Numerical Study on Asymmetric Flame Spread in A Narrow Combustible Channel

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1 Introduction

Flame spread over solid combustibles has been an important topic with regard to fire safety over the past few decades. The features of spreading flames, such as the spread rate, the flammability limit and so on have been investigated for evaluation of the risk of fire. Most of studies have focused on the flame spread in an "open" circumstance, where the fuel and flame are not in proximity to any construction; in other words, there is enough large space perpendicular to the combustibles. On the contrary, studies on flame spread in constrained geometry such as in a narrow combustible channel are limited. However, some recent experimental studies reveal unique features. For example, we showed the flame separation behavior for flaming combustion of thermally thick PMMA slab near the quenching limit [1], as is well-known as fingering in the smoldering combustion of thin paper. According to the experiment, the flame establishes on only one side in between parallel combustible plates when the fingering appears.

More recently, we have found another asymmetric flame behavior in narrow channel. Two leading edges of symmetric flame shift in the flow direction and spread asymmetrically [2]. There are several examples which show similar dynamic behavior. An asymmetric propagation has been reported for lean premixed hydrogen/air flame in a narrow channel less than 7 mm as well [3]. Prasad et al. showed that an opposed and concurrent flame spreading occurs at the same time once the solid fuel is ignited at the center in an uniform flow [4]. Several researchers have mentioned the oscillation behavior for the flame spread as well [5,6]. Especially, Itoh et al. showed a quite similar behavior; the flame in center precedes the flames at sides for flame spreading along several parallel sheets of paper [7]. However, it is observed due to radiative heat transfer from the side flames, hence it may be different from that asymmetrically flame spreading in this study. It is rather important to understand behaviors of the asymmetric flame spread from an engineering point of view, although the phenomenon is interesting from a scientific perspective. Since the combustion characteristic may change after the separation, a conventional model for flame spread is not applicable and eventually causes severe fire hazards.

In the first place, understanding/classifying the conditions for the flame separation to appear is a critical issue from both scientific and engineering perspectives. The asymmetrically flame spreading was successfully observed under certain conditions via a controlled experiment, however, it was actually difficult to control the behavior perfectly because this phenomenon appears at the near-extinction condition and is very unstable. In this regard, an experimental approach may not be suitable to systematically study this interesting phenomenon in a precise manner. Hence, this paper numerically investigates the detail process for the appearance of asymmetrically spreading flames in a narrow channel of combustibles. Numerical simulations using various flow velocities and channel widths are performed to capture asymmetric as well as symmetric flame spread. The asymmetric flame spreading is further distinguished into several modes based on the trajectories of the leading edges. In this work, the occurrence conditions of each spreading mode are summarized on the velocity-channel width diagram, to the best of our knowledge, for the first time ever.

2 Numerical method

Figure 1 shows a schematic illustration of the physical configuration. In order to reproduce the transient process to form asymmetrically arranged spreading flame in between parallel combustible plates, a two-dimensional model is considered in this study, although the flame spread is fundamentally a three-dimensional phenomenon. The origin is located at the bottom and left end of the domain. x-axis and z-axis are normal and parallel to the flow direction, respectively. The gravitational force acts toward negative z direction. The length of the flow channel is 150 mm, while the width, d [mm] is a variable parameter. PMMA is chosen as the combustible material, and PMMA plates of 20 mm thickness are located along x = 0 and d [mm]. Pure oxygen is used as an oxidizer and the inlet flow velocity, V_O [m/s], is chosen as another variable. The flat velocity profile is given at z = 0 mm and the no-slip boundary is considered. The open boundary condition is imposed at z = 150 mm. Note that the parabolic profile was also examined for several certain conditions and it was confirmed that there seemed no significant difference between the velocity profiles. It suggests that the effect of the boundary layer thickness at the point where the separation occurs may not large. As the imposed condition, the two parameters, the channel width and the inlet flow velocity are varied from 5 to 50 mm and from 0.1 to 5 m/s, respectively.

