Temperature Profiles in an Opposed-Flow Flame Spread over Paper

KENJI SATO, KATSUHIRO SUZUKI, YASUHIRO SAKAI, and SETSUKO SEGA
Department of Physics
Toho University
Funabashi, Chiba 274, Japan

ABSTRACT

Temperature profiles around a flame stably spreading downward over a filter paper in an upward air flow were examined for further understanding of the effects of the free-stream velocity on opposed-flow flame spread over thin solid combustibles. Temperature was measured by fine thermocouple, and gas phase temperature profiles were determined as well as surface temperature distributions. In the stable flame spread region, the flame spread rate decreases gradually as the free-stream velocity *U* increases. Although the flame temperature at its leading edge is approximately independent of *U*, in the vicinity of the leading edge the flame temperature gradient along the reaction zone increases with *U*. As *U* increases, the location of the flame leading edge moves to downstream direction toward the pyrolysis zone front and also the gas-phase temperature rising zone ahead of the flame leading edge becomes shorter, with reducing the heat flow from gas phase to the preheat zone surface. The gas phase temperature gradient at the pyrolysis zone surface essentially increases with *U*, and the pyrolysis zone length decreases more rapidly than the flame spread rate. These suggest that as *U* increases the mean ejection velocity of the pyrolysis gas increases in spite of the reduction of the total mass flux of the evolved pyrolysis gas. Based on the experimental results, the effects of the free-stream velocity of opposed air flow on the flame spread processes were discussed.

KEYWORDS: Flame Spread, Thin Solid Combustible, Temperature Profiles, Opposed-Flow

INTRODUCTION

Flame spread over thin solid combustibles in an opposed-flow has been extensively studied as a suitable phenomenon to understand basic mechanisms or features of the processes of flame spread, because the phenomenon is practically steady and also the temperature gradient in the solid phase normal to its surface or solid phase conduction can be essentially neglected in interpreting the processes [1-4].

In most of these previous studies the variations of the flame spread rate and/or flame stability limit with physical parameters were explored in view of the mechanisms of flame spread.

From experimental studies, it has been well recognized that at stable flame spread the flame leading edge precedes the pyrolysis zone front and that the main path of the heat transfer to the unburned solid adjacent to the pyrolysis zone is gas-to-surface heat flux closely related to the flow field [5-12]. On the other hand, for various problems of flame spread, numerical studies have been attempted recently [12-17] in addition to conventional analytical studies. For example, for thin solid combustibles in forced opposed-flow, Chen studied flame spread with a modified model adopting Navier-Stokes equation with one-step overall chemical reactions of finite rate for both of pyrolysis and flame [15], and examined the variations of the flame spread rate and aerothermochemical structure including the pyrolysis zone length. Although the calculated dependence of the spread rate on the free-stream velocity in that study was much greater than that normally observed by experiments, which may be probably due to the neglect of gravity, the effects of convection were feasibly shown. Since these numerical studies described the variations of the two-dimensional profiles, i.e., of flow velocity, temperature, species mass fractions, and reaction rates, corresponding experimental data are desirable. However, in spite the fact that many experimental works elucidated important features of the burning zone the data showing these variations have not been obtained enough, so that discussion of the relation between numerical results and experimental results has not been carried out satisfactory.

In our previous study [18], by using a fine thermocouple, the measurements of two dimensional temperature profiles around the flames spreading stably downward over a filter paper sheet treated with flame retardant were attempted at a fixed air velocity and it was favorably shown that the temperature profiles depend on the type of flame retardant. In the present study, with the same apparatus and experimental techniques, variations of the temperature profiles with opposed-flow velocity, which must be the most basic parameter, were investigated in detail for pure filter paper sheet. Considering the experimental results, the effects of the free-stream velocity of opposed air flow on the flame spread processes were discussed.

