EXPERIMENTAL AND NUMERICAL STUDIES FOR FLAME SPREAD OVER A FINITE-LENGTH PMMA WITH RADIATION EFFECT

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Abstract
The phenomena of ignition delay and subsequent downward flame spread over a finite length PMMA slab under an opposed flow with radiation effect are investigated by using an unsteady combustion model. The corresponding experimental test channel is 700 mm long with 100×100mm² rectangular cross section. The specimens are mounted on the groove of the test section and the groove sides are covered with asbestos plates. The thermocouples and laser holographic interferometer are used to measure the surface and gas temperatures, respectively. The simulated results indicate that the ignition delay time increases as the opposed flow velocity and solid fuel thickness increase and the opposed flow temperature decreases. On the other hand, the ignition delay time becomes longer when the radiation effect is considered. The flame spread rate increases as the opposed flow velocity and solid fuel thickness decrease and the opposed flow temperature increases. However, the influence of radiation effect on the flame spread rate is not significantly. Furthermore, a comparison between the predictions of Wu’s model [1] and present model is given. The downstream size of flame still grows in Wu's model, whereas it contracts over the solid fuel surface in this work due to the finite length solid fuel. As a consequence, the flame spread rate in present model becomes lower and is closer to the experimental measurement. The predicted flame spread rate and temperature distribution have an excellent quantitative agreement with the measurements in high velocity regime. However, the discrepancies between the predicted and experimental results increase in the lower velocity regime. The main reason is believed to the 3D effect, which is not considered in the present simulation.

1 Introduction
This work investigates the ignition and subsequent flame spread characteristics over a finite length of thick solid fuel under a mixed convection condition using an unsteady combustion model with radiation effect in a two-dimensional wind tunnel. It is motivated from a previous work [1], which only considered the ignition and flame spread over an infinite-length fuel plate in an open atmosphere without radiation. In that work, the deviations in predicted flame spread rates from the corresponding experimental measurements were attributed to these effects mentioned above. Therefore, an extensive modification in the unsteady combustion was carried out to mitigate the discrepancy between the predictions and measurements.

Sibulkin et al. [2] investigated the effects of gas phase and surface radiation on the burning of vertical fuel surfaces. It was found that gas phase radiation has a negligible effect on burning rate, whereas the surface radiation strongly affects the combustion. West et al. [3] studied the surface radiation effects on flame spread over thermally thick fuels in an opposing flow. They concluded
that the fuel surface radiation is important for thermally thick fuel at all flow levels, however, and it is important for thermally thin fuel only at low velocity level. Rhatigan et al. [4] investigated the gas phase radiative effects on the burning and extinction of a solid fuel. The computed results indicated that the gas radiative effects are more pronounced at low stretch rates. They also developed a computationally more efficient gray gas model, using a calibrated correction factor for the mean absorption coefficient. It is found that many of the flame characteristics can be computed with sufficient accuracy despite the difference in radiative structure. Lin and Chen [5] investigate how the gas-phase radiation, whose model includes both the cross-stream and stream-wise gas phase radiation coupled with solid phase one, affected the spreading flame. By comparing the results with the predicted ones of Chen and Cheng [6], which only considered the radiation effect in cross-stream direction, they concluded that the stream-wise radiation contributes to reinforce the forward heat transfer rate subsequently increasing the flame spread rate.

Pan [7] and Chen [8] investigated the steady flame spread characteristics over PMMA in an opposed forced convection environment in a wind tunnel. The variable parameters were the velocity and the temperature of flows and the thickness of fuel. They found that flame spread rate increases with an increase of the temperature of flow, a decrease of the flow velocity or the thickness of fuel. Their image results further demonstrated that the thermal boundary layer becomes thicker when the temperature of incoming flow is higher under a fixed flow velocity or the incoming flow velocity is slower at the same flow temperature. Wu et al. [1] developed an unsteady combustion model with mixed convection to investigate the flame spread behaviors of a thick PMMA slab with an infinite length in an opposed flow environment. Simulation results of flame spread rate were compared with the measurements obtained by Pan [7]. The agreements were well in general except at the low-speed flow regime. In addition, this numerical study indicated that the ignition delay time increases with an increase of the opposed flow velocity or a decrease of the opposed flow temperature. The ignition delay time is almost constant at a low opposed flow velocity. Nakamura [9] numerically studied the enclosure effect on flame spread over solid fuel in microgravity. Because the confinement of the flow field and the thermal expansion initiated by heat and mass addition in the chamber, the flame spread rate for the case with enclosure is faster than the one without any enclosure. The predictions also showed that the enclosure effect is more significant at the low flow velocity condition and becomes less important with increasing imposed flow velocity. Fujita et al. [10] experimentally studied the radiative ignition on paper sheet in microgravity. The results showed that the gas phase temperature becomes higher than that of the solid surface before ignition, and the main mechanism of radiative solid ignition here is due to the gas phase reaction. Furthermore, the ignition delay time strongly depends on the oxygen concentration and ambient pressure. It decreases with a higher oxygen concentration or ambient pressure.

