Auto-ignition of lubricating oil working at high pressures in a compressor for an air conditioner

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ABSTRACT

Auto-ignition of lubricating oil working in a compressor for an air conditioner is studied experimentally. The adopted lubricating oil is an unknown mixture with multi-components and known to have flash point temperature of 170 °C. First, its auto-ignition temperature is measured 365 °C at atmospheric pressure. The lubricating oil works under high-pressure condition up to 30 atm and it is heated and cooled down repeatedly. Accordingly, auto-ignition temperatures or flammable limits of lubricating oil are required at high pressures with respect to fire safety. Because there is not a standard test method for the purpose, a new ignition-test method is proposed in this study and thereby, auto-ignition temperatures are measured over the pressure range below 30 atm. The measured temperatures range from 215 °C to 255 °C and they strongly depend on pressure of gas mixture consisting of oil vapor, nitrogen, and oxygen. They are close to flash point temperature and the lubricating oil can be hazardous when it works for high-pressure operating condition and abundant air flows into a compressor.

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1. Introduction

Lubricating oil working in machinery consists of major composition of petroleum hydrocarbon and a little additive less than 0.1%. Its main functions are to guide smooth motion or rotation of a moving part and to reduce mechanical erosion [1]. Sometimes, it contributes to cooling down the mechanical components. Accordingly, it has suitable fluid viscosity and is quite fire-resistant. A compressor used in an air conditioner compresses refrigerant to a specific pressure using a compressor fan rotating with high rotational speed of 3000–4000 RPM. During this compression process, lubricating oil as well as refrigerant in a compressor are working at high pressures up to 30 atm and are exposed to high-temperature environment. In a compressor, there are winding wires generating a magnetic field for rotation of a compressor fan. While the fan rotates with high speed for compression of refrigerant, winding wires is heated by internal heat generation. These heat sources can vaporize lubricating oil into oil vapor and make it heated up. Then, it could be hazardous gas leading to burning or explosion.

Although lubricating oil is heated, it should resist fire or ignition for safety. The fire resistance of lubricating oil is offered by additives. With the aid of the additive, lubricating oil is neither easily ignited nor fired although its major constituent is petroleum hydrocarbon. A manufacturer of lubricating oil provides a user with

MSDS (Material Safety Data Sheet) of specific oil, where information on fire fighting measures is specified. Three critical parameters are flash point temperature, auto-ignition temperature, and flammable limits in air. Based on the data, machines where lubricating oil is working can be designed with suitable specifications and the operating condition can be selected with respect to safety.

The flash point and auto-ignition temperatures (FPT and AIT) are defined as the lowest temperatures at which a fuel in air begins to ignite with and without an external ignition source such as flame or spark, respectively [2,3]. From the definition, flash point temperature is usually much lower than auto-ignition temperature. They are fundamental characteristic parameters on combustion and there can be found lots of previous works on FPT and AIT [4–8].

Ignition or explosion of lubricating oil working at high pressures in a compressor is closer to auto-ignition phenomenon of vaporized oil than to ignition induced by flame or spark. Accordingly, information on AIT of lubricating oil at high pressure is required in designing safety control devices adopted in a compressor and should be obtained before usage of oil. Although there can be found AIT data for various fuels from the previous experimental works [2–8], most of data are for gaseous fuel at atmospheric pressure. Recently, auto-ignition of gaseous fuel at elevated pressures [5–8] and auto-ignition of liquid fuel [9–12] have been studied. But, the previous works are limited to several well-known single fuels and ignition process of isolated droplets. Although there can be found several previous works on auto-ignition of liquid-fuel mixtures [13,14], they were fundamentally dedicated to auto-ignition of gaseous-fuel mixtures produced after complete vaporization.

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Table 1
Major physico-chemical properties of naphthenic base oil adopted.

Molecular weight (g/mol)	325–345	Composition (wt.%)	Petroleum hydrocarbon (more than 99.9%)
Density (g/cm³)	0.909–0.928	Composition (wt.%)	Additive (less than 0.1%)
Viscosity (mm²/s)	53.5–56.9	Vapor pressure (Pa)	<0.03 (at 25 °C)
Pour point (°C)	−35	Vapor density	>10 (air = 1)
Specific gravity	0.91	Flash point temperature (°C)	170 (minimum)

The measurement of AIT of liquid fuel is more difficult than that of gaseous fuel because vaporization process is involved. A reliable test apparatus is a rapid compression machine (RCM), by which ignition delay and AIT can be measured over a wide range of pressures and temperatures [15,16]. But, the RCM apparatus cannot simulate the environment made up by a compressor for an air conditioner. The apparatus cannot be easily adopted for heavy liquid fuel with multi-components vaporizing over a wide range of temperature because vaporized fuel is condensed and separated in part from the fuel-air pre-mixture in a pre-mixture feeding line. And, it is not effective in application to an unknown fuel. That is, a standard method to measure AIT of heavy liquid fuel with multi-components has not been established yet and information on its AIT is not offered experimentally.

In this regard, auto-ignition of lubricating oil is investigated experimentally in this study. A useful experimental approach is proposed to observe oil oxidation and to measure AIT of heavy lubricating oil at high pressures and thereby, its flammable regions are provided with respect to temperature and pressure, which will be more realistic data applicable to the environment in a compressor.

