

Influences of Initial Temperature and Moisture on the Overpressure Rise Due to the Combustion of Alternative Fuel Gases in a Cylindrical Chamber

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In order to obtain the fundamental physical hazard informations of the alternative fuel gases, a series of labo-scale combustion experiments was carried out. In this work, we focused on the behaviour of the flame propagation and the overpressure rise under various conditions of the equivalent ratio, the initial temperature and the initial moisture.

In the present experiment, we used a cylindrical combustion chamber (volume: 1.36 L) made by SUS316. The ignition was initiated by the electric spark generated by a neon transformer. The overpressure was measured by the pressure transmitter, and the flame propagation was taken by the high-speed schlieren camera.

First, we confirmed that the overpressure and the K_G value showed peak value in the case of $\varphi = 0.99$. The measured peak overpressure was slightly smaller than the theoretical peak overpressure whole range of the equivalent ratios.

Secondly, the peak overpressure decreased with the increase of the initial temperature. But the K_G value, which is the deflagration index of gas cloud, was hardly decreased with the increase of the initial temperature. In other words, gradient of overpressure rise due to the combustion of LPG was hardly affected by the initial temperature.

Thirdly, the reduction effect by the moisture on the rise of overpressure due to the burnt LPG-air mixture was hardly observed under the fuel-lean condition. But in the case of the stoichiometric and fuel-rich conditions, the overpressure after the peak value apparently decreased by the influence of moisture. This is mainly because a part of combustion heat was spent as the sensible heat. The reduction effect by moisture on the overpressure rise depends on the flame propagation rate and the chamber size.

1. Introduction

In order to develop and utilize the alternative energy, such as hydrogen, di-methyl-ether, compressed and liquefied natural gas, liquefied petroleum gas, etc. to the social products and infrastructure, the risk management based on the physical hazard of these gases, such as how wide the flammable area is formed and how much damage is caused by what kind of ignition sources, is indispensable.

For that purpose, the data of flammable range, minimum ignition energy, burning velocity, etc., have been obtained by many precious previous researches (ex.: Lewis & von Elbe, 1987, Dobashi et al, 2011). The majority chemical reaction of propane-air combustion has also been clarified (Qin, Z. et al, 2000). However, they are affected by the initial conditions such as ambient temperature, moisture, pressure, size of combustion chamber, etc. In particular, influences of the initial conditions to the overpressure rise due to combustion have not been much clarified. Of course although the influences of the initial conditions to the rise of overpressure can be estimated by the results of the burning velocity, to obtain the data of the overpressure and to clarify the relation between the overpressure and initial conditions are useful to facilitate the practical safety design.

Based on above background, in the present work, we examined the influences of the initial temperature and moisture on the overpressure rise due to the combustion as the first step to develop the database which provides the information of combustion strength of alternative fuel gas under various equivalent ratios.

2. Experiment

2.1 Combustion chamber

Figure 1(a) shows the photograph of the combustion chamber. The combustion chamber is cylindrical shape, which inside diameter is 135 mm, and the height is 135 mm, made by SUS316 stainless steel. A pair of observation windows made by quartz glass which diameter is 30 mm is fixed at the side of the combustion chamber. The gas inlet port and the vacuum port which both diameters are 1/4 inches are provided at the top of the chamber. The combustion chamber was covered with the jacket heater to control the inside temperature. The action of jacket heater was controlled by the temperature controller (AZ ONE, TJA-550).

The strain-gage-type pressure transmitter (KH15-L34, Nagano Keiki Co., Ltd.) and the sheathed K-type thermocouple were fixed at the top of the chamber to measure the pressure rise and temperature, respectively.

