Engineering Failure Analysis 150 (2023) 107362

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

# Analysis of fuel properties in the context of the causes of three marine auxiliary engines failure – A case study

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ARTICLE INFO

*Keywords:*
Marine diesel engine
Heavy fuel oil
Ignition properties
Fuel contamination
Abrasive wear
Cetane number
Jammed valves
Turbocharger explosion
Cat fines

ABSTRACT

This article presents the effects of a severe failure of three four-stroke auxiliary engines in a container ship's power plant. The failure included jammed cylinder valves, fuel equipment damage, a fire in one of the engines and an explosion of its turbocharger. An analysis of fuel as a factor that constitutes the source and common cause of failure of each engine is made. Laboratory analysis of the fuel is performed. Auxiliary indicators describing the fuel properties are determined, including the calculated carbon aromaticity index (*CCAI*) and the calculated ignition index (*CII*). Laboratory analysis of the fuel ignition properties, including the determination of the equivalent cetane number (*FIA CN* and *ECN*) and the delay of self-ignition in test conditions (*ID*). The possible causes of non-compliance with quality standards by the fuel used to power the damaged engines before and during the failure are consulted. Recommendations that may improve safety are presented.

## 1. Introduction

Incorrect fuel characteristics directly translate into the efficiency and durability of engine components. Contaminants cause an increase in the intensity of the corrosive and abrasive wear, and incorrect self-ignition properties result in chronic combustion or no combustion in the cylinders [1–3]. Accumulated excess fuel can damage, seize and disable the air intake and exhaust outlet valves and cause fires in the scavenging air receiver and exhaust manifold [3–5]. The occurrence of these factors may, in turn, result in explosions in the crankcase [6–8], turbocharger explosions [9–11] and fires in the marine power plant [12–14]. A number of examples of the

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*Abbreviations:* $a$ (% m/m), ash content; *CCAI* (-), calculated carbon aromaticity index; *CII* (-), calculated ignition index; CIMAC, Conseil International des Machines à Combustion (the International Council on Combustion Engines); *CN* (-), cetane number; *CP* (ms), combustion period; DNV, classification society Det Norske Veritas; *ECN*, estimated cetane number; EGR, Exhaust Gas Recirculation; $f$, $g$, function designations; FCA, fuel combustion analyser; FIA, fuel ignition analyser; FIA 100/3, apparatus type; *FIA CN*, equivalent of cetane number measured with the use of FIA 100/3; $G$ (MJ/kg), gross specific energy; HFO, heavy fuel oil; *ID* (ms), ignition delay; IFO, intermediate fuel oil; ISO, International Organization for Standardisation; $N_a$ (MJ/kg), net specific energy; NOx, nitrogen oxides; *ROHR* (bar/ms), rate of heat release; $ROHR_{\max}$ (bar/ms), maximum rate of heat release; $s$ (% m/m), sulphur content; SCR, Selective Catalitic Reduction; *SMC* (ms), start of the main combustion; SOx, sulfur oxides; $t$ (°C), temperature of measurement; T22, U15 reference fuels from Phillips Petroleum International; ULO, used lubricating oils; $w$ (% m/m), water content; $\nu$ (mm$^2$/s), measured viscosity; $\rho_{15}$ (kg/m$^3$), density at 15°C; $\tau$ (ms), time during the measurement with the FIA 100/3 apparatus; $\tau_{ROHR\max}$, moment on the time axis where the *ROHR* reaches its maximum value.

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https://doi.org/10.1016/j.engfailanal.2023.107362
Received 29 January 2023; Received in revised form 9 May 2023; Accepted 26 May 2023
Available online 27 May 2023

engine damage and problem cases induced by poor quality fuels are known [15–17]. Nevertheless, each case is different and very often connected with very complex conditions [18,19]. It is why every case can provide a new look on this topic.

The present authors attempt to analyse the factors that affected the severe failure of three auxiliary engines in the power plant of the 34,015 DWT container ship in 2004. Information about the manufacturers of the ship and engines is anonymised since they are irrelevant to the presented research problem. As a result of the failure, there was a fire in the marine power plant, which was extinguished by the crew. Fortunately, none of the ship's crew members was injured because of this incident. Despite the time that has elapsed since the failure, the subject matter remains relevant due to relatively minor changes in the content of normative acts regarding fuel parameters, for which deviations from the norm are observed, and the fact that the engines of the analysed type are still in use on many sea-going vessels [8,20,21]. The above statement motivated the preparation of this article and the presentation of the analysis of the accident in question in the context of the properties of the fuel used to power the engines that failed shortly one by one within less than 30 days.

The incident occurred during a sea voyage. The failure concerned three out of four auxiliary (AE) diesel engines of the ship's power plant. These were 5- and 6-cylinder, four-stroke, medium-speed, trunk piston, turbocharged, single-acting engines with a rated speed of 720 rpm and a cylinder power of 220 kW. The engines were not equipped with SOx and NOx reduction systems, including, in particular, scrubbers, SCR systems, or EGR systems.

The fuel is fed from the return tank (i.e., the deaeration unit) to the auxiliary engines by the booster pumps (one duty pump and one parallel standby pump). The fuel entering each auxiliary engine is filtered into a duplex filter with a filtration accuracy of 50 μm, and then directed to the injection pumps. Each cylinder is equipped with an individual injection pump. A camshaft mechanically drives the pumps. Injection pumps feed fuel to the fuel injectors through the high-pressure lines. Each cylinder has one fuel injector located centrally on the cylinder head. Fuel injection is performed directly into the combustion chamber. The fuel not used by the engine is returned from the injection pumps via the return line to the return tank. The fuel is properly prepared in advance (cleaned in tanks, centrifuged, filtered, and heated). The temperature of the fuel fed into the engines in the fuel preparation units is maintained at a predetermined level by the use of fuel heaters. The viscometer system sets the temperature to such a level that the fuel fed into the engines has the desired viscosity [22]. For the engines in question, according to the manufacturer's guidelines, this should be 12–18 cSt (12–18 $mm^2/s$) before the injectors. The fuel supply system for each auxiliary engine is equipped with control, measurement, and safety equipment, including the monitoring of temperature, pressure, and fuel flow, as well as the pressure drop across the fuel filter.

