The Combustion Characteristics of Residual Fuel oil Blended with Fuel Additives

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잔사유용 연료첨가제 함유 선박 연료유의 연소특성 연구

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Abstract : *Ships are capable of operating on residual fuel oil. Recently, various attempts have been made to meet environmental regulations and with ships operating on residual fuel oil. One way of fulfilling these requirements is by using fuel additives. Dispersants and fuel combustion improvers will have a positive effect on improving the combustion characteristics of the residual fuel oil. As such, this study examines fuel oils blended with additives by using fuel combustion analysis (FIA/FCA) and thermogravimetric analysis (TGA). The results of FIA/FCA focuse only on the amount of work done by the fuel oil. Therefore, it is recommended in this study that a new method to evaluate the combustion efficiency via FIA/FCA processes be developed. The analysis with ROHR curve gained by FIA/FCA brought similar results with pressure trace curve therefore it can be said that new analysis method can be reliable. The TGA, analysis process is very sensitive to the evaporation of fuel, for example, which could be addressed. In the performance-related findings of this study, blended samples with additives containing iron compounds showed a greater improvement in early combustion characteristics than samples without additives.*

Key Words : *Fuel additive, Fuel combustion analysis, Thermogravimetric analysis, Residual fuel oil, Combustion characteristics*

요   약 : 선박엔진은 잔사유를 에너지원으로 활용하여 운항할 수 있으며, 이를 활용한 선박에서 환경 규제와 경제성을 모두 만족시키는 다양한 방안들이 모색되고 있다. 그 중에 한 방안으로 연료 첨가제를 활용하는 기술이 있을 수 있다. 분산제와 연소촉진제는 잔사유 활용 시 엔진의 연소특성 촉진에 기여할 것이라는 기대를 받고 있다. 따라서, 본 연구에서는 연소성 분석 장비(FIA/FCA)와 열 중량 분석 장비(TGA)를 활용하여 잔사유 연료첨가제가 혼합된 잔사유의 연소성을 분석하였다. 연소성 분석 장비(FIA/FCA)의 결과로는 연소에 의한 일의 총량을 분석하도록 분석법이 개발되었으며, 이 때문에 본 연구를 통하여 동일 장비를 활용하면서도 연소 효율을 간단하게 평가할 수 있는 방안을 제시하였다. 연소성 분석 결과인 ROHR 곡선으로부터, 단순한 삼각함수를 활용하여 연소특성을 예측할 수 있는 방안을 제시하였으며, 이 기법을 활용하여 기존의 압력 곡선과 유사한 결론을 도출할 수 있었다. 열 중량 분석(TGA)의 경우 연료유의 증발 특성에 민감하게 반응함을 확인하였고, 첨가제가 연료유 증발에 효과적으로 작용함을 확인하였다.

핵심용어 : 연료첨가제, 연료유 연소성 분석법, 열 중량 분석법, 잔사유, 연소 특성

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1. Introduction

Ships can consume fuel oils of both different quality levels and different kinds, since the ship's energy can be varied from residual fuel oil to distillate fuel oil.

Newly built ships can actively consider adopting new technologies which meet the requirements of maintaining ship stability and emission reduction such as vane wheel, PBCF, duct (Song et al., 2015) and microbubble system (Paik et al., 2015). However, ships that have already been put into commercial operation, such as the 110,000 vessels currently in operation, according to statistics from 2013 (Korea Maritime Institute, 2013), cannot aggressively consider such measures due to a lack of capital. Apart from a major conversion of the main and auxiliary engines, using fuel additives is the most realistic course of action.

Fuel additive technologies have been derived from lubricant additives and the various kinds of fuel additives available on the market. Many varieties of fuel additives can be found in the market, all of which have various applications and have been developed with various purposes in mind. Fuel additives are a particularly prominent subject of research for application in automotive and industrial incinerators due to an increasing interest in bioenergy.

The chemical composition was studied to quantify the concentration of additives in diesel oil. Liquid chromatography, followed by gas chromatography, can be used to identify the additives containing aliphatic alcohols, which are common components of diesel fuel cleaning additives. This second staged processes demonstrates the possibility of accurate determination of the additive in diesel fuel (Boczkaj et al., 2013). The effects of emulsions were investigated by using a 12 % emulsion on a heavy duty (HD) engine and 6 % emulsion on a light duty (LD) engine. Emission of particulate matter (PM) was reduced in both cases, by −32 % on LD and −59 % on HD. The reduction in emission of other pollutants was changeable. Cerium additive was effective in reducing emission in the LD engine but not in HD engine. The possibility of reducing PM emissions was confirmed using a fuel composition change (Farfaletti et al., 2005). Fuel additive effects on a heavy fuel consuming boiler operating in real-time was investigated by Z. Prelec et al., and the study made the conclusion that fuel additives can have a positive effect on boiler combustion (Prelec et al., 2013). Effects of cetane improver on fuel properties and engine characteristics on blended fuel oil mixed with biofuel

were studied by A. Atmanli. Addition of 2-Ethylhexyl nitrate (2-EHN) cetane improver to the mixture increased the cetane number without having any effect on density, viscosity, cloud point, cold filter plugging point, and flash point. According to engine test results, 2-EHN decreased the brake specific fuel consumption while increasing the emissions of NO_x and CO (Atmanli, 2016).