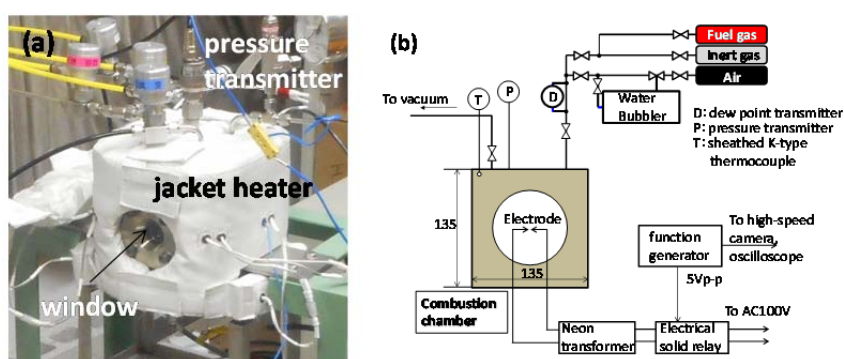


Figure 1 (a) Photo of the combustion chamber, and (b) the schematic diagram of the experimental apparatus.

2.2 Gas supplying system

Figure 1(b) shows the schematic diagram of the overall of experimental apparatus. All of gas lines are 1/4 inches diameters of steel tubes made by SUS304. The air-operated valves (Swagelok, SS-4BK-1C) were fixed in the midway of the lines between the cylinder and the combustion chamber. Supply the air to operate these air-operated valves was controlled with arbitrary timing by using the solenoid valves (CKD, AG31).

The water bubbler unit (TS-02, Taiyo System Corp., volume: 800 mL) was fixed in the midway of the air supply line. The water temperature in the bubbler unit can be controlled by the temperature controller (TS-01, Taiyo System Corp.). The dew point transmitter (SF72, MICHELL Instruments) was fixed in the midway of air gas line to estimate the humidity of the flammable mixture in the combustion chamber.

The gas in the chamber was vacuumed by the vacuum pump (ULBAC, GLD-136C). The fuel and air were supplied into the chamber by the partial pressure method.

2.3 Ignition system

The ignition system consisted of a pair of electrodes, a neon-transformer, a normal-closed type electrical solid relay and a function generator. A pair of electrodes which was made by 2.0 mm of diameter of tungsten needle was fixed at the centre of the chamber. The high-voltage was supplied to a pair of electrodes by the neon-transformer (LECIP Corp., 15 kV, 20 mA). The electrical solid relay (normal-close type) was fixed in the midway of AC100 V line of this neon-transformer to energize the electrodes for arbitrary period. This electrical solid relay was opened by the rectangle wave of 5 Vp-p DC generated by the function generator (Keysight Technologies, 33511B). The gap of electrodes was fixed as 2.0 mm.

2.4 High-speed schlielen photograph system

The schlieren movie of ignition and flame propagation of the flammable mixture was taken by high-speed camera (Photron, FASTCAM SA-X). The combustion chamber was put between a lighting system, which consisted of xenon light source (75 W) and schlieren lens, and a receiving system, which consisted of schlieren lens and knife edge (Katokoken Co., Ltd.,). The shutter speed was set 1/800,000 s, and the flame

speed was set 12,500 fps. The timings of spark generation, taking a movie, and recording overpressure data to the oscilloscope were synchronized by the trigger signal generated by the function generator.

2.5 Experimental conditions and procedures

In the experiment 1, that is to examine the fundamental behaviour under the various equivalent ratios, pure propane (99.9 vol%) was used as the test fuel gas. In the experiment 2, that is to examine the influences of the initial temperature and humidity to the overpressure rise, LPG that is generally used in Japan was used. The components of this LPG were more than 80% of propane or propylene, less than 5 % of the sum of ethane or ethylene, less than 0.5 % of butadiene.

The initial temperature, the initial moisture, and the equivalent ratio of the flammable mixture were varied as the experimental conditions. The initial temperature was controlled by the jacket heater connected with the temperature controller. The moisture was added to the flammable mixture by the following methods; the temperatures in the combustion chamber and in the water bubbler were maintained as the same, and the wet air of a certain partial pressure was introduced into the chamber. The equivalent ratio was varied within the range of 0.64-1.96. The initial temperature was varied within the range of 26.0 - 60.5 °C, and the humidity was varied within the range of 1.4 - 97.8 %R.H..