Each cylinder has two air intake valves and two exhaust gas valves. Air is supplied into the valves through the supply air manifold, which is supplied with air from the turbocharger (T/C) compressor. Each engine equipped with one T/C. The air is sucked in through the air filter and directed into the air cooler (one cooler for each engine). From there, the air is directed into the supply air manifold. The air supply to the cylinders is provided by mechanically actuated intake valves that open the air supply to the cylinders. The camshaft drives the valves via push rods and rocker arms. The exhaust gases are discharged from each cylinder through the exhaust valves, which are driven similarly to the intake valves. The exhaust gases are discharged to the exhaust gas manifold, from where they flow into the funnel through the T/C turbine. The exhaust gases expand in the turbine, which drives the T/C compressor rotor located

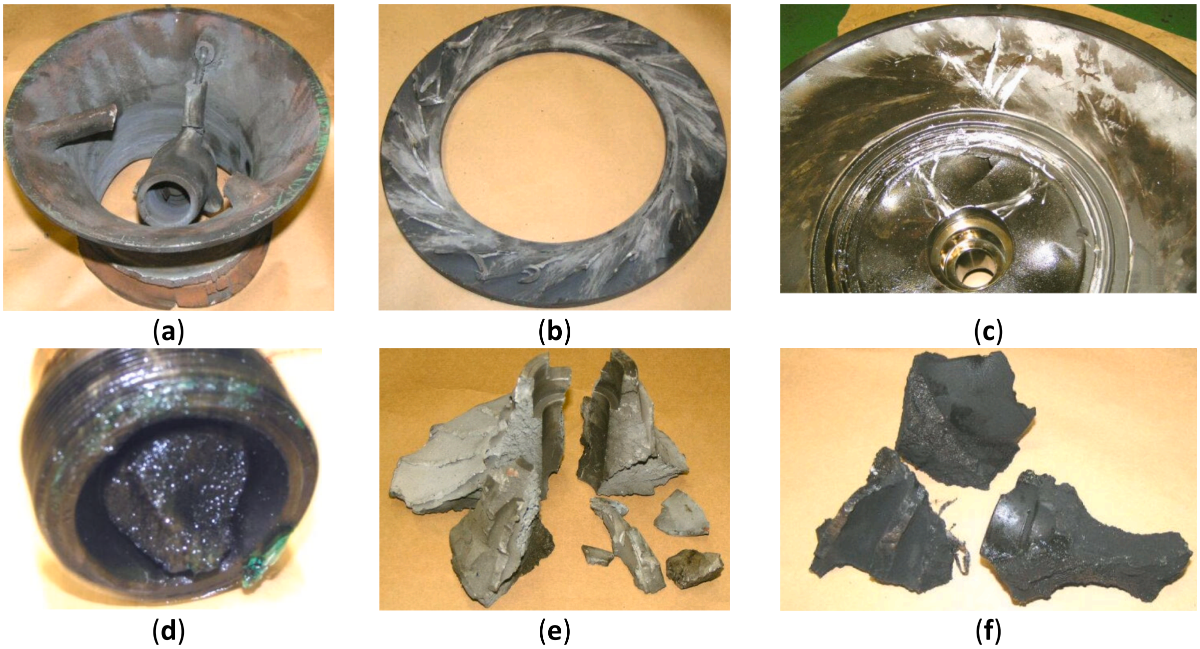

**Fig. 1.** Components of the turbocharger damaged because of its explosion: (**a**) exhaust gas inlet casing, (**b**) exhaust gas nozzle ring, (**c**) inside side cover, (**d**) twisted turbocharger shaft, (**e**) compressor rotor remnants, and (**f**) turbine wheel remnants.

on the same shaft. The air intake and exhaust gas exhaust systems have control and measurement systems. The boosting system is supported by a jet system that enables air to be supplied to the T/C compressor from the engine's starting system (a T/C boosting system). The T/C is protected against overspeed, which causes an emergency stop of the engine when the T/C rotor exceeds the speed of 42680 rpm.

The engines (ship) was 7 years old at the time of the incident. The time of their actual work was in the range of 38 thousand – 41 thousand operating hours. Unfortunately, we do not have the exact information on how much each engine worked. 16 days have passed since the last bunkering to the time of the start of the incident. At the time of the event, engines 1 and 2 worked approximately 550 h, while engines 3 and 4 worked approximately 150 h since the last bunkering. The crew made no adjustments in the engines during the voyage. The number of injector operating hours since the last adjustment/replacement was less than 2000 operating hours. Engines operated at ca. 50–60% nominal load.

The failure occurred due to a common cause [23–25], which was the negative impact of fuel on the engine components. During the power plant operation, three engines were damaged and stopped, and the turbocharger on one of the engines exploded – the view of the essential elements of the turbocharger after the explosion is shown in Fig. 1.

The subsequent verification of the technical condition of the engines showed jammed valves, one of the fuel pumps failed and incorrect operation of the fuel injectors. The list of individual damages is given in Table 1.