Unlike the automotive, boiler and bioenergy fields, research or study of additives on heavy fuel oil has been very limited in the maritime sector. The performance of fuel additives and their effect on the engine has been rarely studied because recently developed additives can be utilized to distillate fuel and additives for residual fuel have just entered the market. Monique Vermeire studied the combustion characteristics and energy efficacy of marine fuel additives (Vermeire et al., 2010).

Therefore, this study could be a stepping stone to understanding the effects of fuel additives on the combustion characteristics and any additive-bound effects for marine heavy fuel oil. This study has compared three different kinds of fuel additives which are representative of marine fuel additives in the Korean market. This study also prepared samples via direct sampling on board the vessel, and Fuel combustion analysis (FIA/FCA) and Thermogravimetric analysis (TGA) were performed to study about the fuel additive effects.

1.1 Marine Residual Fuel Oil

Residual fuel oil is created during the refining process and possesses a complex structure of hydrocarbons. The hydrocarbons which make up residual fuel oils are paraffinic, aromatic, naphthenic, and olefinic in nature. Among these, naphthenic hydrocarbon (C_nH_{2n}-ring type) is commonly found in heavy marine fuel oils. Naphthenic hydrocarbons are extremely stable cyclical compounds and, in most cases, have greater stability than even paraffinic hydrocarbons. The major constituent of residual fuel oil is asphaltene (ABS, 1984). It can be defined as the portion of crude oil insoluble in n-alkanes such as n-heptane or n-pentane, yet soluble in benzene or toluene. The solubility class definition of asphaltenes generates a broad distribution of molecular structures that can vary greatly from one crude oil to another. In general, asphaltenes are characterized by fused-ring aromaticity, small aliphatic side chains, and polar hetero atom-containing functional groups. It is common to characterize asphaltenes by their average properties as shown in Table 1 (Spiecker, 2003). Asphaltene has a

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comparably low combustion speed and it also can create bigger droplets when fuel injected. Bigger droplets can create carbon deposits after combustion finishes, thereby contributing to the creation of particulate matter (PM) (Kim et al., 2008).

The various types of fuel oil additives and their major benefits are mentioned in Table 2 (Stratas Advisors, 2013). Historical development of fuel oil additives had a tendency to focus on improving fuel conversion efficiency, but trends tend to change because of the adoption of emission regulations on maritime engines. As a result, any kind of fuel additive can be effective in meeting recent emission requirements. In the future, the market will demand fuel oil additives with the ability to reduce PM, NOx and greenhouse gasses.

Table 1. Conventional values of elemental composition of asphaltene

Element	Concentration (wt.%)
H/C atomic	1.0 ~ 1.2
Nitrogen	1.0 ~ 1.2
Sulfur	2.0 ~ 6.0
Oxygen	0.8 ~ 2.0
Vanadium (ppm)	100 ~ 300

Table 2. Types of fuel oil additives and their typical use

Type	Benefit	Typical use
Cetane improver	Ignition improver Reduce vehicle exhaust emission	Meet cetane number spec in refineries Improve engine performance via diesel detergency package
Stabilizer	Improve storage and thermal stability	In refineries to increase use of less stable, lower value components
Corrosion inhibitor	Protect metal parts against steel, copper & silver corrosion	Protect refinery and distribution component Give vehicle parts added corrosion protection via detergency packages
Cold flow improver	Delay wax formation in cold weather Improve fuel flow	Meet winter cold flow spec limits Improve cold storage and handling via winter diesel detergency packages

The United States Environmental Protection Agency (USEPA) has investigated the effects of additives at power plants and collected reliable information on PM reduction due to use of fuel additives. However, the EPA put off the decision of effect of fuel additives on NOx reduction due to lack of experimental data (EPA, 1977).

Transition metals (Fe, Mn, Cu) and alkali earth metals (Ba, Ca) are representative constituents of a fuel combustion improver. Ferrocene, the major iron compound, is used to remove carbon deposits from the combustion chamber of a diesel engine, and also acts as a catalyst at the combustion surface as long as a high concentration of 20~30 ppm is maintained. Hence, the field of organometallic compound synthesis has various studies to create products with a high concentration of iron (Lissianski et al., 2001).

