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Category

Research Article

Abstract

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Keywords

Capsule extinguishment, Diffusion flame, Inert gas, Rubber balloon

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Extinguishment of diffusion flames formed over a porous plate burner using rubber balloons filled with inert gases

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Abstract

We have proposed an inert gas, rubber-balloon extinguishing method which might increase the effectiveness of extinguishing flames and decreasing the amounts of agents needed for fire suppression. Hence, extinguishing experiments have been performed to further clarify possible extinguishing characteristics, mechanisms and scaling effects of this method. Carbon dioxide, nitrogen, argon and helium gases were used as the extinguishing agents. Methane-air and propane-air diffusion flames were formed on two different diameter, round porous plate burner and used as the targets for extinguishment. The extinguishing probabilities were measured, and the extinguishing processes were observed with a high-speed camera. As a result, an effectiveness ranking of an inert gas in the rubber-balloon extinguishing method was in agreement with that of a cup-burner method. Moreover, determinations of extinguishing limits were accomplished, defined as the minimum volume of the inert gas required for successful extinguishment of flames; these limits depended on the balance of the heat loss caused by an inert gas and the heat production within the flame, and also on the forming process of a flammable premixing layer near the surface of the burner. In addition, all the extinguishing limits were represented by a unique, constant relationship depending on the non-dimensional number of the ratio of the heat absorbing rate of the inert gas to the heat release rate of the flame multiplied by the Schmidt number of the fuel species.

Keywords: Capsule extinguishment; Diffusion flame; Inert gas; Rubber balloon

Introduction

Water is the most common firefighting agent because it removes heat from fire sites [1]. Moreover, water vapor extinguishes diffusion flames by absorbing heat from the flame reaction zone and reducing oxygen and fuel concentrations in the combustion region. However, by using water in firefighting, water damage can occur to electronic equipment, paper and construction materials. Dry chemical powders are also used for firefighting and can be effective in suppressing fires by interfering with the chemical chain reaction; however, extensive clean-up for the extinguished area is also required after its use. Inert gases (carbon dioxide, nitrogen, argon and helium) can extinguish fire through absorbing heat from the flame reaction zone and reducing oxygen and fuel concentrations in the combustion zone. These inert gases are environmentally

friendly and do not cause the secondary damage that water and dry chemical powder do. Hence, inert gases are able to extinguish fires more cleanly than water and dry chemical powder. However, an extinguishing gas is easy to diffuse into and mix with the surrounding air and its concentration rapidly decreases as it travels from the application location to the combustion region. Consequently, in order to reduce oxygen concentrations below a limiting value [2-5] and to extinguish fires completely, a large amount of inert gas needs to be released at the vicinity of the flames or into a confined space containing fires. Complete evacuation of personnel is needed before the extinguishing gas is discharged in a confined space

To avoid the above-described firefighting problems, the authors have proposed an extinguishing capsule method that uses a capsule filled with an extinguishing agent [6–9]. It is seen to have several advantages. Firstly,