Kumar et al. [11] used a two dimensional flame spread model with flame radiation to compare the extinction limits and spreading rates in opposed and concurrent spreading flames over thin solids. The varying parameters were oxygen percentage, free stream velocity, and flow entrance length. Numerical results showed that at low free stream velocities with shorter entrance length, the flame spread rates are higher and have a lower oxygen extinction limit, whereas in high free stream velocities, the flame spread rates are lower and have a higher oxygen extinction limit. The flame spread rate in opposed flow varies with free stream velocity in a non-monotonic manner, with a peak rate at an intermediate free stream velocity. The flame spread rate in concurrent flow increases linearly with free stream velocity. Kumar et al. [12] also presented a numerical study on flame-surface radiation interaction in flame spread over thin solid fuels in quiescent microgravity and in normal gravity environments. It was observed that the flame in microgravity is very sensitive to the surface radiation properties. The fuel with high solid absorptivity can absorb substantial
flame radiation and flame spreads faster than the corresponding adiabatic case irrespective of value of solid emissivity.

As mentioned previously, the modifications of present work from the original combustion model of Wu et al. includes the several effects, such as the enclosure, the finite-length fuel plate and the radiation. The entire process from ignition to subsequent flame spread will be examined and depicted in detail, and the simulated results will compare with the predictions of Wu et al. [1] and the measurements of Pan’s experiment [7].

2 Mathematical Model

Figure 1 illustrates the physical configuration of two-dimensional ignition over a vertically oriented thick solid fuel in a mixed convective environment. The test section of wind tunnel is 70 cm long with 10 cm height. The solid fuel plate used in present simulation is 30 cm long and the thicknesses are 0.82 cm and 1.74 cm, respectively, which are exactly the same as those used in Pan’s experiments [7]. For \( t < 0 \), a steady flow in wind tunnel is built up in advance over entire test section. As \( t \geq 0 \), an external heat flux in Gaussian distribution, in which the width is 0.5 cm with a peak value of \( 5 \text{ W/cm}^2 \), is imposed on the solid surface. Its center is aimed at \( x=0 \), the connecting point between the solid fuel and adiabatic plate. In other words, only half of the radiation energy is used to heat up the PMMA fuel directly.

The unsteady combustion model basically is modified from that developed by Lin and Chen [13]. Also, a radiation model developed by Wu and Chen [14] is adopted in this unsteady combustion model. The mathematical model consists of both gas- and solid-phase equations, which are coupled together at the interface. The corresponding assumptions and normalization procedure can be found in Wu [15] and are not represented here for brevity. The numerical scheme adopts the SIMPLE algorithm [16]. The unsteady governing equations as well as the interface and boundary conditions are solved at each time step until a convergence criterion (residual < 0.01) is satisfied. After that, they are marched to the next time step. Computations are carried out on non-uniform mesh distribution. The smallest grid size is 0.01 cm. Grid points are most clustered in external radiative heating region to capture the drastic variations in the flame, the grids then expand upstream and downstream. A grid-size independence test was conducted in advance, and the selection of non-dimensional time step of \( \Delta t = 10 \) (equivalent to real time 0.02 s) and non-uniform grid distribution of 290×95 was found to achieve an optimal balance among the solution resolution, computational time and memory space requirements. The computational time for a case is typically about 4 days on a PC at National Chiao Tung University.

