Influence of Fire Suppressant Powders on Burning Velocity of Laminar Premixed Flame

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ABSTRACT

In the present study, an experiment was carried out to evaluate the fire suppression efficiency of NaCl and $NaHCO_3$ powders for laminar premixed methane-air flame. Hybrid flame burner and shadowgraph technique were used to measure the burning velocity with powders over different concentrations at two equivalence ratios (0.9, 1.0), and an improved model was employed to explore the competitive process between the physical and chemical effects of the two powders. It was observed that both the two powders show their efficiency in reducing the burning velocity, and the suppression behavior of $NaHCO_3$ can be more pronounced than NaCl. The agreement between the theoretical and experimental results for NaCl-addition flames indicates that the powders absorbing heat, which is also known as the physical heat sink effect, is the major fire suppression mechanism for NaCl. However, there is a large discrepancy between the predicted and observed results for $NaHCO_3$-addition flame, which suggests that the physical heat sink effect only behave as a part of the suppression process for $NaHCO_3$ and, therefore, the apparent efficiency of $NaHCO_3$ can be attributed to the powders decomposition and further chemical reactions. Furthermore, the chemical effect of $NaHCO_3$ increases with the decrease in equivalence ratio, evidenced by the increase of experimental results and the similar value of the model-based results in lean- and stoichiometric-flames.

KEYWORDS: Powder suppressants, burning velocity, physical heat sink.

NOMENCLATURE

B	frequency factor characterizing rate of gas phase oxidation of gaseous fuel (1/(mol·s))
C_p	heat capacity of air (J/K)
C_s	heat capacity of powders (J/K)
E	activation energy cahracterizing the gas phase reaction (kJ/mol)
k	thermal conductivity (W/(m·K))
n_p	moles of products (mol)
n_s	number of powders (-)
n_s'	moles of powders per unit volume per unit time passing through the flame (mol/(m^3·s))
n_{air}'	moles of air per unit time (mol/s)
T_f'	flame temperature with powders (K)
T_u	temperature of unburned gas (K)
U	flow velocity at burner nozzle (m/s)
V^*	volumetric flow rate (m^3/s)
V	volume (m^3)
Δx	entire fire suppression effect (NaCl or NaHCO3)

Greek

α	flame half cone angle (°)
ε	expansion parameter (-)
γ	physical heat sink effect (NaCl or NaHCO3)
δ	chemical reaction effect (NaCl or

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Q^*	heat release rate (W)
R	universal gas constant (J/(mol·K))
S_0	burning velocity without powders (m/s)
S_u	burning velocity with powders (m/s)
S_p	burning velocity based on physical heat sink effect (m/s)
T_0	atmosphere temperature (K)
T_f	flame temperature without powders (K)

NaHCO3)

ρ	density (kg/m^3)
ϕ	gaseous mixture equivalence ratio (-)

Subscripts

g	gas phase
s	powders
s.p	solid products of powders
g.p	gaseous products of powders

INTRODUCTION

Dynamics of fire suppression is of both scientific interest and practical importance. The fire extinguishing powders, such as sodium chloride (NaCl) and sodium bicarbonate ($NaHCO_3$), have been widely used in many fire extinguisher devices due to the environment-friendly features, low costs and high efficiencies [1, 2].

The existing works on fire inhibitors tend to restrict their attentions to the physical behaviors of powders, such as the extinguishing time, critical concentration and flame temperature. Ni et al. [3-5] conducted experimental studies to evaluate the performance of different types of fire suppressant for the pool fires located within confined spaces. The results show that the inhibitors can significantly reduce the flame temperature and extinction time. Adam and Ewing [6, 7] investigated the impacts of dry-chemical powders on n-heptane diffusion flames, and the minimum weights of the powders required for flame extinction were determined. Krasnyansky [8] explored the influence of a mixed extinguishing agent on the dynamics of temperature change over tunnel fires. These studies, however, were generally based on the systems with high experimental costs, and the inherent combustion-related properties for the extinguishing powders are believed to be an area for further investigations.