The fuel combustion improver (FCI) can be directly used to reduce pollutants and also effectively enhances combustion by encouraging complete burning of fuel, thus reducing the emission of PM which is mostly created because of incomplete combustion. Hence, it is also known as a fuel combustion catalyst. Ba, Ca, Mn, Ni, Co, Mg and Fe are well known for producing a higher degree of combustion enhancement. Ba, Ca and Mg are known as alkali earth metals which are known for decomposing water in heavy fuel oil, thereby reducing the concentration of unburnt carbon. Mn and Fe are transition metals which catalyze oxygen from the air, resulting in enhanced oxidation. Out of all the different kinds of active metals, Fe is the cheapest and most widely used element. In the field of chemical engineering, an iron compound known as ferrocene is most widely used because a high concentration of Fe is directly proportional to improved combustion characteristics. However, ferrocene tends to have poor solubility in organic solvent, making it too expensive to manufacture.

2. Experimental setup

This study aims to investigate the combustion characteristics of marine residual fuel blended with additives. A well-known method was adopted to analyze the combustion of the given sample. The details of the fuel sample, fuel combustion characteristics, and experimental conditions are given below.

2.1 Specification of fuel oil

Table 3 provides the specifications of a sample of residual fuel oil used in marine engines. The fuel oil viscosity is 357.4 mm^2/s, a sufficiently high value for this kind of oil. The density of the fuel oil is 989.5 kg/m^3. The methods for analysis of fuel oil combustion characteristics explained hereafter utilized this fuel sample and another sample blended with fuel additive.

Table 3. Specifications of the sample residual fuel oil

Parameters	Values
Kinematic viscosity at 50℃	357.4 mm^2/s
Density at 15℃	989.5 kg/m^3
Flash point at 100.2 kPa	85.5℃
Water content	0.1 % (V/V)
Carbon content	85.4 %
Hydrogen content	10.5 %
Sulfur content	3.2 %
Nitrogen content	0.2 %
Oxygen content	1 %

2.2 Specification of fuel oil additives

The exact specifications of the additives applied to this study cannot be revealed as they are within the scope of marketing secrets. However, its purpose, major constituents, and rough concentration are summarized in Table 4.

Blank refers to the residual fuel oil which is can be obtained on board the ship. Sample A is specified as a dispersant and its manufacturer's recommended dosage is in the ratio of 1:8000. Samples B and C are hybrid-type fuel oil additives. The term "hybrid-type" means that a single additive can serve two or more functions to the fuel oil. In this case, the additives act as dispersant and combustion improvers. Sample B is a ferrocene-based combustion improver with a concentration of about 4.8 %. Sample C is an iron based combustion improver and its composition is about 25~30 %. The base material of samples B and C may be similar (i.e. iron), but the difference between them is in their concentration and their effect on improving combustion characteristics. These combustion properties will be discussed later in the study.

Table 4. Representative specifications of the samples of fuel oil additives

	Blank	Sample A	Sample B	Sample C
Type	Heavy fuel oil	Dispersant	Dispersant + Combustion improver	Dispersant + Combustion improver
Dosage	N/A	1:8,000	1:20,000	1:20,000
Major constituent	N/A	Fatty acid/Soap	Ferrocene	Nano particle of oxidized iron
Content (wt.%)	N/A	52.2	4.8	25~30

2.3 Fuel Ignition Analysis−Fuel Combustion Analysis

The fuel combustion characteristics were confirmed via the IP 541/06 standard. The IP 541/06 standard is used to study the ignition and combustion characteristics of residual fuel oil used in reciprocating internal combustion (IC) engines. The standard can also be used to determine fuel characteristics when the density of residual fuel oil is up to 2000 mm^2/s@50℃, but the measurement is only reliable when fuel density is in the range of 25~800 mm^2/s@50℃.

The blended fuel sample is injected into a constant volume combustion chamber (CVCC), which has been set to 500℃ temperature and 45 bar pressure, before commencing analysis. The change in pressure during ignition and combustion is recorded within a differentiated time frame, and the data is transferred to a data acquisition system for additional calculation and reporting. The data in the present study is the average value calculated after 25 iterations of this process, and the FIA-100/FCA apparatus in this study was taken from FUELTECH.

The pressure trace curve and rate of heat release can be obtained via the FCA process. The detailed list of parameters of the FCA and their definition is displayed in Fig. 1.