EXPERIMENTAL

The flame spread experiment was conducted in a vertical duct having a 4X4-cm cross section that provides uniform flow [18]. The duct was mounted on the exit of the converging nozzle of a wind tunnel, and air was supplied by a compressor. The filter paper sheet has a surface of 3.9X13-cm and is 0.26 mm thick (Advantec No. 2). The paper was stored in a desiccator for more than 24 hours until experimental run. In the experiment, the paper was installed vertically along the center of the duct with two lines of needle, and its top edge was ignited simultaneously by thin torch.

Flame spread was observed through two quartz plates serving as duct walls normal to the paper surface. The flame spread rate in each run was determined at vertical centerline as a mean value in a 3-cm-long zone starting from the location 4 cm from the ignited end, by measuring the elapsed time for the movement of the pyrolysis zone front which was identified as the starting point of blackening of the paper surface. Throughout the measurement zone, the distance between the flame leading edge and the pyrolysis zone front was practically constant, and also overall flame spread phenomena showed little change.

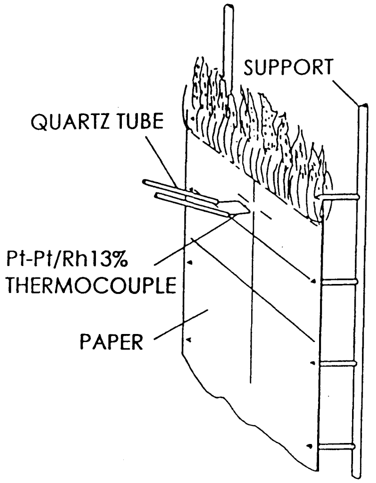

FIGURE 1. Setup of temperature measurement.

Temperature of gas phase or paper surface was measured by a thermocouple prepared from 25 μ diameter Pt-Pt 13% Rh wires coated with silica. The junction was at the center of a horizontal straight part of the wire parallel to the paper surface so that the part would pass the same temperature and it minimizes the error due to the conduction along the wire (Fig. 1). The thermocouple was placed at a fixed position in the middle of the measurement zone for flame spread rate, i.e., 7.5 cm from the upstream end of the paper. The temperature-time diagram was recorded by digital recorder and PC, and the recorded data were transformed into temperature-position diagram in order to produce temperature profiles. The location of the thermocouple relative to the paper surface was determined carefully from enlarged video image so as to eliminate the influence of the fluctuation of the paper surface position due to distortion during a run. The thermocouple error due to radiation was not corrected.

RESULTS AND DISCUSSION

Flame Spread Behavior

Behaviors of downward flame spread in an opposed air flow have been well recognized from many previous experimental studies [7-10,18]. Figure 2 shows the variation of the flame spread rate V_f with free-stream velocity U of air flow measured at the duct inlet. For U up to ca. 55 cm/s, V_f decreases gradually with U. In this range, after the paper is ignited uniformly, a stable straight burning zone spreads downward. In the range of $55 < U < 70$ cm/s, where V_f decreases steeply, the flame leading edge cannot keep straight line and local blow offs occur, i.e., unstable flame spread appears. At $U \geq 70$ cm/s, a complete blow off occurs before flame spreads beyond the measurement zone of flame spread rate. The change of V_f with U in the unstable spread region observed in this study is more sharp than that observed in the study by Hirano et al. [10]. The difference must be primarily due to the difference of the boundary layer thickness over the paper; in this study the distance from the upstream end of the paper to the center of measurement is 7.5 cm and is about a half of that in the previous study.

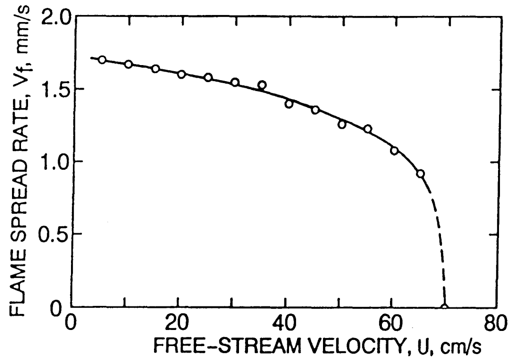

FIGURE 2. Variation of the flame spread rate V_f with the free-stream velocity.

