The Effect of the Solid Fuel Dimensions on the Downward Flame Spread

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Abstract

The combustion process of polymer is a complex coupling of energy feedback from a flame to the polymer surface with gasification of the polymer to generate combustible degradation products. In this paper the effect of the dimension of the polymer sheets upon the downward flame spread is studied by theoretical and experimental methods. In the theoretical method the effect of the dimensions of the solid fuel on the energy balance in the solid phase is studied by scale up method. This study show that the flame spread over the solid fuel is independent of the width of the sample if the ratio of the width to the thickness of the solid is higher than ten. The experimental results confirm the theoretical results.

Keywords: Downward flame spread – PMMA – Combustion – Scale up

1- Introduction

Synthetic polymers are pervasive part of today's society. It can be found in every commercial buildings, residential houses, transportation vehicles, and etc. Today's, synthetic polymer materials are rapidly replacing more traditional materials such as steel, non ferrous metals, and natural polymeric materials such as wood, cotton, natural rubber, and so on. However, one weak aspect of synthetic polymer materials compared with steel and other metals is that these materials are combustible under certain condition.

With technological advancement, larger numbers of potentially combustible materials have been used in transportation vehicles. The precise reasons are many, although two prominent designs have been considered as follows: - mass reduction that causes increased efficiency - reduced manufacturing costs.

Therefore, it is important to understand how polymers burn and how to modify the materials to make them less flammable. Thus, the majority of polymers – containing end products must pass some type of regulatory test to help assure public safety from fire.

Many experimental and theoretical methods have been developed for investigation of ignition and material flammability. Generally the fuel sample, whether in a vertical or horizontal position, is exposed to external radiation or pilot flame. Bhattacharjee [1] studied a general opposed flow flame spread with uses the novel time scale analysis. The purpose was to bring together various sub regimes of fundamental topic by examining the characteristic time of participating physics. Lefebvre et al [2] studied flame spread of flexible polyurethane foam and provide basic correlation between some existing fire test methods and the data recorder under cone colorimeter condition. They show that a high density leads to a lower flame spread and to a longer step of melting of the foam. Fujita et al [3] experimentally studied the radiative ignition of a paper sheet in a quiescent microgravity environment. The experimental results indicated that the ignition delay time decreases with an increasing in oxygen concentration or pressure. Several experiments [4-7] have investigated the effect of the temperature of the opposed flow on a flames behavior. It was found that ignition delay time decreases and flame spread rate increases with the increasing temperature of the opposed flow. Lin and Chen [8] develop an unsteady two dimensional combustion model, that include radiative ignition and the subsequent transition to flame spread over a vertical thermally thick solid fuel under normal gravity. In the first stage, heating stage, the maximum temperature increases with time but the rate of increase slows down because of the pyrolysis reaction. In the second stage, the flame is formed and propagates over the solid. Higaera [9] studied the steady two dimensional downward flame spread on a vertical surface of a thermally thick solid fuel, and shows the flame moved into the gas immediately upon inception. Wu et al [10] studied downward flame spread over a thick PMMA slab in a mixed convection environment, both experimentally and unsteady numerical modeling. They show that flame spread rates increased by decreasing the velocity or increasing the temperature of free

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stream in opposed flow. Di Blasi [11] and Lin and Chen [12] investigated how the thickness of the solid fuel influenced the behavior of spreading flames, under natural and forced convection. Three main flame-spread regimes were identified. In the first regime, the solid fuel is very thin (2 mm) and hence the flame spread rate increases with increasing the solid fuel thickness. In the second regime, the solid fuel is also thin (2 mm) but the flame spread rate decreases with increasing the thickness of solid fuel. Finally in the third regime, the flame spread rate becomes almost constant when the fuel thickness increases over a certain amount. Ayani et al [13] studied downward flame spread over PMMA sheets, and show that the flame spread rate decreases with increasing thickness of the sheets. They studied the spread rate for the various solid thicknesses with constant width samples.

