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Structure of Solid–Gas Hybrid Flames[#]

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ABSTRACT

Herein, the flame structure of a “hybrid fuel” as a mixture of combustible gas and solids in powder form was studied experimentally. A circular burner was used, and a rich premixed flame was achieved. The results showed that the powder underwent high-temperature pyrolysis in the region sandwiched by the inner and outer flames to gasify quickly. The gasification efficiency was estimated experimentally to prove that a sufficient amount of powder could be burned out in this system.

Keywords: hybrid fuel, powder, premixed flame, gasification, high-temperature pyrolysis

1. INTRODUCTION

Fuels in use are broadly classified by their phase, namely, gas, liquid, and solid fuels. Gas fuels have excellent controllability, ensuring safety when used in combustion. Beyond such merits, the density is low compared to the other phases, so the heat release performance per unit volume becomes less. In contrast, solid fuels have a much larger energy density than gas fuels. However, a pyrolysis process is required before burning. A relatively large sensible heat is required to start the pyrolysis due to some burning “delay,” making it difficult to control. To quickly burn solid fuels, fuels are often used in powder form to increase the surface-to-volume ratio. However, the powder could explode (so-called dust explosion [1]); thus, careful treatment is mandatory. In this way, burning the solid in a controllable and safe way, just like gas fuels, seems hopeless. If its explosive nature is well-controlled, powder (fine solid matter) could be expected as a fuel whose burning velocity is relatively large to release a sufficient amount of heat in a short time, just like gaseous fuel with a high heating value. Then, we can utilize the solid matter as handling a friendly fuel and use it as a substitute gas fuel (which has excellent handling features against the solid fuel). Thus, this study aims to explore how attaining “controllability without any explosive danger” is a crucial issue through utilizing “hybrid” fuel [e.g., 2].

When combustible powder (cloud of the particles) is used as a fuel, the nonpremixed-type combustion system is applied (e.g., coal dust combustion). This combustion process works well; however, the controllability is severely managed through the following two items. One controls the particle number density to achieve continuous burning (flame propagation beyond the particles) and prevent extinction [3], and the other needs a relatively long residence time outside flame zone to ensure the complete burning of the loaded particles [4]. They are actually quite difficult, so this technique is only adopted in the limited engineering field (e.g., large-scale furnaces). To utilize “hybrid fuels,” the abovementioned difficulties could be relaxed, especially considering premixed-type burning systems [5]-[8]. The conceptual system is quite simple; gaseous flame can act as a pilot heat source to promote the burning of the solid particles, which are loaded into the premixed flame zone. Because we have additional gaseous fuel in the system, self-propagation through solid particles is not needed so that the particle density can be freely determined. Using rich premixed flames, a “high-temperature” zone exists between two flame sheets, such as inner-premixed and outer-nonpremixed flames. If the particles are successfully loaded into such a zone to promote gasification, immediate conversion of solid particles to the gaseous fuel could be attained. Indeed, when we consider the biomass (organic matter with a certain amount of water) as the source of particles, the entire gasification process, including vaporization and pyrolysis, may easily occur at such a high-temperature zone, so that pretreatment (e.g., drying biomass before loading) is not necessary. Thus, this concept would be useful for biomass fuel utilization without pretreatment.

Herein, to reveal the feasibility of the abovementioned concept, the combustion system was first developed. Further, a mixing device to load the particles into the premixed gas was developed. A combustor system is similar to a Bunsen burner [5,6,8]. Furthermore, with a high-speed camera having a laser sheet, the particle motion was captured. Next, the

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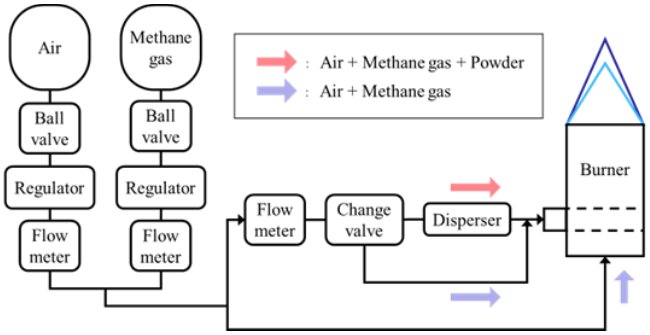
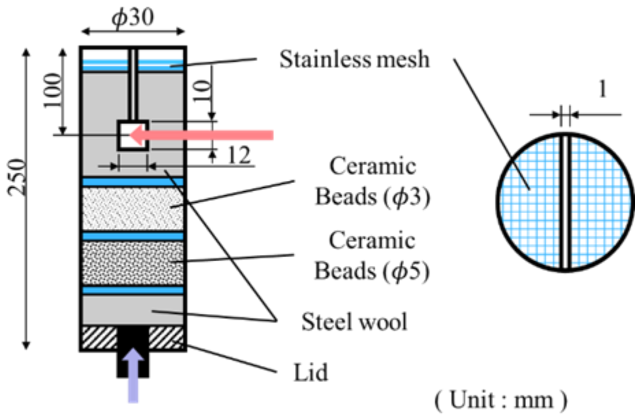
results are presented, and the gasification/combustion process of the solid particles is discussed.