Surface Temperature Distribution

Figure 3 shows the variation of the distribution of temperature T_s at the paper surface with the free-stream velocity U. In the figure, x indicates the distance along the paper surface measured from the pyrolysis zone front toward burned side. In the coordinate system, the paper moves toward positive x with V_f and the free-stream air also goes to the same direction with the velocity $U + V_f$. The surface temperature at the unburned part rises as it approaches to the pyrolysis zone front, and just behind the front the temperature curve takes a peak. After the peak, with slight decrease the temperature keeps essentially constant value over several distances. It is seen that the pyrolysis zone temperature is essentially independent of U and is around 800K. The rear end of this temperature plateau practically coincides with the blackening zone rear-end from which deep-black carbonized residue zone continues. At satisfactory high temperature region, this carbonized residue zone starts to glow. As U increases, the preheat zone length decreases with producing steeper temperature rise, and also the pyrolysis zone length decreases significantly. Behind the front of the carbonized residue, the tempera-

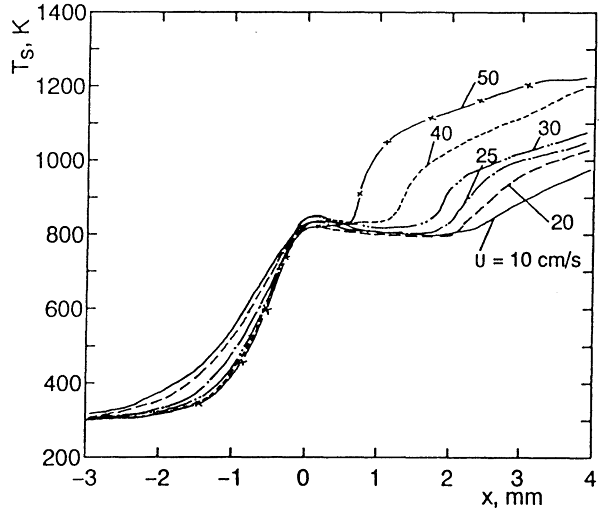

FIGURE 3. Temperature distributions at the paper surface.

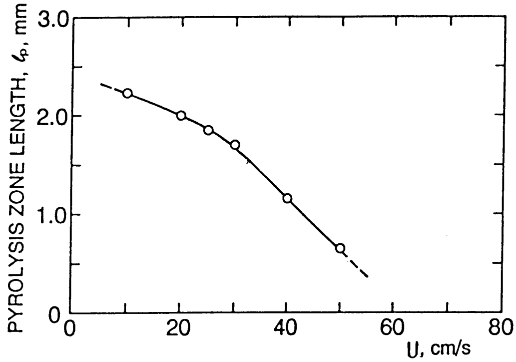

FIGURE 4. Variation of the pyrolysis zone length l_p with the free-stream velocity.

ture slope becomes steeper as U increases though the slope drops to smaller value from 900 or 1000 K.

Figure 4 indicates the variation of the pyrolysis zone length l_p with U. In the figure, l_p was determined as the distance measured from $x = 0$ to the pyrolysis zone rear-end which was defined from Fig. 3 as the intersection between the tangent line of the plateau zone and the tangent line at the point of maximum gradient in the carbonised residue zone. The value of l_p at $U = 50$ cm/s is about one fourth of that observed at $U = 10$ cm/s.