In the present work, the flame spread over the solid fuel is studied by scale analysis and investigates the effects of the dimension of solid fuel on the flame spread rate. Downward flame spread over PMMA sheets is studied experimentally. Comparison of experimental results with the analytical results shows a good agreement.

2- Physical model

Fire initiation occurs when ignition yields self-sustained combustion, such as a propagating flame in a gas or a spreading flame over a solid. Initiation is influenced by geometry (position and placement of material), air flow, type, duration and position of ignition source, ambient temperature, temperature of ignition source, and heat flux from the ignition source. For the solid fuels, the simplest case of fire initiation is the one-dimensional. Fire initiation on the semi infinite slab of materials subjected to the thermal source may thus be visualized as a one-dimensional. It is noted that the fire above a solid fuel requires gasification of the condensed-fuel phase because the flame is commonly situated in the gas phase.

Fire is a dynamic process of interacting physics and chemistry, thus, predicting what is likely to happen be difficult. Combustion of synthetic polymer materials is characterized by a complex interaction between condensed and gas phases. Furthermore, each phase consist of a complex coupling of chemical reactions with heat and mass transfer processes. One of the predictive methods for the behavior of fire is the algebraic equations. In the present work, the effect of the dimension of the solid fuel on the flame spread is studied. When the temperature in the solid is increased to a specified value, thermal degradation in the solid fuel is begun and evolves small gaseous degradation products. There are several books and articles that describe thermal degradation chemistry in detail [14, 15]. The type of polymer structure, thermal properties, and the amount of heat transferred to the polymer predict the depth over which the polymer is heated sufficiently to degrade. Energy could be from an external heat source, in the case of an ignition event, or from an adjacent flame as energy feedback in the case of flame spread and burning. Thermal radiation is a primary mode of energy transfer from the flame to the polymer surface except for small samples [16, 17]. The amount of energy absorbed by the polymeric materials depends on the type of polymer, the spectral characteristic of the radiant flux, the absorption characteristic of the material, and the material surface reflectance with respect to the emission spectrum of the incident radiation [18-20].

The physical model of the sample sheet is shown in Fig.1. A sheet of PMMA is exposed to a high heat source (burner) from its top surface and the bottom side of sheet is held in the quiescent air in an open space. Heat could be transferred by convection and radiation from the top of the solid fuel to air with convective heat transfer coefficient, h, and ambient temperature, T_∞.

In Fig. 1 q''_e is the heat flux that emitted from the solid surface(w/m^2), q''_c is the free convection heat flux from the solid surface to the environment(w/m^2), q''_r is the reflected heat flux from the solid surface to the surrounding(w/m^2), q''_I is the penetration of heat flux through the solid(w/m^2), q''_K is the conduction of heat flux in the solid phase formulated by Fourier's law(w/m^2) [21], q''_a is the advection heat flux that transferred by volatiles(w/m^2), S is the rate of degradation of the solid fuel(kg/m^3.s) and I_0 is the constant heat flux or radiant heat source(w/m^2) .
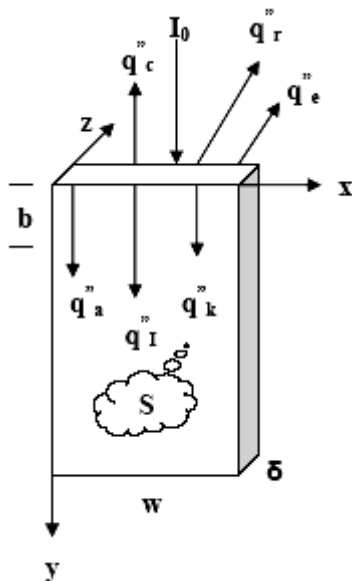
Fig. 1. The physical model and the coordinate system fixed on the sample sheet.