Among the many different parameters measured in this study, the most important ones are injection delay (ID), end of combustion (EC), and after burning period (ABP) as stated in Fig. 1.
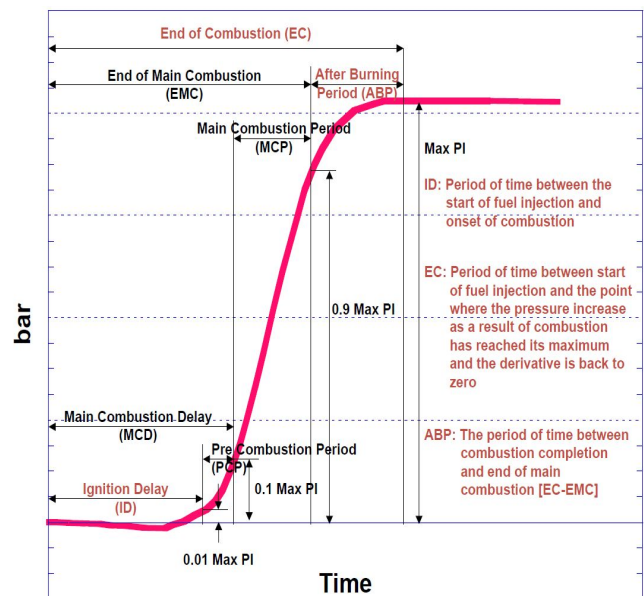

Fig. 1. List and definition of parameters attainable via fuel combustion analysis.

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2.4 Thermo Gravimetric Analysis

TGA measures the change in sample weight with a variation in time and temperature. The principle of the analysis is based on fuel oil weight loss under heating, with the ratio of weight loss acting as one of the characteristics of fuel combustion. This study utilized the Q500 system manufactured by TA Instruments, with its detailed specifications given in Table 5.

Thermogravimetric analysis heats up the sample cells to 900℃ in an environment of air or nitrogen. The specific temperature at 10 %, 50 % and 90 % weight loss can be measured, and the total weight loss ratio at 750℃ or 900℃ is used as the criteria for combustion characteristics in this analysis. During the process, combustion characteristics in different environments were not determined and hence, the test results with air alone are mentioned in this paper. The measuring conditions of reaction temperature and volume were placed at 900℃ and 40℃/min, respectively, with the rate of air purging set to 35 mL/min.

Fig. 2 represents schematic principle of FIA/FCA and TGA analyzers.

3. Results and Discussion

3.1 Result of Pressure Trace Analysis

Monique Vermeire et al. (2007) studied the combustion characteristics using simple analyzers. It was reported that ignition delay (ID), end of combustion (EC) and after burning period (ABP) are the major criteria of combustion characteristics. EC-ID refers to the duration for which the complete flame lasts when the fuel burns. Therefore, this period can be regarded as an important criteria for combustion properties. The difference in time between the end of main combustion and the end of combustion is specified as ABP. The period is related to the creation of carbon deposit, soot and PM after burning. While that study is acknowledged to be correct, the change in energy magnitude according to the time frame is an important parameter which can also be regarded as a fuel combustion characteristic. It also means that only the combustion characteristics verified by FIA/FCA can be generated under CVCC conditions. Internal heat flow and environmental conditions inside an actual engine are noticeably different from CVCC and quite complex conditions. Hence, the data given by FIA/FCA analysis shall only be limited to understanding simple combustion in steady state.

The result of FIA/FCA analysis is given in on Fig. 3. ID is 5.97 ms for the blank and 6.11/6.04/5.91 for samples A/B/C respectively. ID for samples A and B has been extended compared

Table 5. Specification of thermo gravimetric analyzer

Temperature compensated Thermobalance	Included
Maximum sample weight	1 g
Weighing precision	+/- 0.01 %
Sensitivity	0.1 μg
Baseline dynamic drift	< 50 μg
Furnace heating	Resistance wound
Temperature range	Ambient to 1000℃
Isothermal temp. accuracy	+/- 1℃
Controlled heating rate	0.01 to 100℃/min
Furnace cooling [Forced air/N$_2$]	1000 to 50℃ < 12 min

From 50 to 1000℃ at 20℃/min using empty pans, no baseline/blank subtraction.