3 Results and Discussion

In order to make the fair comparisons with Pan (1999) and Wu et al. [1], the parametric studies are performed by changing the opposed flow velocity and the flow temperature, respectively, which are also the same as those in experiments of Pan [7]. A comparison between the predictions of Wu’s model [1] and present model will be given first. Note that in the simulation of Wu et al. [1], the fuel slab is extended infinitely in both directions, the ignition/combustion is in an open atmosphere and the radiation effect is not considered.
Figure 2 shows the ignition delay time versus the opposed flow temperature under three different opposed flow velocities for $u_\infty = 40 \text{ cm/s}$, $70 \text{ cm/s}$, and $100 \text{ cm/s}$, and the solid fuel thicknesses are $0.82 \text{ cm}$ and $1.74 \text{ cm}$, respectively. Remind that the present simulation includes the consideration of radiation effect. The values expressed by solid lines are the ignition delay times for $\tau = 0.82 \text{ cm}$, whereas the ones by dashed lines are for $\tau = 1.74 \text{ cm}$. In this figure, it can be seen with an increase of the incoming flow velocity. This is because that the thermal boundary layer becomes thinner in the higher opposed flow velocity regime, which carries more produced fuel vapors to the downstream to make the accumulation of fuel vapor near the solid fuel surface to become more difficult that increases the formation time of the flammable mixture and so delays the ignition. On the other hand, with a fixed incoming flow velocity, the ignition delay time decreases with an increase of the incoming flow temperature. This is because that the higher temperature flow can heat the solid fuel more effective to generate more fuel vapors to form the flammable mixture earlier, as a consequence, to shorten the ignition time. Furthermore, the ignition delay time for $\tau = 1.74 \text{ cm}$ is longer than the one for $\tau = 0.82 \text{ cm}$ under the fixed flow velocity and temperature. Comparing with the thinner solid fuel, the thicker one has greater thermal inertial that requires more energy to reach the ignition temperature, increasing the ignition delay time. The above trends have been confirmed by the predictions of Wu et al. [1] and Wu [15] and the experimental observations of Pan [7], Chen [8].

Figure 3 presents the ignition delay time as a function of the opposed flow temperature under a fixed flow velocity ($u_\infty = 40 \text{ cm/s}$) with and without radiation effects. In general, the ignition delay time decreases with an increase of the opposed flow temperature no matter what the effect of radiation is considered or not. However, the ignition delay time without radiation effect is shorter than the one with radiation effect. It can be explained as follow. Figure 4 displays the distributions of heat fluxes along the solid fuel surface at the instant just before ignition ($t = 13.72 \text{s}$). $q_{ex}$ and $q_c$ are the external input radiant heat flux in Gaussian distribution and the conduction heat flux from the gas, and the gas phase radiation feedback and radiation heat loss from the solid fuel surface are represented by $q_{gr}$ and $q_{sr}$. The sum of total heat fluxes is the net heat flux on the solid fuel surface, $q_{net}$. The positive value indicates the solid fuel gains energy from the gas phase and the negative one

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Figure 2. Ignition delay time versus the opposed flow temperature under different opposed flow velocity for $\tau = 0.82 \text{ cm}$ (by solid lines) and $\tau = 1.74 \text{ cm}$ (by dashed lines), respectively.

Fig. 3. Ignition delay time versus the opposed flow temperature under a fixed opposed flow velocity $u_\infty = 40 \text{ cm/s}$ with and without radiation effect, respectively.
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Fig. 4. The distribution of heat fluxes along the solid fuel surface at $t = 13.72s$, $\tilde{T} = 313K$, $\tilde{\alpha}_{in} = 40cm/s$ with and without radiation effects, respectively.

represents the heat loss from the solid fuel surface. From this figure, it can be found that the net heat flux ($q_{net}$) near the origin is higher in the case without radiation effect. The solid fuel can receive more energy for pyrolysis and produces the fuel vapor more effective, shorting the formation time of flammable mixture. Therefore, the ignition becomes faster without the radiation effect. The inset of Figure 5 shows the distributions of solid fuel temperature and density contours at the instant just before ignition. Comparing with the case with radiation effect, it can be seen that the solid fuel temperature is higher such that pyrolyzes more fuel vapor when the radiation effect is not considered. Intensive pyrolysis also makes the gas phase chemical reaction rate increase. Note that the peaks of the temperature and density distributions are not exactly at the origin but shifted slightly. It is because that the solid fuel tip not only receives the energy from the external input heat flux but losses heat to the ambient simultaneously.

Furthermore, comparing the ignition delay times with and without radiation in Fig. 3, the differences between them increase with an increase of the incoming flow temperature. It is because the radiation heat loss from the solid fuel surface becomes greater as the incoming flow temperature increases. The surface temperature becomes higher when the solid fuel is immersed in a hotter flow. Since $q_{sr}$ is proportional to $T^4$, the radiation heat loss from the solid fuel surface to the ambient becomes greater. In other words, the solid fuel needs more time to receive more energy to rise its temperature for pyrolysis. Therefore, the ignition delay time in the case with radiation effect increases with an increase of incoming flow temperature. Regarding the effect of solid fuel length on ignition delay time, the difference between the finite and infinite lengths is insignificant. This is because that the ignition delay time is dominated mainly by the incoming flow velocity and temperature and the solid fuel thickness, but not length.