The fuel that was used to power the engines just before the crew defined the failure as a mix of two fuels from two bunker tanks, which contained fuels taken in two different ports from two different suppliers. In this article, we added anonymized data on suppliers and tank numbering. The fuel was bunkered in the ports of Port 1 - fuel A (to tanks 1, 2, 7, and 8) and Port 2 - fuel B (3, 4, 5, 6, 7, and 8). Thus, storage tanks 7 and 8 contained fuel mixed from two different suppliers in ratio of fuel A/fuel B equals to ca. 80/20 % v/v.

Before bunkering, the storage tanks were entirely emptied to the extent allowed by technical solutions, i.e., there are always small amounts of fuel from previous bunkers, which is the so-called dead fuel. Mixing of fuel types, even of the same type, should not occur and, if necessary, it should be preceded by appropriate tests to check fuel compatibility, which was not performed in this case (tanks 7 and 8).

The laboratory results of fuel A showed full compliance with the requirements of the then-applicable standard 8217:1996 in relation to the fuel RMG 35 class (formerly CIMAC IFO 380). On the other hand, laboratory tests of fuel B showed a slight increase in sodium and water content.

During the voyage that preceded the accident, fuel B was used from tanks 3, 4, 5, and 6, i.e., except for tanks 7 and 8, in which there was a mix of fuels A and B.

All the events occurred over a short period of less than 30 days. We do not provide exact dates due to the anonymization of the course of events, but only present individual events on a relative scale that are counted against the initial event (day 0), the moment of fuel bunkering A. The chronology of events was as follows:

- Day 0–1180 MT of fuel A was bunkered in the first port.
- Day 3–619 MT of fuel B bunkered.
- Day 16 - engine No. 3 failure - both exhaust valves on each cylinder jammed, and one fuel injection pump became blocked.
- Day 26 - engine No. 1 failure - jammed one inlet and both exhaust valves on one of the engine cylinders, fire in the scavenge air receiver and exhaust gas manifold and, finally, the explosion of the turbocharger. These events occurred almost simultaneously within a few minutes (less than 30 min).
- Day 29 - engine No. 2 failure - jammed both exhaust valves on the two engine cylinders.

## 2. Materials and methods

Fuel samples used by the auxiliary engines before and at the time of the failure were tested by a certified testing laboratory of DNV. The samples taken during the accident investigation were taken from the fuel supply manifold that supplies fuel to the auxiliary engines (the samples were collected in the fuel conditioning unit of the auxiliary engine fuel supply system). According to the supplier's documentation, the fuel met the requirements of the RMG 35 class following ISO 8217:1996 (formerly CIMAC IFO 380) [26].

In the following years, the requirements of the ISO 8217 standard changed [27]. The individual values of the characteristics of the tested fuel are compared with the requirements of the valid at the time of incident ISO 8217:1996 standard. Nevertheless, where applied we extend our comments taking into account later standards [28]. Information specified for the fuel samples is as follows:

- kinematic viscosity at 40 °C, 80 °C and 100 °C ($mm^2/s$),

**Table 1**
A list of damages to the engines of the ship's power plant resulting from the analysed failure.

| Auxiliary engine | AE1 | AE2 | AE3 |
|---|---|---|---|
| Fuel injector nozzles leaking | Yes | Yes | Yes |
| Fuel injection pump blocked up | No | No | Yes |
| Cylinder valves blocked up | Yes | Yes | Yes |
| Piston and liner damages | No | No | No |
| Turbocharger explosion | Yes | No | No |

- density at 15 °C (kg/m$^3$),
- micro-carbon residue (% m/m),
- total sediment potential (% m/m),
- ash content (% m/m),
- water content (% m/m),
- aluminium content (mg/kg),
- total content of aluminium and silicon (mg/kg),
- calcium content (mg/kg),
- iron content (mg/kg),
- lead content (mg/kg),
- magnesium content (mg/kg),
- nickel (mg/kg),
- phosphorus content (mg/kg),
- sodium content (mg/kg),
- silicon content (mg/kg),
- sulphur content (% m/m),
- vanadium content (mg/kg),
- zinc content (mg/kg),
- used lubricating oil content (Ca + Zn and Ca + P) (mg/kg).

The measured physicochemical parameters are compared with the ISO and CIMAC standards to determine the deviations from the norm. Moreover, based on the measured parameters, the lower and upper calorific values of the fuel are calculated, as well as the computational indices used to determine the self-ignition properties of the residual fuels, i.e., the calculated carbon aromaticity index (*CCAI*) and the calculated ignition index (*CII*) [29].

To evaluate calorific value of the fuel, we used the formulas for determining the net specific energy $N_a$ and gross specific energy $G$ for residual fuels indicated in the CIMAC recommendation (Annex 1 of ref. [30]) following the then applicable ISO/TR 18,455 standard. For residual fuels, net specific energy, $N_a$ (MJ/kg), and gross specific energy, $G$ (MJ/kg), can be calculated with of accuracy acceptable for normal purposes from the equations [30]:

$$\begin{aligned} N_a = {} & \left(46.704 - 8.802 \bullet {\rho_{15}}^2 \bullet 10^{-6} + 3.167 \bullet \rho_{15} \bullet 10^{-3}\right) \\ & \bullet [1 - 0.01 \bullet (a + s + w)] + 0.0942 \bullet s - 0.024 \bullet w, \end{aligned} \tag{1}$$

$$G = \left(52.190 - 8.802 \bullet {\rho_{15}}^2 \bullet 10^{-6}\right) \bullet [1 - 0.01 \bullet (a + s + w)] + 0.0942 \bullet s, \tag{2}$$

where: $\rho_{15}$ (kg/m$^3$) is fuel density at 15 °C, $a$ (% m/m) is the ash content, $s$ (% m/m) is the sulphur content, and $w$ (% m/m) is the water content.