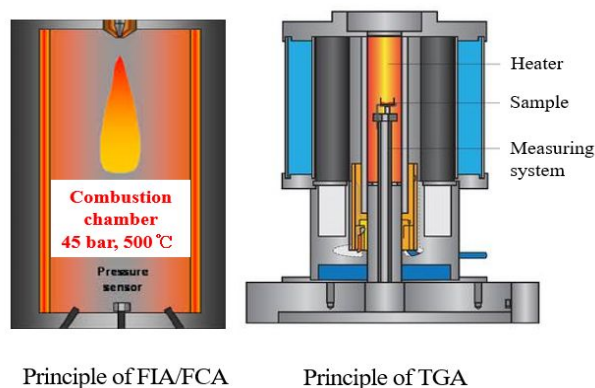Principle of FIA/FCA   Principle of TGA
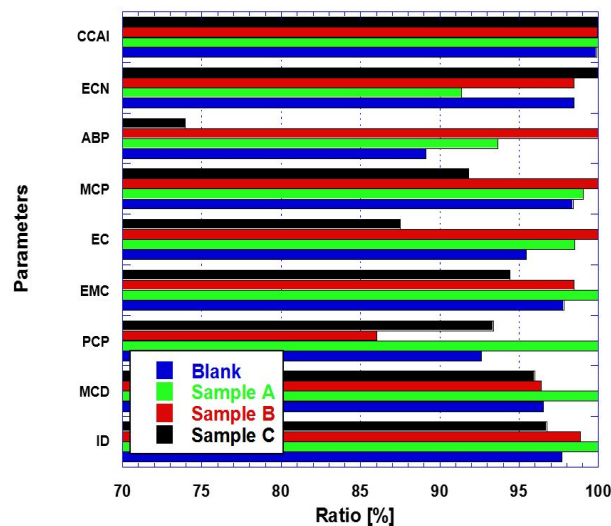
Fig. 2. Schematic of analyzers principle.

Fig. 3. Comparison of pressure trace analysis parameters obtained via FIA/FCA.

to the blank. Sample C recorded a shortened ID compared to blank.

The Ignition characteristics of a compression ignition engine are indicated by its cetane number (Borman and Ragland, 2005). The FIA/FCA analysis can expressed via a similar index known as the Estimated Cetane Number [ECN] (CIMAC, 2011). Hence, the present study compare ignition characteristics by using both ID and ECN. The value of ECN is 19.4/18/19.4/19.74 as per the order on the Fig. 3. Sample C recorded the shortest ID followed by blank. Both samples recorded highest ECN.

Combustion characteristics were evaluated by calculating the value of (EC-ID). This value refers to the entire flame propagating period of the analysis and the result is 14.87/15.4/15.79/13.19. Hence, as far as only time frame is concerned, Sample C finalize the combustion at the earliest, implying that combustion happens the fastest in Sample C. But the time frame alone cannot be a criteria for fuel combustion characteristics. Hence, the rate of heat release, which will be explained in the next chapter, is also considered at the same time to understand the amount of work done by combustion of fuel.

The end of main combustion (EMC) is defined as the period between fuel injection and the time taken to reach 90 % of maximum combustion pressure. End of combustion is defined as period between fuel injection and time to reach maximum combustion pressure. After burning period is defined by (EC-EMC) and the analyzer manufacturer has specified that this value may be proportional to the emission of black smoke from residual fuel oil. This implies that if the ABP is comparatively longer, the fuel oil will have a greater tendency to emit black smoke in actual combustion. The present study anticipated above relation. ABP of Sample C is the shortest as 6.19 ms followed by blank and sample A. Sample B recorded the longest ABP. Hence, the tendency to emit black smoke can be given by Sample B > Sample A > Blank > Sample C. But this expectations is purely based on the test at CVCC and the result could be different if the fuel combustion take place inside a real reciprocating engine. This is because the piston is continuously in motion inside the engine, keeping the temperature high and creating various orders of vibrations. These factors will affect the emission of black smoke, possibly causing the actual result to deviated from expectations.

CCAI refers to the 'Calculated Carbon Aromaticity Index' which is the representative index for ignition quality of residual fuel oil established by ISO since the 1970s. Result of CCAI for this study is 851.08, 851.91, 851.78, 852.14 respectively in the order of Blank, Sample A, Sample B and Sample C. It can be calculated

Maximum ROHR [bar/ms]	
Blank	1.88
Sample A	1.94
Sample B	1.8
Sample C	2.16

Position of ROHR [ms]	
Blank	8.43
Sample A	8.56
Sample B	8.34
Sample C	8.16

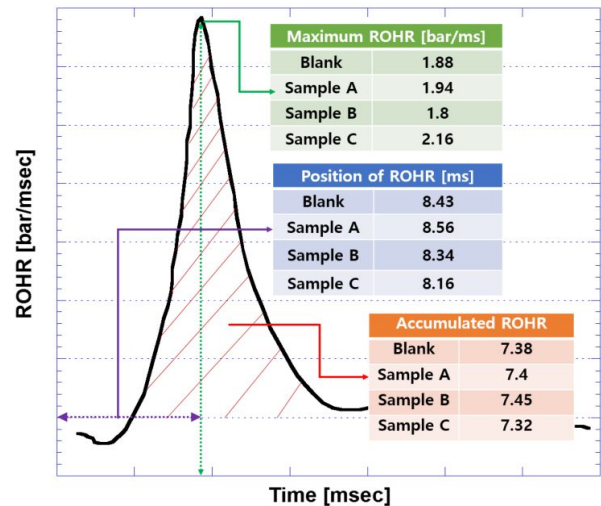| Accumulated ROHR	
Blank	7.38
Sample A	7.4
Sample B	7.45
Sample C	7.32

