A Study of Methane Hydrate Combustion Phenomenon Using The Porous Cylindrical Burner

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Introduction

There is a large amount of methane hydrate reserves in the permafrost, the mainland coast and the deep waters all over the world [1]. According to the estimation of Milkov [2], global methane hydrate contains about 2.5×10^{15} m^3 methane gas. Methane hydrate refers to methane molecules are surrounded by water molecules with crystalline structure and it is formed as an ice-like solid structure (SI structure). Methane hydrate is usually expressed by the chemical formula of $CH_4 \cdot nH_2O(s)$ ($CH_4(g) + nH_2O(s \rightarrow l) \rightarrow CH_4 \cdot nH_2O(s)$). N is the hydrate number and its theoretical value is 5.73 [3]. The literature shows that approximate 160 m^3 methane will be released from the decomposition of 1 m^3 methane hydrate [4]. Methane hydrates can be stably stored at the temperature of -15 ℃ under the atmospheric pressure [5]. However, liquefied natural gas can be stably delivered when the temperature attains -160 ℃ at atmospheric pressure. Methane hydrates have higher storage capacity and safety.

The mining technology of methane hydrate is not yet mature and many countries around the world are committed to the exploitation of methane hydrate. At present, methane hydrate mining can be divided into (1) depressurization Method [6], (2) thermal stimulation method [7,8], (3) chemical injection method [9], (4) hydraulic fracturing method [10], (5) CO_2 injection method (inject CO_2 into hydrate reservoirs to replace methane) [11] and (6) solid mining method. Methane is a greenhouse gas and its greenhouse effect is 20 times than that of carbon dioxide. Once the methane produced from the careless exploitation of methane hydrate is released into the atmosphere, it will significantly accelerate the global warming phenomenon. In addition, methane dissolved into the seawater will also cause harm to the marine ecology of organisms. The use of solid mining methods for methane hydrate can avoid leakage of methane into the atmosphere and the seawater in the mining process and the mined methane hydrate is relatively stable for transportation.

The literature on the use of methane hydrate for energy purpose and even the research concerning direct combustion of methane hydrate is rather limited. To stimulate the combustion of methane hydrate, some studies used the counterflow reactor to investigate the combustion characteristics of premixed methane and water vapor [12]. The flame temperature is decreased dut to the absorption of heat by steam. Yakushev et al. [13] found that a layer of ice formed in the periphery of methane hydrate when it decomposed at atmospheric pressure, causing the reduction of surface porosity and thus blocking the further release of methane. This phenomenon is also known as self-preservation effect of methane hydrate.

Maruyama et al. [14] experimentally investigated flame spreading over pure methane hydrate in a laminar boundary layer. Two types of flame spreading were observed; “low speed flame spreading” and “high speed flame spreading”. However, such direct combustion of methane hydrate will also be extinct due to self-preservation effect and it is unable to get complete combustion of methane hydrate. Roshandell [15] studied the combustion of methane hydrate and found the water layer thickness on the hydrate surface had an effect on the temperature gradient through the dissociated zone, played a significant role in the hydrate dissociation rate and methane release rate. In order for a continuous dissociation and methane release, some of the water from the dissociated zone needs to be drained.

From these studies of methane hydrate, it is obvious that how to exclude the effect of water is a very important issue in the combustion process. The flame phenomenon and pattern of methane hydrate and how to overcome the problem of flame extinction are still not clear. Therefore, we have designed a new type of combustor to maintain stable combustion of methane hydrate and the flame patterns and phenomenon are investigated experimentally. Theoretical models are also established and used to compare with the experimental results.

The manufacture of methane hydrate

In this study, the methane hydrate is synthesized using the seeding method and the experimental setup is shown in figure 1. Experimental devices include a gas booster, a circulating ethanediol bath, a high pressure vessel, and so on. The methane hydrate is synthesized using the ice seed with the particle size of 180-250μm and high-purity methane gas under the condition of high pressure and low temperature. In this way, the synthesized methane hydrate would have a fixed and higher purity. In addition, by changing the initial temperature, different patterns of methane hydrated can be synthesized, which can be divided into the solid form and the powder.

