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Experimental investigation of flame spreading over pure methane hydrate in a laminar boundary layer

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Abstract

Flame spreading over pure methane hydrate in a laminar boundary layer is investigated experimentally. The free stream velocity (U_∞) was set constant at 0.4 m/s and the surface temperature of the hydrate at the ignition (T_s) was varied between -10 and -80 °C. Hydrate particle sizes were smaller than 0.5 mm. Two types of flame spreading were observed; “low speed flame spreading” and “high speed flame spreading”. The low speed flame spreading was observed at low temperature conditions ($T_s = -80$ to -60 °C) and temperatures in which anomalous self-preservation took place ($T_s = -30$ to -10 °C). In this case, the heat transfer from the leading flame edge to the hydrate surface plays a key role for flame spreading. The high speed flame spreading was observed when $T_s = -50$ and -40 °C. At these temperatures, the dissociation of hydrate took place and the methane gas was released from the hydrate to form a thin mixed layer of methane and air with a high concentration gradient over the hydrate. The leading flame edge spread in this pre-mixed gas at a spread speed much higher than laminar burning velocity, mainly due to the effect of burnt gas expansion.

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Keywords: Flame spreading; Methane hydrate; Laminar boundary layer

1. Introduction

Methane hydrate is an ice-like clathrate compound of water and methane, formed under high pressure and low temperatures. A volume of methane hydrate contains more than 170 times the amount of methane than an equal volume of meth-

ane gas contains at standard temperature and atmospheric pressure. Its nominal equilibrium temperature is 193 K (-80 °C) at 1 atm. Stern [1] reported that at above 193 K (-80 °C), hydrate dissociation rates increase monotonically with increasing temperature, in the ranges 193 (-80 °C) to 240 K (-33 °C) and 271 (-2 °C) to 290 K ($+17$ °C). However, the “anomalous preservation” thermal regime at 242 (-31 °C) to 271 K (-2 °C) is characterized by markedly depressed dissociation rates.

Methane hydrate has become widely known as a potential new energy source in recent years. It is

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now well known that huge deposits of natural gas in the form of hydrate exist in marine sediments throughout the world [2]. At the same time, as a new method of natural gas transportation, methane hydrate is considered to be an alternative to liquefied natural gas (LNG), as the storage conditions of methane hydrate (around $-20\text{ }^{\circ}\text{C}$ at atmospheric pressure under self-preservation state) are not as harsh as that of LNG (boiling point temperature $-162\text{ }^{\circ}\text{C}$ at atmospheric pressure) [3–5]. If methane hydrate becomes widely utilized in the future, accidental ignition and flame spreading during transportation and preservation would become a great safety concern.

Although there are few studies on combustion over methane hydrate, ignition and flame spreading over combustible materials, such as solid fuels and/or liquid fuel pools have been widely investigated. These issues are known as “The Emmons problem”, “film combustion” or “boundary layer combustion”. Emmons [6] firstly modeled the combustion of large droplets in a flat plate laminar boundary layer over a liquid fuel surface theoretically and showed the importance of heat and mass transfer between the flame and liquid surface. De Ris [7] elucidated the effects of radiation and fuel-bed conduction taking into additional account the heat and mass transfer between the flame and fuel surface. McAlevy and Magee [8] viewed the flame spreading as continuous diffusive gas-phase ignition and showed that the flame spread velocity is correlated in a power-law relationship with gas-phase physical parameters, pressure and reactive component mole fraction. Lastrina et al. [9] showed the importance of different physical parameters over a thermally thick fuel bed and a thermally thin fuel bed. The heat conduction through fuel becomes important to the flame spreading in the case of thermally thick fuels in addition to the heat transfer between the flame and fuel surface, which plays a key role for thermally thin fuels [9–14]. Hirano and Suzuki [15] discussed the effect of the temperature of flammable liquids on flame spreading. When the initial temperature of a flammable liquid is below the flash point, preheating the liquid ahead of the leading flame edge is necessary for flame propagation. In our research, the above resembles the heat transfer that occurs from the leading flame edge to the methane hydrate ahead of the flame. On the other hand, when the initial temperature is above the flash point, a flammable mixed layer of fuel and air with a high concentration gradient is established over the liquid surface, so that the flame is enabled to propagate through the mixed layer. Ishida and Kenmotsu [16] experimentally studied flame spread in opposed flow through a layered flammable gas mixture along the ground with high-volatile liquid fuel. They observed different types of flame spreading as a function of the free stream velocity, including the “fast” flame spread-

ing. Takeuchi et al. [17] also studied flame spread through a laminar boundary layer with uniform methane injection from a porous wall. When the fuel injection velocity is relatively high, a mixture of fuel and air is formed in front of the leading flame edge causing the flame to oscillate with a large amplitude. Flame propagation through a mixture of gas with a high concentration gradient occurs as a partially premixed flame, in other words, as a triple flame or a tribrachial flame. Chung [18] reviewed tribrachial flames and addressed the propagation speed of a tribrachial flame, including the effects of concentration gradient, velocity gradient and burnt gas expansion.

Study on flame spreading over combustible hydrate is comparatively limited, and was first examined by using tetrahydrofuran (THF) hydrate by our research group [19]. It was made clear that the flame over THF hydrate spreads in the upstream direction against the air flow with an almost constant spread speed at around 0.2 mm/s . In addition, we observed the oscillation motion of the leading flame edge when the air flow velocity was decreased. We then investigated the flame spreading over methane hydrate numerically [20] and experimentally [21]. The flame spread speed was estimated to be $1.0\text{--}1.5\text{ mm/s}$ as a result of numerical calculations using a simple one-dimensional thermal model of hydrate, and experimental observations showed flame spread speed over methane hydrate to be around 2 mm/s . These experimental and numerical studies revealed that the flame spreads over methane hydrate at a similar spread speed of a few mm/s and that the heat transfer from the leading flame edge to the hydrate surface ahead plays an important role in sustaining the flame spreading. We also elucidated that the flame extinguishes due to the self-preserving mechanism of hydrate, before all of the hydrate burns out [21]. Detailed mechanisms of flame spreading over methane hydrate, however, have not yet been discussed. In this study, then, we experimentally observe flame spreading phenomena by varying the hydrate surface temperature at ignition to elucidate the flame spreading mechanism over methane hydrate.

2. Experimental apparatus and procedure

2.1. Flow system and test section

Figure 1 shows the flow system of the present study. The laminar boundary layer of the air flow formed on the bottom wall of the wind tunnel is used for the methane hydrate combustion experiments. The hydrate surface is set flush with the bottom wall of the wind tunnel. The velocity profile in the laminar boundary layer fits with the Blasius velocity profile [22] and the turbulent intensity of velocity fluctuation in the boundary

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