When it comes to evaluating the efficiency of fire suppressant, the burning velocity is considered to be one of the useful variables [9, 10]. In laminar flames, the effects of extinguishing powders are directly reflected by the burning velocity, which shows the coupling of chemical reaction, thermal diffusivity and heat release. The flame inhibition effect of powders can be attributed to chemical and physical effects [11]. Considering previous works [12, 13] and the feasibility of the analysis, the physical effect in this paper is dominated by the heat absorption of powders and gases rather than other factors, which is known as the physical heat sink effect, whereas the chemical effect comprised of inhibition of the chain reactions via the active species and endothermic reactions [14, 15] can also bring forth influence to the inhibition process when the powders are thermally decomposed. Although the physical and chemical extinction mechanisms were already known by Thorn [13], the coupling of the two effects, however, indeed exists in experiments, and it is difficult to evaluate the importance of a certain effect independently from the other. In addition, different powder could undergo different combustion process which causes the complexity of the two effects. We need to take deep research on the two effects to understand the mechanism of the powder suppressant better. Therefore, a modified model was employed to shed light on the competition between the powder physical and chemical effects.

This paper was motivated to seek insights into the impact of fire extinguishing powders on the burning velocity variation in a laminar premixed flame, which aims to provide a solid basis on which to expand the understanding of the suppression mechanisms of fire extinguishing powders. A hybrid flame burner was employed to perform the methane-air flames with NaCl and $NaHCO_3$

powders over a wide range of powder concentrations, and the shadowgraph method is utilized in an attempt to describe the nature of inhibition by burning velocity as a function relating to both the powder concentrations and gas stoichiometries. Finally, a comparison between the experimental and theoretical results was carried out to distinguish the importance of physical and chemical effects for the two kinds of powders.

THEORETICAL AND EXPERIMENTAL METHODS

Theoretical model of physical heat sink effect

Experimental results [15] suggested that the powders in laminar premixed flame absorb the heat from flame and behave as the heat sink, which results in the reduction of the burning velocity when the powders move across the reaction region. Furthermore, due to the low thermal stability of powders, the endothermic decomposition can also affect the reaction process by producing water vapor and carbon dioxide, and the subsequent reaction and inhibition of the decomposed species are also responsible for the reduction of burning velocity. In this way, the fire suppression effect of the the NaCl and $NaHCO_3$ powders can be expressed as:

$$\Delta x_{\mathrm{NaCl}} = \gamma(\mathrm{NaCl}) + \delta(\mathrm{NaCl}), \tag{1}$$

$$\Delta x_{\mathrm{NaHCO_3}} = \gamma(\mathrm{NaHCO_3}) + \delta(\mathrm{NaHCO_3}), \tag{2}$$

where γ denotes the physical heat sink effect, δ denotes the chemical reaction effect and Δx is the entire fire suppression effect, which is determined by:

$$\Delta x = \frac{S_0 - S_u}{S_0} \times 100\%, \quad \gamma = \frac{S_0 - S_p}{S_0} \times 100\%, \tag{3}$$

where S_0 is the burning velocity of methane-air flame without powders, S_u is the burning velocity under the total influence of the powders (given by experiments) and S_p is the theoretical burning velocity which only affected by the physical heat sink effect (calculated by the model).

In order to evaluate the impact of the physical heat sink effect, a modified model based on Xie et al. [12] and Seshadri et al. [16] is adopted to predict the burning velocity over a wide range of powder concentrations at mixture stoichiometries. From the chemical reaction for combustion process, the heat released from flame without any powders is calculated by:

$$\frac{\phi}{2}\mathrm{CH_4} + (\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow \frac{\phi}{2}\mathrm{CO_2} + \phi\mathrm{H_2O} + 3.76\mathrm{N_2} + 2(1-\phi)\mathrm{O_2}. \tag{4}$$

With the assumption that all the heat release is used to raise the temperature of the mixture, the heat release rate of a pure methane-air premixed flame for a given flow of air and the equivalence ratio is calculated by:

$$Q^* = \frac{n'_{air}}{4.76}(T_f - T_0)\sum C_p n_p, \tag{5}$$

where n_p is the moles of the products which depends on the equivalence ratio ϕ. When the absorbing heat effect of powders is introduced, the extra heat release term Q_s^* should be added into the right-hand side of Eq. (5) to ensure the conservation of energy. Finally, the flame temperature with powders can be estimated by following equation:

$$Q^* = \frac{n'_{air}}{4.76}\left(T'_f - T_0\right)\sum C_p n_p + Q_s^* . \tag{6}$$