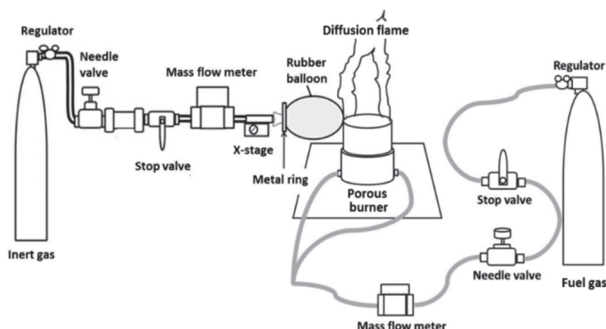
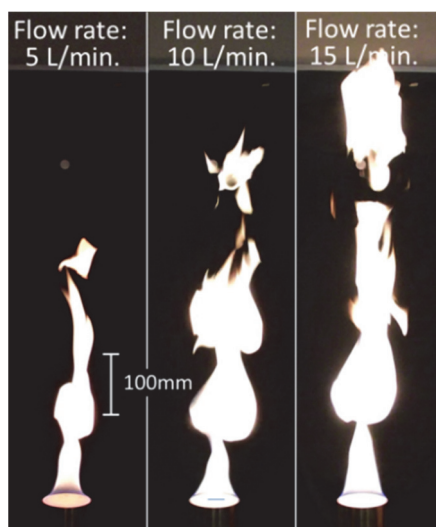
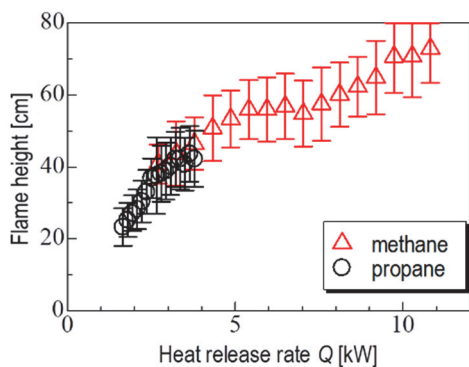


Fig. 1. Experimental setup.



(a)



(b)

Fig. 2. Methane-air diffusion flames formed on the 80-mm-diameter porous plate burner: (a) methane-air diffusion flame formed over the porous plate burner; and (b) relationship between the flame height and the heat release rate.

when a gaseous extinguishing agent is filled into a capsule, the capsule membrane inhibits the mutual diffusion between the extinguishing gas and the surrounding air during transport of the gas. Secondly, if the extinguishing capsule ruptures due to contact with

flames, the high concentration extinguishing gas can be easily and directly supplied to the combustion zone. Thus, by using an extinguishing capsule, it may be possible to increase extinguishing effectiveness and decrease the amount of the extinguishing gas needed.

On the other hand, there are various candidates for the extinguishing capsule, such as a soap bubble [6], rubber balloons [7] and an ice capsules [8, 9]. In this study, a rubber balloon was chosen and used because of its advantages. Firstly, a rubber balloon can be filled with any inert gases. Secondly, when a rubber balloon contacts with a flame, the membrane easily ruptures due to melting. Thirdly, the tensile force of the stretched rubber membrane causes a large pressure difference between the inside and outside of a rubber balloon [10]. Therefore, when a rubber balloon bursts, a high-speed flow is released from the bursting balloon.

Moreover, fundamental research of fire phenomena and extinguishment are usually performed with simple and small-scale experiments. Therefore, when the results derived from the basic studies are used for practical fire situations, scaling effects have to be considered [11]. However, very few scaling laws have been assessed for fire extinguishment.

In the present study, the extinguishing mechanism and the scaling effects of using a rubber balloon inflated with an inert gas, and extinguishing experiments of methane-air and propane-air diffusion flames formed on two different diameter porous plate burners, have been performed. Extinguishing processes have been observed with a high-speed camera. Carbon dioxide, nitrogen, argon, and helium were used as the extinguishing agents.

Experimental setup and method

Flow path diagram and a porous plate burner

Fig. 1 shows the experimental apparatus used during the extinguishing experiments. Carbon dioxide, nitrogen, argon and helium gases were used as the extinguishing agents and were supplied from high pressure cylinders to rubber balloons; volumetric flow rates were regulated with a needle valve and measured with a flow meter (Azbil, CMS0020 and KOFLOC, Model 8550).