2. Basic analysis of oil properties

There are several brands of lubricating oil for an air conditioner. Each manufacturer has its own knowhow of blending hydrocarbonaceous components with additives. Lubricating oil to be studied in this work is naphthenic base oil called mineral oil. It has been widely used as a lubricant in a compressor for an air conditioner. Major physico-chemical properties described in its MSDS are listed in Table 1. The notable point is that its molecular weight is much larger than that of air of 28.9 g/mol and its FPT is known to be 170 °C. The MSDS says that AIT and flammable limits in air are not known and boiling or vaporization temperature has a wide range. Heavy fuel raises difficulties in making homogeneous pre-mixture prior to the entrance to a test chamber due to gravity. A wide range of vaporization temperature indicates that the lubricating oil is a mixture with various components.

Before ignition test, first of all, oil properties are analyzed based on known analysis methods. To evaluate composition of the oil, TGA (thermo-gravimetric analysis) and DSCA (differential scanning calorimetry analysis) are conducted [17,18]. In these analyses, the sample oil is heated and oil-weight change, oil temperature, and heat flow are measured as a function of time. The results are shown in Figs. 1 and 2. From Fig. 1, it is found that oil weight begins to decrease at 200 °C and appreciable decrease in the weight is detected in the range from 240 to 300 °C. Heat flow in Fig. 2 shows 5–6 peaks and the variable heat flow is caused by vaporization of a specific component of oil. Accordingly, the temperature, at which each heat-flow peak is observed, corresponds to vaporization temperature of each component. That is, the sample oil consists of 5–6 components and their vaporization temperatures are approximately 90 °C, 240 °C, 300 °C and so on in ascending order. All of the components are complex species and information on their AITs is not available. From Figs. 1 and 2, it is noteworthy that the second and third components vaporizing at 240–300 °C are dominant in weight and they vaporize abruptly and massively. DSCA provides the additional chemical parameter of E/R, which indicates activa-
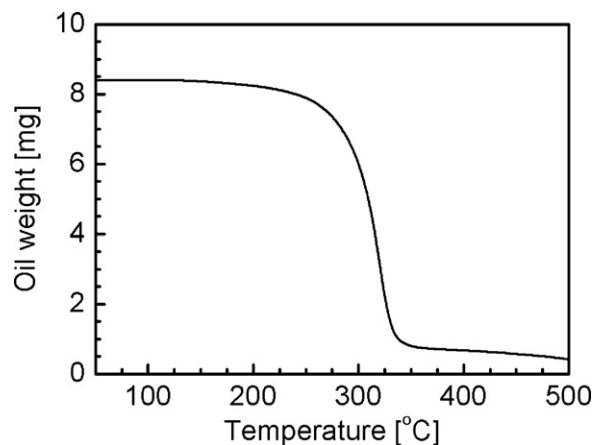

Fig. 1. Oil weight as a function of temperature during heating process of oil as a result of thermo-gravimetric analysis.

tion energy divided by a universal gas constant. With the sample oil, the value of E/R is evaluated to be 6128 K. The value is much less than typical value of 15,000 K applicable for most of heavy hydrocarbon fuels [19]. This indicates that a little amount of an additive added to the sample oil works an appreciable change in chemical characteristics of the oil.

Auto-ignition temperature at atmospheric pressure is useful in characterizing the sample oil with respect to ignitibility although the AIT is not a suitable parameter for the situation in a compressor, where lubricating oil is compressed to high pressure. The AIT is measured by a standard test method. The measurement procedures of AIT are specified in detail by ASTM and can be found in the literature [20]. As a result of the measurement, the AIT of the sample oil is found to be 365 °C or so. It is much higher than the FPT of 170 °C described in Table 1 and the oil would be rarely ignited without an external ignition source at atmospheric pressure. From Fig. 2, most of components are vaporized at the AIT of 365 °C. Accordingly, it is predicted that the third and the fourth components would contribute to auto-ignition of the oil at atmospheric pressure.
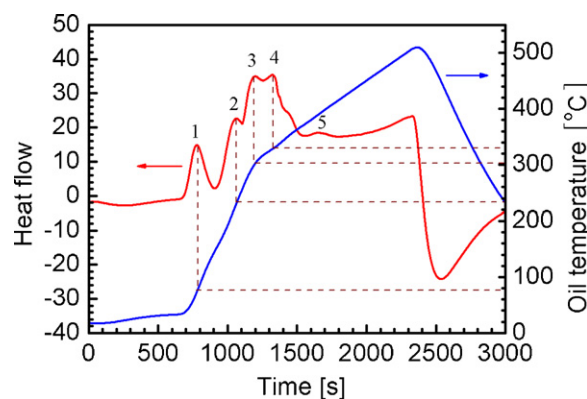

Fig. 2. Heat flow and oil temperature as a function of time as a result of differential scanning calorimetry analysis.
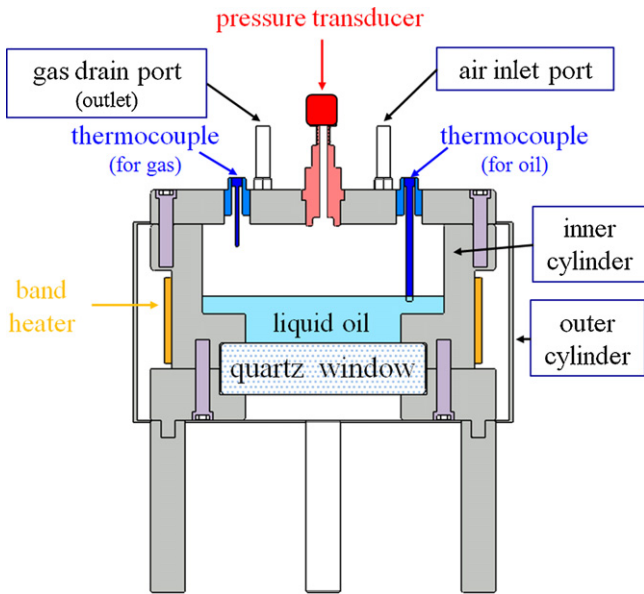
Fig. 3. Cross-sectional view of the ignition chamber devised with inner volume of 915 cm^3.