3. Results and discussions

3.1 Influence of the equivalent ratio on the combustion behaviour

Figures 2 show the schlieren images of burnt mixture of pure propane and air with various equivalent ratios (ϕ) under the dry condition. In the case of $\phi = 0.66$ which is the fuel-lean condition shown in Figure 2(a), the flame front propagated with weak turbulence, and it seemed that the flame front propagated chaotically. In the case of $\phi = 1.93$ which is the fuel-rich condition shown in Figure 2(b), growing rate of flame size was slower than the case of $\phi = 0.66$. In other words, the flame propagation rate in the case of $\phi = 1.93$ was smaller than the case of $\phi = 0.66$. The flame front also propagated chaotically. In the case of $\phi = 0.99$ of pure propane which is the approximately stoichiometric concentration shown in Figure 2(c), flame shape is a little elliptic shape which height is longer than its wide and uniform propagation of the flame front to the all directions was observed. The growing speed of flame size was much larger than the cases of $\phi = 0.66$ and $\phi = 1.93$, so the flame propagation rate was also much larger.

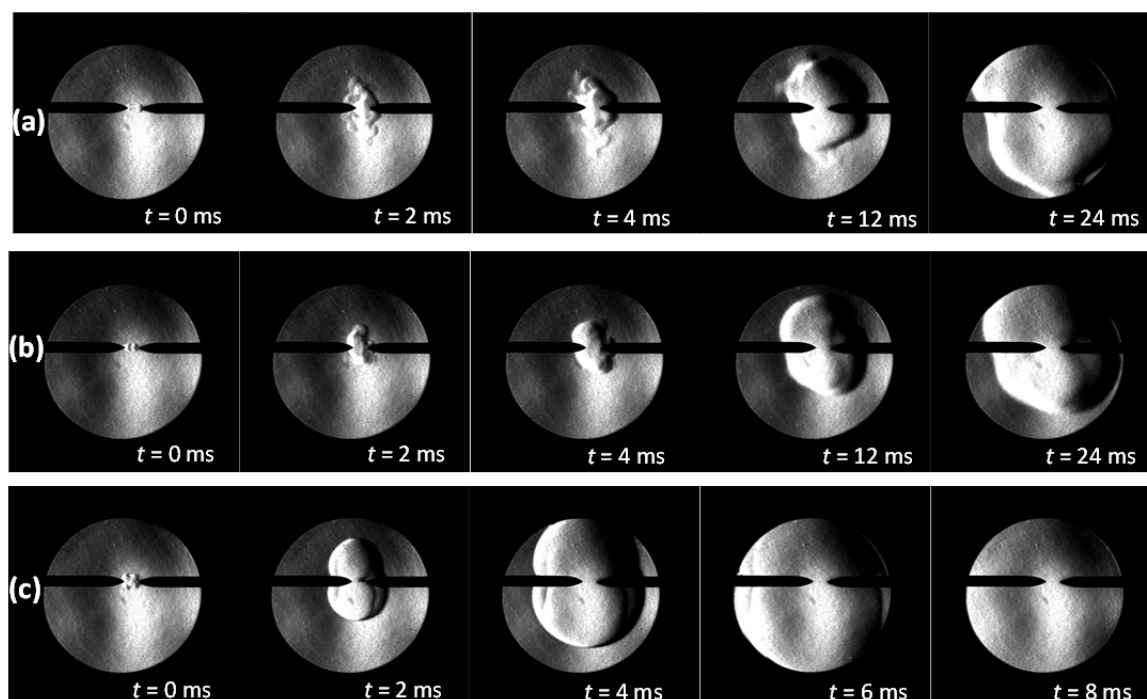


Figure 2 High-speed schlieren images of burned pure-propane with air with various equivalent ratios. (a) equivalent ratio $\phi=0.66$ (b) equivalent ratio $\phi=1.93$ (c) equivalent ratio $\phi=0.99$

Figure 3 shows an example of time history of the overpressure rise with various equivalent ratios. The deflagration index, called the K_G value, was calculated by Eq.(1).