*CCAI* is Shell's calculation of the autoignition capability of residual fuels (HFO), which is calculated based on the measured viscosity $\nu$ (mm$^2$/s) for a given fuel determined at $t$ (°C) and the density at 15 °C $\rho_{15}$ (kg/m$^3$). *CCAI* can be determined from one of the equivalent formulas [31]:

$$CCAI = \rho_{15} - 140.7 \bullet \log[\log(\nu + 0.85)] - 80.6 - 210 \bullet \ln\left(\frac{t + 273}{323}\right), \tag{3}$$

$$CCAI = \rho_{15} - 140.7 \bullet \log[\log(\nu + 0.85)] - 80.6 - 483.5 \bullet \log\left(\frac{t + 273}{323}\right). \tag{4}$$

CII is BP's calculation of the autoignition capacity of residual fuels (HFO), which is calculated based on the measured viscosity $\nu$ (mm$^2$/s) for a given fuel determined at $t$ (°C) and the density at 15 °C $\rho_{15}$ (kg/m$^3$). The values obtained from the calculation of *CII* for residual fuels are interpreted analogously as CN for distillate fuels. *CII* is determined from the formula [31]:

$$CII = (270.795 + 0.1038 \bullet t) - 0.254565 \bullet \rho_{15} + 23.708 \bullet \log[\log(\nu + 0.7)]. \tag{5}$$

In the last stage of the experiment, bearing in mind that the *CII* and *CCAI* indices do not always describe the properties of the so-called problematic fuels [32], which were signalled in earlier publications [33], the fuel ignitability was analysed using the Fuel Ignition Analyzer FIA 100/3 apparatus. A detailed description of this apparatus can be find in [33].

The FIA 100/3 apparatus works efficiently in assessing the ignition properties of marine fuels and allows to determine CN equivalent called *FIA CN* [34]; it acts as one of the alternatives in this type of research [35,36]. The value of the cetane number, or its equivalent, should be within the range that ensures reliable and safe operation of the engine, depending on the type of engine and the anticipated loads [17,37,38] at which the engine will be used. Failure to follow these guidelines may result in severe engine damage [39,40]. After 2004 fuel ignition analyser FIA analyser were substituted by fuel combustion analyser FCA and instead of *FIA CN* a new parameter called estimated cetane number *ECN* were introduced [41]. The recommended estimated ECN values and the potential impact of the fuel on engine operation are shown in Fig. 2.

The apparatus enables determination of the ignition delay and maximum heat release rate under test conditions and, on this basis, establishes the equivalent cetane number (*CN*), marked as *FIA CN* (FIA cetane number). Interpretation of the indicators describing the self-ignition properties of the fuel is presented in Table 2. The FIA device and its subsequent versions (i.e., fuel combustion analyser (FCA)) are used to assess the ignition quality for four-stroke engines at low loads [42].

The apparatus, in controlled conditions in a chamber with a constant volume, performs the combustion process while recording the course of pressure p (bar) as a function of time τ (ms):

$$p = f(\tau). \tag{6}$$

Ignition delay *ID* (ms) in this apparatus is defined as a time delay from the start of injection until an increase in pressure of 0.2 bar above the initial chamber pressure has been detected. From the end of the ignition delay to the end of the combustion process, the combustion period *CP* (ms) occurs. In turn, the start of the main combustion *SMC* (ms) phase is determined as the time when an increase in pressure of 3 bars above the initial chamber pressure has been detected. The *SMC* indicator is used to establish the ignition quality of a fuel tested in the form of *FIA CN* (cetane number). The *f* function used to determine the *FIA CN* is the reference curve for the FIA 100/3 instrument, which shows the ignition properties for mixtures between the reference fuels U15 and T22 from Phillips Petroleum International. The calibration procedure is analogous as in previous version of apparatus [32]. This reference curve establishes the relationship between the ignition quality (recorded in milliseconds) and the cetane number for the different mixtures of the reference fuels [44]. For HFOs, *FIA CN* values typically range from 18.7 to over 40, and the functional dependency can be represented in general as:

$$FIACN = g(\tau = SMC). \tag{7}$$

In the current version of IP 541/06 standard the *FIA CN* is substituted by *ECN*, which in new FCA apparatus is calculated according to the formula [41]:

$$ECN = 153.15 \bullet e^{-0.2861 \bullet SMC}. \tag{8}$$

Pre-2004 versions of the FIA equipment were individually calibrated for conversion from SMC to ECN. A such apparatus was used for analysis of the problematic fuel in the presented case study. In this case *FIA CN* can be converted to *ECN* with use of the equation [41]:

$$ECN = 1.2175 \bullet FIACN - 3.5713 \tag{9}$$

To determine the parameters describing the ignitability of a given fuel sample, the apparatus performs a minimum of 12 injections/ignitions in each test. Based on this data, the mean pressure trace and mean value for *ID, SMC, FIA CN* and *CP* are defined. In addition, the device calculates and determines the course of the rate of heat release (ROHR), which is determined according to the following:

$$ROHR = f'(\tau) = \frac{dp}{d\tau}. \tag{10}$$

In addition to the listed indicators, the maximum $ROHR_{\max}$ value (bar/ms) and the moment when this maximum occurs $\tau_{ROHR\max}$