Fig. 4. Analysis result of the rate of heat release.

using the viscosity and density of fuel. Although it is widely used, the deviated order cannot be easily compared with each sample, and the FIA/FCA analysis gives more coherent information to evaluate fuel ignition quality for the purpose of this study.

3.2 Analysis of Rate of Heat Release

FIA/FCA analysis also provides information about the rate of heat release. Maximum ROHR (M.ROHR), Position of ROHR (P.ROHR) and Accumulated ROHR (A.ROHR) are the parameters derived from this process. The result of ROHR analysis is shown in Fig. 4.

According to given figure, M.ROHR is the highest for Sample C at 2.16 bar/ms and the values for the other samples can be given by: Sample A > Blank > Sample B. However, the position of M.ROHR displays the time at which maximum ROHR was reached, indicating that the shortest position with a value of 8.16ms is found in Sample C. The order for the remaining samples is once again given by : Sample B > Blank > Sample A. The tendency of these values implies that the M.ROHR can be varied with different fuel oils and the P.ROHR, which is the index of combustion speed, can also be varied accordingly.

Fig. 5 shows the graphs for ROHR and P.ROHR. Since the data for the samples are similar, the magnified graph can be added to easily evaluate the result.

According to IP 541/06, accumulated ROHR [AR] is the area under the ROHR plot and can be an indicator of energy conversion by fuel oil combustion. Based on IP 541/06, the AR of Sample B is the highest at 7.45 and the order for the remaining sample is given as Sample A > Blank > Sample C with the values being 7.4,
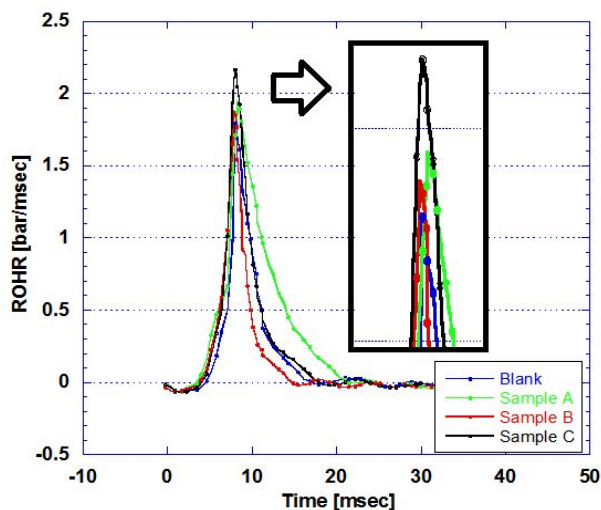
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Fig. 5. Curve of rate of heat release.

Fig. 6. Simplified ROHR curve and suggestion of new parameters for consideration.

7.38 and 7.32 respectively. These values are related to the energy conversion of fuel oil and Sample C shows the least amount of fuel-to-energy conversion. When it comes to other parameters, Sample C shows better results than the others but in the case of AR the tendency is different.

For this reason, the study assumes that the ROHR analysis does not consider the combustion efficiency. The analysis is focused solely on time and the amount of energy produced. The IP 541/06 standard and references only focus on the time up to P.ROHR. The actual combustion continues after P.ROHR and until EC. Hence, combustion characteristics after P.ROHR should also be considered to determine the combustion efficiency.

The iron acts as combustion catalyst which enhance combustion speed. The iron can be characterized to metalloid which is stable, easily maintainable and it has high reactivity. Precious metal has good metalloid characteristics but the iron also has good reaction and economically available.

This study investigates a simple method to evaluate combustion characteristics during the entire combustion period center around P.ROHR. Pre-P.ROHR characteristics and Post-P.ROHR characteristics could be evaluated individually and their average value calculated. This simple consideration can be attained from Fig. 6.

