

Downward flame spread over PMMA sheets in quiescent air: Experimental and theoretical studies

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Abstract

To explore the flame spread mechanisms over noncharring material, downward flame spread over polymethyl methacrylate (PMMA) sheets from 1.5 to 10 mm thick is studied experimentally in the quiescent air in an open space.

The experimental results show that the flame spread rate decreases with increasing thickness of sheet and it tends to a constant value for thick samples. Also the angle of the pyrolysis region is roughly constant for different sheet thicknesses.

In this study, a heat transfer model is proposed to examine the rate of heat transfer for noncharring materials. Based on this model and the experimental results, a correlation between the flame spread rate and thickness is derived, in which the flame spread rate is inversely proportional to the sheet thickness. The proposed model estimated the convection heat flux and the gradient of temperature in the solid and gas phases. The experimental data are in good agreement with the results of the theoretical model.

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1. Introduction

Flame spread means the rate of flame movement across a fuel surface. Because the flame spreads over a surface, many complications arise that are not found in simple gas-phase combustion problems. Consequently, studies of flame spread may be classified in several ways, e.g. physically (whether the fuel is solid or liquid), chemically (type of fuel), geometrically (shape of fuel), dynamically (direction and character of free-stream flow), etc. In this study, downward flame spread over noncharring solid fuel is discussed.

Reviews of the extensive literature existing on this problem are available in [1–4]. On the theoretical and experimental side, deRis [5] proposed a model in which the velocity of the gas is uniform and vaporization occurs at a constant surface temperature. This is a crucial stage of investigation on the controlling mechanism of flame spread because he did not have an existing base of knowledge on

which to build his inquiries, although, on the other hand, he had more freedom, not being constrained by previous work. The deRis model has been very much discussed and extended by many researchers. Sirignano [6–8], in his initial review, cites two negative features of deRis' work: (i) thick fuel flame spread formula predicts that velocity of the gas is independent of the solid phase conductivity in the direction of spread. Sirignano has pointed out that, intuitively it is expected that the spreading rate should depend very strongly on this conductivity, increasing as it increases. The absence of the solid phase conductivity in the deRis formula was also a sore point for other investigators. (ii) deRis' vaporization temperature hypothesis is incorrect. Sirignano observes that T_v depends on specific heats, chemical-kinetic constants, ambient pressure, ambient temperature, fuel-bed thickness, etc. Therefore, they studied the spread rate under the simplifying assumptions that combustion occurs in a heterogeneous reaction at the surface of the solid and the rate of reaction is estimated by a modified first-order Arrhenius law.

The influence of the solid phase conductivity continued to interest many investigators. For downward spread over

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Nomenclature

| | |
|----------|---|
| a | height ahead of pyrolysis region (m) |
| b | width of control volume (m) |
| C | specific heat of solid (J/kg K) |
| h_{de} | enthalpy of degradation (J/kg) |
| h_i | enthalpy of solid at T_0 (J/kg) |
| h_o | enthalpy of volatiles at T_p (J/kg) |
| k_g | thermal conductivity of volatiles (W/m K) |
| k_s | thermal conductivity of solid (W/m K) |
| m_i | mass flow of solid (kg/s) |
| m_o | mass flow rate of volatiles (kg/s) |
| q_p | heat transfer penetrating through the vaporized surface (W) |

| | |
|-----------|---|
| q_s | heat transfer through the solid surface ahead of the leading edge of the pyrolysis region (W) |
| q_{tot} | total heat input from the flame to the solid fuel (W) |
| T_0 | ambient temperature (K) |
| T_p | pyrolysis temperature (K) |
| T_{ref} | reference temperature (K) |
| V | flame spread rate (m/s) |

Greek letters

| | |
|----------|-------------------------------------|
| α | angle of pyrolysis region (degrees) |
| δ | thickness of PMMA sheet (m) |
| ρ | solid density (kg/m ³) |

thin fuels, Hirano [9] demonstrated that heat conduction through the gas dominates the spread process. The available experimental data [10,11] implied that solid phase conduction becomes dominant as the material thickness increased. On the basis of their experiments, Fernandez-Pello and Williams [11] developed a theory of flame spread in which the boundary layer approximation is applicable to the gas, allowing a rigorous computation of the velocity field, at least in principle, and high activation energy asymptotes are used to analyze ignition in a premixed region upstream of the diffusion flame, which leads to an expression for the flame spread rate. Solid heat conduction dominance has been questioned subsequently by Ito and Kashiwagi [12].