3- Mathematical model

Figure 2 shows a control volume in the sample sheet. The penetration of heat flux through the solid is formulated by Beer's law [22],

$$q''_I = (1 - r)I_0 \ exp(-\beta x) \tag{1}$$

which r and β is the reflectivity of the solid surface and radiation absorption coefficient in the solid(m^{-1}), respectively.
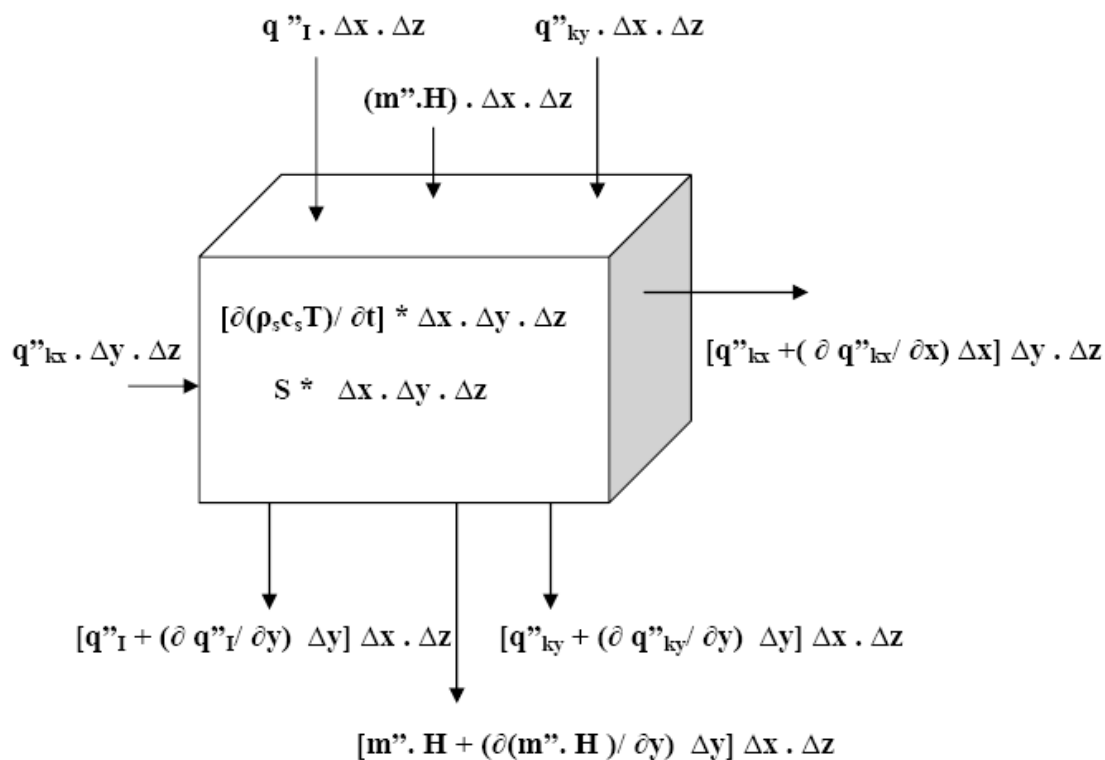

Fig. 2. A control volume in the sample sheet

As the solid surface exposed to the heat source, the radiation is absorbed in depth of the solid and causes to increase the temperature in the solid so that after a period of time the thermal degradation is begun in the solid. The rate of degradation of the solid fuel can be represented by Arrhenius law [23],

$$S = -A_0 \, exp\left(-E/RT\right). \rho \tag{2}$$

where A_0, E, R, T and ρ are the zero order pre-exponential factor(s^{-1}), the activation energy(J/kg), the gas constant(J/kg.K), the temperature in the solid fuel(K) and the density of solid fuel(kg/m^3), respectively. Then the rate of heat consumption due to thermal degradation(j/s.m^3) can be determined as follows:

$$q = q_p . S \tag{3}$$

where q_p is the heat of degradation per unit mass(J/kg).
The advection heat flux that transferred by volatiles formulated as:

$$q_a'' = m''. h \tag{4}$$

and $h = c_{pg} . T$ and $m'' = \int A_0 \exp\left(E/RT\right). \rho. dy$ \hfill (5)

where h, m'', and c_{pg} are the enthalpy of volatiles(J/kg), the rate of mass loss(kg/s.m^2), and the specific heat capacity of gases(J/kg.K) respectively. Since radiative beam is assumed to be in y direction, thus, q''$_1$ and q''$_a$ are in the same direction. In the steady state process without any radiation heat source, by use of the eqs. (1-5), the first law of thermodynamics for the control volume in the solid phase that is shown in Fig.2 is obtained as follow:

$$k\left(\partial^2 T / \partial x^2 + \partial^2 T / \partial y^2 + \partial^2 T / \partial z^2\right) - A_0 \, \rho \, q_p \exp\left(-E/RT\right) + \partial(m''. h) / \partial y = 0 \tag{6}$$

where k is the conductivity of solid(w/m.^{o}c).