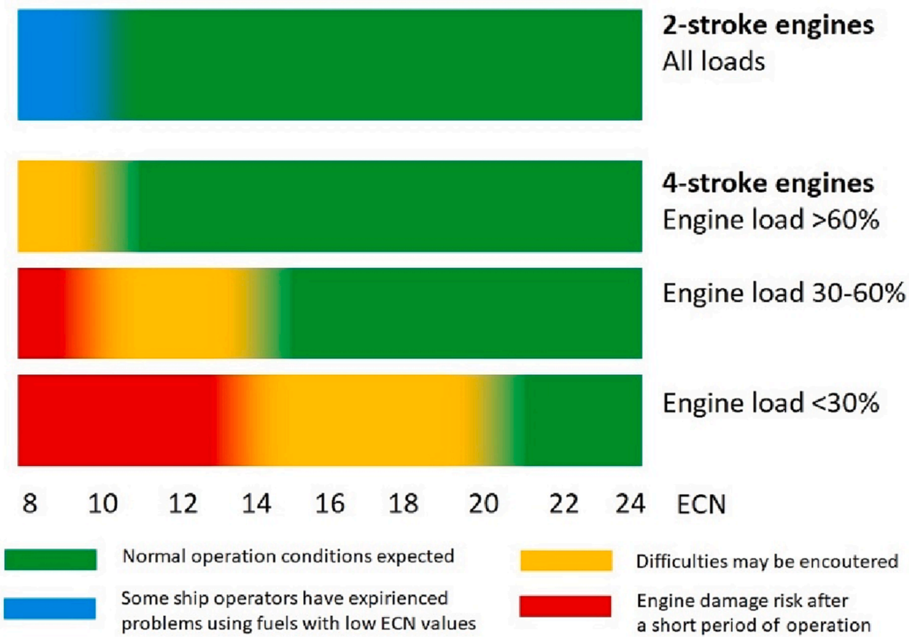

**Fig. 2.** Recommended ECN operational reference ranges (modified from [16]).

**Table 2**
Ranges of *CCAI* and *CII* values for residual fuels of different ignition quality (based on [43]).

| Qualitative description | CII / FIA CN | CCAI |
|---|---|---|
| Very bad ignition properties | < 25 | 900 – 950 |
| Bad ignition properties | 25 – 28 | 870 – 900 |
| Acceptable to good ignition properties | 28 – 35 | 850 – 870 |
| Good ignition properties | 35 – 40 | 830 – 850 |
| Very good ignition properties | > 40 | 790 – 830 |

(ms) are used to describe the ignition and flammability properties of the tested fuel sample, so that:

$$ROHR_{\max} = ROHR(\tau = \tau_{ROHR\max}) = \max_{\tau \to \infty}[ROHR(\tau)]. \tag{11}$$

Exemplary results of the analysis of ignitability of residual fuels with extreme ignition properties is presented in [43]. All the mentioned indicators are determined for the tested fuel sample, and they are used to draw conclusions summarising the tests.

## 3. Results and discussion

All the quantitative results of the analysed fuel are summarised in Table 3. The results of standard tests of physical and chemical properties, computational auxiliary indicators and the results of fuel ignitability tests performed using the FIA 100/3 apparatus are indicated here. The results were compared with the standard ISO 8217:1996 for the required quality of residual fuel of this grade (RMG 35). We agree that this standard is applied for bunkered fuel not for the fuel at the inlet of the engine, nevertheless the RMG 35 grade fuel were approved by the engine manufactures for the analysed engines. Taking it into account we used this standard as a reference in the performed comparative analysis of used fuel properties against requested properties [45].

The course of the pressure during the combustion process and the rate of heat release (ROHR) of the tested fuel are shown in Figs. 3 and 4, respectively.

The viscosity, density, micro-carbon residue and flash point that are determined as a result of the tests are within the correct range, indicated by the fuel quality standards displayed in Table 3. The content of the elements, such as phosphorus, sodium, sulphur, vanadium and zinc in the fuel samples, is also within the norm. On the other hand, fuel components whose content exceeds the permissible standards are ash, aluminium, total aluminium and silicon, water and calcium.

Although the total sediment potential is normal, a high value close to the limit and other fuel components indicates significant fuel contamination. Ash-contaminating fuel increases the abrasive wear of elements in contact with these substances. Ash is non-flammable foreign fuel components such as sand, which is a product of corrosion processes of elements and catalyst fines (cat fines). The latter group of pollutants in HFOs stems from catalytic cracking processes. Cat fines have a diameter of 100 μm and smaller ones are as small as 1 μm [46]. These are usually aluminium oxides and silicon oxides, which cause high abrasive wear in the injection system (seizing pairs of precision injectors and fuel pumps) and in the engine (wear of piston rings and cylinder liners) and formation of deposits [47]. These are very hard particles with a hardness of up to 8.2 on the Mohs scale. For this reason, it is necessary to monitor the aluminium and silicon content in the fuel [48]. In the analysed case, aluminium and silicon were detected in excessive amounts. In the presented case, all three engines suffered fuel injector nozzle leaks, which is one of the common symptoms of abrasive wear of the nozzle and needle sealing surface. It is very likely that elevated ash content, including hard cat fines, significantly contributed to this. Additional failure of the fuel pump also indicates a similar nature of the malfunction.