There are some studies [16-18] regarding the Q_s^* of inert powders, i.e. sand and SiC, which only consider the heat absorption effect of powders:

$$Q_s^* = n'_{sp} C_{sp}\left(T'_f - T_0\right), \tag{7}$$

actually, due to the different physico-chemical properties, the powders could absorb heat and begin to pyrolysis when the flame temperature reaches the critical value. The decomposition products may include gases and solids which could further absorb heat and decompose. Thus, the absorbing heat of powders Q_s^* in this work is modified to be in line with the real situation. Summarizing the various burning process of these powders, the Q_s^* is composed of the heat absorption rate of gaseous products and solid products, and it is estimated by the improved form shown in Eq. (8):

$$Q_s^* = \left(T'_f - T_i\right)\sum C_{gp} n'_{gp} + \sum_{i=1}^{n} n'_{sp} C_{sp}\left(T_i - T_{i-1}\right), \tag{8}$$

where n'_{sp} is the moles of solid products per unit volume per unit time passing through the flame calculated by $n'_{sp} = \left(V^*_{air} + V^*_{CH_4}\right) n_s \rho_s V_s$, and n'_{gp} is the moles of gaseous products per unit volume per unit time. $i = 1, 2, 3 \cdots$indicates the first, second and third decomposition process of powders and so on. T_i denotes the decomposition temperature, T_0 denotes the atmosphere temperature. The first item on the right-hand of Eq. (8) demonstrates the heat absorption of gaseous products and the second item demonstrates the heat absorption of solid products. For the absorbing heat effect of gaseous products, the $(T'_f - T_i)$ do not need to be calculated, unless there are gaseous products in the i decomposition process. For the absorbing heat effect of solid products, when the last solid product keep its stability in flame zone, T_i is equal to T'_f.

Based on the flame temperature with powders, the burning velocity is given by the expressing from Seshadri et al. [15].

$$S_p = \sqrt{\frac{2Bk\varepsilon^2}{\rho_g C_g}\exp\left(-\frac{E}{RT'_f}\right)}, \tag{9}$$

$$\rho_g = \frac{\rho_{air}V_{air} + \rho_{CH_4}V_{CH_4}}{V_{air} + V_{CH_4}}, \quad \varepsilon = \frac{RT'^2_f}{E\left(T'_f - T_0\right)} . \tag{10}$$

To match the burning velocity of no powder conditions, the $B = 3.9 \times 10^{10}/(\mathrm{mol} \cdot \mathrm{s})$ and $E = 89.8\ \mathrm{kJ/mol}$. Should be noted, the expressing of calculating burning velocity applies in lean- and stoichiometric-burn [16].

Hybrid flame burner

A laminar premixed flame experiment was employed to estimate the entire fire suppression effect, and the hybrid flame was generated by Bunsen burner on account of simple and easy to operate. Bunsen burner has been adopted previously for many studies that involved with the hybrid flames of coal dust and metal particles with methane, such as Rangwala et al. [12, 17] and Goroshin et al., Philippe et al. [18-20].

A schematic of the hybrid gaseous-powder fuel burner is shown in Fig. 1. The burner has an inner diameter of 9.7 mm and a length of 110 cm to ensure a fully developed laminar flow profile. To shield the flame from ventilation and dust of the ambiance, it was surrounded from a coaxial coflow with honeycomb. The dust feeder is controlled by a variable speed screw which is pre-calibrated. Many pre-calibrated sonic nozzles (O'Keefe Metal Orifice Assemblies) and pressure regulators are used to control the gas flow.

It’s necessary to adopt the shadowgraph technique because of the flame edges become hardly visible in direct flame images with the powders burning in the flame. The shadowgraph system includes a point light source, a convex lens with diameter of 10 cm and a Nikon camera (D7500 with AF-S 105mm f/2.8G IF-ED VR). The camera is placed behind the flame along the centerline of the parallel beam of light to capture the shadowgraph images and is set with a shutter speed of1/6000, ISO of 100, and an aperture of f/3.0.