As an extinguishing target, methane-air and propane-air diffusion flames were formed on two different diameter, circular porous plate burners. The circular porous plates with filtering plates of 40 μm diameter and a porous plate thickness of 10 mm, was made of bronze; the outer diameters were 80 mm and 100 mm. The porous plates were embedded into brass tubes whose outer diameters were 83 mm and 105 mm. Methane and propane gases were supplied from high pressure cylinders to the burner. The fuel flows were regulated with a needle valve and measured with a flow meter (Azbil, CMS0050). Fig. 2 shows the appearance of the methane-air diffusion flames formed on the 80 mm-

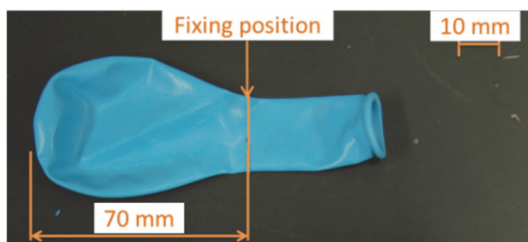


Fig. 3. Rubber balloon.

diameter porous plate burner and the relationship between the flame height and heat release rate, calculated from multiplying the volumetric flow rate of the fuel gas and its lower heating value. The flame height was defined as the distance from the burner surface to the top of the flame. From Fig. 2(a), puffing flames were recognized to be formed on the burner. From Fig. 2(b), it is seen that the flame heights of methane-air and propane-air diffusion flames increased monotonically as the heat release rate increased.

Rubber balloon

Natural rubber balloons (Marusa Saito Rubber Co., Ltd.) were used, as shown in Fig. 3. One end of a tube was used to fill the inert gas into a balloon by inserting it at the balloon mouth up to the solid line shown in Fig. 3, and the balloon was fixed at the line position to the tube. The extinguishing gas volume filled into the

balloon was determined from multiplying the constant inert gas flow rate and the elapsed time. In this study, the extinguishing experiments were performed using various ranges of inert gas volumes; at higher volumes the inner pressure of the gas in the rubber balloons increased as the filled gas volume increased. Therefore, the flow speed released from the bursting balloon became higher as the volume of the filled gas became larger.

Extinguishing experiment

The extinguishing experiments were performed in the following manner. First, a stable diffusion flame was formed on the burner and the rubber balloon was inflated with a certain gas volume. Second, the rubber balloon was moved laterally to the flame base of the diffusion flame, and then the balloon burst due to contact with the hot flame. After that, we checked whether the flame was extinguished or not. When the flame disappeared, it was recorded as a successful extinguishment. An extinguishing probability was computed as the ratio of the number of successful extinguishments to the number of total experiments of 10.

Observation of extinguishing process

To examine the extinguishing phenomena in detail, the flame behavior in the extinguishing process was recorded and observed with a high-speed camera (NAC, Memrecam HX-3) at a recording speed of 2000 frames