Problem of primary combustion of methane hydrate

In this study, two different patterns of methane hydrate are used to investigate the combustion phenomena of methane hydrate. The combustion processes of the original type of methane hydrate are shown in figure 2 (a) and the radius of the sample is about 6.5 mm. It is hard to predict the ignition position of the sample. After ignition, there would be water layer and the ice layer gradually formed around the sample surface and the flame wrapped the sample without regularity. During the burning process, more and more ice melted and the water will continue to drip down along the sample. At the same time, the water layer on the sample surface hindered the porosity and prevented the methane from sustaining to release. This phenomenon is called self-healing or self-preservation and it will eventually extinguish the flame of methane hydrate. The total burning time of the sample was about 11 seconds. Another way is to utilize the pellet type of methane hydrate (see Figure 2 (b)), and the radius of the sample is roughly 5 mm. Although the flame wrapping the sample is more stable when compared to the former. There were still the same problems during the combustion process. The flame was quenched and the overall burning time was about 3.5 seconds.

Develop a novel burner and Discussion

Due to the self-preservation process, it is difficult to maintain a stable flame of methane hydrate. Accordingly, a novel porous cylindrical burner system is designed and utilized in the study as depicted in figure 3. In figure 3, the yellow region within the porous area is the area for placing powdered methane hydrate. A circulating bath is used to keep the temperature of the burner at about 281 K, which avoids methane hydrate releasing a lot of methane before attending the porous section. The temperature inside the burner is monitored by a sheathed T-type thermocouple. The force generated by the deformation of the rear end of the spring is used to push the rod and the interior of the prose section can be continually filled with methane hydrate. The burner is ignited by a torch and the digital SLR camera is used to record the whole process of the combustion phenomenon.

From the experimental results, we can clearly distinguish the positions of burner radius (r_s) and flame radius (r_f) as depicted in figure 4(a). The radius of the sample filling in this burner is about 5.25 mm. From the experimental results shown in figure 4 (b), the advantage of the porous cylindrical burner is significantly displayed. It can provide a stable combustion of methane hydrate and effectively solves the burning issues, such as the water dripping and the water layer blocked methane release from the surface of the sample. The overall combustion processes compared to the former two patterns are more stable. The flame location and patterns are easier for prediction and analysis. The burning time was about 11 seconds. At the end of the experiment, it was found that only a very small amount of water remains in the burner. The average flame radius is about 9.80mm as shown in figure 5 (a).

The flame pattern of the porous cylindrical burner can be analyzed by theoretical models. The one-dimensional theoretical model is used to identify the diffusion flame of methane hydrate. The energy conservation equation is solved on the theoretical model and the empirical formula of methane mass release rate is obtained from the experimental results (as shown in Figure 5 (b)). The average mass flow rate is about 0.008 g/s in this study. This model is utilized to predict the overall temperature distribution of this burner.

A commercial code with the SKELWS mechanism of methane/air is used for numerical simulation. Figure 6 is the schematic of the computational domain. The inlet gas is the mixture of methane and water vapor and the velocity is uniform and laminar. The inlet temperature is 333K and the outlet condition is fixed pressure. Non-uniform grids are used with more grids distribution in the reaction region to provide enough grid resolution. Different cases have been performed and the results are shown in table 1. From the numerical results, the flame temperature is between 2137 K and 2011 K and the flame radius will decrease with the addition of the water vapor. The flame radius identified by H radical concentration is roughly between 11.45 mm and 10.91 mm. Figure 7 shows the H and OH concentrations. Because the heat loss from the wall is not included and water vapor not water liquid is used in the numerical simulation, the comparison of experimental and numerical results has slightly deviated. However, the comparison is satisfactory.

The real flame temperature of the porous cylinder burner will be measured by Thin-Filament Pyrometry (TFP). Then, the theoretical results will be validated by the experimental data and numerical simulation using Ansys Fluent is performed to investigate the combustion process of the porous cylindrical burner.

Conclusion

From preliminary experiments of methane hydrate combustion, it is found that methane hydrate has the phenomenon of self-preservation effect, irregular melting, unstable flame and liquid water dripping during combustion processes. Referable to the self-preservation effect, it is difficult to maintain a stable flame of methane hydrate. Consequently, a novel porous cylindrical burner is designed and utilized in this study. It effectively solves the burning issues and sustains a stable flame. The flame radius and methane release rate can be determined from the experiments. The cylindrical diffusion flame model based on modified mass conservation equations and energy conservation equations can estimate the flame temperature and flame radius. The estimated results from the model will be further validated against the experimental result. In addition, the numerical simulation will be performed to investigate the effects of water on methane/air diffusion flame in the porous cylindrical burner.