Figures 5a and 5b display the flame spread rate as a function of the incoming flow temperature under three different flow velocities for solid fuel thickness of 0.82 cm and 1.74 cm, respectively. The solid and dashed lines display the simulated results by the present work and the predictions of Wu’s model [1], respectively, and the symbols show the measured data of Pan [7]. It can be found that the flame spread rate increases with an increase of flow temperature under a fixed incoming flow velocity. The reason can be explained as follow. From the Figs. 6a(a), 6b(a) and 6c(a), which illustrate the temperature contours of gas and solid phases and vector distribution under a fixed opposed flow velocity of $\tilde{\alpha}_{in} = 40cm/s$ and the opposed flow temperatures are 313K, 333K and 353K, respectively. As expected, hotter opposed flow leads to a stronger flame. For example, the non-dimensional maximum flame temperatures are 5.3624, 5.4195 and 5.5168 for the incoming flow temperatures of 313K, 333K and 353K, respectively. The solid fuel receives more energy from the stronger flame, enhancing the upstream pyrolysis length (and the preheat length) and intensity that shortens the formation time of flammable mixture ahead of the flame front. Consequently, the flame spread rate becomes faster with a higher flow temperature. As to the effect of incoming flow velocity, it can be found that the flame spread rate decreases with an increase of incoming flow velocity under a fixed
flow temperature. This is because that the higher incoming flow velocity increases the flame stretch. In the meantime, the heat transfer from the flame front to preheat the solid fuel becomes more difficult and the most of fuel vapors generated from the pyrolysis zone are carried to downstream. These factors results in a weaker flame that the corresponding flame spread rate becomes lower. The mentioned phenomena can be observed from the Fig.s 6a(a), 6d(a) and 6e(a), which are for different incoming flow velocity varied form 40 cm/s to 100 cm/s and the flow temperature is fixed at 313K.

For the effect of solid fuel thickness, it is found that the flame spread rate decreases with an increase of solid fuel thickness at the same incoming flow velocity and temperature. This is because the thicker solid fuel has greater thermal inertial that needs more energy to rise its own temperature to pyrolyze that needs more time to form the flammable mixture and results in a lower flame spread rate. Figures 6a(a)-6e(a) and 6a(c)-6e(c) are for solid fuel thickness 0.82cm and 1.74cm under different opposed flow velocities and temperatures. They also show that the flame spread is faster for the thinner solid fuel. The flame size and upstream preheated area are all greater in the thinner ones. The above trend has been confirmed by the predictions of Wu et al. [1] and West [3] and the experiments of Pan [7], Chen [8].

Comparing with the simulated results of Wu et al. [1] in the Figures 5a and 5b, the predictions of present model are closer to the Pan’s experimental measurements [7]. It can be explained as follow. Figures 6a(b)-6e(b) present the temperature contours of gas and solid phases and vector distribution under different opposed flow velocities and temperatures for solid fuel thickness is 0.82cm. Remind that the radiation effect is not under consideration in these cases. Comparing the gas phase temperature contours in Fig. 6a(a) and 6a(b), the non-dimensional maximum flame temperatures are 5.3624 and 5.8236, respectively. The upstream preheated area of solid fuel is longer in the case without radiation effect. It indicates that the heat loss from solid fuel is reduced and it gains more energy from the stronger flame and enhances the pyrolysis intensity. The downstream size of flame still grows in Wu’s simulation, whereas the present one contracts slightly over the fuel surface and the downstream flame temperature decreases. The formation time of flammable mixture becomes longer, resulting in a lower downward flame spread. However, this phenomenon becomes insignificantly when the flow temperature increases.
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4 Conclusions
This work utilizes an unsteady radiation combustion model, using the incoming flow velocity and temperature and the solid fuel thickness as parameters, to investigate their effects on the ignition delay and the subsequent downward flame spread over a finite length PMMA slab under a mixed convection condition in a wind tunnel. The simulated results of present work are compared with the corresponding simulated predictions and experimental measurements. In general, the qualitative trends between the present predicted results and the experimental measurements are the same. It is found that the ignition delay time increases with an increase of incoming flow velocity, the solid...
fuel thickness and a decrease of flow temperature. The ignition delay time with radiation effect takes longer than the one without radiation effect. Furthermore, the differences of the ignition delay time between with and without radiation effects increase when the flow temperature becomes higher under a fixed incoming flow velocity. The flame spread rate increases with a decrease of the incoming flow velocity and solid fuel thickness, and an increase of the flow temperature. The radiation effect in the lower flow velocity regime is found more effective. The downstream flame size still grows over an infinite length fuel plate, whereas the present one contracts over a finite length fuel plate. The effects of gas phase radiation and
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finite fuel length mentioned above result in a lower flame spread rate, so that they mitigates the discrepancies between the present simulated predictions and the experimental measurements. The predicted flame spread rates have an excellent quantitative agreement with the ones by experimental measurements. However, it still exists a discrepancy at low velocity regime. The main reason can be attributed to the 3D effect which is not included in the present two dimensional model.

Reference