2. EXPERIMENTAL SETUP

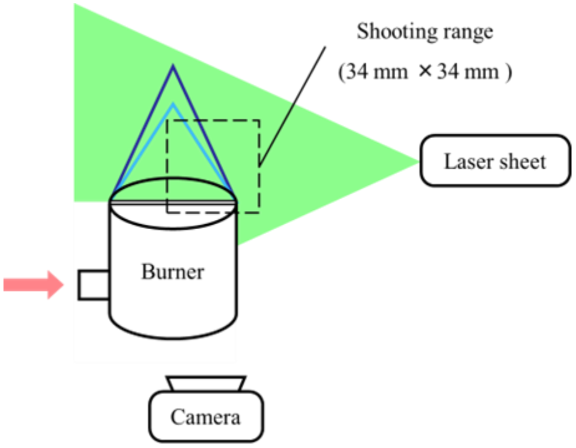
Herein, flour was used as a model for the solid particles (called powder; solid fuel), and methane–air premixture was used as gaseous mixture combustibles. Hence, “hybrid fuel” herein means methane–air-powder mixture. Note that the equivalence ratio of the methane–air mixture is above unity so that a rich mixture is considered.



(a) Experimental flow path diagram



(b) Conceptual diagram of the burner interior



(c) Camera and laser sheet layout

Fig. 1 Experimental apparatus adopted herein

Figure 1 shows the experimental apparatus schematic utilized herein. The flow path diagram used herein is shown in Fig. 1(a). Air and methane are mixed after adjusting the flow rate, and the mixture path is split into two. One goes to the burner directly (main), and the other goes through a powder-mixing device (sub). Initially, only the main path is open, and the subpath is closed by the branching cock. By switching the cock, the powder is loaded into the system.

A conceptual diagram of the burner interior is shown in Fig. 1(b). The structure inside the burner comprises two types of ceramic beads of different sizes, stainless steel mesh, and steel wool stacked on each other to form a uniform flow field. The powder mixture can only be loaded into a 1 mm–thick slit channel equipped with the burner, thereby forming a “sheet-like” powder dispersion zone over the burner.

A diagram of the camera/laser sheet arrangement is shown in Fig. 1(c). The combustion morphology was captured by a high-speed camera (FASTCAM Mini AX50, lens: AF-S MICRO NIKKOR 105 mm) installed perpendicular to the slit. In this imaging system, the focus is adjusted to the powder-sheet-zone to visualize particle motion behavior clearly. The observation area is a 34 mm × 34 mm–region of the flame base. To observe the trajectory of the particles, a 532-nm laser sheet for scattering was irradiated parallel to the slit from the middle of the powder jet.

A slit-like structure was introduced to avoid any potential problem of particle insertion into the combustion system. Generally, in the burner, the fine porous matter is employed for rectification [9]. However, when the powder is included, the powder may conjunct at the opening pore, and the rectifying performance will be lost [10]. To avoid such a problem, the flow paths without any porous matter for powder insertion are preferred [11]. With a slit-like channel, potential disturbance of the flow can be easily suppressed because of the boundary layer formed inside the channel. Furthermore, a large aspect ratio of the slit-opening can form a “sheet-like” zone. Although the velocity profile of the ejected surface is nonuniform because of the slit, the merits mentioned above are further meaningful.

3. EXPERIMENTAL CONDITIONS

To avoid the agglomeration of particles, the powder is dried in a furnace before the test. Five different amounts of powder were introduced: 0.1, 0.3, 0.5, 0.7, and 1.0 g. For the gas fuel, the overall flow rate was fixed at 51.2 L/min, the air and methane flow rates were adjusted, and the equivalent ratio ϕ [-] was set to 1.3, 1.4, and 1.5. The observed flame is a conical flame formed on a typical Bunsen burner. The shooting conditions of the high-speed camera were set to a frame rate of 50 fps and a shutter speed of 1/9000 s to obtain a clear image of the particle and flame.