The simple method involves the simplification of ROHR curve. Simplify the ROHR curve as shown in Fig. 6. The angle θ_1 can be obtained by using the information of P.ROHR, M.ROHR and a trigonometrical function. Time after P.ROHR [TPR] can be calculated from EC-P.ROHR, and the result displayed in Table 6 as the parameter TPR. The angle θ_2 can be attained by using TPR, M.ROHR and trigonometric function repeatedly. The sum up
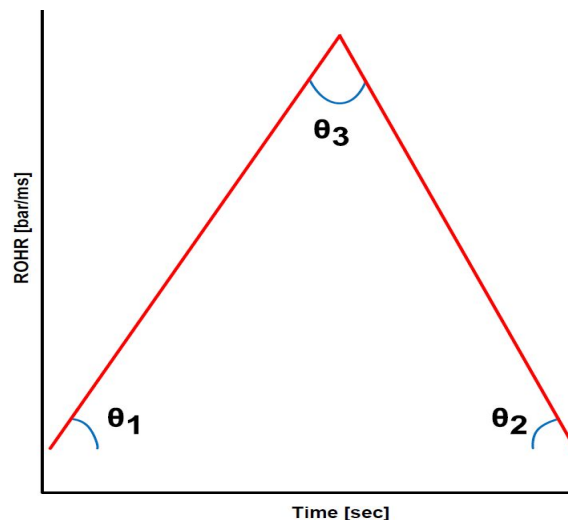
of the value of $(\theta_1 + \theta_2)$ can be evaluated by its proximity to 180°. Calculating the angle θ_3 can be an alternative measure because of the simplified ROHR curved-shaped triangle.

This simple method is derived from the concept that the ROHR and the Position of ROHR shall simultaneously be considered. Therefore, it could be theorized that stronger combustion occurs at larger angles of θ_1 and θ_2 than at smaller angles of θ_1 and θ_2. In case of θ_3, a smaller angle can be indicative of more active combustion.

However, it is important to note that vigorous combustion is not always good for the internal combustion engine. This is because vigorous combustion will lead to high combustion temperature and subsequently higher emission of NOx.

Table 6. Example of simplified calculations of relative combustion characteristics

	Unit	Blank	Sample A	Sample B	Sample C
Time after P.ROHR (TPR)	ms	12.41	12.95	13.49	10.94
Angle of M.ROHR (θ_1, AMR)	°	87.43	87.47	87.35	87.84
Angle of Time After ROHR (θ_2, ATR)	°	86.22	86.18	85.71	87.1
Sum of Angles ($\theta_1 + \theta_2$)	°	173.65	173.65	173.06	174.94
Simple indication		6.35	6.35	6.94	5.06

The result of calculation, performed by utilizing the method described above, is that Sample C is the closest to 180 ° with only 5.06 ° remaining, blank and Sample A record a value of 6.35 ° and Sample B has recorded the lowest level at 6.94 °. Such a trend was similar to the analysis trend of (EC-ID) value obtained from the Pressure trace curve.

3.3 Thermogravimetric Analysis

Fig. 7 displays the result of TGA analysis on the fuel oil, with mass reduction (mg) on the Y-axis. To perform this analysis, each fuel oil sample was transferred into a sampler. The mass of the injected fuel oil was differentiated for each sample due to a measurement error, but the error itself is not significant since the data can be analyzed using the mass conservation ratio. The process commenced with different masses of samples: 39.355 mg of blank, 29.547 mg of sample A, 17.112 mg of sample B and 21.036 mg of sample C.

Fig. 7 indicates arch-shaped loss in mass from the beginning to up to 500℃ for samples A, B and C. A remarkable mass loss in mass cannot be seen from 500℃ to 900℃. On the other hand, Blank maintains an arch-shaped mass loss from the beginning to the end of the analysis, I.e., up to 900℃.

Fig. 8 represents mass conservation ratio of Fig. 7 at the same temperature scale.

Similarly, as observed on Fig. 7, the mass conservation ration of samples A, B, C drop to 10 % up to 500℃ with an arched shape. Even after 500℃, the mass conservation ratio has not decreased noticeably. On the other hand, the mass conservation ratio of Blank steadily arched down from the initial value until the final value at 900℃. Finally, mass conservation ratio at 900℃ is about 25 %.

In Fig. 7 and Fig. 8, the effects of additive can be clearly seen. These phenomena can be explained by the fact that a common effect of the constituents of the additive is to reduce the surface tension of the fuel oil. These phenomena can be caused by the fuel additive which acts as a dispersant and combustion improver, because the ultimate purpose of both is to enhance the availability of residual fuel. They are also specifically designed to make the fuel droplets smaller, and in order to achieve this, reduction of surface tension takes priority. The surface tension in this study was calculated based on the sample fuel analysis.