Other controlling parameters of flame spread are related to the environmental conditions, such as the oxygen concentration or the direction of the gas flow relative to the direction of flame spread. Esfahani [13] studied the effect of oxygen concentration on the degradation of polymethyl methacrylate (PMMA) by numerical methods. There is an interest in using numerical methods to investigate details of fire initiation and spread on solid fuels. Among others, Esfahani and Sousa [14] studied the ignition of Epoxy by a high radiation source by numerical techniques. They solved the transient two-dimensional governing equations for both gas and solid phases separately. They estimate the ignition delays for Epoxy along with the location of ignition, which is to the side of the heated area. Sousa and Esfahani [15] also studied the ignition of PMMA by numerical methods when induced by monochromatic radiation.

Heat transfer to the preheat region is one of the most important parameters that has a strong influence on the flame spread. Several heat transfer models have been proposed to explain the flame spread rate [5,9]. However, the proposed simplified analytical models are not practicable to estimate the flame spread rate if the fuel is neither thermally thin nor thermally thick. Suzuki et al. [16] proposed a theoretical model for the flame spread over paper sheets with different thicknesses. They use the global

energy conservation equation in the virgin material and estimated the flame spread over paper sheets with different thicknesses. They did not consider the effect of the angle of the pyrolysis region.

In the present study, the downward flame spread and the angle of the pyrolysis region for PMMA sheets of different thickness is measured experimentally and a simple theoretical model is proposed to describe spread processes controlled by heat transfer through the solid. Based on the theoretical model a simple relation between V and δ is given and the value of heat flux through the solid surface ahead of the leading edge of pyrolysis region and that penetrating through the pyrolysis region are calculated and the gradient of temperature in the solid and gas phases are estimated. The experimental results are consistent with the results of the theoretical model.

2. Experimental setup

Sample PMMA sheets are made of various thicknesses from 1.5 to 10 mm. The sheets are made by R.C.Acrylic Enterprise Co., Ltd. in Taiwan. Fig. 1 shows the arrangement of apparatus that is used in this study. A sample sheet is clamped between pairs of metal straps at both sides and suspended in the quiescent air in an open space. The PMMA sheets are clamped 40 cm above the floor to avoid any effect that the floor might have on the entrainment of air around the sheets. The dimensions of the sample sheet were 120 × 100 mm. A slit burner is used to ignite the sample sheet along its top edge. To observe spreading behavior, surfaces of the sheet are videotaped during the flame spread. The rate of flame spread is measured by videotape for the time required to spread between previously specified distances. The specified distance is 10 mm. The first 10 mm and the last 30 mm of the height of the sample are not included in the measurement of the flame spread rate because of the need to reach a steady state as well as ensure a uniform air flow profile. For each thickness, the test is repeated 10 times to minimize experimental errors.

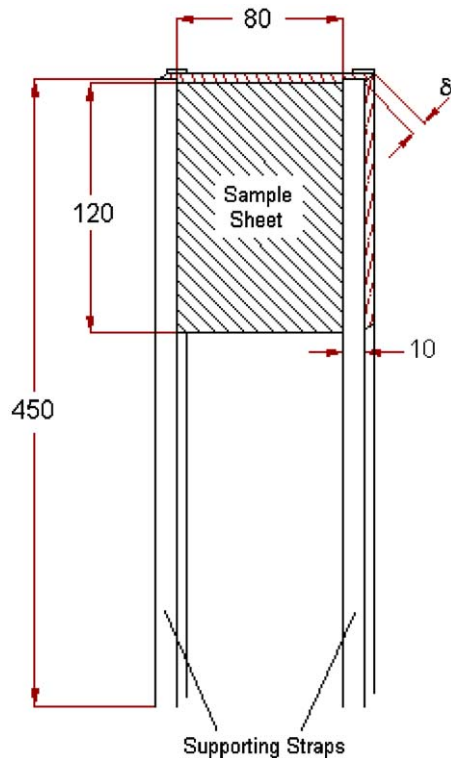


Fig. 1. Experimental apparatus arrangement used in the study (dimension in millimeter).