$$K_G = \left(\frac{dP}{dt} \right) \cdot V^{1/3} \quad (1)$$

dP/dt : gradient of overpressure rise (Pa/s), V : volume of combustion chamber (m^3)

In the case of $\phi = 0.99$ which is the stoichiometric concentration, the overpressure rose very fast after the ignition was initiated, and the overpressure reached about 620 kPa, and the K_G value reached about 55. It is a little smaller than the reference value of 790 kPa (NFPA 68-2013) and $K_G = 100$ (NFPA 68-2007). It is because the flame contacted to the wall of the combustion chamber before the temperature of burnt gas reached the maximum temperature, so that the heat loss was larger than the theoretical situation. In the case of $\phi = 0.66$, the overpressure rise became slower than the case of $\phi = 0.99$, but it was more rapid than the case of $\phi = 1.93$. The arranged equivalent ratio in larger order of K_G value were $\phi = 0.99 > 0.66 > 1.93$. Based on these results, the gradient of the overpressure rise majorly depended on the flame propagation rate.

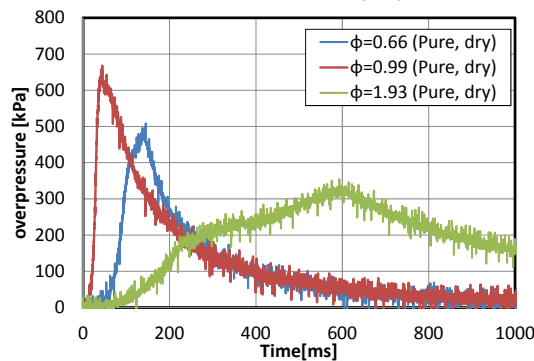


Figure 3 Time history of the overpressure under various equivalent ratios.

3.2 Influence of the initial temperature on the combustion behaviour

Figure 4(a) shows the relation between the peak overpressure due to the combustion of LPG-air mixture and the initial temperature with stoichiometric concentration, and Figure 4(b) shows the relation of it about the K_G value. The theoretical value was calculated based on the ideal gas law shown in following Eq.(2).

$$\frac{P_2}{P_1} = \frac{n_2 T_2}{n_1 T_1} \quad (2)$$

P : absolute pressure (Pa), n : amount of substance (mol), T : temperature (K), subscript 1: unburnt state, subscript 2: burned state

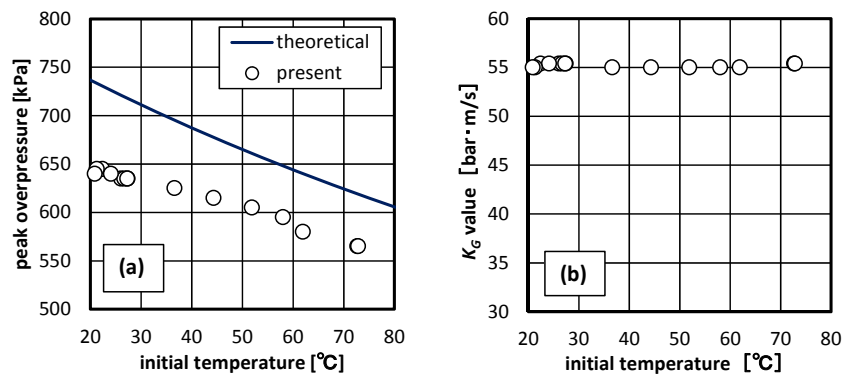


Figure 4 Relations between the peak overpressure and the K_G value and initial temperature.

The value of T_1 corresponds to the initial temperature of unburnt flammable mixture, and the value of T_2 corresponds to the adiabatic flame temperature of it. The adiabatic flame temperature was calculated by using the software for solving chemical equilibrium provided by Konishi (Konishi, 2015), regarding the fundamental properties of LPG as them of pure-propane. It was observed that the peak overpressure decreased with the increase of the initial temperature. This is because the amount of substance of flammable mixture in the

chamber was decreased with the increase of the initial temperature. However, the influence of initial temperature on the K_G value was hardly observed. In other words, gradient of overpressure rise due to the combustion of LPG was hardly affected by the initial temperature.