The coordinate system fixed at the leading edge of the sample sheet is shown in Fig. 1. w, b, and δ are the width of the sample in the x direction, the length of the pyrolysis region ahead of the flame in the y direction, and the thickness of the sample in the z direction, respectively. With the following dimensionless definition of the parameters:

$$\bar{x} = x/w; \bar{y} = y/b; \bar{z} = z/\delta; \overline{m''} = m''/m''_{ref}; \overline{T} = (T - T_\infty)/(T_v - T_\infty) = \theta/\theta_v \tag{7}$$

where w, b, δ, T_∞ and T_v are the width of sample(mm), the pyrolysis regime ahead of the flame(mm), thickness of the sample(mm), the ambient temperature(K) and the burned temperature(K), respectively. The Eq.6 is being non-dimensional as follow:

$$(\delta/w)^2 \partial^2 \overline{T}/\partial \bar{x}^2 + (\delta/b)^2 \partial^2 \overline{T}/\partial \bar{y}^2 + \partial^2 \overline{T}/\partial \bar{z}^2 - C_2 \exp\left\{-E/\left[R\left(\overline{T}\theta_v + T_\infty\right)\right]\right\} + C_1 \partial\left(\overline{T}.\overline{m''}\right)/\partial \bar{y}$$
$$+ C_1\left(T_\infty/\theta_v\right)\partial\overline{m''}/\partial \bar{y} = 0 \tag{8}$$

and $C_1 = m''_{ref} c_{pg} \delta^2 /(bk)$ and $C_2 = A_0 \, \rho \, q_p \, \delta^2 /(k\,\theta_v)$

In Eq. (8) the gradient temperature in the Z direction can be neglected because the thickness of the solid is very thin. The major part of heat transfer through the pyrolysis region takes place in the first 2 mm distance ahead of the flame[24-27], and therefore the order of δ approximately equals the order of b(b≈ 2 mm) . If δ<<w, the first term in energy balance can be neglected. Thus, the temperature distribution being one-dimensional (y direction) as follow:

$$(\delta/b)^2 \partial^2 \overline{T}/\partial \bar{y}^2 - C_2 \exp\left\{-E/\left[R\left(\overline{T}\theta_v + T_\infty\right)\right]\right\} + C_1 \partial\left(\overline{T}.\overline{m''}\right)/\partial \bar{y} + C_1\left(T_\infty/\theta_v\right)\partial\overline{m''}/\partial \bar{y} = 0 \tag{9}$$

Therefore, the theoretical model shows the temperature distribution under large width and negligible thickness is one dimensional in y direction. The extent value of w/δ is determined by the experimental data, that is explained at section experimental.

4- Experimental apparatus and conditions
4-1-Testing methodology

The factors which affect the rate of flame spread across a surface listed by Drysdale [28]. These factors include the time and magnitude of an imposed heat flux, the composition of the atmosphere, the surface orientation, direction of flame propagation, air velocity, surface roughness, geometry, sample thickness, and etc. In addition the properties of the solid fuel such as specific heat, thermal conductivity, density, fire point temperature have contributions to the flame spread. The complex matrix of material properties, environmental conditions, sample geometry and configuration can give greatly different levels of flame spread, depending upon the exact test conditions used. It should be mention in a real fire, many of these parameters are always changed (such as temperature, imposed heat flux, oxygen concentration) but, in some test these parameters are constant, so the rate of flame spread will also change.