To determine the cross-section profile and estimate the angle of the pyrolysis region α , after each experiment the sheets were cut along a vertical cross section and polished. The profile of the cross section of these surfaces was determined by a Digitizer machine. This was repeated twice for each thickness. The Reni Shaw Digitizer, cyclone series with 1 mm diameter rubi ball is used, which has an accuracy of 0.01 mm.

3. Experimental results

To show the actual profile of the cross section of the samples after burning, the sheets were cut along a vertical section and a photo of the section was taken as shown in Fig. 2. In this figure, the bubbles established in the solid are shown, especially in the thick samples. It seems the angle of pyrolysis region α is similar for all thicknesses.

Fig. 3 shows a cross-section profile of a burnt sample which is indicated by Digitizer machine. The angle of pyrolysis region α is shown, defined by drawing two tangential lines to the profile of the cross section. The variation of α with respect to the thickness of sheets is shown in Fig. 4. This figure shows the angle of pyrolysis region is approximately independent of the sheet thickness and is estimated to be 33.4° .

During the flame spread, the height of the flame sometimes increases randomly. The geometrical configuration of a diffusion flame depends on the balance of mass transfer rates of fuel and oxidizer gases, so that it is



Fig. 2. The actual profile of cross section of burning surfaces $\delta = 1.5, 3, 4, 5, 6, 8, \text{ and } 10 \text{ mm}$.

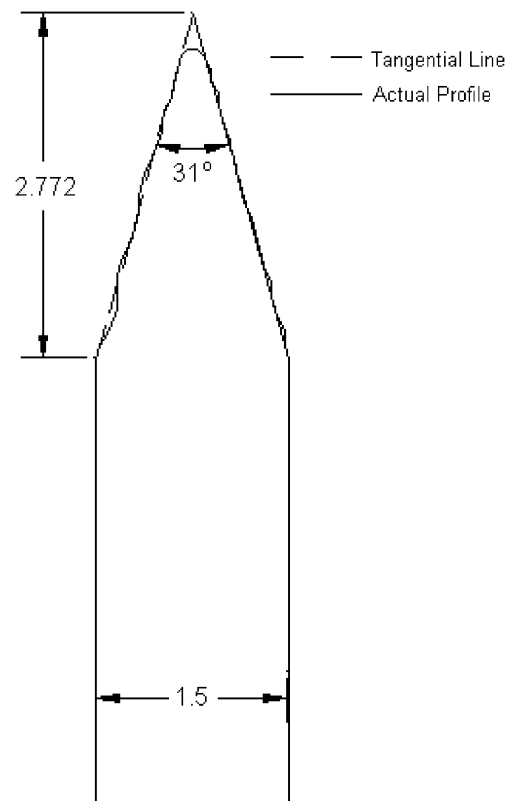


Fig. 3. The schematic profile of cross section of burning surface of $\delta = 1.5 \text{ mm}$.

considered during the degradation of PMMA, bubbles are established in pyrolysis region, which can be observed in Fig. 2. When they burst at the vaporization surface [17,18], they release liquid droplets into the gas phase. These droplets affect the flame and its length.

The variation of the flame spread rate V with respect to sheet thickness δ for all tests is shown in Fig. 5. The experimental results of Fernandez-Pello and Williams [10] for downward direction are also shown in Fig. 5. The

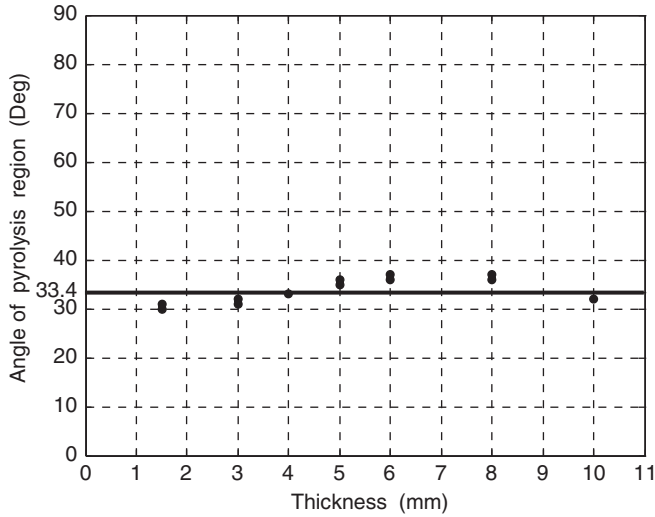


Fig. 4. The variation of the angle of pyrolysis region α with respect to sheet thickness δ .