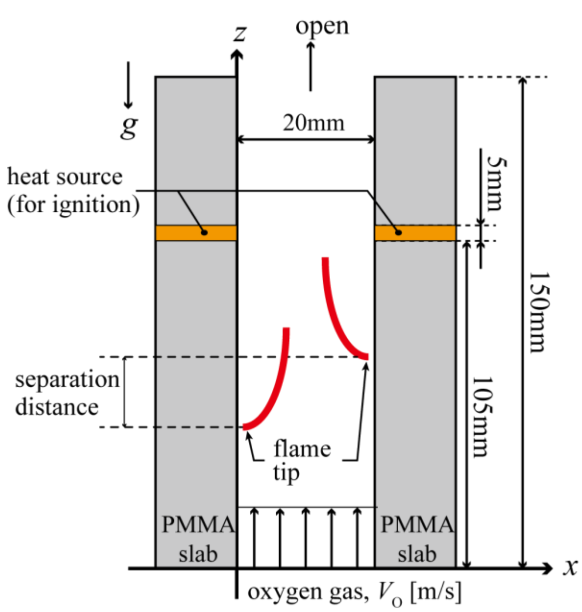

Figure 1. Schematic illustration of numerical model

2-D, time-dependent mass and energy transport process in gas phase is solved by the Fire Dynamics Simulator (FDS 6.5.2) developed by the National Institute of Standards and Technology (NIST) [8]. FDS also solves time-dependent mass and energy conservation equations in solid phase. The cell size in x and z directions are both 1 mm in the whole domain. The cell size dependence was preliminary confirmed for V_O = 0.1 m/s and d = 10 mm with double and half sizes. From the examination, the flame spread rate as monotonically increases as the cell size decreases. It indicates that 1 mm is too large to coincide the simulated spread rate and other characteristics with the actual phenomenon quantitatively. However, the simulation cost with a cell smaller than 1 mm is too high. Fortunately, the trend of the flame spread rate dependence on the flow velocity shows reasonably agreement with the experiment. In addition, this study simulates the extinction behavior based on an empirical extinction model used in FDS. The model determines whether the flame extinguishes or not based on critical flame temperature [7]. In this respect, the local extinction and subsequent asymmetric flame spread were taken into account in the present model.

Heat sources are inserted on PMMA as shown in Fig. 1. The region is set to 3000 °C until 5 s, then the temperature is gradually reduced to 0 °C within another 5 s. During the ignition period, the flow velocity is set to a smaller value than the given parameter and then it increases to the desired value. Once the fuel is heated, the gaseous fuel (MMA) evolves from the surface and reacts with the oxidizer to maintain combustion. The pyrolysis reaction is calculated according to the physical and chemical parameters of PMMA, which are the same as those available via GitHub for FDS [9]. A global one-step, irreversible reaction of MMA is considered and the combustion is modeled based on the mixing-limited, infinitely fast reaction.

3 Results and discussion

Figure 2 shows sequential images of the 2-D distribution of heat release rate per unit volume. The left shows a typical example of symmetric flame spreading, while the right shows one of asymmetric flame spreading. When the channel width is 20 mm, the symmetric flame is established after the forced ignition, and the flame height gradually increases as the computation proceeds until about 10 s. After the ignition sequence is terminated, the flame spreads upwardly against the opposed flow. As shown later, the flame spread rate becomes almost constant and this implies that the effect of thickness of the local velocity boundary layer [10] is minor . For d = 12 mm, the asymmetric flame spreading was observed. The left flame slightly precedes the right one at the end of the ignition sequence (t = 10 s). The separation distance between the leading edges increases gradually as the time elapses until about t = 20 s. Once the left flame precedes at a certain distance, both flames then spread together while keeping the separation distance constant. It is obvious that the asymmetrical configuration gives a temporary stable condition to burn. Enlarging the mutual space to a certain distance is necessary to maintain the combustion of the solid fuel pair.

For the symmetric flame spreading, the heat release rates at the leading edges of both sides are nearly identical. Conversely, for the asymmetric flame spreading, the heat release rate of posterior flame (right flame in Fig. 2b) is relatively larger than that of anterior flame (left flame in Fig. 2b). It is considered that the hot oxidizer gas, which is heated when it passes through the anterior flame, reacts with the evaporated fuel in the downstream. This result implies that not only the positional relation but also the flame structures are different for the asymmetric flame spreading. Interestingly, it is noticed that the spread rate of each leading edge seems almost the same within the time range of this study (see Fig. 3c), indicating that there is no significant difference between the corresponding heat transfers to the solid phases, although the heat release rate of the posterior flame is increased. Thus, the increment of the heat released from the posterior flame is not mainly used to enhance the pyrolysis reaction, but it transferred to the downstream to heat-up the downward gas. In fact, compared to the symmetric flame, the temperature in the downstream becomes higher for the asymmetric flame (data not shown here). Although the imposed conditions where the asymmetric flame is observed is different, the numerical result successfully reproduces the characteristics observed experimentally [2].