3. Experimental methods

3.1. Ignition chamber

If the AIT of 365 °C is still valid at high pressures, the oil would not be hazardous and ignition or explosion of the oil in a compressor is actually impossible because the temperature is far outside the operating condition approachable in a compression process. To simulate auto-ignition under the situation in a compressor, an ignition chamber is devised and shown in Fig. 3. The chamber consists of inner and outer cylinders and the upper plate is equipped with the measurement sensors of two thermocouples and a pressure transducer. One thermocouple is for the measurement of gas temperature and the other is for liquid-oil temperature. Inlet and outlet ports are made on the plate for air supply and gas drain, respectively. The inner diameter and the effective volume of the chamber are 14 cm and 915 cm^3, respectively. The two cylinders and the upper plate are made of stainless steel. The lower plate is made of transparent quartz to observe flames in the chamber and it functions as a quartz window. The chamber is designed to be pres-

surized up to 100 atm. The outer cylinder is surrounded by a band heater with maximum electric power of 1000 kW.

3.2. Ignition-test apparatus and experimental procedures

As mentioned in the preceding section, vapor of heavy oil is easily separated from the vapor-air pre-mixture although oil vapor and air are well mixed artificially. The direct supply of the pre-mixture to the ignition chamber is not guaranteed and it does not correspond to the actual situation which the oil encounters in a compressor. Accordingly, two test apparatuses are devised to simulate oxidation or ignition of lubricating oil more realistically. They are shown in Figs. 4 and 5, which are called experimental apparatuses 1 and 2, respectively.

The experimental procedures with the apparatus 1 are as follows. First, liquid oil of 290 ml is charged in the bottom space of the ignition chamber as shown in Fig. 3. The initial pressure in the chamber, p_{in} is adjusted to a specific value by high-pressure air supplied through the inlet port from the air chamber. Then, at room temperature, the chamber begins to be heated by the band heater and liquid oil vaporizes slowly. Temperature of the mixture of oil vapor and air continues to increase as time goes on. Whether ignition is induced or not is decided from the recorded temperature and pressure signals as well as observation of flame through the quartz window. In this experiment, the upper limit of the mixture temperature is set to be 365 °C, which corresponds to AIT at 1 atm and is sufficiently high for the oil to be considered not hazardous. That is, the band heater stops heating the mixture at 365 °C. If ignition is not observed up to 365 °C at a specific pressure, all of gases in the chamber are drained and the test moves to the next round, where the initial pressure in the chamber is increased further and the same procedures are repeated at the increased pressure.

The apparatus 2 is shown in Fig. 5, where a gaseous nitrogen (N$_2$) cylinder and a mass flow controller (MFC) are added to the apparatus 1. The experimental procedures with the apparatus 2 are a little different from those with the apparatus 1 in adjusting the initial chamber pressure. The first step of oil charge is the same as with the apparatus 1. Next, gaseous nitrogen is supplied to the chamber instead of air. This N$_2$ supply exhausts any residual gases and deposits in the chamber and it is called purge by an inert gas. The chamber is kept clean by N$_2$-purge although carbon deposits do not affect auto-ignition of the oil due to their high ignition temperature over 365 °C [21]. At the same time, a specified initial pressure, p_{in} is attained by N$_2$ supply. Then, the chamber begins to be heated by the band heater. When the mixture of oil vapor and N$_2$ reaches
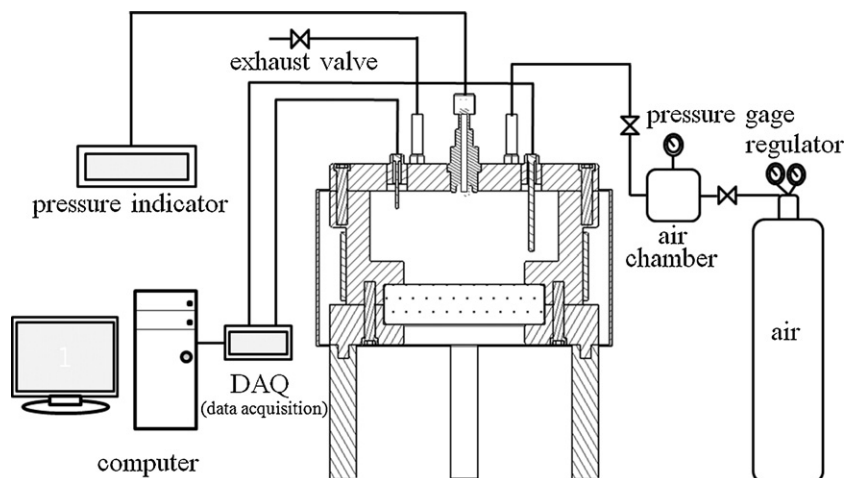