3.3 Influence of the initial moisture on the combustion behaviour

Figures 5 show the time histories of the overpressure rise with dry and wet conditions in various equivalent ratios. In the case of fuel-lean condition shown in Figure 5(a), the start of overpressure rise was earlier than the case of dry condition, but the peak overpressure was hardly differed regardless of the moisture. In the case of stoichiometric condition shown in Figure 5(b), the start of overpressure rise and the peak overpressure were hardly influenced by the moisture, but the overpressure after 100 ms since the ignition was apparently decreased more than that of dry condition. In this experiment, the difference of decreasing mode of overpressure after 100 ms since the ignition was hardly observed in the condition of more than 67%R.H. In the case of fuel-rich condition shown in Figure 5(c), the peak overpressure was slightly decreased by the moisture, and especially the overpressure of burnt gas after the peak time was apparently decreased by the moisture. Figure 6(a) shows the relation of peak overpressure and the absolute humidity, and Figure 6 (b) shows the K_G value and the absolute humidity. Both of them were hardly influenced by the moisture.

Yoshida and Yukawa (2013) conducted the numerical analysis to examine the effect of water mist on the flame speed and the structure of propane-air premixed flame. They examined three effects of the latent heat of water mist, the sensible heat of water mist, and the restriction effect of chemical reaction (including suffocation effect) on the quenching of the flame. They said that the burning velocity apparently decreased with the increase of the amount of water mist, and the ratio of influence by the sensible heat was 62 %, it by latent heat was 30 %, and it by the restriction effect of chemical reaction was 8 %, therefore the water mist has not only the thermal cooling effect but also the restriction effect of chemical reaction which cannot be ignored. In the present experiment, the major effect of moisture to reduce the overpressure was originated by the sensible heat because the reduction effect was only confirmed after the overpressure reached to the peak value. In other words, moisture did not influence to restrict the chemical reaction because the overpressure rise and the K_G value were hardly varied regardless of the humidity. In the present experiment, the combustion chamber is comparatively small, so that in the case of near the stoichiometric concentration, the flame immediately propagated to the entire of the chamber, so that the water molecule does not have enough time to cool the flame temperature. However, in the case of $\phi = 1.93$, which the flame propagation rate was much slower than the case of $\phi = 0.99$, the water molecule has some extent time to cool the flame. Therefore the reduction effect on the rise of overpressure more than the case of $\phi = 0.99$ was confirmed. In other words, the reduction effect by moisture on the overpressure rise depends on the flame propagation rate and the chamber size.