There are a variety of test which have been developed to establish the manner in which materials will be have in fires [28, 29]. These are principally small scale standard tests [30], full scale tests and finally newer test which examine a material reaction to fire (such as the cone calorimeter) [31]. So there are many different tests for assessing the flammability of materials. In general, all of the traditional tests express their results in terms of certain observation or measurements. Unfortunately, the base of these ranking scale are arbitrary, and therefore, results from one test do not necessarily agree with another one [32], nor do they reflect how a material might behave in a real fire. However, more recent test methods tend to measure various flammability properties of materials well - defined conditions and the results used as inputs to fire growth models or the results are analyzed using theories of combustion to drive values of critical parameters that determine flammability properties [32].

4-2- Experimental set up

Figure 3 schematically depicts the experimental set up. Sample of PMMA sheets are made of various thicknesses from 1.5 to 10 mm with the various widths from 10 to 100 mm. A sample sheet is clamped between pairs of metals straps that suspended in the quiescent air in an open space. A slit burner is used to ignite the sample along its top edge. To observe spreading behavior, surfaces of the sheet are videotaped during the flame spread. Test sample are mounted on the load cell (GF series 400/GF from A&D Company with 0.001 gr minimum display) which records the mass of the specimen during process at each time. The rate of flame spread is measured by the videotape for the time required to propagate the flame through specified distance (10 mm), or by mass reduction rate from load cell. For each thickness and width, the test is repeated 5 times to minimize experimental errors.

5- Results and discussion

The variation of burned height of sample sheets with respect to time is obtained by two methods as follows: - The time required to flame propagates between the specified distance which is determined by the videotape results. - The mass of the sample that is measured by the load cell at each time. The burned height of sample at each time can be determined by transforming the load cell data using the following relation:

$$Y = (m_0 - m)/(\rho.A) \tag{10}$$

were Y, m_0, m and A are the burned height of sample sheet(mm), the initial mass(g), the instantaneous mass of the sample(g) and the area of the sample(m^2), respectively.
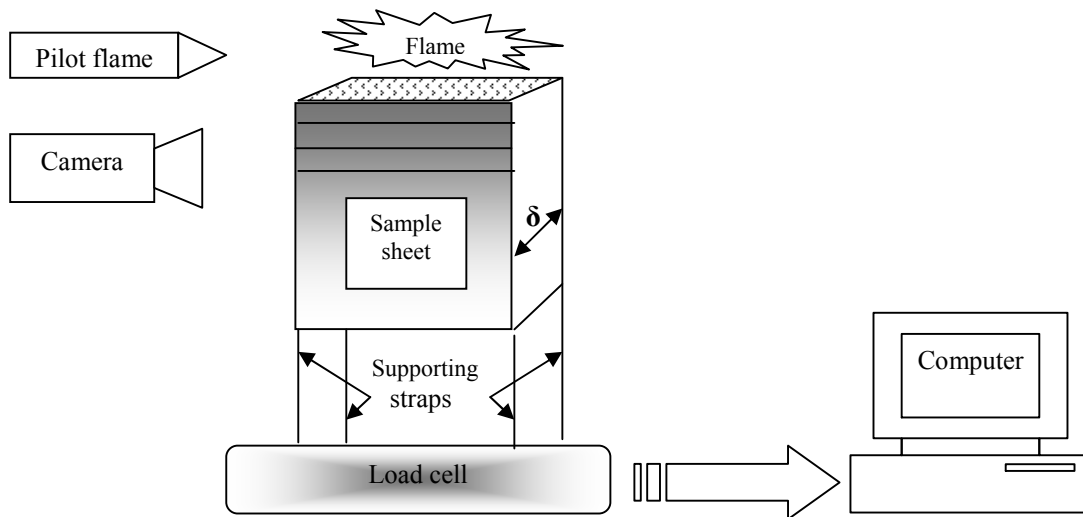

Fig. 3. Scheme of experimental apparatus arrangement.