Based on the preliminary test, the average powder loading period is ~0.8 s. During the entire period, nearly constant powder loading was achieved, at least 0.5 s of the duration. Thus, we consider that the steady burning of the hybrid fuel was maintained in the test.

4. RESULTS AND DISCUSSION

4.1 Visualized powder burning behavior in hybrid combustion systems

Figure 2 summarizes the results of injecting a certain amount of flour powder onto a Bunsen-type premixed flame whose equivalent ratio φ is 1.3, 1.4, and 1.5, respectively. The three images at the top and bottom from left to right represent the flame before and after the particle loading (0.3 g in total). Only particle-inserted images (bottom) and the laser sheet are illuminated to visualize the particle dispersion status in the burning system. The two dashed curves embedded in the top figures show the inner and outer flame locations (shape) for the case without powder loading (taken by the top images).

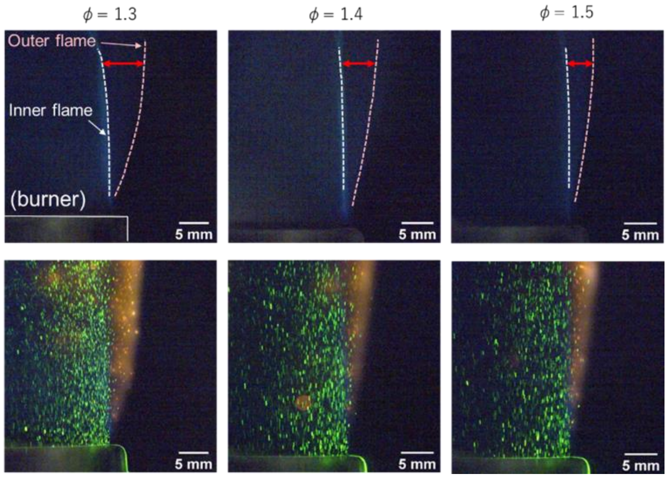


Fig. 2 Direct still picture of the hybrid-fuel flame (powder loaded amount is 0.3 g, range of equivalence ratio, φ, of the premixed gaseous flame: 1.3–1.5). Top and bottom images correspond to before and after the particle loading, respectively.

As understood from the series in Fig. 2, obviously, the inner flame angle becomes gentle as the equivalence ratio increases due to the lower burning rate. This trend causes the zone sandwiched by the inner and outer flames to become narrower accordingly. Green spots illuminated by the 532-nm laser sheet are found only inside the inner (premixed) flame surface, whereas yellow spots are mainly found outside the inner-flame zone. Interestingly, the width of the yellow-spot zone decreases as the equivalence ratio increases, which is quite a similar trend of the "sandwiched zone" as described above. Both the green and yellow spots are identified outside the outer-flame zone, suggesting that particles hardly survived there.

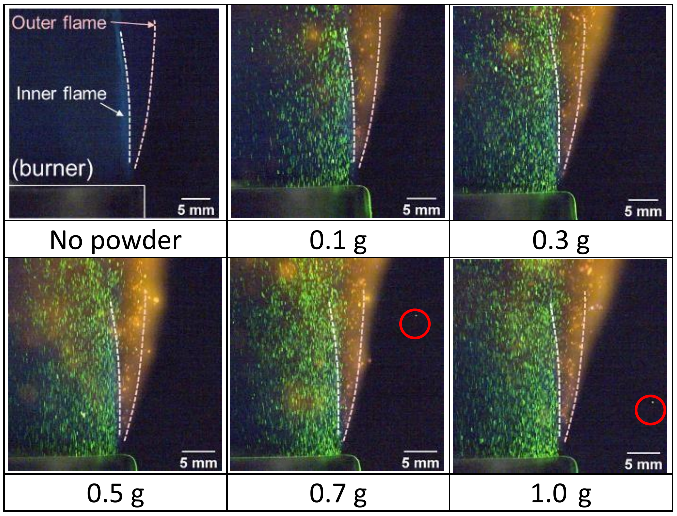
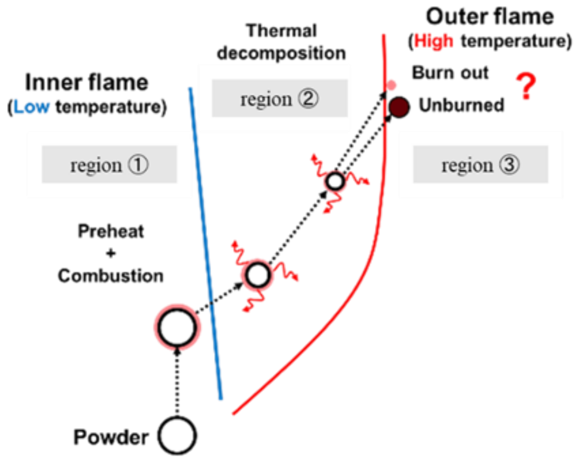