Fig. 4. Experimental apparatus for ignition test of the mixture of oil vapor and air (experimental apparatus 1).
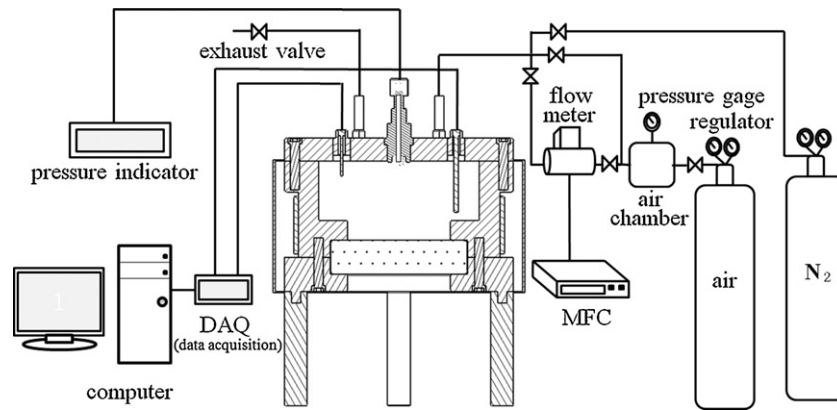
Fig. 5. Experimental apparatus for ignition test of oil vapor by air supply (experimental apparatus 2).

a specified temperature, T_{ig}, air is supplied into the chamber for an instant. Air flow rate is controlled by an MFC. Ignition failure or success is decided at the moment of air supply from the recorded temperature and pressure signals. If ignition fails, gas mixture in the chamber is drained by N_2-purge and oil vapor is pressurized again up to the original pressure, p_{in} by gaseous nitrogen. And then, air is supplied at higher T_{ig} and ignition failure or success is decided. With the specified initial pressure, p_{in}, the experiment is repeated until the minimum ignition temperature, T_{ig} is found. And then, the test moves to the next round and the next steps are the same as with the apparatus 1. In this experimental method, pressure of gaseous mixture at the instant when it reacts with air is higher than p_{in} due to additional air supply and the pressure is denoted by p_{ig}. Accordingly, flammable regions are expressed by the two parameters of p_{ig} and T_{ig}. With the apparatus 2, the situation of unexpected air inflow into a compressor is realistically simulated and flammable regions are measured where auto-ignition is induced by air inflow. These two experimental methods are devised and proposed in this study to investigate oxidation or ignition characteristics of heavy lubricating oil with various components.

4. Results and discussions

4.1. Ignition test of the mixture of oil vapor and air

First, the experiments with the apparatus 1 are conducted over a wide range of initial pressure, p_{in}. With a specified p_{in}, the chamber begins to be heated. During the heating process, the oil begins to vaporize, leading to generation of oil vapor. The oil vapor is mixed with the air in the chamber, resulting in gaseous mixture. Because the molecular weight of the oil is nearly 11 times larger than that of air, spatially non-homogeneous mixture is produced and there will be formed a mixing layer between the upper air side and the lower oil-vapor side.

Temperatures of liquid oil and gaseous mixture are measured with p_{in} of 12.8 atm and shown in Fig. 6. In Fig. 6a, the temperatures in a full range of heating time are shown and both of them increase slowly and smoothly with time, showing a little difference between them. They indicate that there is no ignition in the chamber at any moment during heating process. To examine temperature variation on a short time scale, two time-ranges with the span of 100 s are magnified and shown in Fig. 6b and c, respectively. The latter figure shows the data measured for a later heating period. The liquid-oil temperature increases linearly with time and the temperature fluctuation is rarely observed in Fig. 6b and c. On the other hand, the gaseous temperature shows appreciable fluctuation and the fluctuation level increases further for a later period shown in Fig. 6c. That is, there are observed the liquid-oil temper-
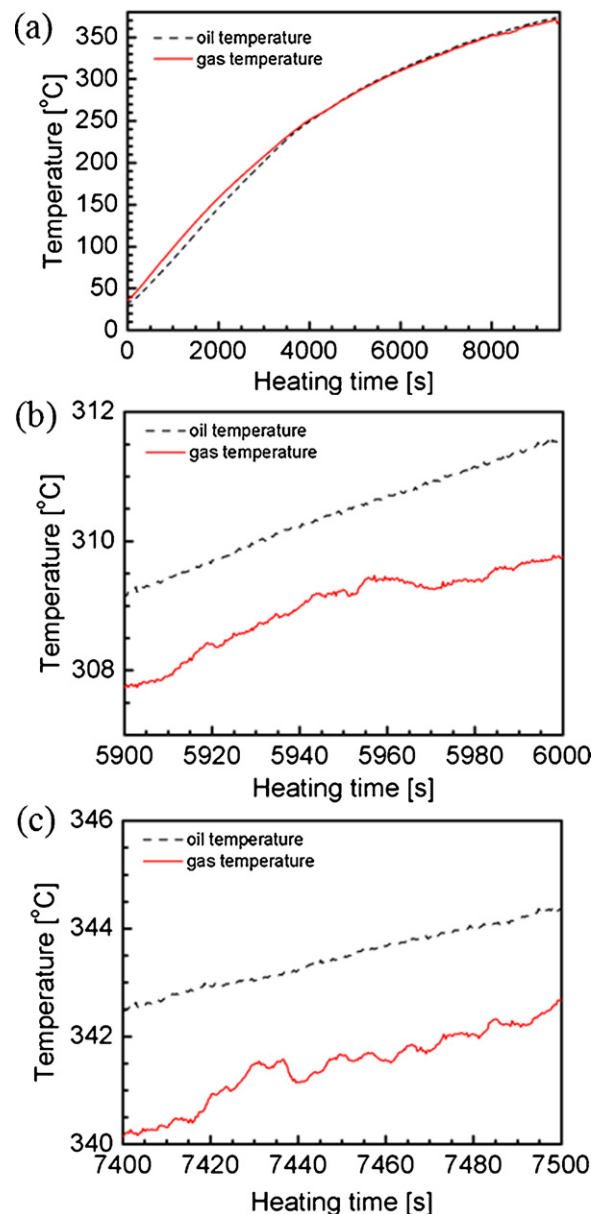