Gas Phase Temperature Profiles

Figure 5 shows the variation of gas phase temperature contours with free-stream velocity U. In the figure, y is the distance from the unburned paper surface, and the shade along the abscissa indicates the range of the pyrolysis zone. By comparison between the isotherm contours of examined three cases, it is seen that for all cases in the vicinity of flame tip the space between adjacent isotherms changes at 1400 K contour. Accordingly, the apex of the 1400 K contour must practically corresponds to the flame leading edge or the leading edge of the reaction zone, at least within examined range of U. This leading edge practically agrees with the end of luminous zone.

The value 10 cm/s of the free-stream velocity is almost the same as that of the surrounding flow induced by buoyancy due to the flame in normal-gravity field [6]. At this free-stream velocity, flame size is large and the maximum distance between the bow-shaped flame and paper surface is about 3 mm. The flame leading edge precedes the pyrolysis zone front about 0.5 mm, and is 0.5 or 0.6 mm from the paper surface, i.e., the flame stand-off distance is 0.5 or 0.6 mm. As is well known, for this type of diffusion flame stabilized in boundary layer, the stream line or mass flow penetrates the flame from upstream air side toward fuel side for most kinds of fuels or combustibles. Then, the distance between the adjacent isotherm contours in air side is usually smaller than that in the fuel side. The tip of 400 K contour in gas phase is located at $x \cong - 2.4$, $y \cong 0.8$ mm, and the contours in the preheat zone in air are smoothly rounded. At far upstream the temperature of the paper is a little higher than the surrounding air so that the heat flows from the paper to gas phase. For the temperature range shown as

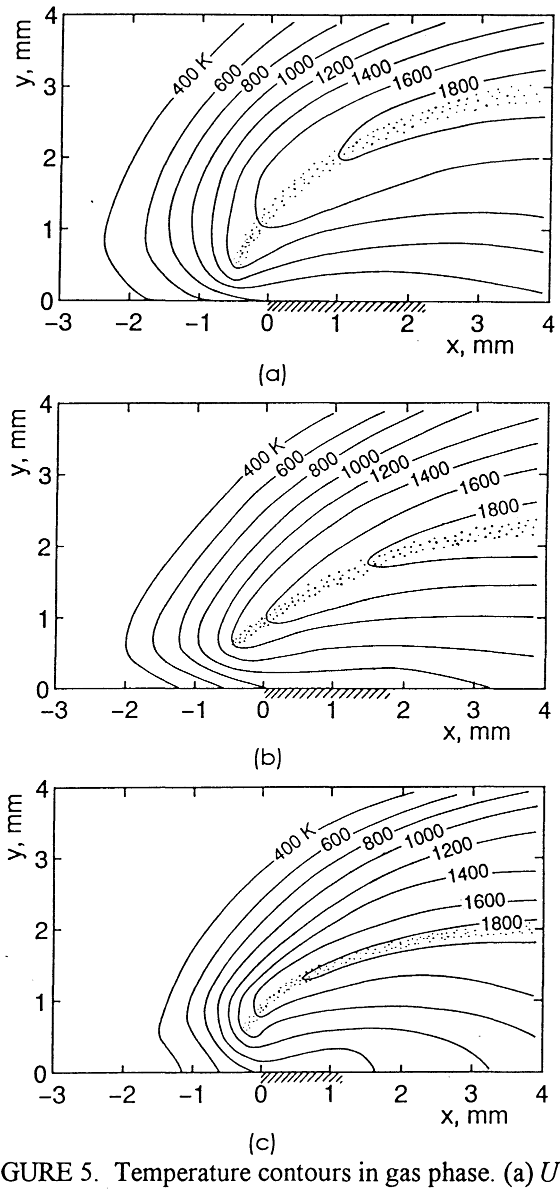

FIGURE 5. Temperature contours in gas phase. (a) U= 10 cm/s, (b) 25 cm/s, (c) 40 cm/s. Shade along the abscissa indicates the extent of the pyrolysis zone.