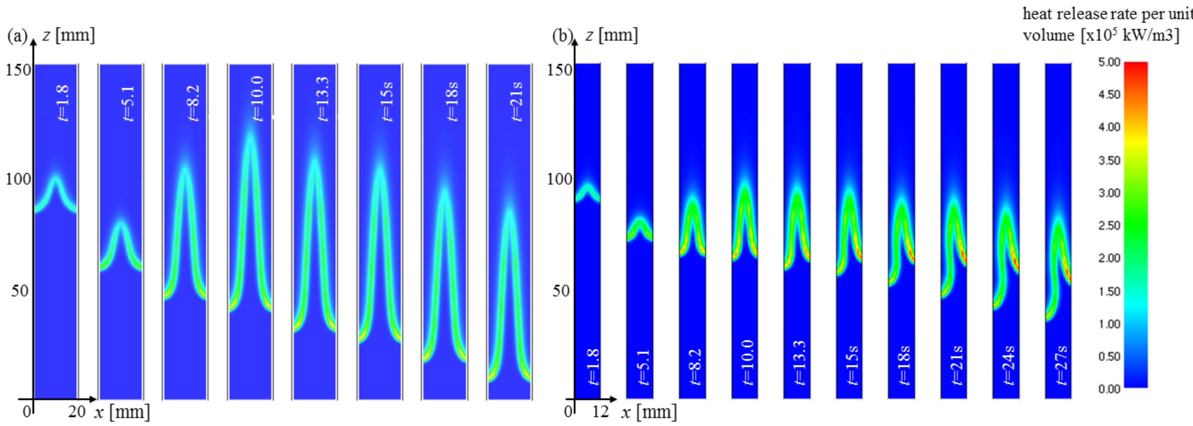

Figure 2. Sequential images of 2-D distribution of heat release rate per unit volume. (a) d = 20 mm, V_O = 0.3 m/s, (b) d = 12 mm, V_O = 0.3 m/s.

According to the results obtained with various oxidizer velocities and channel widths as numerical parameters, seven different spreading modes were distinguished. Typical examples of time histories of flame locations for the various flame spreading modes are shown in Fig. 3. Modes (a) and (b) are distinguished as symmetric flame spreading, while modes (c) to (g) as asymmetric flame spreading. Figure 4 presents the velocity-channel width diagram which summarizes flame spreading modes. While the effects of initial/boundary conditions on flame structure and the separation mechanism will be discussed in upcoming study, each combustion mode is characterized in the following section.

For mode (a), the flames spread symmetrically against the opposed flow. It has been identified as a conventional case of the phenomenon and appears in moderate conditions where the channel width is large enough for the flames to exist side by side. As the velocity increases, the symmetric flames spread downwardly as shown in Fig. 3b. The modes (c) ~ (f) are all considered as asymmetric flame spreading, but the transition behavior varies somewhat between these modes. For mode (c), the flame on one side is delayed, while the other one keeps spreading upwardly with slightly changing its flame spread rate. As already mentioned, once the separation distance becomes sufficiently large, both flames spread with a constant separation distance. When the velocity becomes higher or the width becomes wider, the mode shifts to (d). For (d), a flame moves backward during the transition possibly due to the local extinction. Although the mixture limited model is considered, the extinction takes place according to the extinction model incorporated in FDS. Since the pair of flames struggle with the oxidizer gas, the combustion on one side is weakened and results in deficiency of the evaporated fuel. The heat released on the side is reduced, accompanied by a reduction in temperature. The local extinction eventually occurs once the temperature becomes lower than the critical flame temperature. However, the heat transfer from the anterior flame envelope enhances the combustion in the downstream. The excess heat relaxes the extinction limit of the posterior flame. Then, the flame is re-stabilized at the certain distance behind the anterior flame and the posterior flame moves upwardly again. As the velocity further increases (or the channel width decreases), mode (e) appears. Mode (e) is similar to mode (d) but the anterior flame stays and does not move upwardly. A unique flame spreading mode (f) appears under the limited combination of channel height and velocity. In this case, the posterior flame overtakes the anterior flame and shows oscillation-like behavior, though the computation time is limited. Modes (b) and (g) may correspond to the extinction limit of the whole system, as either or both flames move backwardly. Since the results show various flame spreading modes in a limited domain size and computation time, further study is needed to confirm their long-term behavior such as the oscillation mode.