Fig. 6. Temperatures of liquid oil and gaseous mixture as a function of heating time with p_{in} of 12.8 atm.
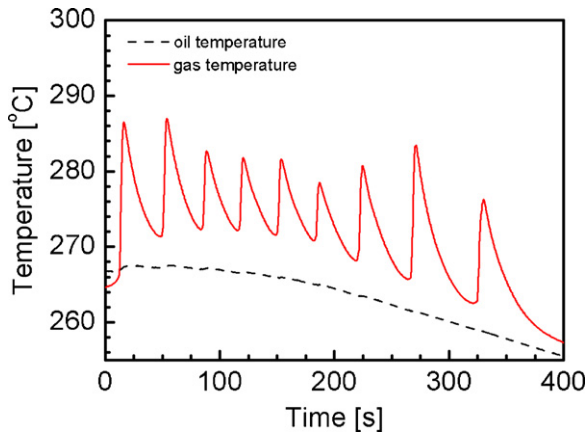
Fig. 7. Temperatures of liquid oil and gaseous mixture as a function of time at air flow rate of 1 lpm for atmospheric condition.

Fig. 8. Gaseous temperature as a function of time at p_{in} = 2.7 atm and p_{ig} = 24.9 atm for variable T_{ig} of 205, 215, and 220 °C, respectively.

ature with little fluctuation and at the same time, the appreciable temperature variation in the gaseous mixture of oil vapor and air. This indicates that slow or gradual oxidation of oil vapor proceeds in the thick mixing layer, but fast chemical reaction leading to instantaneous ignition does not occur. To verify this gradual oxidation, oxygen concentration of gaseous mixture in the chamber is measured by a gas analyzer (Testo 330-2) after heating time reaches the final instant. The oxygen concentration is only 2.2% in volume fraction. From these results, the lubricating oil vaporizes continuously by heating and the oil vapor continues to be oxidized gradually by the surrounding air in a mixing layer. Finally, the oxygen is almost consumed out and auto-ignition fails under this environment.

For the lack of oxygen concentration, rapid chemical reaction and abrupt temperature rise are not induced even at high temperature in the chamber. As an attempt to enhance chemical reaction of the oil vapor with air, additional air is supplied into the chamber at the instant when the liquid-oil temperature reaches an arbitrary value of 267 °C. At the same time, the heating is stopped and air is supplied continuously at the flow rate of 1 lpm (liter per minute). At the chamber pressure of 1 atm, the temperatures of liquid oil and gaseous mixture are measured and shown in Fig. 7. The oil temperature continues to decrease with time. But, the gas temperature oscillates with small amplitude of about 5–10 °C while its mean temperature decreases by slow degrees. The oscillating gas temperature indicates that chemical reaction occurs intermittently without flame propagation through the chamber. Judging from the peak temperature of each oscillation, oil vapor is mixed with the in-flowing air and mild combustion is induced. Auto-ignition or explosion still fails for this condition. But, it is found that the attempt of additional air supply can be one of the methods for successful ignition and based on this trial, air supply is adopted in the experiments with the apparatus 2.

4.2. Ignition test of oil vapor by air supply

As the second method, the experiments with the apparatus 2 shown in Fig. 5 are conducted. As aforementioned, the oil vapor is pressurized by nitrogen gas and air is supplied into the chamber when a specific chamber pressure and an oil-vapor temperature are attained. When air is supplied at an initial chamber pressure, p_{in}, the chamber pressure is increased by the supplied air, leading to p_{ig}. And, the gas-mixture temperature at the instant is denoted by T_{ig}. For one condition, the experiments are conducted for variable T_{ig} at p_{in} = 2.7 atm and p_{ig} = 24.9 atm. From the instant of air supply, the temperature history is measured and shown in Fig. 8. Air is supplied three times and each air supply is made at T_{ig} of 205, 215, and 220 °C, respectively. Whenever air is supplied, gas tem-
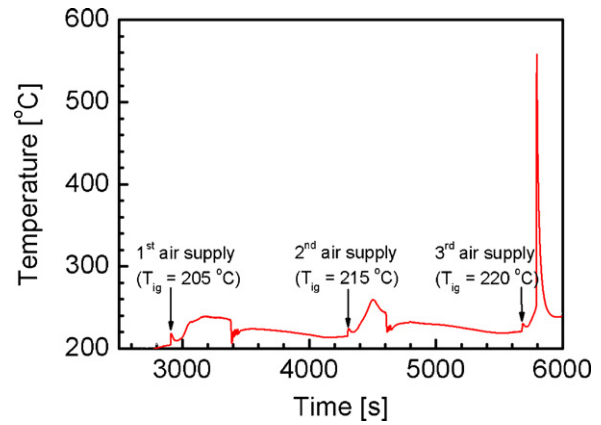
perature rises immediately due to the instantaneous reaction, but shortly, it decreases due to heat diffusion or loss. With delay time of 50–100 s, the temperature rises again. In cases of the 1st and 2nd air supply, the increments of the second rise in temperature are only 30 °C and 40 °C, respectively. The temperature rise is induced by heat release resulting from chemical reaction, but heat release rate from chemical reaction is not sufficiently high to overcome heat loss and eventually, gas temperature falls down in both cases. The increase rate of the gas temperature during the 2nd chemical reaction period is a little higher in the case of T_{ig} of 215 °C than in the case of 205 °C because the chemical reaction rates increase appreciably with temperature of the mixture. On the other hand, the 3rd air supply at T_{ig} of 220 °C results in abrupt temperature rise with short delay time as shown in Fig. 8. The temperature rise and the peak temperature are quite different from those in the two preceding cases. That is, successful ignition occurs in the chamber and this ignition test is effective to measure auto-ignition temperature. As a result, it is found that AIT of the oil vapor at the mixture pressure, p_{ig} = 24.9 atm is between 215 °C and 220 °C.

