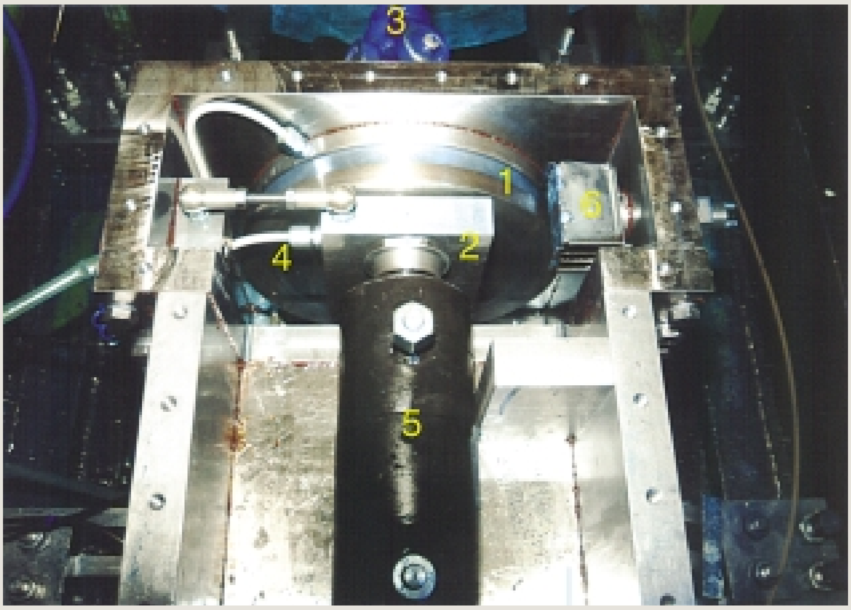


Figure 15: Test bench for sliding block experiments
1: Disc 300 mm
2: Sliding block
3: Drive wheel
4: Lubricating oil supply
5: Hydraulic cylinder for axial force
6: Opacity sensor
The plexiglass cover for the measuring chamber has been removed

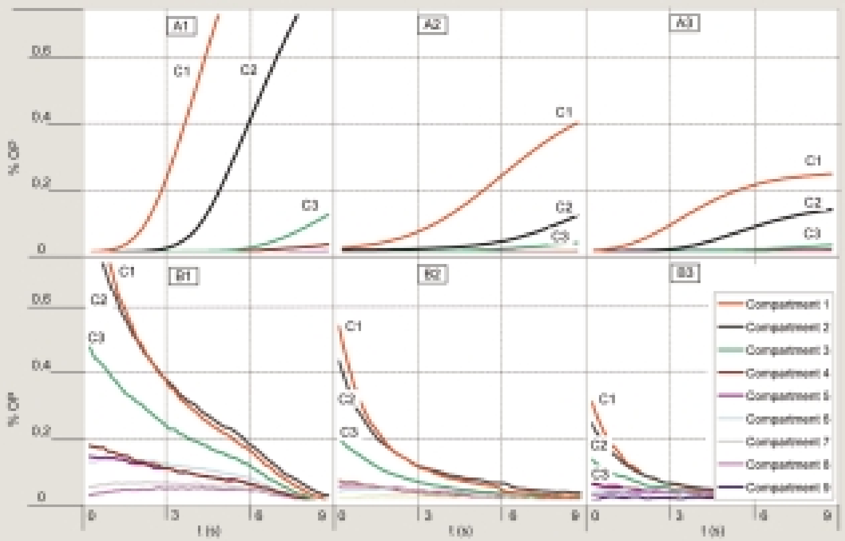


Figure 16: Oil mist induction A, Oil mist dissipation B for the consecutive compartments 1 to 9 of the medium speed engine (Opacity: % OP)
A1/B1 for idling speed
A2/B2 for 500 1/min without load
A3/B3 für 500 1/min with load

experimental investigations, show that purposeful effort can indeed result in the measures required in order to extensively limit the latent operational danger of large diesel engines installed in ships and land-based power stations. Even when used alone, the measures introduced with the OMDEA project will constitute substantial progress. The symptomatic oil mist dispersion arising from damage, as depicted in Figure 16, A1 to A3, will enable damage recognition without false alarms, using intelligent software.

The inclusion of the BEAROMOS sensor provides a correlative sensor system whose intelligent evaluation enables very efficient engine protection to be implemented at a relatively low procurement cost.

The use of an additional sensor system called IGMOS (Ignition Monitoring System), which was developed by Schaller Automation, will enable the continuous monitoring of the pressure in the combustion chamber. The protection efficiency is maximised by the comprehensive system called DIEMOS (Diesel Engine Monitoring and Security), which is currently in the final stages of development at Schaller Automation. Not only does this system represent state-of-the-art technology with a high ability to provide engine protection, its procurement cost is drastically lower than the extreme costs encountered when crankcase damage occurs as a result of unsuitable devices, in addition to the fact that the numerous sensors currently required for traditional control and measuring are no longer required.

It is hoped that the efforts to collect new knowledge and the opportunities presented in this article can be of benefit to the specialists involved, and that the necessary acceptance of an effective implementation of engine protection measures to minimize the risk of the latent operational danger of large diesel engines can be improved.

The authors would like to thank all those who supported their efforts, and

they would feel rewarded if this article were discussed, with critical emphasis, in the Internet Forum at www.dieselsecurity.org

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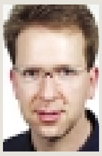

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DIEMOS

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