The burning velocity is obtained by using cone angle method:

$$S_u = U\sin(\alpha), \qquad (11)$$

where S_u represents the burning velocity, U is the unburned gaseous mixture velocity at the exit of the burner and α is the cone half-angle of shadowgraph image. Due to the influence of flame, the mixture gas flows faster at the exit of the burner than at the inner of it. Thus $U = U_0 \cdot T_u/T_0$ is used to calculate U where U_0 is the mixture velocity at the inner of burner; $T_u$is the temperature of unburned gas at the exit of burner. A MATLAB script is used to extract the average flame edge based on the Sobel operator, then to get the slope of the edge and the cone half-angle:

$$\alpha = \frac{\tan^{-1}(\alpha_1) + \tan^{-1}(\alpha_2)}{2}, \qquad (12)$$

where α_1 and α_2 are the slopes.

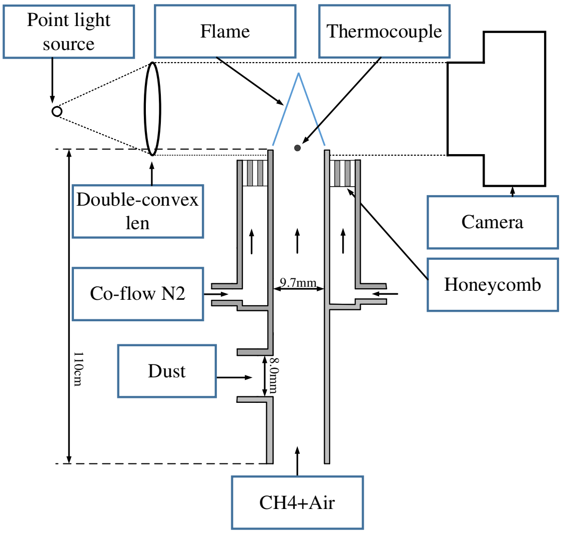

Fig. 1. The hybrid flame burner.

RESULTS AND DISCUSSION

Burning velocity of hybrid flame

As indicated in Fig. 2, the measured methane-air burning velocity is in well agreement with the experimental data [21-24] and calculated flame speed by GRI-mesh 3.0 [25]. This confirms that the experimental configuration used in the present work is sufficient to display the flame behaviors, and furthermore, the velocity variation could be predicted by the shadowgraph method. It should be noted here that the Bunsen method is not the most accurate method to measure the burning velocity but, it could provide the trend of the CH4-air burning velocity variations with different powders.

The burning velocity of methane-air with NaCl and $NaHCO_3$ powders is shown in Fig. 3. It is obvious that there is a negative correlation between the powder concentration and the burning velocity, which suggests that two types of powders have good fire suppression effect. It also can be seen that the flame with NaCl powders has velocity exceeding that with $NaHCO_3$ that the former is greater than the latter with 34.5 and 29.6 cm/s comparing 33.2 and 27.9 cm/s at 250 g/m^3 concentration of lean- and stoichiometric-burn condition, which indicates that the $NaHCO_3$ powders have better fire suppression efficiency than NaCl in laminar premixed flame.

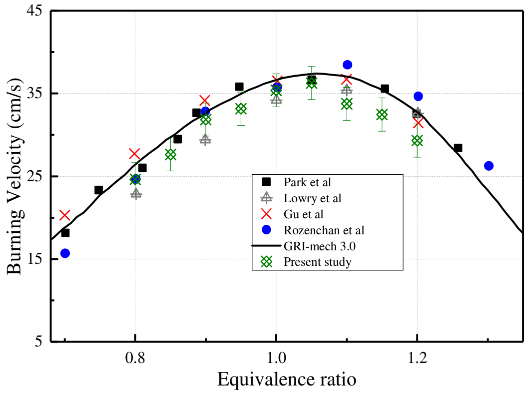

Fig. 2. The methane-air burning velocity without powders.