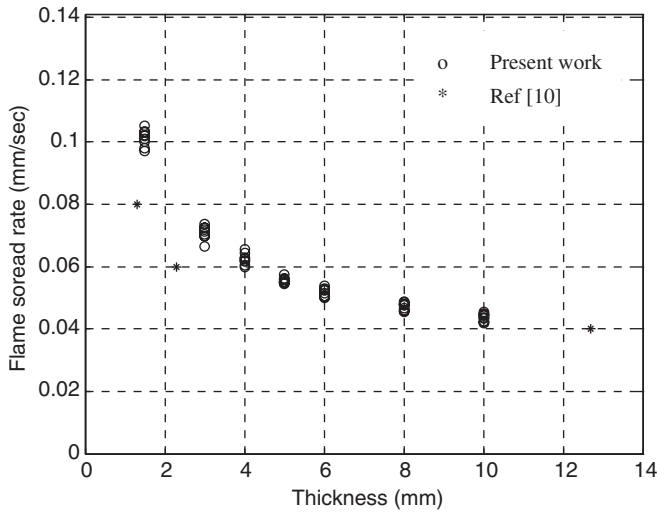


Fig. 5. The variation of the flame spread rate V with respect to the sheet thickness δ .

discrepancy between those results could be as a result of different properties of PMMA sheets and measurements. As shown by Fernandez-Pello and Hirano [19], these results also show that the downward flame spread rate over PMMA sheets decreases asymptotically with increasing the sheet thicknesses. Fig. 5 shows that the asymptotic value is about 0.04 mm/s.

4. Theoretical models

Fire spread can occur only if there is some type of communication between the burning region and the nonburning fuel. The critical problem in ascertaining mechanism of fire spread is to establish the character of this communication.

The theoretical model follows closely that reported in Suzuki et al. [16]. The unique feature of the present model

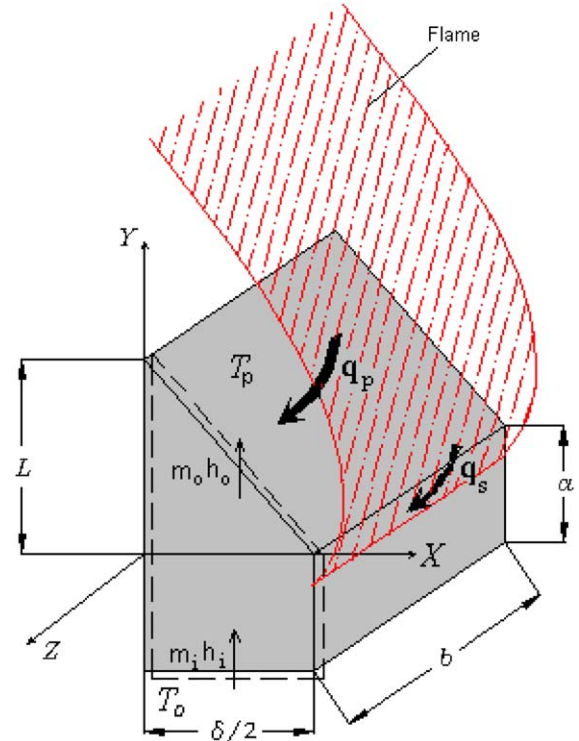


Fig. 6. Sketch of the heat flow, input and output enthalpies into the control volume.

is adding the effect of the angle of pyrolysis region to the model. Fig. 6 shows a sketch of an assumed heat flow model. The horizontal and vertical axes are indicated by X and Y , respectively. The distance from the center line of the sample is represented by X , and the vertical distance from the leading edge of the pyrolysis region is represented by Y . On the fixed X – Y coordinate, there is a movement of solid fuel in the positive direction of Y at the velocity of V . The temperature in the preheat region change from initial temperature T_0 at $Y = -\infty$ to the pyrolysis temperature T_p at the vaporized surface. In such a situation, the energy equation for a control volume defined by the central plane and $Y = -\infty$ and the boundary of vaporization surface in the gas phase is represented as follows:

$$q_{\text{tot}} + m_i h_i - m_o h_o = 0, \quad (1)$$

where the first term, q_{tot} , indicates the rate of total heat input from the flame to the solid and m_i , h_i , m_o , and h_o are the mass flow rate of solid fuel, the enthalpy of solid fuel at T_0 , the mass flow rate of volatiles, and the enthalpy of volatiles at T_p , respectively.