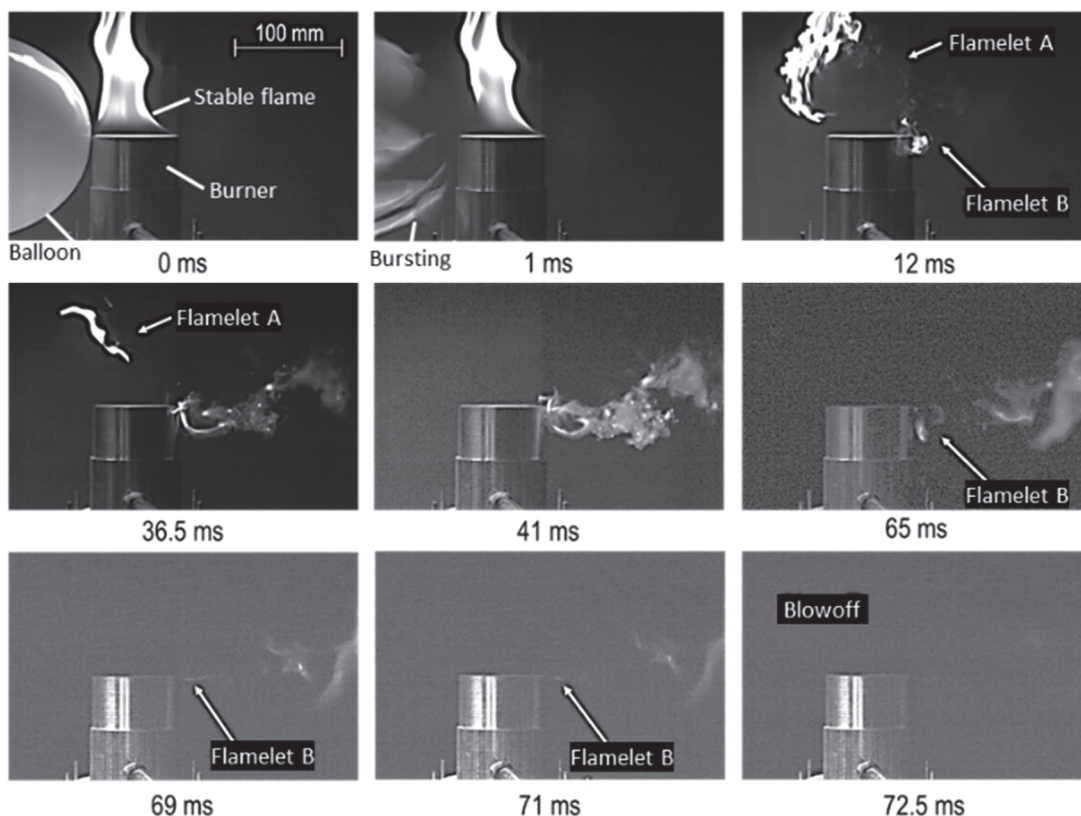


Fig. 4. Extinguishing process of the flame formed on the 80-mm-diameter porous plate burner.

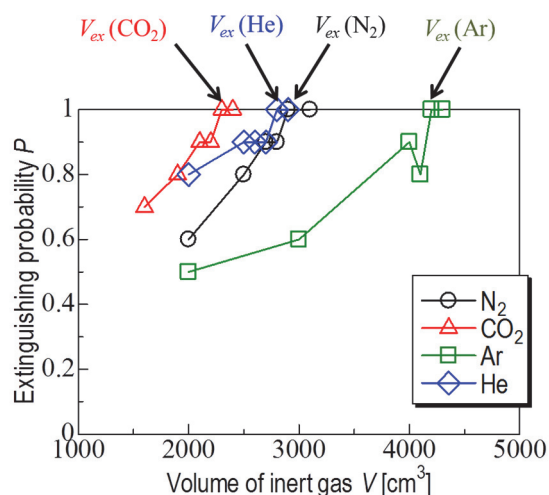


Fig. 5. Extinguishing probability profiles for the propane-air diffusion flame formed on the 80-mm-diameter porous plate burner (heat release rate of 2 kW).

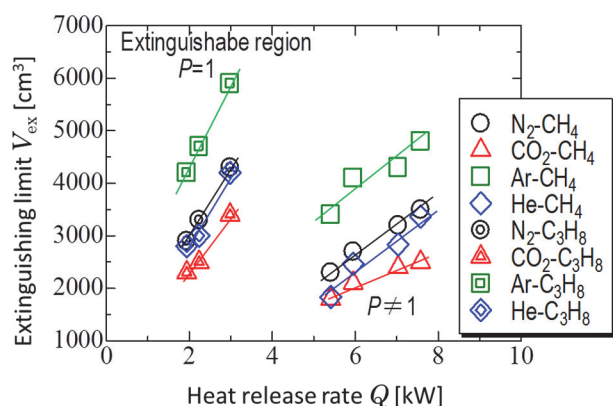


Fig. 6 Relationship between the extinguishing limit and the heat release rate (80-mm-diameter porous plate burner).

per second. From analyses of the camera images, a extinguishing time was defined as the elapsed time from bursting of the rubber balloon to achieving complete extinguishment of the flame.