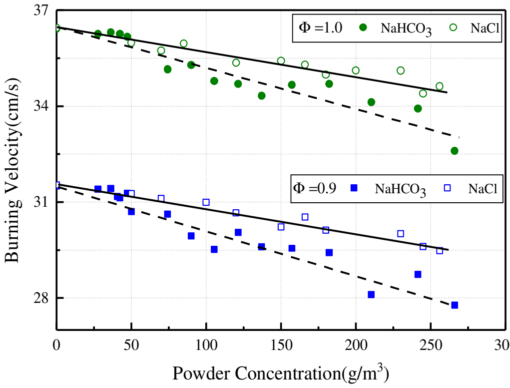

Fig. 3. The experimental results of methane-air burning velocity with NaCl (hollow symbols) and $NaHCO_3$ (solid symbols) powders. Square symbols for Φ=0.9, and circular symbols for Φ=1.0.

Fire suppression effect analysis

Due to the high thermal stability of NaCl powder that has been previously proved [26], we assumed the powder is inert in flame. However, for $NaHCO_3$ powders, they could react in flame as follows [27-29]:

$$2NaHCO_3 \rightarrow Na_2CO_3(s) + H_2O(g) + CO_2(g), \tag{13}$$

$$Na_2CO_3 + H_2O \rightarrow 2NaOH + CO_2(g). \tag{14}$$

The NaOH will react with free radicals, i.e. OH, H, and other species, which these reactions were not be considered in this model. For gaseous products, the absorption heat of CO_2 should be taken into account. For solid products, the absorption heat of $NaHCO_3$ and Na_2CO_3 should be calculated, and the decomposition temperatures are 543 K and 1017 K respectively [30]. It is necessary to assume the decomposition reactions are completed instantly [15]. So based on the combustion process of the two powders and the theoretical model, the variety of burning velocity under the impact of the physical heat sink effect can be calculated.

The comparison of the experimental data and theoretical results are shown in Fig. 4, according to the experimental data, the fitting lines are achieved by the least-squares method. The reasonable agreement in NaCl powders condition, which indicates the NaCl powders just as inert substance in flames and the decreasing of burning velocity mainly owning to the physical heat sink effect. And the acceptable experimental error results in the small discrepancy.

However, for $NaHCO_3$ powders condition, the burning velocity calculated by model much less than that of experimental. When equivalence ratio $\Phi = 1.0$, the burning velocity of theoretical model is 35.9 cm/s at 250 g/cm^3 powders addition which is larger than the 33.4 cm/s of experimental. This evidence certainly indicates that the entire fire suppression effect is greater than the physical heat sink effect in $NaHCO_3$ flames. This argument indirectly proves that the chemical reaction effect of $NaHCO_3$ plays an important role in the inhibition of flames. Furthermore, it can also be seen the burning velocity predicated by model with $NaHCO_3$ powders exceeding that with NaCl at almost any concentration values and different equivalence ratios. At fuel lean condition, the predicated result with is $NaHCO_3$ 31.2 cm/s which is larger than the 29.9 cm/s of NaCl with 250 g/m^3 addition. Thus, regarding the entire fire suppression effect, $NaHCO_3$ powders have better efficiency while show lower physical heat sink effect, because of the influence of chemical reaction effect. On the contrary, NaCl powders exhibit higher physical heat sink effect with poorly total efficiency.

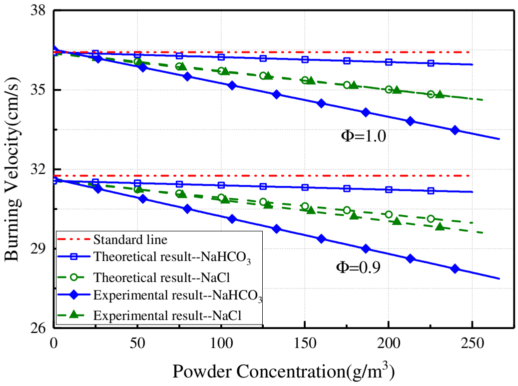

Fig. 4. The theoretical (hollow symbols) and experimental results (solid symbols) of methane-air burning velocity with NaCl (dash lines) and $NaHCO_3$ (solid lines) powders.