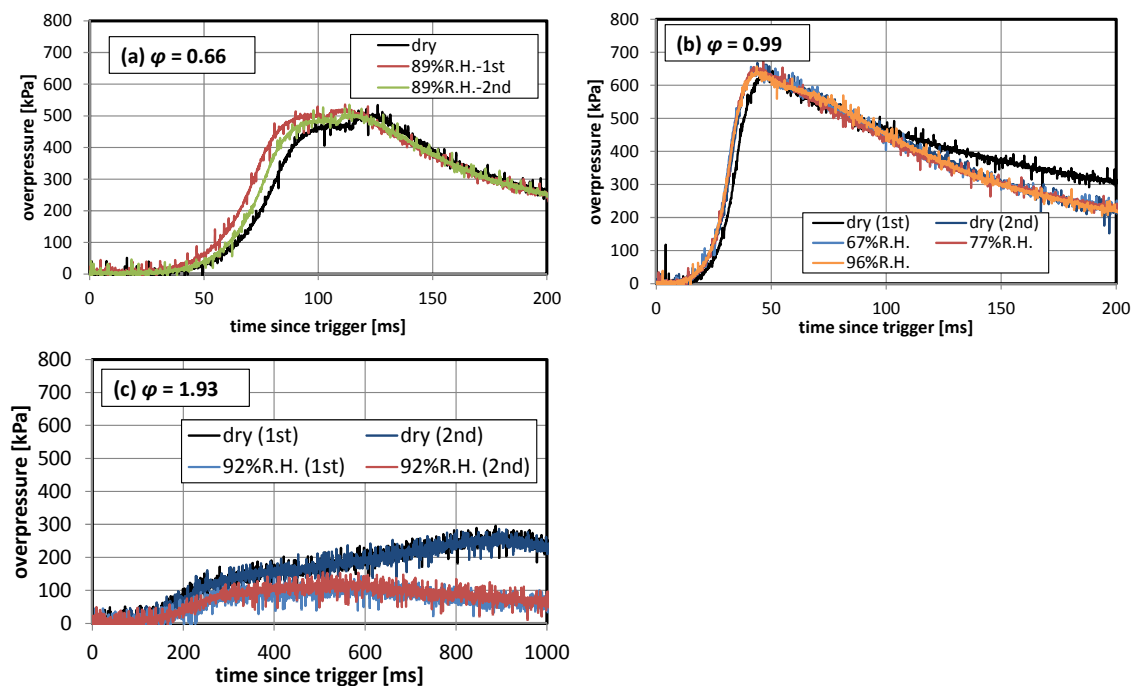


Figure 5 Time histories of overpressure under the various equivalent ratios. (a) $\phi = 0.66$ (b) $\phi = 0.99$ (c) $\phi = 1.93$

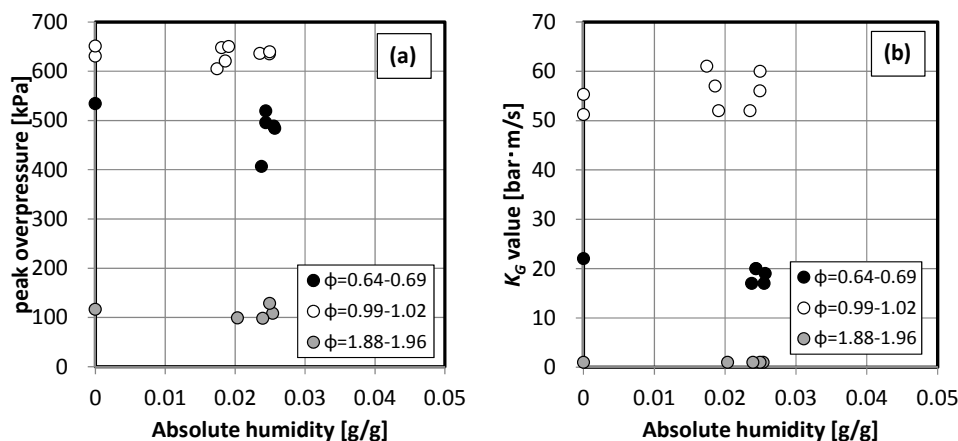


Figure 6 Relations of the overpressure (a) and the K_G value (b) with the absolute humidity.

4. Conclusions

We conducted a series of experiments to examine the influences of the initial temperature and moisture to the overpressure rise of the propane-air mixture in the labo-scale combustion chamber, and then the following knowledge was clarified.

- (1) The increasing mode of the overpressure due to the combustion of pure-propane-air mixture was influenced by the equivalent ratio. It shows the largest value in the case of the stoichiometric concentration, and the gradient of the overpressure rise majorly depended on the flame propagation rate.
- (2) The values of peak overpressure decreased with the increase of the initial temperature regardless of the values of the equivalent ratio. However, the influence of initial temperature on the K_G value was hardly observed. In other words, the gradient of overpressure rise due to the combustion of LPG was hardly affected by the initial temperature.
- (3) In the case of the stoichiometric and fuel-rich conditions, the overpressure of the burnt gas after it reached the peak value apparently decreased by the moisture. This is mainly because a part of combustion heat was spent as the sensible heat. The reduction effect by moisture on the overpressure rise depends on the flame propagation rate and the chamber size.

Acknowledgements

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