Results and discussion

Extinguishing process in rubber balloon extinguishing methods

Fig. 4 shows a typical extinguishing process in which the extinguishing target was the propane-air diffusion flame formed on the 80-mm-diameter porous plate burner whose heat release rate was set at about 3 kW. The extinguishing gas was argon and the gas volume filled into the rubber balloon was 5900 cm³.

Firstly, the rubber balloon contacted with the flame base. Then, at between 0 ms and 1 ms, the rubber membrane ruptured and an argon gas flow was re-

leased into the flame. At 12 ms, the flame shape was deformed drastically, and local extinction occurred due to the argon flow. As a result, the flame was separated into the upper yellow flame region (flamelet A) and the lower blue flame region (flamelet B). After that, flamelet A disappeared at 41 ms whereas flamelet B remained attached in the wake region of the porous plate burner. Finally, flamelet B was extinguished and disappeared at 72.5 ms. Thus, the flame extinguishment with the rubber balloon filled with an inert gas was achieved in a rather short period of time.

On the other hand, when the flame failed to be extinguished, the process was almost the same as successful ones up to about 65 ms, as shown in Fig. 4. However, in this case, flamelet B was maintained in the wake region behind the porous plate burner and then propagated on the porous plate burner from the right side to the left side in the image. This behavior was a result of premixing layer of air and propane gas in the flame region on the porous plate burner. As a result, flamelet B spread through the pre-mixing gas layer as a partially premixed flame and the diffusion flame was re-stabilized on the porous plate burner after the spreading.

Thus, in the rubber balloon extinguishing testing, it was seen that the behavior of flamelet B shown in Fig. 4 played an important role in determining whether a flame could be extinguished completely or not.

Extinguishing probability of inert-gas filled balloon

Fig. 5 shows the typical profiles of the extinguishing probability, *P*, as a function of an extinguishing gas volume; the diameter of the porous plate burner was 80 mm. As the inert gas volume increased, all extinguishing probabilities increased monotonically and became unity at various gas volumes. From Fig. 5, the smallest inert gas volume needed to extinguish the flame was indicated as *P* = 1, and considered to be the extinguishing limit for each inert gas. By comparing the magnitudes of the extinguishing limits, the extinguishing capabilities of each inert gas could be evaluated. In other words, the lower the extinguishing limit the better was the extinguishing performance of an inert gas.

In addition, when a rubber balloon was inflated with air, *P* was always less than one. Hence, using only air flow released from a bursting balloon could not attain an extinguishing limit for diffusion flames tested in this study.

Extinguishing limit of inert-gas filled balloon

Fig. 6 shows the relationships between the extinguishing limits of methane and propane flames and the heat release rates when flames were formed on an 80-mm-diameter porous plate burner. All extinguishing limits increased with increasing heat release rates, regardless of fuel species. Moreover, by comparing extinguishing limits at equal heat release rates it was found that the extinguishing effectiveness ranking of

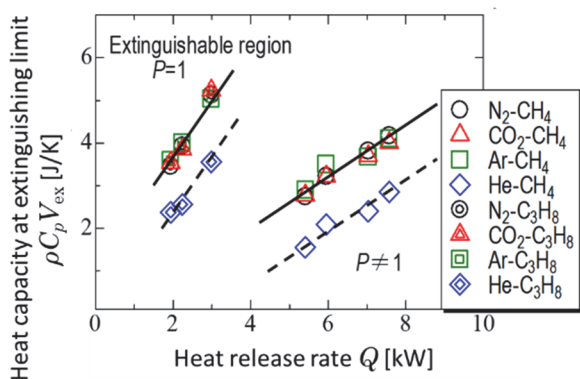


Fig. 7. Relationship between the inert-gas heat capacity at the extinguishing limit and the heat release rate (80-mm-diameter porous plate burner).