On the other hand, water in the fuel causes chemical and electrochemical corrosion, accumulation of deposits and emulsification, and also favours the emergence and development of living organisms in the fuel, especially sulphur bacteria, which cause the clogging of filters, corrosion and worsens the quality of fuel atomisation and fuel pumpability. Water also lowers the specific energy of fuel: 1% H2O m/m causes energy loss of more than 1% compared to reference conditions [42]. Water can enter the fuel during storage, transportation and preparation due to leaks in heat exchangers, heating coils in tanks, malfunctioning fuel centrifuges, damaged or improperly maintained debris drainage systems, etc. High water content could cause fuel emulsification and, consequently, insufficient atomization. Together with the increased level of hard particles, conditions have been created to transfer pollutants behind the cylinder, into the exhaust ducts and even into the turbocharger. Over time, the hard particles accumulated in the turbocharger could hinder the free movement of the impeller and, consequently, its seizing and, eventually, its ignition and explosion. Another possibility observed in the case of engines operating only on residual fuels is incomplete combustion during the starting up and low load operation. Both conditions may result in the transfer of some amount of incomplete combusted fuel droplets towards the exhaust duct, where they stick and build up. Higher water content in the fuel may intensify this negative process.

The calcium content is high, and although phosphorus and zinc are normal, calcium should not usually be present in the fuel. However, in small amounts, calcium, along with vanadium, sodium and nickel, may originate from crude oil and may arise as a result of fuel contamination during transport. It is a component of lubricating oils. Fuel should be free from used lubricating oil (ULO), however it was not specified in the standards valid when the event occurred. According to the later standards e.g. ISO 8217:2017, it should be considered as containing ULO when either one of the following conditions is met:

- calcium above 30 mg/kg and zinc above 15 mg/kg,
- calcium above 30 mg/kg and phosphorus above 15 mg/kg.

**Table 3**
Measured and calculated parameters of the analysed fuel and their comparison with various specifications describing the same fuel class.

| Limit | Parameter | CIMAC 1990 / ISO 8217:1996 *RM-35G / IFO-F RMG 35* | Analysed fuel *RM-35G* | Normal or alarm level |
|---|---|---|---|---|
| Max. | Viscosity at 50 °C ($mm^2/s$) | 380 | 285 | OK |
| Max. | Viscosity at 100 °C ($mm^2/s$) | 35 | 29.4 | OK |
| Max. | Density at 15 °C ($kg/m^3$) | 991 | 986.4 | OK |
| Max. | Conradson carbon residue / micro carbon residue (% m/m) | 18 | 11 | OK |
| Max. | Total sediment potential (% m/m) | To be developed | 0.07 | OK |
| Max. | Ash (% m/m) | 0.15 | 0.11 | OK but higher required in later standards (>0.1) |
| Max. | Water (% V/V) | 1.0 | 2.1 | HIGH |
| Max. | Aluminium (mg/kg) | 30 | 44 | HIGH |
| Max. | Aluminium + silicon (mg/kg) | N/A | 103 | OK (not specified in this standard) but higher required in later standards (>60) |
| Max. | Calcium (mg/kg) | N/A | 124 | OK (not specified in this standard) but higher required in later standards (>30) |
| Max. | Phosphorus (mg/kg) | N/A | 3 | OK (not specified in this standard but in limit according to later standards) (<15) |
| Max. | Sodium (mg/kg) | N/A | 43 | OK (not specified in this standard but in limit according to later standards) (⟨100) |
| Max. | Sulphur (% m/m) | 5.0 or statutory requirements | 1.7 | OK |
| Max. | Vanadium (mg/kg) | 300 | 112 | OK |
| Max. | Zinc (mg/kg) | N/A | 5 | OK (not specified in this standard but in limit according to later standards) (<15) |
| Max. | Used lubricating oils (ULO): Calcium and Zinc; or Calcium and Phosphorus (mg/kg) | N/A | Calcium > 30 and zinc < 15; or Calcium > 30 and phosphorus < 15. | OK (not specified in this standard but according to the later standards the fuel shall be free from ULO, and shall be considered to contain ULO when either one of the following conditions is met: Calcium > 30 and zinc > 15; or Calcium > 30 and phosphorus > 15). |
| Min. | Flashpoint (°C) | 60 | 70 | OK |
| | Net specific energy, $N_a$ (MJ/kg) | There is no direct reference to these parameters in the standards, while the increased water content reduces the'engine's energy efficiency. | 41.21 | – |
| | Gross specific energy $G$ (MJ/kg) | | 43.62 | – |
| Max. | Calculated carbon aromaticity index $CCAI$ (-) | To be developed | 850 | OK (not specified in this standard but in line with later requirement ⟨870) |
| Min. | Cetane number $CN$ (or equivalental parameter) | There is no direct reference to this parameter in the standards. The interpretation of the CN/CII value for HFO is given In Table 2. However, exemplary FIA CN values in relation to average intermediate fuel oil are shown In [43]. | $CII = 34$ | OK |
| | | | $FIA\ CN < 18.7$ | LOW |
| | | | $ECN < 19.2$ | LOW |
| | Ignition delay $ID$ (ms) | There is no direct reference to these parameters in the standards. The interpretation of the values in relation to average intermediate fuel oil is given In [43]. | 9.95 | HIGH |
| | Start of main combustion $SMC$ (ms) | | 14.8 | HIGH |
| | Maximum ROHR level $ROHR_{\max}$ (bar/ms) | | 1.4 | LOW |
| | Maximum ROHR position $\tau_{ROHR\max}$ (ms) | | 15.0 | LOW |
| | Combustion period $CP$ (ms) | | 15.1 | OK |

In this case, these conditions are not met. However, the calcium content indicates contamination of the fuel with external substances that should not typically be included in the composition of marine fuels. The fuel also contained metals such as iron, lead, magnesium, nickel and silicon, which presumably wear parts of engines, machines and devices that come into contact with fuel before it is delivered to the engine injection system. The calorific value, calculated on the basis of the chemical composition, is close to the average for residual fuels. However, reducing the water content in the fuel, due to a properly implemented centrifugation and sedimentation process, would increase the net and gross calorific value.