Flame evolution or propagation throughout the chamber accompanies successful ignition. For the condition of p_{in} = 1.3 atm, p_{ig} = 5.9 atm, and T_{ig} = 250 °C, where mass of supplied air is 2.02 g, successful ignition is observed and the photographs of flame evolution for the condition are taken through the quartz window. They are shown in Fig. 9a–h in time series. First, flame kernel is generated near the air-inlet port as shown in Fig. 9a and flame propagates throughout the chamber. Finally, it fades out and the supplied air is almost consumed. It is observed that there is much soot or carbon attached to the inner surfaces of the chamber after each test. This indicates that oil vapor is abundant species rather than oxygen. Accordingly, the quantity of air supply is a critical variable affecting the auto-ignition phenomenon. The effect of the quantity of air is investigated in this work although the quantity is not adjusted over a wide range.

All data of ignition tests by air supply are assembled and flammable regions, where successful ignition is observed, are demonstrated on the coordinate of T_{ig} and p_{ig} in Fig. 10. The solid and dotted lines indicate minimum AIT or lower flammable limit with respect to temperature in cases of a small and a large quantity of air supply, respectively. Approximately, the latter is twice larger than the former and the mass of air, m_{air} supplied in each test is described in the figure. For comparative work with each other, the quantity of air is adjusted with p_{ig} maintained. For example, the first data of the solid line is from the test conducted at p_{in} = 2 atm, m_{air} = 0.73 g, and p_{ig} = 3.7 atm and the first of the dotted line at p_{in} = 1.3 atm, m_{air} = 1.19 g, and p_{ig} = 3.7 atm. Accordingly, the solid line shows flammable temperature-limit for the condition
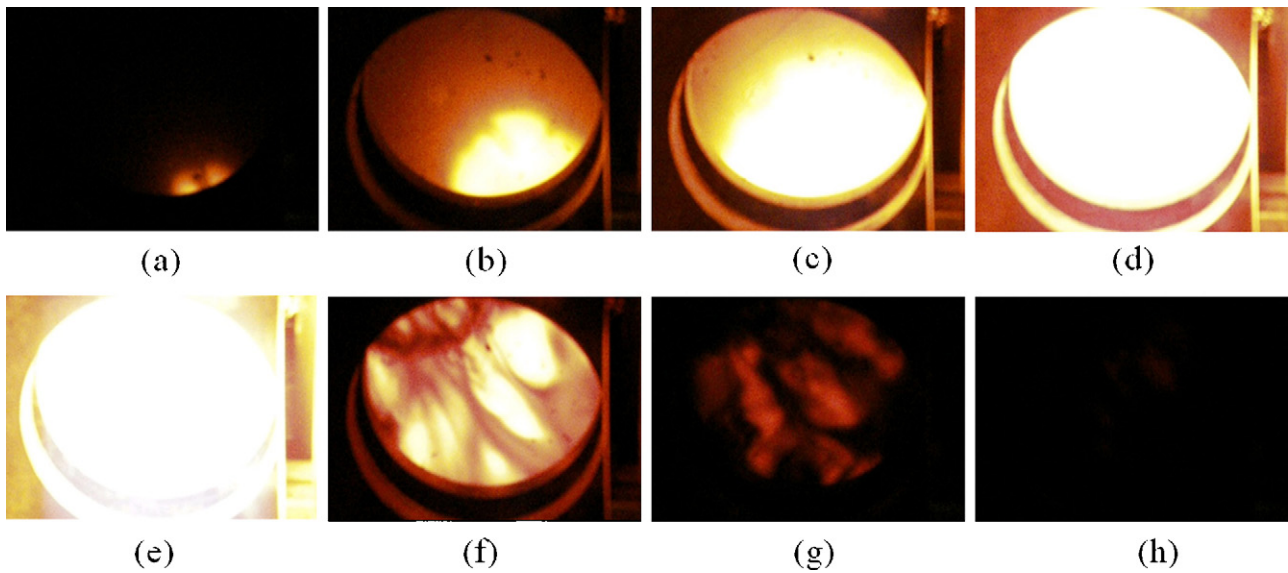
Fig. 9. Time-series photographs of flame evolution or propagation for the condition of p_{in} = 1.3 atm, p_{ig} = 5.9 atm, and T_{ig} = 250 °C, where successful ignition is observed.

of relatively higher initial pressure, p_{in}. In this case, auto-ignition temperature, T_{ig} decreases slightly as the pressure, p_{ig} increases. It reaches the minimum at a specific p_{ig} and finally, it increases again. Auto-ignition temperatures are within the range of 250–255 °C. From Fig. 2, it has been found that the second component of the lubricating oil vaporizes in this temperature range. Accordingly, the vaporization and chemical reaction of the component affects AIT in this regime. It is well known that the vaporization or boiling temperature of any liquids usually rises with the ambient pressure and the gaseous chemical reaction rate increases with the mixture pressure. In this experiment, the ambient pressure and the mixture pressure correspond to p_{in} and p_{ig}, respectively. In the case of a small quantity of air supply, p_{in} increases appreciably with p_{ig}. As both p_{in} and p_{ig} increases, chemical reaction process is enhanced, but vaporization process suppressed. These two processes are competitive in determining auto-ignition temperature, T_{ig}. Accordingly, AIT is not sensitive to pressure change. When p_{in} increases over 12 atm, AIT begins to increase with pressure. This indicates that AIT in this regime is controlled by vaporization process of liquid oil rather than gaseous chemical reaction rate.