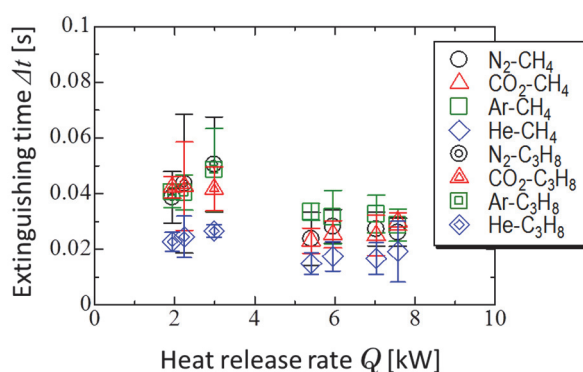


Fig. 8. Relationship between the extinguishing time and the heat release rate (80-mm-diameter porous plate burner).

the inert gases was $CO_2 > He \approx N_2 > Ar$. This ranking agrees with that derived from a cup-burner method [3].

The cup-burner method determines a minimum extinguishing concentration (MEC) at which an inert gas has to be concentrated in an oxidizer flow to be able to extinguish a laminar diffusion flame formed on a coflowing burner [3–5]. From the MEC values, the extinguishing effectiveness of inert gas species was evaluated. The ranking within the MEC values for inert gases, except for helium, was shown to depend on the magnitude of the heat capacities of the gases.

From the thermodynamics of combustion [12] it is understood that, when oxidizer and fuel gases are at standard temperature and pressure conditions and a combustion reaction occurs, flame temperatures are considered to be determined by dividing the amount of the heat released from the combustion reaction by the sum of heat capacities of the combustion products. Moreover, according to the law of Burgess and Wheeler, the critical flame temperatures at lean flammability limits of hydrocarbon-air premixed flames are always almost the same, values for which are around 1450 K [12]. In the same way, hydrocarbon diffusion flames also

show almost the same critical flame temperature at each MEC value [3–5]. Therefore, as the heat capacity of an inert gas was larger, the inert gas displayed better extinguishing effectiveness.

On the other hand, helium gas causes greater heat dissipation from a diffusion combustion zone because its thermal conductivity is much larger than those of other inert gases. Consequently, although the heat capacity of a helium is smaller than that of the nitrogen, its extinguishing effectiveness was very close to that of nitrogen, as shown in Fig. 6 [3].

Heat capacity of inert gas at extinguishing limit

Fig. 7 shows the relationship between the heat capacities of the inert gases at the extinguishing limit and the heat release rates of the diffusion flame; the heat capacity of each inert gas was obtained by multiplying the extinguishing limit by the gas density and specific heat at constant pressure. As a result, for each diffusion flame the data of all inert gases except for the helium gas lie on single straight lines, respectively. These results indicate that, when the heat release rates are equal, a critical value of the inert-gas heat capacity exists at which extinguishment of diffusion flames can be accomplished. In addition, the critical heat capacity of the helium gas always was smaller than those of the other inert gases because the thermal conductivity of helium is much larger than those of the other gases. Thereby, the profiles of the critical inert-gas heat capacities are considered to depend on produced fuel species.

The ratio of heat absorbing rate of inert gas to heat release rate of diffusion flame

The vertical axis of Fig. 7 was nondimensionalized by calculating the ratio of the heat absorbing rate of an inert gas-to-the heat release rate of the diffusion flame; this ratio eliminated dependencies of inert gas types and fuel species. Fundamentally, the ratio of the heat loss rate from a flame and the heat release rate in a flame determines the flame temperature.

To convert the heat capacities into heat absorbing rates of the inert gases for the vertical axis of Fig. 7, it was necessary to use the extinguishing time and the differences between the stable flame temperatures-to-the flame temperatures at extinction for each gas; fortunately, the extinguishing time was able to be experimentally determined. Fig. 8 shows the extinguishing time for the 80-mm-diameter porous plate burner.