For steady-state situation m_i and m_o are equal and they can be expressed as follows:

$$m_i = m_o = bV\rho\delta/2, \quad (2)$$

where ρ and b are the density of solid fuel and the width of the control volume, respectively. From the definition of the heat capacity, h_i and h_o can be calculated from the

following relations:

$$h_i = C(T_0 - T_{\text{ref}}), \quad (3)$$

$$h_o = C(T_p - T_{\text{ref}}) + h_{\text{de}}, \quad (4)$$

where C and h_{de} are the heat capacity of solid fuel and the enthalpy of degradation, respectively. The effect of radiation is not significant in this kind of flame spread [1,2,10,20] and therefore the total heat, which is transferred to the solid fuel, can be calculated from the following relation:

$$q_{\text{tot}} = (q_s + q_p)_{\text{conv}}. \quad (5)$$

In this relation, q_s and q_p are the heat transfer through the solid surface ahead of the leading edge of the pyrolysis region and the penetration of heat through the vaporization surface, respectively, as shown in Fig. 6. If the heat transfer q_s'' and q_p'' are assumed to be uniform over the entire of their surfaces then they can be expressed by the following relations respectively:

$$q_s = baq_s'', \quad (6)$$

$$q_p = \frac{b\delta}{2 \sin(\alpha/2)} q_p'', \quad (7)$$

where q_s'' and q_p'' are heat fluxes and a is the length of the pyrolysis region ahead of the flame which is shown in Fig. 6. By substituting the relations (2)–(7) in Eq. (1) and rearranging, the flame spread rate V can be calculated from the following expression:

$$V = \frac{2aq_s''}{\rho[C(T_p - T_0) + h_{\text{de}}]} \left(\frac{1}{\delta} \right) \frac{q_p''}{\rho \sin(\alpha/2)[C(T_p - T_0) + h_{\text{de}}]}. \quad (8)$$

Since all of the parameters except V and δ are assumed to be constant then this indicates that the relationship between V and $1/\delta$ is linear. The variation of the experimental flame spread rate versus $1/\delta$ is shown in Fig. 7. The curve describing the experimental results is as follows:

$$V = 1.038 \times 10^{-7} \left(\frac{1}{\delta} \right) + 3.471 \times 10^{-5} \quad (\text{m/s}). \quad (9)$$

The goodness of fit is 9.312×10^{-6} and 1.365×10^{-3} for the sum of squares of errors (SSE) and the root mean squared error (RMSE), respectively. This figure shows that the variation of V with respect to $1/\delta$ in the range of $\delta < 10$ mm, is approximately linear and agrees well with the curve of Eq. (8). The coefficients of $2aq_s''/\rho[C(T_p - T_0) + h_{\text{de}}]$ and $q_p''/\rho \sin(\alpha/2)[C(T_p - T_0) + h_{\text{de}}]$ are the slope and the intercept on the V axis, respectively. These values are estimated from Fig. 7 as follows:

$$2aq_s''/\rho[C(T_p - T_0) + h_{\text{de}}] = 1.038 \times 10^{-7} \quad (\text{m}^2/\text{s}), \quad (10)$$

$$q_p''/\rho \sin(\alpha/2)[C(T_p - T_0) + h_{\text{de}}] = 3.471 \times 10^{-5} \quad (\text{m/s}). \quad (11)$$

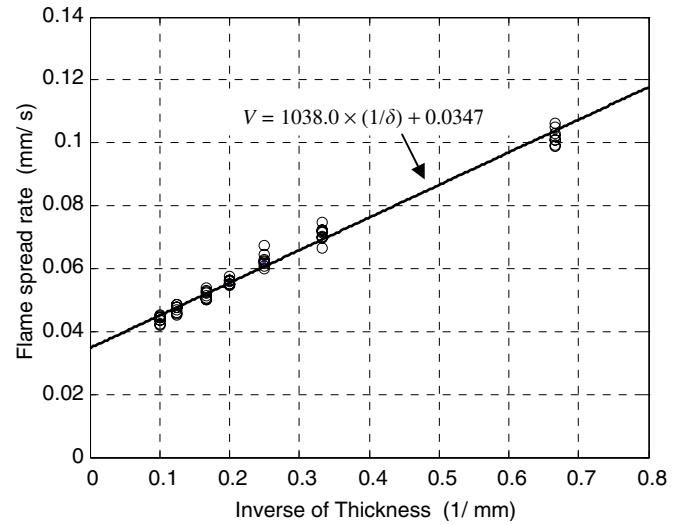


Fig. 7. Variation of the flame spread rate V versus inverse of thickness $1/\delta$.