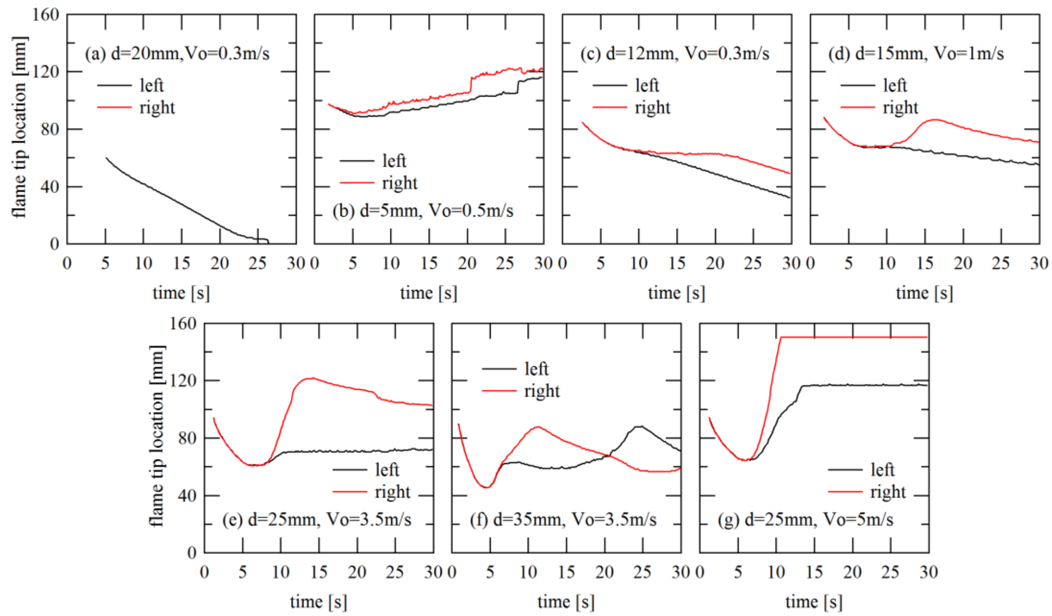

Figure 3. Time-histories of the locations of flame leading edges

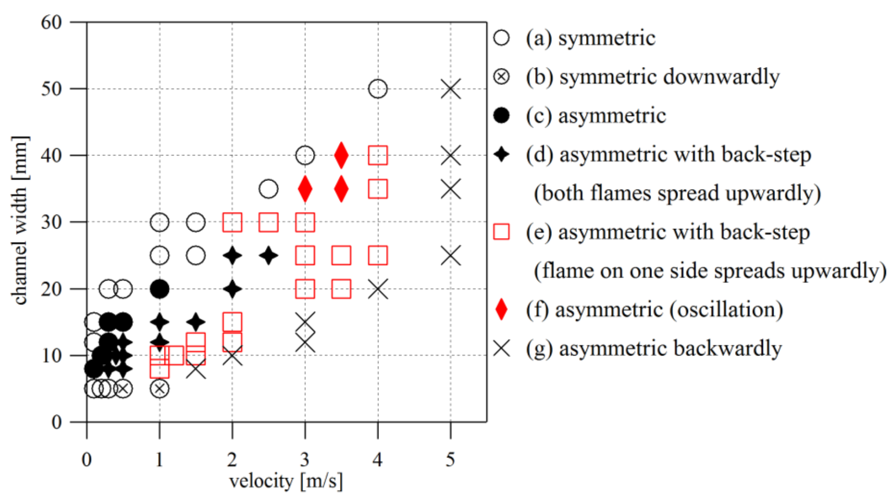

Figure 4. Flame spreading mode diagram

4 Conclusions

Numerical simulations with various flow velocities and channel widths are performed in order to investigate the detail process for the appearance of asymmetrically spreading flames in a narrow channel of combustibles. The transient process to form an asymmetrically arranged spreading flame is successfully reproduced with the Fire Dynamics Simulator. Results show that there are various flame spreading modes based on the time-histories of flame locations, i.e., two kinds of symmetric flame spreading and five kinds of asymmetric flame spreading. The imposed conditions where each flame spreading mode is observed are summarized on the velocity-channel width diagram. It is suggested that the local extinction or weakening of the flame on one side initiates flame separation, and thus the asymmetrical configuration gives a temporary stable condition for burning. Though the flame spreading modes proposed in this study are based on qualitative observation, further study will reveal the separation mechanism in detail and update the temporal classification.

Acknowledgement

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