The variation of burned height of PMMA sheet with respect to time for different thicknesses are shown in Figs. 4-7 These figures show that the burning of the solid fuels consists of two regimes, i.e. unsteady regime (approximately the burning of the first 15 mm of the solid fuel) and steady–state regime. Figure 4 display the burned height of PMMA sheet versus time under different width for fuel thickness of 1.75 mm. The flame spread rate determine from slope of curve, and it increases with increasing w/δ from five to ten, and for w/δ equal ten and fifteen it is approximately constant and independent of w/δ. In Figs. 5-7 the same results are shown for fuel thicknesses of 4 mm, 5.7 mm and 7 mm, respectively. They also show that the flame spread rate increases with increasing w/δ when w/δ <10, and for w/δ >10 all of the curves fit together.
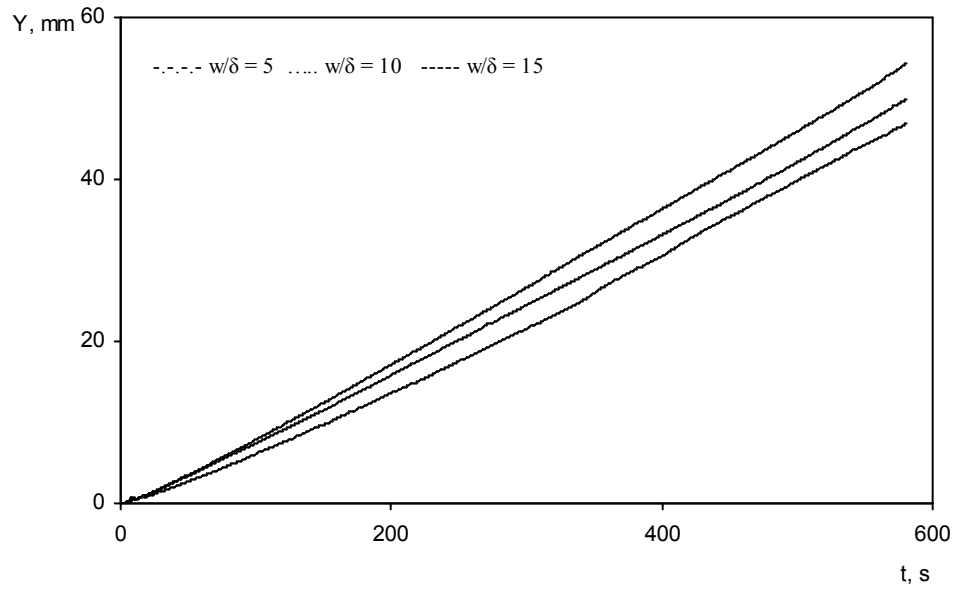
Fig. 4. The variation of burned height of PMMA sheet versus time (δ =1.75 mm)
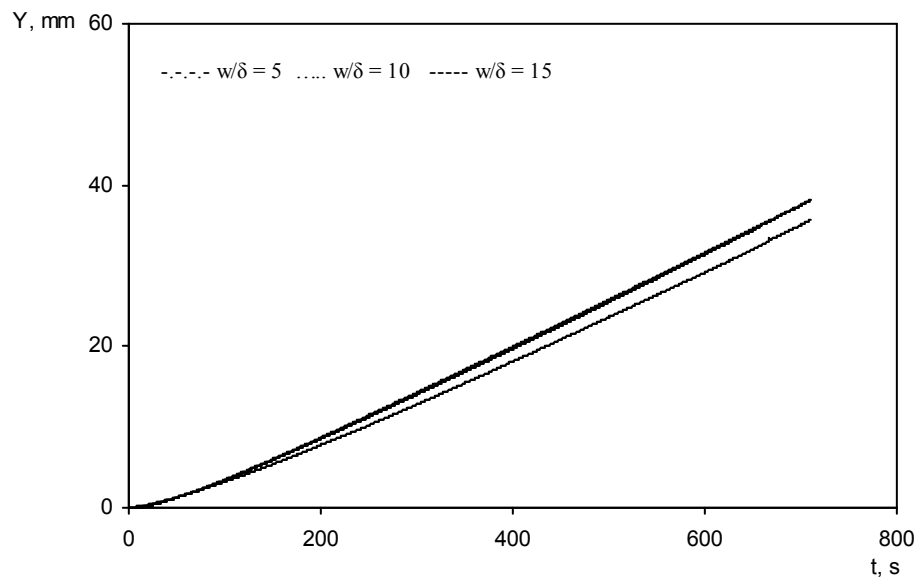