contours (> 400 K) in this figure, the heat flows from gas phase to the solid surface. Between the flame leading edge ($x \cong -0.5$ mm) and the nearest paper surface, the space between contours becomes minimum and consequently $\partial T/\partial y$ is largest. Since the heat flux from gas phase to the paper surface by convective heat transfer is the product of the thermal conductivity of gas and the gradient $(\partial T/\partial y)_S$ of the gas phase temperature at the surface, the largest heat flux from gas phase to the paper surface takes place there. This aspect may be closely related to the appearance of a convex slope part of the surface temperature observed for -1 mm < x < 0 (Fig. 3). Near the pyrolysis zone the 1000 K contour once gradually goes away from the surface, and then it turns to approach to the high-temperature carbonized residue surface. The flame temperature along the reaction zone increases toward downstream direction.

As *U* increases to 25 cm/s, the flame stand-off distance seems to increase slightly, and the overall flame position approaches to the paper surface. At most part the distance between adjacent contours decreases. The flame leading edge also moves slightly toward downstream direction. The tip of 400K contours approaches to the surface a little and goes back 0.3 or 0.4 mm toward downstream direction, and contours facing the preheat zone surface have relatively straight shape rather than rounded shape. Together with these changes, $(\partial T/\partial y)_S$ at the preheat zone and the preheat zone length decrease. On the other hand, in the vicinity of the pyrolysis zone surface, The contours are essentially parallel and closer to the surface. Consequently $(\partial T/\partial y)_S$ increases, suggesting the increase of heat flux to the pyrolysis zone surface.

When *U* is 40 cm/s, the flame leading edge goes back further and approaches $x = 0$, where the contour of 1000 K passes the nearest point to the surface. The length of gas phase preheat zone is smaller, and at the preheat zone surface the angles between the isotherm contours and paper surface become much larger except the location close to $x = 0$. Around the first part of the pyrolysis zone the values of $(\partial T/\partial y)_S$ is locally very large, and over the pyrolysis zone the 1000 K contour goes outward with the increase of x. Therefore, it can be inferred that the heat flux from gas phase to the pyrolysis zone surface changes by location. Behind the front of the carbonized residue, the high temperature region of gas phase quickly approaches to the surface, which may correspond to the steep rise of the surface temperature shown in Fig. 3.

As the critical free-stream velocity for the stable spread in this study is about 55 cm/s, the temperature profiles at $U = 40$ cm/s may not represent the exact feature to be observed at or close to the critical velocity. Then, measurement of the gas phase temperature profiles at 50 cm/s was tried. However, due to the sensitivity to small disturbance caused by thermocouple and the influence of the distorted residue or ash, reliable temperature profiles have not been obtained yet while the location of the flame leading edge was supposed to be close to $x = 0$.

From the comparison between the temperature distributions along the flame reaction zone, it is seen that as *U* increases the gradient of the flame temperature near the flame leading edge increases or the reaction zone temperature near the flame leading edge becomes higher.

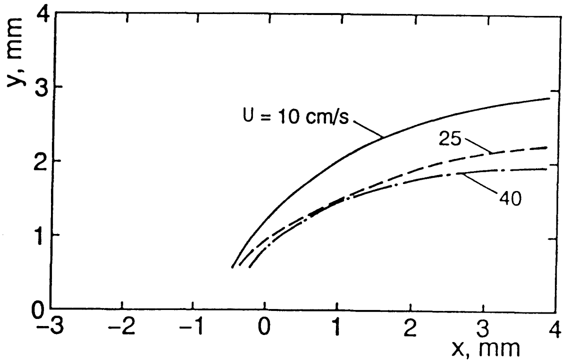

FIGURE 6. Flame locations.

Figure 6 shows the variation of the flame (reaction zone) location. It is seen that as U increases from 10 to 25 cm/s, the location remarkably approaches the surface except the leading edge. The most distant position moves 0.6 or 0.7 mm toward the surface. However, when U increases from 25 to 40 cm/s, the space between the flame and the paper surface at $x \cong 1$ mm changes scarcely though the leading edge goes back and also the downstream portion approaches to the surface.