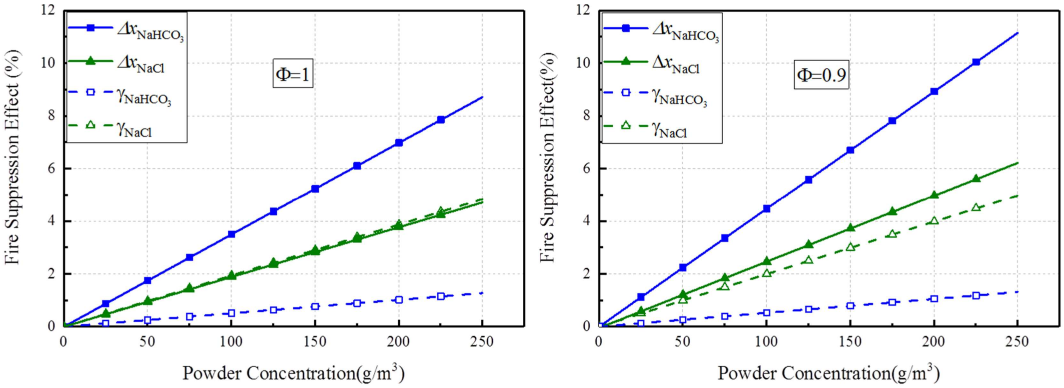

Fig. 5. The fire suppression effect with powders.

The fire suppression effect of NaCl and $NaHCO_3$ powders is shown in Fig. 5. No matter which effect, the values raise continuously with increasing of powders concentration. The fire suppression effect and physical heat sink effect of NaCl (Δx_{NaCl} and γ_{NaCl}) are aggrement well at all conditions. When equivalence ratio $\phi = 1$, the entire fire suppression effect of $NaHCO_3$ ($\Delta x_{\mathrm{NaHCO_3}}$) approach

9.5% at 250 g/cm^3 powders addition which more than twice that of NaCl powders (Δx_{NaCl}), which demonstrate $NaHCO_3$ powders have better suppression efficiency. It is directly seen that the physical heat sink effect of $NaHCO_3$ ($\gamma_{\mathrm{NaHCO_3}}$) is just about 1.3% at 250 g/cm^3 powders addition, which suggests that the chemical reaction effect ($\delta_{\mathrm{NaHCO_3}}$) is about 8.2% and plays a significant role in extinguishing process with $NaHCO_3$ powders. Moreover, the $\Delta x_{\mathrm{NaHCO_3}}$ in lean-burn is always larger than that of stoichiometric-burn with the same powders concentration condition, which indicates the fire extinguishing powders have better efficiency in lean-burn condition. And based on the similar value of the model-based results in lean- and stoichiometric-flames, the chemical reaction effect becomes largrer in learn-burn condition.

CONCLUSIONS

In this paper, we provided a method to measure the burning velocity of methane-air with powder and took this as a criterion to evaluate the suppression efficiency of powder. In addition, a modified model was adopted to strengthen the understanding of physical heat sink effect and chemical reaction effect of fire suppression mechanism.

Experiments were carried out to evaluate the effectiveness of NaCl and $NaHCO_3$ powders in extinguishing a laminar premixed methane-air flame. The burning velocity, as a function of powder concentrations and equivalence ratios, was measured to characterize the fire suppression efficiency of powders. The results showed that the fine effectiveness in extinguishing flame of the two types of powders. And the $NaHCO_3$ powders have better fire suppression efficiency than NaCl.

A modified model which was based on the different process in flame of different powder was developed to estimate the physical heat sink effect, and distinguish the physical heat sink effect from chemical reaction effect in the different process of flame suppression. The reasonable agreement between the theoretical and the experimental results with NaCl powders addition demonstrates that the effectiveness of NaCl powders is mainly determined by the physical heat sink effect. On the contrary, the physical heat sink effect of $NaHCO_3$ is just about 1.3% and the chemical reaction effect is 8.2% at 250 g/cm^3 powders addition and $\Phi = 1.0$, which suggested that the $NaHCO_3$ powder is primary attributed to the chemical reaction effect.

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