Fig. 5. The variation of burned height of PMMA sheet versus time (δ =4 mm)
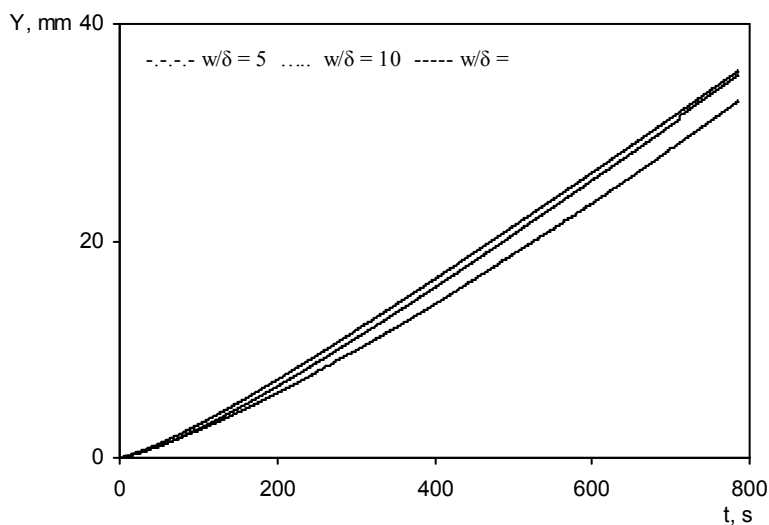
Fig. 6. The variation of burned height of PMMA sheet versus time (δ =5.7 mm)
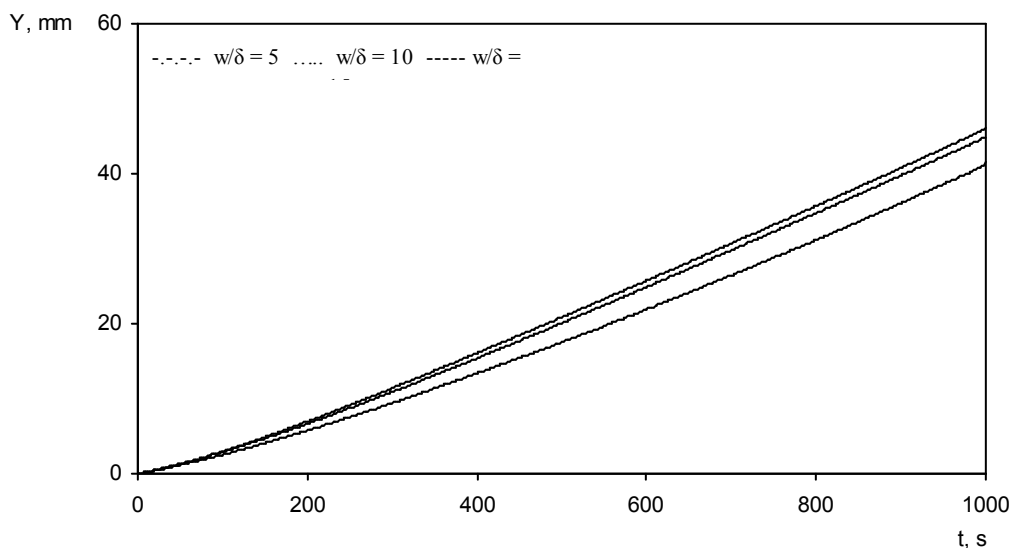

Fig. 7. The variation of burned height of PMMA sheet versus time (δ =7 mm)

At the present work, the flame spread rate is determined by two methods as follows: - Videotape, V is calculated from the time required that flame to spread between the pen lines marked beforehand (10 mm). - Slope of burning mass curve, in Figs. (4-7) since Y = Vt + a, then the slope of curves shows V. The results obtained from both methods are compared with data obtained from experimental results of Ayani [13]

$$V = 0.1038(1/\delta) + 0.03471 \qquad\qquad (11)$$

where V is the flame spread rate (mm/s), and experimental results of Fernandes-pello and Williams [33].