Moreover, the stable flame temperature of each diffusion flame was assumed to be the same as the adiabatic flame temperature, which can be obtained for methane-air and propane-air flames by using the CEA code of Gordon and McBrfide [13]; they are 2226 K and 2257 K, respectively. On the other hand, the flame temperatures at extinction caused by the inert gases were estimated from experimental data derived from a

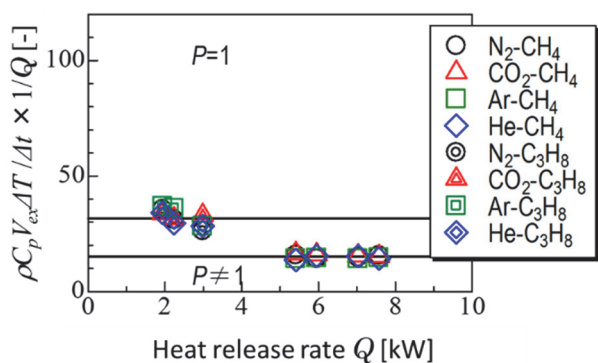


Fig. 9. The ratio of the heat absorbing rate of the inert gas to the heat release rate of the diffusion flame (80-mm-diameter porous plate burner).

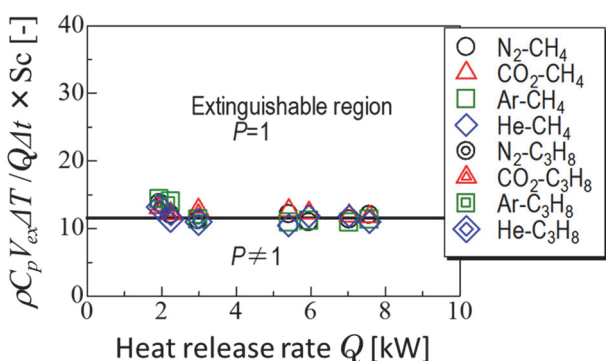


Fig. 10 Ratio of the heat absorbing rate and the heat release rate times Schmidt number of fuel species (the 80-mm-diameter porous plate burner).

counterflow diffusion flame formed on a Tsuji-Yamaoka burner [2]. These critical flame temperatures for methane counterflow diffusion flames extinguished with carbon-dioxide, nitrogen, argon and helium were 1473 K, 1483 K, 1443 K and 1623 K, respectively [2]. Furthermore, the propane counterflow diffusion flames extinguished with inert gases were assumed to have the same extinction flame temperature as the methane counterflow diffusion flames.

Based on the above considerations, the relationships between the ratio of the heat absorbing rate of the inert gas-to-the heat release rates of the diffusion are shown in Fig. 9. From these results, it was determined that, when the fuel gas was the same, all experimental data had constant and equal values regardless of the inert-gas species and heat release rates. However, a difference depending on the fuel species still can be seen in Fig. 9.

Effect of Schmidt number

As shown in Fig. 4, the behavior of the flamelet B formed in the extinguishing process determined

whether the flame could be extinguished. When flamelet B propagated upstream through the premixing layer between the fuel gas and air in convective flow on the porous plate burner the extinguishment with inert-gas balloons was not successful. Based on these observations, the formation process within the premixing layer of the burner was evaluated by examining the Schmidt number, a dimensionless number representing the ratio of momentum diffusivity and mass diffusivity.

In Fig. 10 is displayed the value of the ratio of heat absorbing rates of the inert gases-to-the heat release rates of the diffusion flame multiplied by the Schmidt number of fuel species; for methane and propane, the values of the Schmidt numbers are 0.768 and 0.387, respectively. Also, the diffusion coefficients of methane and propane relative to nitrogen, the major species in air, had values of 22.2 and 11.4 mm²/s, respectively.