On the other hand, AIT expressed by the dotted line continues to decrease with pressure, p_{ig} as shown in Fig. 10. In the case of a large quantity of air supply, p_{in} increases slightly with p_{ig} and thus, vaporization rate of liquid oil maintains nearly constant value irrespective of p_{ig}. Accordingly, AIT in this regime is controlled mainly by gaseous chemical reaction rate, resulting in lower AIT at higher pressure.

Auto-ignition is accompanied by high pressure rise and it can do considerable mechanical damage to the chamber or closed vessel. The maximum or peak pressures, which gas products from combustion reach, are measured and shown in Fig. 11. As the pressure, p_{ig} increases, the peak pressure of combustion gas increases appreciably.

The measured auto-ignition temperatures, AITs in Fig. 10 are illustrated again by three parameters of T_{ig}, p_{ig}, and oxygen concentration in Fig. 12. In this experiment, mass of oil vapor cannot be measured and the oxygen concentration is defined as $p_{O_2}/(p_{O_2} + p_{N_2})$. The aforementioned dependences of AIT on the three parameters are clearly shown in the figure. In the usual operating range or window, AIT of this lubricating oil decrease as pressure of the mixture and oxygen concentration increase. But, when vaporiza-
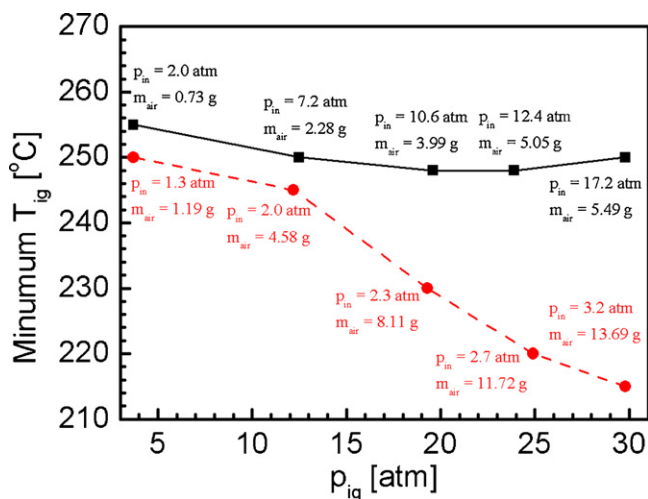

Fig. 10. Flammable temperature-limits demonstrated on the coordinate of T_{ig} and p_{ig} (flammable in the regions above the lines).
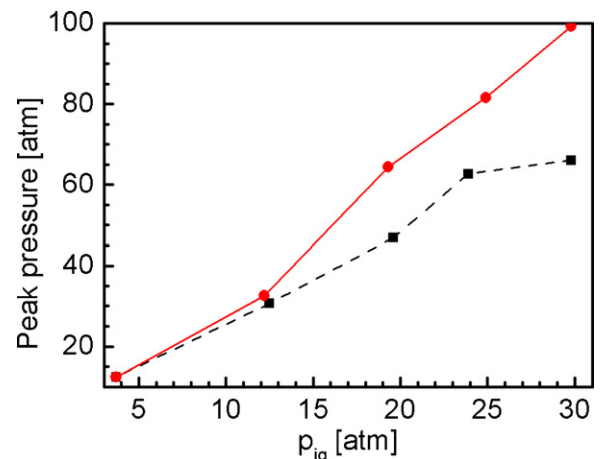

Fig. 11. Maximum or peak pressures of combustion gases as a function of p_{ig} (the solid and dotted lines correspond to those, respectively, in Fig. 10).
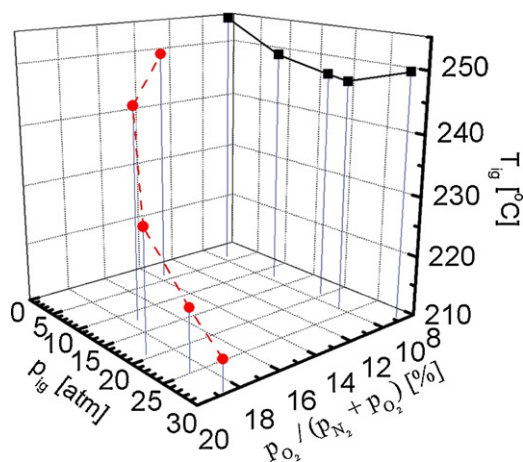
Fig. 12. Auto-ignition temperatures as a function of three parameters of T_{ig}, p_{ig}, and oxygen concentration.

tion of liquid oil is suppressed and oxygen concentration is low, AIT depends little on pressure of the mixture.

5. Conclusion

Auto-ignition temperature of lubrication oil adopted in a compressor for an air conditioner is investigated experimentally for fire safety in this study. Although lubricating oil is manufactured to include fire-resistant additives for safety, it can be hazardous for high-pressure and high-temperature condition. Because major components of lubricating oil are fundamentally hydrocarbon species.

Usually, lubricating oil is an unknown mixture with multi-components and has large molecular weight. Furthermore, it is working at high pressure in a compressor. At present, there is not a standard experimental apparatus to measure auto-ignition temperature of lubricating oil because there are several difficulties in making homogeneous pre-mixture of oil vapor and air at high pressure. Accordingly, in this study, an effective ignition-test method is devised to simulate auto-ignition under the situation in a compressor and auto-ignition phenomenon is studied experimentally.