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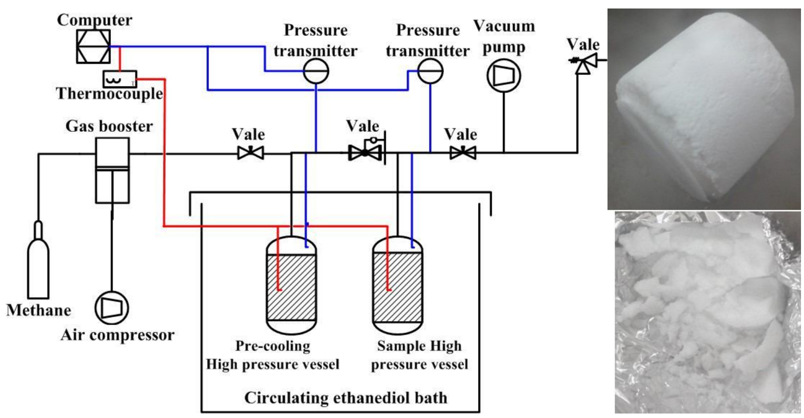

Figure 1. Schematic diagram of the hydrate fabrication system and the methane hydrate samples

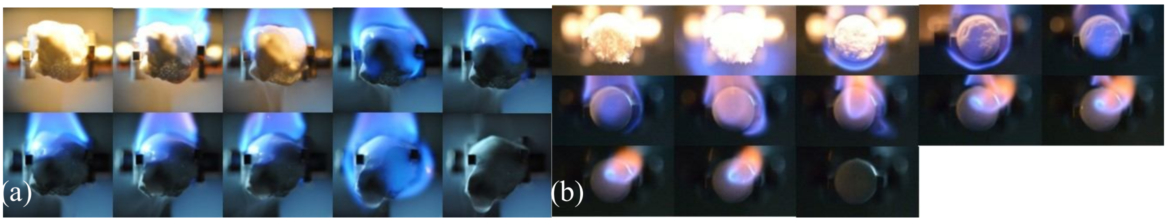

Figure 2. The combustion phenomenon with different types of methane hydrate.

(a) irregular type. (b) pellet type.

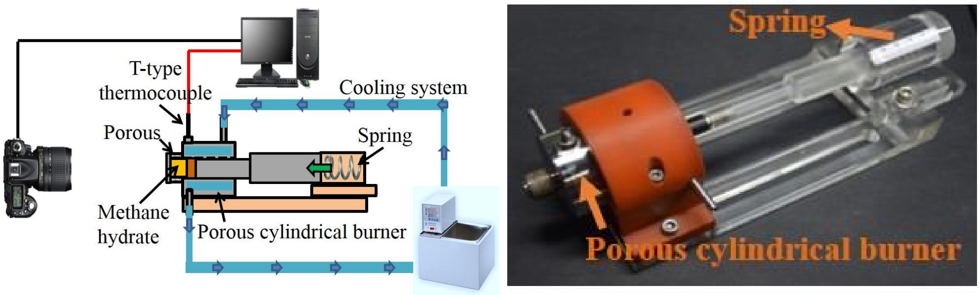

Figure 3. Schematic diagram of the porous cylindrical burner

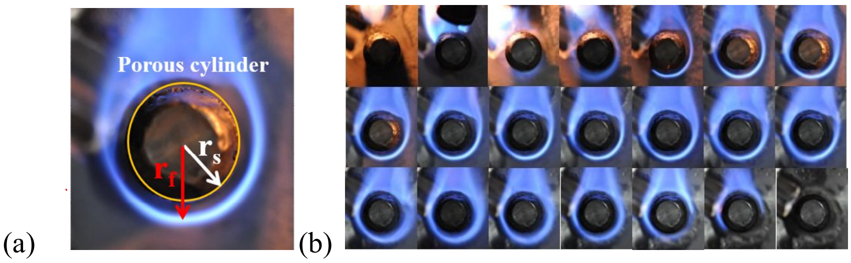

Figure 4. (a) The position of flame radius (r_f) and surface radius (r_s) and (b) the combustion phenomenon of porous cylindrical burner