From Fig. 10 it is clear that all experimental data became to lie on a single straight line independent of fuel species, inert gases and heat release rates. As a result, it was concluded that the determination of the extinguishing limits for the rubber balloon extinguishing method depended on two factors. First is the balance of the heat loss caused by the inert gas flow released from the bursting balloon and the heat production in the combustion zone. The second is the formation of a flammable premixing layer in front of the flame which can be blown off the burner by the flow of the inert gas from the balloon.

Scaling effect

To confirm scaling effects the extinguishing limits obtained while using a 100-mm-diameter porous plate burner was assessed by using the non-dimensional number shown in Fig. 10. However, we did not have the extinguishing time data at the extinguishing limits of the methane-air and propane-air diffusion flames formed on the 100-mm-diameter burner. Thereby, the extinguishing times of the flames on the 100-mm-diameter burner had to be estimated. From analyses of images of extinguishing processes for the 80-mm-diameter burner the relationship between extinguishing time and the time during which the inert gas moved from the rupture location of the bursting balloon to the opposite end of the porous plate burner was determined; all extinguishing times were approximately ten times larger than the traveling times of the inert gases from one side of the burner to the other side. It was assumed that a similar time relationship existed for flames on the 100-mm-diameter burner.

From the imaging of the 80-mm-diameter burner, the traveling time for an inert gas to move up to 100 mm from the balloon rupture location was obtained. Then, the extinguishing times for each inert gas were calculated by multiplying ten times the traveling time. As a result, the ratios of the extinguishing time for the 80-mm-diameter burner and that for the 100-mm-diameter burner for each inert gas were about 1.3, a

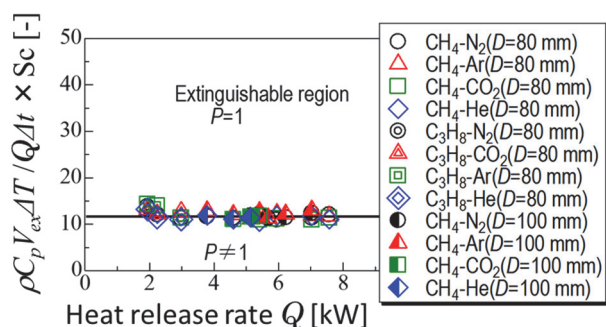


Fig. 11 Extinguishing limits of the flames formed on the 100-mm-diameter burner organized by the non-dimensional number.

value close to the 1.25 ratio of the burner diameters. The non-dimensional number was calculated using this extinguishing time for the 100-mm-diameter burner.

Fig. 11 shows the results for the 100 mm diameter burner; it is clear that all extinguishing data were on the same straight line as in Fig. 10. As a result, the non-dimensional number derived in this study included scaling effects for flame extinguishment by inert gas balloon.

Concluding remarks

The mechanisms and scaling effects of flame extinguishment by using a rubber balloon inflated with inert gas were determined for two diffusion flame burners of 80- or 100-mm diameter. Carbon dioxide, nitrogen, argon and helium gases were the inert gases used during the extinguishment experiments for methane-air and propane-air fuels. Extinguishing probabilities of the inert gases were measured and the extinguishing processes were determined.

From the experimental results, the extinguishing limit or minimum volume of the inert gas required for successful flame extinguishment was obtained. As a result, an effectiveness ranking of the inert gases when using this method of flame extinguishment was determined and it was in agreement with previously reported values from cup-burner experiments. The extinguishment of the diffusion flames was ascribed to be a result of heat loss due to the ingress of inert gas into the flames.

By using a non-dimensional number calculated from the ratio of the heat absorbing rate-to-the heat release rate multiplied by the Schmidt number of fuel species all extinguishing limits were relegated to a single straight line regardless of fuel species, inert gases, heat release rates and burner diameters. Therefore, it is

concluded that the determination of the extinguishing limits of these inert gases depends on the balance of heat loss caused by the inert gas flow released from the bursting balloon and the heat production in the combustion zone, and also on whether a flammable premixing layer in front of the flame is blown off by an inert gas flow supplied from the balloon.

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