Table 1

Physical and thermo-physical properties of PMMA

| Property | Value | Units | Reference |
|---|---------------------|-------------------|-----------|
| Density of virgin PMMA, ρ | 1190 | kg/m ³ | [13] |
| Specific heat of virgin PMMA, C | 1465 | J/kg K | [13] |
| Heat of degradation, h_{de} | 1.356×10^6 | J/kg | [13] |
| Thermal conductivity of virgin PMMA, k_s | 0.21 | W/mK | [13] |
| Thermal conductivity of vaporized PMMA, k_g | 0.041 | W/mK | [13] |
| Pyrolysis temperature, T_p | 673 | K | [16] |
| Ambient temperature, T_0 | 298 | K | |

The major part of heat transfer through the pyrolysis region takes place in the first 2 mm distance ahead of the flame [12,19], and therefore a in Eq. (8) is approximately equal to 2 mm. By substituting this value in the slope of line, the value of $q_s''/\rho[C(T_p - T_0) + h_{\text{de}}]$ is estimated to be equal to 2.595×10^{-5} (m/s). The physical properties of PMMA are listed in Table 1. The denominator of Eqs. (10) and (11) are based on data in Table 1 and the result of Fig. 4 ($\alpha = 33.4^\circ$), can be determined and therefore two types of heat flux can be estimated as follows:

$$q_p'' \cong 2.2 \times 10^4 \quad (\text{W/m}^2), \quad (12)$$

$$q_s'' \cong 5.8 \times 10^4 \quad (\text{W/m}^2), \quad (13)$$

where q_p'' is estimated to be smaller than q_s'' but is of the same order which confirm the results of Suzuki et al. [16]. However, q_p is higher than q_s , because the vaporization surface is bigger than the surface ahead of the leading edge of the pyrolysis region especially for the thick samples. Under the assumptions that the thermal conductivity of both solid and gas fuel and the gradient of temperature are

constant, q_p'' and q_s'' can be written as follows:

$$q_p'' = -k_g \left(\frac{\partial T}{\partial n} \right)_{\text{gas}} = -k_s \left(\frac{\partial T}{\partial n} \right)_{\text{solid}}, \quad (14)$$

$$q_s'' = -k_g \left(\frac{\partial T}{\partial x} \right)_{\text{gas}} = -k_s \left(\frac{\partial T}{\partial x} \right)_{\text{solid}}, \quad (15)$$

where n is the normal direction to the inclined vaporized surface (Fig. 6).

The temperature gradient in the solid and gas phases at their interface can be estimated as follows:

$$\left(\frac{\partial T}{\partial x} \right)_{\text{gas}} \cong 1400 \quad (\text{K/mm}), \quad (16)$$

$$\left(\frac{\partial T}{\partial x} \right)_{\text{solid}} \cong 280 \quad (\text{K/mm}), \quad (17)$$

$$\left(\frac{\partial T}{\partial n} \right)_{\text{gas}} \cong 530 \quad (\text{K/mm}), \quad (18)$$

$$\left(\frac{\partial T}{\partial n} \right)_{\text{solid}} \cong 100 \quad (\text{K/mm}), \quad (19)$$

where the values of $(\partial T/\partial x)_{\text{solid}}$ and $(\partial T/\partial n)_{\text{solid}}$ are confirmed by the experimental values that are reported by Ito and Kashiwagi [12].

5. Conclusions

The rate of downward flame spread over PMMA sheets in quiescent air in an open space is studied experimentally. A theoretical model based on the first law of thermodynamic is proposed to predict the temperature gradient. The experimental results confirm the results of the theoretical model. The principal results described in this study may be summarized as follows:

The flame spread tends to an asymptotic value of 0.04 mm/s as the thickness of the sample is increased.

The relationship between V and $1/\delta$ is linear.

The heat flux through the solid surface ahead of the leading edge of the pyrolysis region is of the same order as that penetrating through the pyrolysis region and they are comparable.

The angle of pyrolysis region α is approximately independent of sheet thickness and is about 33.4° .

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