The calcium and ash content are slightly affected by separation (filtering) processes. On the other hand, aluminium and silicon can

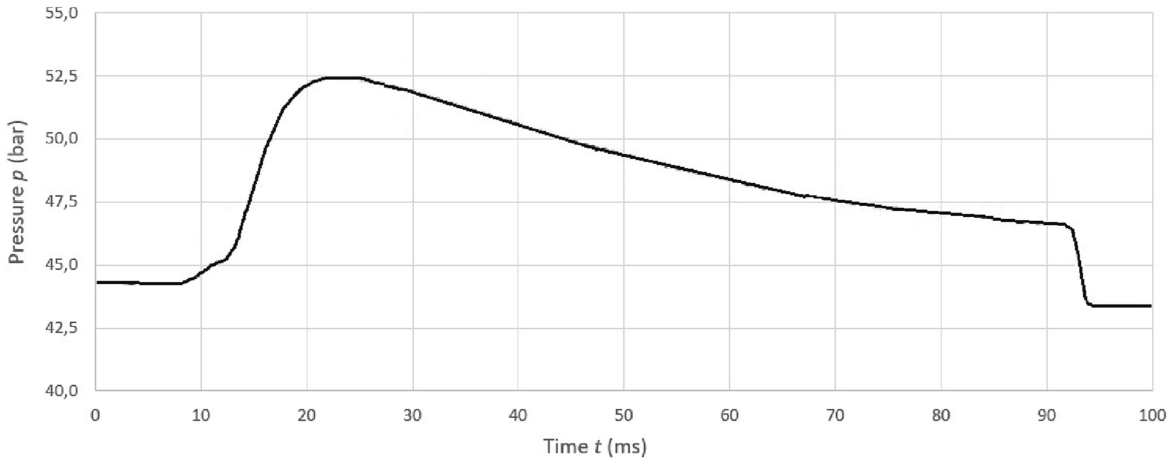

**Fig. 3.** Averaged pressure changes in the chamber of the FIA 100/3 apparatus during the ignitability tests of the tested fuel (modified from [14]).

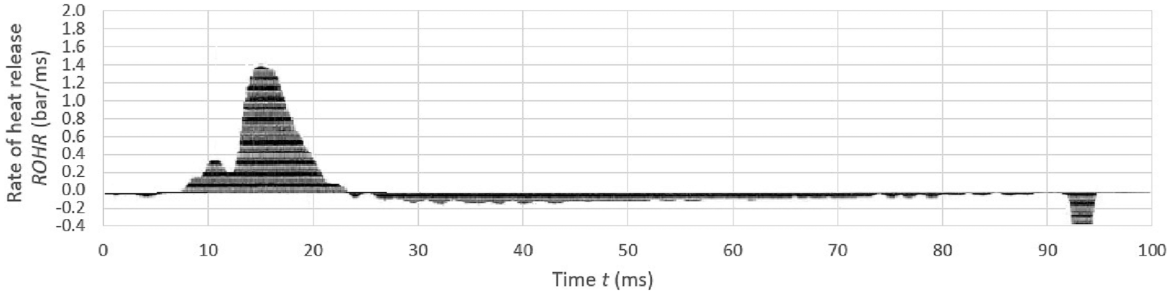

**Fig. 4.** Averaged change in the rate of heat release in the chamber of the FIA 100/3 apparatus during the ignitability tests of the tested fuel (modified from [14]).

be strongly reduced by separation [42]. Thus, a high content of aluminium and a high total content of silicon and aluminium imply improperly conducted service processes in the ship's fuel purification system and/or disturbances in the operation of fuel centrifuges. High water content in the analysed fuel also indicates improper fuel cleaning.

The calculated *CCAI* and *CII* indexes indicate proper ignition properties. However, it should be remembered that these values are only supplementary to the detailed laboratory analysis of the fuel. The fuel centrifugation purification process itself does not affect significantly parameters such as density and viscosity and, therefore, does not significantly alter the calculated values of indicators such as *CCAI* and *CII* [47]. In the analysed case, both of these indicators corresponded to the correct fuel ignition properties. To avoid similar situations, engine manufacturers e.g. MAN B&W [47] recommend additional tests (e.g., FIA) when *CCAI* exceeds 840. On the other hand, when *FIA CN* is below 20, engine operation problems can be expected, especially at low loads [49–51].

Although the *CCAI* and *CII* values are normal, fuel ignitability tests performed with the FIA 100/3 apparatus clearly show that the tested fuel has very poor self-ignition properties. Thus, unburned fuel accumulates in the engine, which causes engine damage. When the accumulated fuel suddenly ignites, it causes fires in the exhaust manifold and air tank, which may lead to the explosion of the turbocharger. All these factors were at play in the present case of the severe accident in the ship's power plant.

The tested fuel had a much longer ignition delay *ID* and the period from fuel injection to the start of main combustion *SMC* was significantly longer than the average for residual fuels. However, the maximum value of the *ROHR* level, and its position on the time axis, are lower than the average. The summary of the laboratory fuel ignitability analysis is the *FIA CN* index, which in the present case is below the value of 18.7, that corresponds to very poor self-ignition parameters of the fuel and can cause serious problems when operating four-stroke engines at low loads, e.g., when a ship is manoeuvring into or out of a harbour.