Effects of Opposed-Flow Velocity on Flame Spread

Based on the variation of the temperature profiles, the effects of the opposed-flow velocity on the flame spread will be discussed briefly. The flame spread rate V_f also represents the spread rate of the pyrolysis zone front that is proportional to the heat input to the paper at $x < 0$. By rough estimation, the heat input necessary to heat up half thickness of the burning filter paper per unit width and unit time from room temperature to 800 K (approximately equal to the temperature at the pyrolysis zone front) are 0.65, 0.63, and 0.55 W/cm for $U = 10$, 25, and 40 cm/s.

Since Fig.3 indicates that the surface-temperature gradients $\partial T_S/\partial x$ along the preheat zone increase as U increases, it can be said that the conductive heat flux from the pyrolysis zone to the preheat zone increases as U increases. However, roughly estimated contributions of the heat flux from the pyrolysis zone are approximately 6, 8, 11 % at most, for $U = 10$, 25, and 40 cm/s, respectively. Thus, it is seen that for thin solid combustibles the heat transfer from the gas phase to the preheat-zone surface dominates stable flame spread phenomena even for relatively high flow velocity. The variation of the temperature profiles in gas phase supports the dominant roles of the gas-to-surface convective heat transfer. The values of gas-to-surface heat flux by convective heat transfer per unit width estimated from $(\partial T/\partial y)_S$ are 0.67, 0.64, and 0.47 W/cm, for above three cases, respectively. There are some discrepancies between the necessary heat input and the sum of gas-to-surface heat transfer and inside conduction. The main cause of the discrepancies may be the effects of radiative heat transfer. The heat transfer by radiation should consist of the outflow to low-temperature surroundings and the inflow from the flame, and may increase with the preheat zone length.

Since the structure around the flame leading edge strongly controls the flame spread phenomena, the aspects of the pyrolysis-gas evolution are very important as well as the air flow velocity. If the rate of conversion α of the unburned paper into the pyrolysis gas is assumed to be independent of the flow velocity at the stable spread region, which may be adequate because the pyrolysis zone temperature is essentially independent of U, the total mass of the pyrolysis gas generated from whole pyrolysis zone per unit time is proportional to the flame spread rate V_f. That is,

$$m_{pm} l_p = \int_0^{l_p} m_p dx = \alpha \delta \rho_s V_f / 2, \quad (1)$$

or

$$\rho_p v_{pm} l_p = \rho_p \int_0^{l_p} v_p dx = \alpha \delta \rho_s V_f / 2, \quad (2)$$

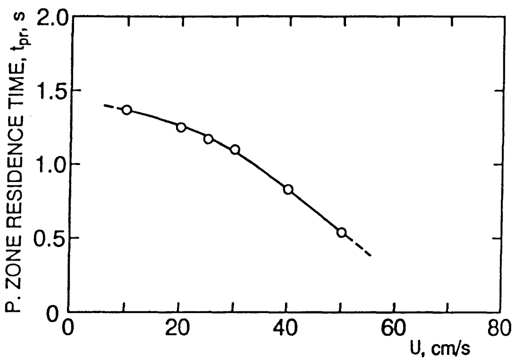

FIGURE 7. Variation of the residence time of a paper element in the pyrolysis zone with free-stream velocity.

where m_{pm}, m_p are mean and local mass flux of the pyrolysis gas, ρ_p is the density of the pyrolysis gas at the surface, v_{pm}, v_p are mean and local pyrolysis gas ejection velocities, and δ and ρ_s represent the thickness and density of the unburned paper sheet. Therefore, m_{pm} or v_{pm} is proportional to V_f/ℓ_p. With providing that the shrinkage of the paper in the pyrolysis zone is negligible, V_f/ℓ_p is equal to the inverse of the (maximum) residence time of a paper element in the pyrolysis zone. Accordingly, the mean ejection velocity of the pyrolysis gas is proportional to the inverse of the residence time t_{pr}, i.e.,

$$v_{pm} = \frac{V_f}{l_p}\frac{\alpha\delta\rho_s}{2\rho_p} = \frac{1}{t_{pr}}\frac{\alpha\delta\rho_s}{2\rho_p}. \tag{3}$$