However, if the additive manufacturer only concentrates on the result of TGA, its actual effect on real engine combustion can be in questioned. Therefore, other reliable analysis method shall be
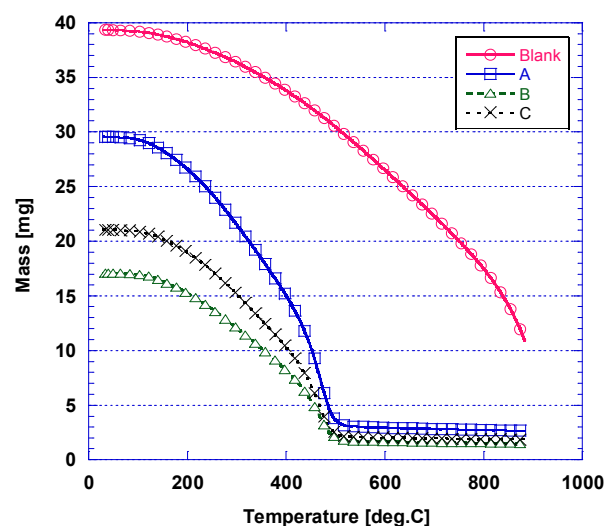

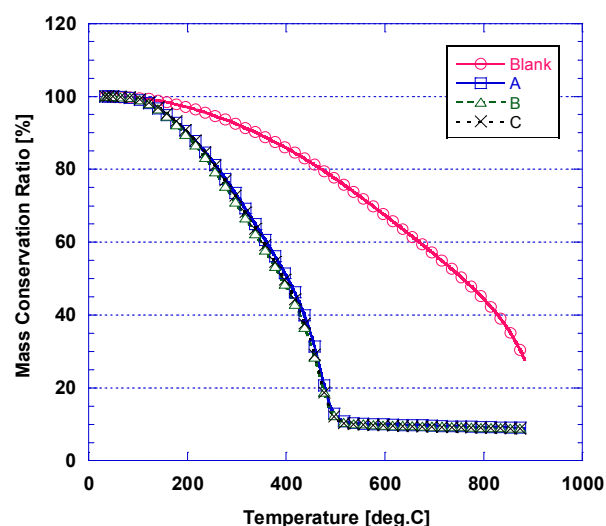Fig. 7. TGA analysis of fuel mass reduction with respect to temperature.

Fig. 8. TGA analysis of mass conservation ratio with respect to temperature.

referred to along with TGA for development.

If the effects of the iron-based fuel additives were to be discussed based on the result of Fig. 7 and Fig. 8, it could be said that, regardless of the various kinds of additives, there is still a positive and clear effect on the more rapid reduction of fuel mass compared to the blank fuel oil.

Based on components stated on Table 4, iron-based fuel additives have a greater effect on reducing thermo gravimetric characteristics. However, it is interesting to note that the concentration of iron itself was not a criteria for the additive's performance. Although the additive does not contain iron, the

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dispersant alone has also shown a similarly good thermo gravimetric performance.

However, it should be noted that the study involved two kind of analyses to evaluate combustion characteristics of fuel additive, and the results were not similar from both processes. In case of FIA/FCA analysis, the pressure trace and ROHR tendency were not very clear except in Sample C. Otherwise, the distinguished result of additive effects can be found in the TGA analysis. This paper cannot currently decide which process is more reliable due to lack of references and data. Hence, the reliability of the processes need to be studied further.

The above mentioned analyses was conducted on a stable and steady laboratory-scale, and it is definitely different from heat flow and combustion conditions in a real engine. Therefore, data obtained by laboratory-scale analysis can only be used as a reference for simulation of real engine combustion. This must be followed by a test on a real engine to objectively evaluate fuel additive performance. In case of the tests on a real engine, the combustion characteristics of four stroke cycle engine and a two stroke cycle engine will provide different results.

4. Conclusion

Marine residual fuel and a fuel additive were blended together and combustion characteristics of the samples were analyzed using FIA/FCA and TGA processes. The results can be summarized as follows:

1. Sample C recorded the fastest combustion speed according to the pressure trace analysis obtained using FIA/FCA. And, Sample C also recorded the most vigorous combustion according to the analysis of ROHR curve obtained using FIA/FCA. These resulted in a high concentration of iron in the additive.

2. Accumulated ROHR which can be obtained via FIA/FCA, does not indicate combustion efficiency. It only shows the amount of work done during combustion. Other parameters also do not consider the efficiency of combustion. Therefore, the study suggests simplified efficiency related parameters using ROHR, P.ROHR and trigonometric function.

3. When blank fuel is analyzed via TGA, mass conservation ratio decreases smoothly up to a temperature of 900℃. In case of samples dosed with additives, mass conservation ratio sharply decreases after 500℃ and mostly maintains the mass up tp 900℃. This is because the TGA process is sensitive to the reduced surface tension caused by the fuel additive.

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