In the presented case, it was found that the fuel sampled from the engine's fuel supply system was of poor quality. It is uncertain whether the bunkered fuel was of poor quality or was contaminated and deteriorated on board. There is insufficient evidence to judge it with the available data and methods. However, the contamination likely occurred on board because the fuel samples were taken during the bunkering process for laboratory analysis. One of the possible explanations is the insufficient draining of the sludge and water from the settling and service tank and, eventually, improper operation of the fuel purification system. Interestingly, the additional analysis of the signs of ULO detected such contamination. Again, there is no evidence regarding the origin of this contamination – was it bunkered with it or contaminated on board? However, regardless of the origin of the contamination, damage to the engines shows the validity of the later introduction of restrictions for markers of admixtures of used oils in marine fuels in the standard.

After the failure of each of the engines, the auxiliary engines were overhauled [52,53]. The remnants of fuel mix A and B contained in storage tanks 7 and 8 were handed over to the port, proper drainage of all tanks was ensured, fuel filters were cleaned, and the operation of fuel centrifuges was checked and adjusted. Strict procedures have also been introduced to increase the frequency of the draining fuel tanks and to test fuel in service tanks and fuel supply manifolds of the auxiliary and main engines more frequently on board for water content.

Due to the lack of injured people, external bodies performed no investigation, such as marine accident investigation committees. However, given the stressful situation during the incident, it can be assumed that such information could contain subjective opinions of the crew members. It is also difficult for us to refer to the specific actions of the crew members during the event. There is no doubt, however, that several acts of negligence (as indicated in the article) have contributed to the accident. Negligence could result from the crew's lack of proper training, sluggishness in operation and ignoring operational procedures, crew fatigue (e.g., in connection with the performance of other duties), lack of adequate control of subordinates by the management, and falling into the so-called routine. However, considering the chronology of events, if the crew had drawn the correct conclusions after the failure of engine 3 and taken appropriate corrective actions as soon as possible, the failures of engines 1 and 2 could have been prevented. However, this did not occur. One of the reasons in relation to this may be the low level of training of the crew.

## 4. Conclusions

The performed fuel tests showed that the fuel might the leading and common cause of failure of all three auxiliary engines in the present case. Based on the detailed observations, arising from the discussion of the results of the tests, several general conclusions regarding the failure in question can be drawn:

1. It cannot be ruled out that the combination of fuel parameters that contributed to the failure of the engines could have resulted from contamination of the fuel taken from the bunker with fuel residues left in the bunker tanks, and the synergistic effect of the composition and properties of these fuels on the physical and chemical properties of the fuel formed after their mixing.
2. High content of water, aluminium and silicon in fuel is associated with improperly conducted cleaning processes in filters, centrifuges and tanks. However, it cannot be ruled out that the composition of the fuel was a factor that deteriorated the quality of cleaning with the use of standard equipment used in installations for transporting, cleaning and supplying marine engines with fuel.
3. The present case shows that the calculated indexes of residual fuels' self-ignition capacity, such as *CCAI* or *CII*, can be used as information about the poor fuel quality in the case of extremely unfavourable combinations of fuel rheological properties. On the other hand, the indication of proper quality by these indicators does not necessarily reflect the actual correct ignition delay of fuel. The case in question shows a very high ignition delay described by a low *FIA CN* value, despite the normal *CCAI* and *CII* values.
4. Particularly unfavourable factors related to the fuel properties could rapidly intensify their synergistic effect, as a result of the gradual deterioration of the engine's technical condition and operating conditions. Namely, an increase in specific fuel consumption as a result of a decrease in engine power and the related increase in the thermal and mechanical load of the engine.
5. Poor ignition properties could additionally contribute to high-pressure peaks and increased heat load of the combustion chamber. All these factors contribute to a noisy, hard and knocking running engine, which was not observed by the crew. Of course, the reason could be due to the rapid development of the sequence of events leading to the failure.
6. Additional accumulation of individual negative factors contributing to the failure takes place when the engine is operated at low load, which may intensify the accumulation of impurities in the combustion chamber, burnout the piston crown, damage the piston rings, create a loss of lubrication of the cylinder liners and cause possible fatigue damage, especially under metal-to-metal conditions.
7. Incomplete combustion at jammed exchange valves causes unburnt fuel to flow out and accumulate outside the combustion chambers, in the exhaust manifold and scavenging air accumulator. This, in turn, can cause fires and explosions in the engine's exchange system.

Based on the conclusions presented above, some recommendations can be made to avoid similar situations in future. For this purpose, we propose the following improvements:

1. Conducting proper supervision over fuel, which should be checked each time in laboratory conditions before their initial use as fuel for powering engines. If possible, it is advisable to perform complete tests (as much as possible) of the fuel taken into the storage tanks during bunkering, including an assessment of self-ignition properties (especially for fuels with a *CCIA* value above 840).
2. Do not mix different types of fuels (or worse, add used oil or crude oil waste to fuel for engines).
3. Fuel bunkering should be performed only in the case of tanks with the minimum possible content of the so-called dead fuel (fuel remaining in empty tanks). If this is not possible, additional tests of fuel compatibility and self-ignition properties of the mixture of two fuels should be carried out.
4. It is also necessary to strictly monitor the quality of the fuel on board and to take care of the fuel, including monitoring the fuel's water content in settling and outgoing service tanks and constantly supervising the proper operation of fuel purification devices, such as centrifuges and filters.
5. The technical condition of the engine components (i.e., combustion chambers, fuel apparatus, and valve timing system) should also be monitored on an ongoing basis, strictly adhering to the schedule of maintenance works and the guidelines of the engine manufacturer contained in the manuals and service lists.

## Data availability statement

All data are presented in the paper.

## Funding

Costs associated with the preparation and publication of the article were funded by the Ministry of Science and Higher Education (MEiN) of Poland, grant number 1/S/KPBMiM/23.

## CRediT authorship contribution statement

**Leszek Chybowski:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jarosław Myśków:** Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Przemysław Kowalak:** Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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