Figure 7 indicates the variation of t_{pr} determined from the temperature history with U. Since t_{pr} decreases with the increase of U, as U increases the mean ejection velocity increases while the total amount of the ejected mass gradually decreases. Though it is well known that the air flow ahead of the flame leading edge is once decelerated and that the dependence on U of the local flow velocity at the decelerated region is relatively small [7], the increase of U may drive the location of flame leading edge to downstream direction more if the ejection velocity is kept constant. The facts that the distance between the flame and the surface at $x \cong 1$ mm scarcely change from $U = 25$ to 40 cm/s and that the flame temperature near the leading edge increases with U are considered to be closely related to the increase of ejection velocity. That is, it is expected that the increase of the free-stream velocity increases the supplies both of oxygen and fuel gas to the reaction zone in the vicinity of the flame leading edge through the increase of concentration gradients so that the reactions are enhanced effectively. These consideration may suggest that for most velocity range of stable flame spread the spread process is controlled by heat and mass transfer rather than the effects of the decrease of Damköhler number due to the reduction of flow residence time while the spread rate gradually decreases with the increase of U. There is a possibility further that if severe reduction of flame size occurs at larger U it may increase the heat loss from the rear end of the reaction zone. However, this role is not clear.

The mean ejection velocity of the pyrolysis gas must be proportional to the mean heat input per unit area of the pyrolysis zone. The value of mean heat flux at this zone by gas-to-surface convective heat transfer, estimated from temperature profiles, is approximately 3.9, 5.6, and 6.2 W/cm^2, for $U = 10, 25, 40$ cm/s, respectively. From the consideration of the heat balance at the pyrolysis zone it was expected that the effect of radiative heat transfer may not be negligible in this region though it is smaller than that of the convective heat transfer. The detail of the heat balance will be discussed elsewhere. Although the heat flux to the pyrolysis zone by convective heat transfer increases with U, an upper limit of the flux is expected to appear, because the flame stand-off distance cannot decrease beyond a certain level due to quenching effect at the surface and also the flame leading edge goes back. It should be reasonably expected also that, when the pyrolysis zone length ℓ_p decreases to very small values as critical free-stream velocity is approached, the values of ℓ_p and $\delta/2$ become the same order and then the heat input to the pyrolysis zone from the carbonized residue may not be negligible because at large U the temperature gradient in the residue is very large.

In the present study, it is suggested as mentioned before that, for the flame spread over thin filter paper, in most part of the stable spread region the flame spread process is controlled by heat and mass transfer processes. However, for appropriate understanding of the critical condition for stable flame spread, the relation between the role of heat and mass transfer processes and the role of the decrease of Damköhler number should be studied further by considering the structure of burning zone.

CONCLUSIONS

By using fine thermocouple technique, variations of temperature profiles around a flame stably spreading downward over a filter paper with opposed-flow velocity were examined. Main conclusions are as follows.

From the two-dimensional temperature profiles, it was confirmed that the decrease of the flame spread rate with the increase of the free-stream velocity U is due to the decrease of convective heat transfer to the preheat zone surface.

As U increases, the ejection velocity of the pyrolysis gas increases while the total mass flux of the pyrolysis gas decreases. This increase corresponds to the increase of convective heat transfer to the pyrolysis zone surface.

The temperature at the flame leading edge was found to be essentially independent of U. However, the flame temperature near the leading edge increases with U, and it can be suggested that in most velocity range where the flame spread rate gradually decreases with U the flame spread is controlled by heat and mass transfer processes.