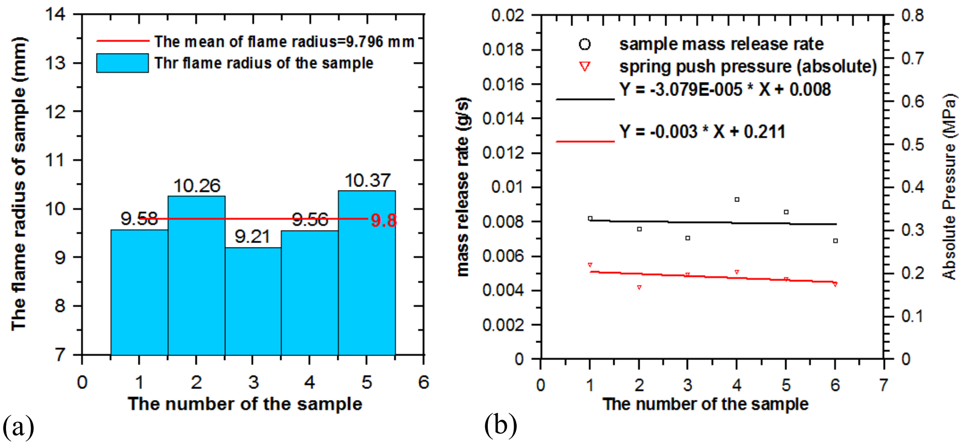

Figure 5. (a) The flame radius of experimental results and (b) methane release rate and the spring push pressure during the combustion process

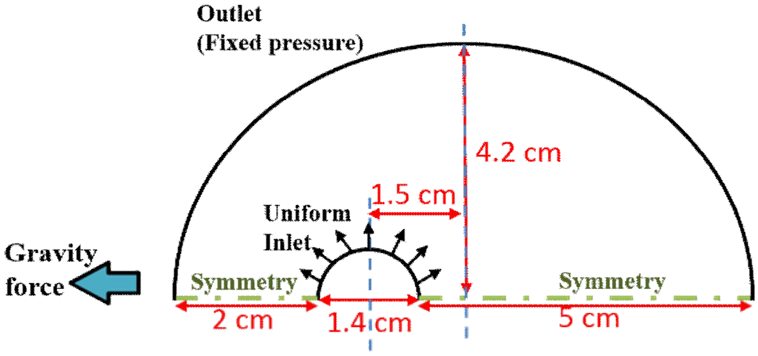

Figure 6. schematic of computational domain

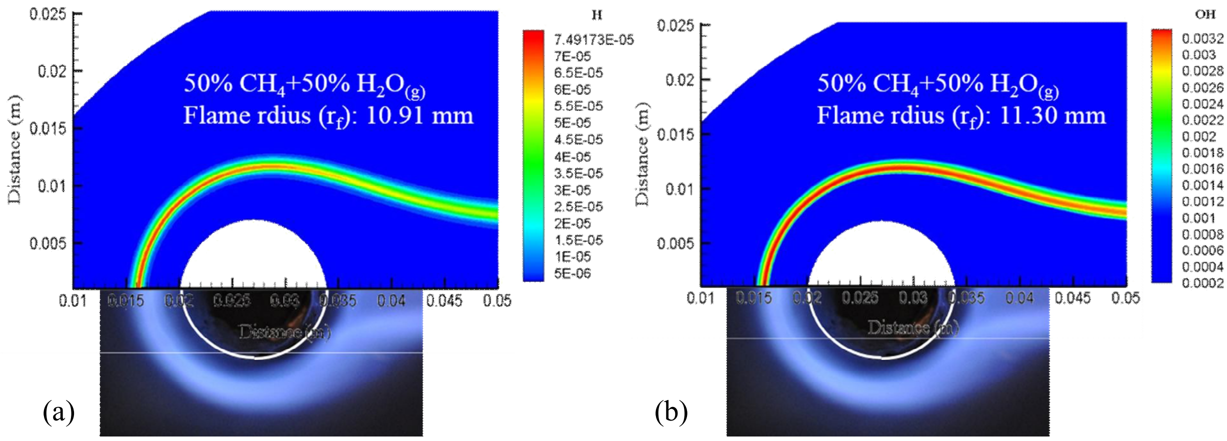

Figure 7. (a) H concentration and (b) OH concentration at fuel inlet: 50%CH_4+50%$H_2O_{(g)}$

Table 1. The flame radius and flame temperature with different percentage of water vapor

Numerical simulation result		
	Flame radius (r_f) (mm)	Temperature (K)
10 % water vapor	11.45	2137.5 K
20 % water vapor	11.36	2115.7 K
30 % water vapor	11.23	2090 K
40 % water vapor	11.18	2056.3 K
50 % water vapor	10.91	2011 K