Fig. 3 Change in combustion form with a change in the powder loading amount (φ = 1.3)

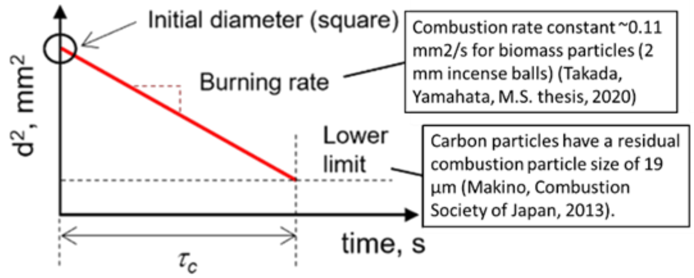
To understand the burning behavior with various powder amounts, the equivalence ratio is fixed at 1.3 and various amounts of powder are loaded. The results are summarized in Fig. 3. Evidently, two dashed lines identifying the inner and outer flame surfaces are embedded. As clearly found in the figure, the inner flame location (shape) changes slightly irrespective of the loaded amount of the powder herein (to 1.0 g), suggesting that the powder does not affect any flame structure of the inner flame and that no explosive features exist. Notably, in most cases, the yellow-spot zone fairly corresponds to the "sandwiched" zone between the inner and outer flames. As the loaded amount increases, even if not very frequently, the separated yellow spot is found outside the outer flame zone. Further, the yellow zone is expanded outside the outer-flame zone, suggesting that the powder combustion could not be completed inside the gaseous flame. These results clearly demonstrate a maximum loading amount of the solid matter is required for complete combustion.

4.2 Expected reaction of powder in the "sandwiched" zone

The expected burning status of the powder in this hybrid combustion system is depicted in Fig. 4. The vertically-loaded powder remains unchanged until it is exposed to the inner cone (premixed flame surface); this is called "region 1." After passing through the inner flame, due to the sudden volume expansion caused by the inner flame, the particles are directed perpendicularly to the inner flame surface. Simultaneously, the particles are exposed to the high-temperature zone sandwiched by the inner and outer flames, called "region 2." During this regime, the powder might experience quick pyrolysis assisted by the oxygen-deficit zone surrounding the hot product gasses (oxygen might be entirely consumed by the inner flame surface because the adopted equivalence ratio exceeds unity). Then, d^2- law [12] might be acceptable to describe the shrinking speed. If the exposure time is long enough, nearly-completed gasification may be attained. Although some small (hot) particles remain, they might have been oxidized and completely consumed at the outer flame, resulting in no particle being identified outside the outer-flame zone (called region 3).



(a) Combustion with high-temperature pyrolysis



(b) Quick decomposition in region 2

Fig. 4 Expected image of burning powder in the hybrid combustion system

Although this interpretation seems sound, unfortunately, there is little evidence to prove it. To support this scenario, we estimated the amount of gasified fuel oriented from the powder to identify the promised amount of gasification attained in this system.

4.3 Estimation of powder gasification amount utilizing Burke–Schumann theory

Figure 5 shows the entire view of the flame before and after the loading of the powder (left and right, respectively).

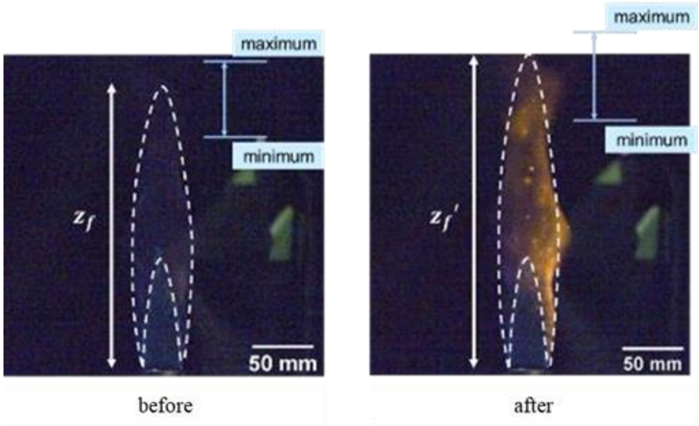


Fig. 5 Entire image of the flame before and after powder loading

As noted clearly, the inner flame appearance changes slightly before and after the powder loading. However, the outer flame height is enlarged after the powder loading. Because the outer flame is a nonpremixed flame (in a laminar regime), the flame height is determined by the diffusion flame theory, e.g., the Burke–Schumann theory [13]. According to the Burke–Schumann theory, flame height z_f is given as follows [14]:

$$z_f = \frac{U r_b^2}{4D \ln(1/(1 - Z_{st}))}$$

where

$$Z_{st} = \frac{\nu_F W_F Y_{O,O}}{\nu_O W_O Y_{F,F} + \nu_F W_F Y_{O,O}}$$

U is the jet velocity, r_b is the fuel-port radius, D is the diffusion coefficient, and Z_{st} is the stoichiometric mixture fraction of the fuel and oxidizer, respectively. Further, ν_F and ν_O are the stoichiometric coefficients of the fuel and the oxidizer. Furthermore, $Y_{F,F}$ and $Y_{O,O}$ are the mass fraction of the fuel and the oxidizer. Because Z_{st} is a function of the fuel concentration, as described above, we estimated the amount of fuel to exhibit the observed flame height. Because the observed outer flame height is unidentical before and after the powder loading, the fuel concentration to form the outer flame is unidentical. The difference stems from the pyrolysis reaction in region 2. According to this prediction methodology, we investigated the conversion efficiency of the powder to the gasified fuel. The results are summarized in Fig. 6.

This prediction assumes that no regression occurs when the powder passes through the inner flame. Thus, the calculated conversion efficiency is underestimated. In addition, the combustible gaseous component may vary based on the exposure temperature of the particle, so the number has some degree of uncertainty. However, it might be true that the particles cannot achieve complete burning by only passing through a single flame (inner flame in this case). However, following a hot-vitiated sandwiched zone can help promote the further pyrolysis of the unburned particle. Thus, a rich premixed flame structure is one of the favorable options when solid (powder)–gas hybrid combustion is considered. Although further study is needed to reach a more solid conclusion, this study is informative enough to initiate a discussion on the effectiveness of considering hybrid-fuel combustion.

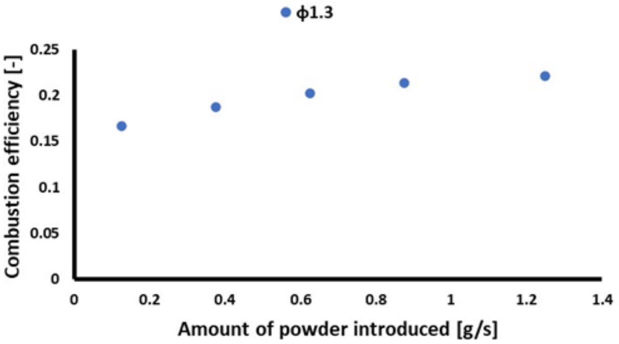


Fig. 6 Change in combustion efficiency with powder loading rate

Finally, note that complete combustion of 0.3 g of powder per 0.8 s of the loading duration would achieve 5.86 kJ/s of heat generation. Because the gaseous fuel with an equivalence ratio of 1.3 (without powder loading) does reach 3.40 kJ/s of the heat release rate, the inclusion of powder in this system (note that we only load powder at a 1 mm–thick slit) delivers comparable energy release. If we could load the powder from the entire burner port (not limited to a 1 mm–thick slit), more than 20 times of powder can burn, and a sufficient amount of heat release from the powder can be achieved. In this way, the present methodology ensures that heat generated by the hybrid-fuel combustion mainly comes from the solid and that gas fuel only works as an initiator (pilot purpose).

CONCLUDING REMARKS

The following findings were obtained from an experimental investigation to determine the possibility of understanding the powder combustion state and load control in premixed hybrid-fuel combustion.

- The experimental apparatus (burner with slit) used herein was effective as a device for introducing only powder in the flame and to realize the observation of only the combustion part.
- With this premixed hybrid combustion system, the introduced powder passes between the inner and outer flames, accelerating high-temperature pyrolysis and enabling efficient solid combustion.
- By applying the diffusion flame theory, it was estimated that at least ~20% of the material is pyrolyzed at high temperatures between the inner and outer flames.

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