ACKNOWLEDGMENT

The authors would like to thank Mr. K. Yamashita for his help in conducting experiments.

REFERENCES

1. Williams, F. A., "Mechanisms of Fire Spread", Sixteenth Symposium (International) on Combustion, The Combustion Institute, pp. 1281-1294, 1977.
2. Fernandez-Pello, A. C., and Hirano, T., "Controlling Mechanisms of Flame Spread", Combustion Science and Technology, 32, pp.1-31, 1983.
3. Fernandez-Pello, A. C., "Flame Spread Modeling", Combustion Science and Technology, 39, 119-134, 1984.
4. Wichman, I. S., "Theory of Opposed-Flow Flame Spread", Progress of Energy and Combustion Sciences, 18, 553-593, 1992.
5. Sibulkin, M., Hetelhut, W., and Feldman, S., "Effects of Orientation and External Flow Velocity on Flame Spreading over Thermally Thin Paper Strips", Combustion Science and Technology, 9, 75-77, 1974.
6. Hirano, T., Noreikis, S. E., and Waterman T. E., "Measured Velocity and Temperature Profiles near Flames Spreading over a Thin Combustible Solid, Combustion and Flame, 23, 83-96, 1974.
7. Hirano, T. and Sato, K., "Effects of Radiation and Convection on Gas Velocity and Temperature Profiles of Flames Spreading over Paper", Fifteenth Symposium (International) on Combustion, The Combustion Institute, pp. 233-241, 1975.
8. Hirano, T., Sato, K., and Tazawa, K., "Instability of Downward Flame Spread over Paper in an Air Stream", Combustion and Flame, 26, 191-200, 1976.
9. Hirano, T. and Tazawa, K., "Effect of Thickness on Downward Flame Spread over Paper", Bulletin of Japanese Association of Fire Science and Engineering, 26, 7-13, 1976.
10. Sato, K., Hirano, T., and Miki, K., "Flame Spread over Paper in an Air stream with a Velocity Change", Journal of Heat Transfer, 106, 707-712, 1984.
11. Olson, S. L., "Mechanisms of Microgravity Flame Spread over a Thin Solid Fuel: Oxygen and Opposed Flow Effects", Combustion Science and Technology, 76, 233-249, 1991.
12. Bhattacharjee, S. and Altenkirch, R. A., "A Comparison of Theoretical and Experimental Results in Flame Spread over Thin Condensed Fuels in a Quiescent, Microgravity Environment", Twenty-Fourth Symposium (International) on Combustion, The Combustion Institute, pp. 169-1676, 1992.
13. Frey, A. E., and T'ien, J. S., "A Theory of Flame Spread over a Solid Fuel Including Finite-Rate Chemical Kinetics, Combustion and Flame, 36, 263-289, 1979.
14. Mao, C. P., Kodama, H., and Fernandez-Pello, A. C., "Convective Structure of a Diffusion Flame over a Flat Combustible Surface", Combustion and Flame, 57, 209-236, 1984.
15. Chen, C. H., "A Numerical Study of Flame Spread and Blowoff over a Thermally-Thin Solid Fuel in an Opposed Air Flow", Combustion Science and Technology, 69, 63-83, 1990.
16. Due, F. C. and Chen, C. H., "A Theory for Downward Flame Spread over a Thermally-Thin Fuel", Combustion Science and Technology, 77, 291-305, 1991.
17. Karpov, A. I. and Bulgakov, V. K., "Prediction of the Steady Rate of Flame Spread over Combustible Materials, Fire Safety Science, Proceedings of the Fourth International Symposium, pp. 373-384, 1994.
18. Sato, K., Suzuki K., Sakai, Y., and Sega, S., "Effects of Flame Retardant on the Behavior and Temperature Profiles Spreading over Paper", Fire Safety Science, Proceedings of the Fourth International Symposium, pp. 503-514, 1994.