Inflow of oxygen is indispensable for oxidation of lubricating oil working in a compressor. From the ignition experiments, it is found that auto-ignition of lubricating strongly depends on vaporization rate, pressure of the mixture, and oxygen contents. Auto-ignition temperatures are measured over a range of pressure below 30 atm and the measured ignition temperatures ranging from 215 to 255 °C are quite lower than AIT of 365 °C measured at atmospheric pressure in the open environment. The measured AITs are rather close to flash point temperature of 170 °C. Accordingly, the present experiments show that oil vapor from lubricating oil reacts chemically with oxygen and the chemical reaction can lead to explosive auto-ignition. That is, lubricating oil can be hazardous for an operating condition, which is not extreme.

Auto-ignition temperature of lubricating oil is required in designing safety control devices adopted in a compressor and

selecting operating conditions with respect to fire safety. The present study provides useful quantitative data on flammable regions for the purpose and a useful ignition-test method applicable to heavy liquid fuel at high pressure. In the present study, mixture ratio of oil vapor to oxygen is not considered. To get a complete dependence of lubricating-oil ignition on the physico-chemical parameters, it should be considered additionally. It will be a subject of future works.

References

[1] Th. Mang, W. Dresel (Eds.), Lubricants and Lubrication, 2nd ed., Wiley-VCH Verlag GmbH&Co. KGaA, Weinheim, 2007.
[2] Y. Pan, J. Jiang, R. Wang, H. Cao, J. Zhao, Prediction of auto-ignition temperatures of hydrocarbon by neural network based on atom-type electrotopological-state indices, J. Hazard. Mater. 157 (2008) 510–517.
[3] J. Tetteh, E. Metcalfe, S.L. Howwells, Optimisation of radial basis and back-propagation neural networks for modelling auto-ignition temperature by quantitative-structure property relationships, Chemom. Intell. Lab. Syst. 32 (1996) 177–191.
[4] D. Kong, R.K. Eckhoff, F. Alfert, Auto-ignition of CH_4/air, C_3H_8/air, CH_4/C_3H_8/air and CH_4/CO_2/air using a 1 l ignition bomb, J. Hazard. Mater. 40 (1995) 69–84.
[5] M. Caron, M. Goethals, G. De Smedt, J. Berghmans, S. Vliegen, E. Van't Oost, A. van den Aarssen, Pressure dependence of the auto-ignition temperature of methane/air mixtures, J. Hazard. Mater. 65 (1999) 233–244.
[6] F. Van den Schoor, F. Verplaetsen, The upper explosion limit of lower alkanes and alkenes in air at elevated pressures, J. Hazard. Mater. 128 (2006) 1–9.
[7] F. Norman, F. Van den Schoor, F. Verplaetsen, Auto-ignition and upper explosion limit of rich propane–air mixtures at elevated pressures, J. Hazard. Mater. 137 (2006) 666–671.
[8] O.G. Penyazkov, K.A. Ragotner, A.J. Dean, B. Varatharajan, Autoignition of propane–air mixtures behind reflected shock waves, Proc. Combust. Inst. 30 (2005) 1941–1947.
[9] S. Schnaubelt, O. Moriue, T. Coordes, C. Eigenbrod, H.J. Rath, Detailed numerical simulations of the multistage self-ignition process of n-heptane isolated droplets and their verification by comparison with microgravity experiments, Proc. Combust. Inst. 28 (2000) 953–960.
[10] Q.S. Khan, S.W. Baek, H. Ghassemi, On the autoignition and combustion characteristics of kerosene droplets at elevated pressure and temperature, Combust. Sci. Tech. 179 (2007) 2437–2451.
[11] D. Segawa, T. Kadota, A. Nakainkyo, S. Hirota, H. Enomoto, Effects of ambient pressure on autoignition of a fuel droplet in supercritical and microgravity environment, Proc. Combust. Inst. 28 (2000) 1063–1069.
[12] R. Stauch, S. Lipp, U. Maas, Detailed numerical simulations of the autoignition of single n-heptane droplets in air, Combust. Flame. 145 (2006) 533–542.
[13] L.R. Cancino, M. Fikri, A.A.M. Oliveira, C. Schulz, Autoignition of gasoline surrogate mixtures at intermediate temperatures and high pressures: experimental and numerical approaches, Proc. Combust. Inst. 32 (2009) 501–508.
[14] H. Machrafi, S. Cavadias, P. Gilbert, An experimental and numerical analysis of the HCCI auto-ignition process of primary reference fuels, toluene reference fuels, and diesel fuel in an engine, varying the engine performance, Fuel Process. Tech 89 (2008) 1007–1016.
[15] K. Kumar, G. Mittal, C.J. Sung, Autoignition of n-decane under elevated pressure and low-to-intermediate temperature conditions, Combust. Flame. 156 (2009) 1278–1288.
[16] K. Kumar, C.-J. Sung, A comparative experimental study of the autoignition characteristics of alternative and conventional jet fuel/oxidizer mixtures, Fuel 89 (2010) 2853–2863.
[17] D.A. Skoog, F. Tamesholler, T.A. Nieman, Principles of Instrumental Analysis, 5th ed., Thomson Learning, USA, 1998.
[18] G.D. Christian, J.E. O'Reilly, Instrumental Analysis, 2nd ed., Allyn and Bacon, Inc, Boston, 1986.
[19] S.R. Turns, An Introduction to Combustion, 2nd ed., McGraw-Hill, New York, 2000.
[20] ASTM International, ASTM Standard Test Method E659-78, The American Society for Testing and Materials, West Conshohocken, PA, 2005.
[21] R.K. Herz, R.M. Sinkevitch, Reactors for investigation of soot combustion on filter surfaces, Carbon 24 (1986) 457–462.