The variation of the flame spread rate V with respect to sheet thickness δ for PMMA is shown in Fig. 8. This figure shows that the downward flame spread over the PMMA sheet decrease and approaches to a constant value as the sample thickness increased.

The experimental results show that the slope of curves reach to a constant value if w/δ >10. In other words, if w/δ >10 then the flame spread rate for all the values of width of sheet is constant, and it can be consider one-dimensional analysis. This experimental result is determined the criteria value for w/δ that is obtained in the analytical analysis.

6- Conclusions

This study investigated downward flame spread over a thin PMMA sheets in the quiescent air in an open space, both experimentally and by scale up of steady state energy equation. The parametric study is based on the variation of temperature and the scale up model. The experimental results are used to obtain the criteria value for the relation between width and thickness of sheet. The theoretical consideration shows the temperature distribution and consequently the downward flame spread over the sheet independent of the x and z direction. Generally, the theoretical results and measurements give identical qualitative trends for the flame spread rate if $w/\delta > 10$.
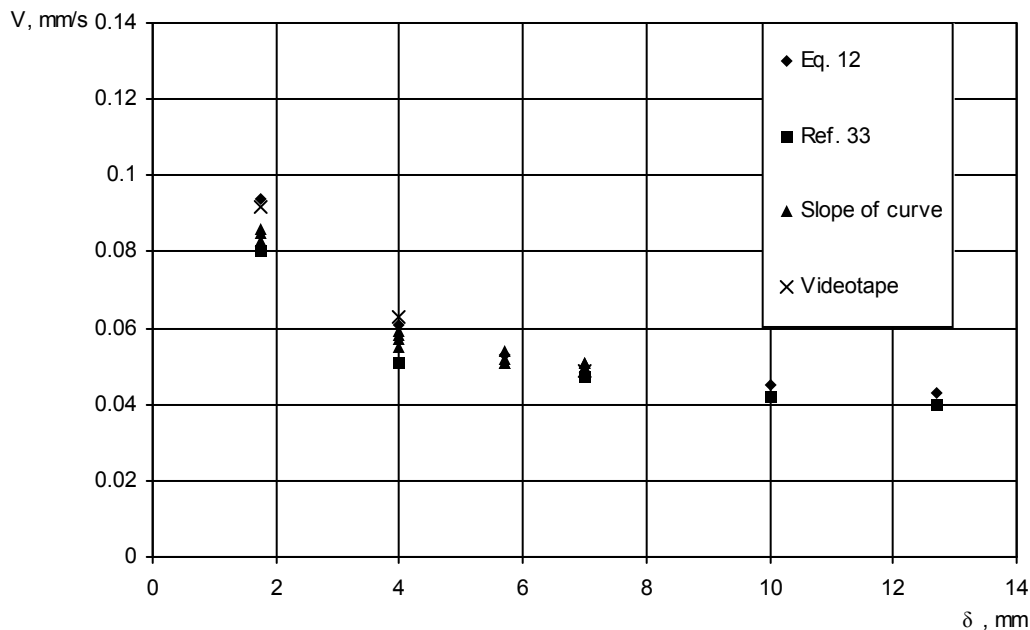

Fig. 8- The variation of the flame spread rate of PMMA with respect to the sheet thickness

References

1- Bhattacharjee, S., Wakai, K., Takahashi, S., "Predicting of critical fuel thickness of flame extinction in a quiescent microgravity environment," Combustion and flame, Vol. 132, pp. 523-532, 2003.

2- Lefebvre, J., Bastin, B., Bras, M. L., Duquesne, S., Ritter, C., Paleja, R., Poutch, F., "Flame spread of flexible polyurethane foam: comprehensive study," Polymer Testing, Vol. 3, pp. 281-290, 2004.

3- Fujita, O., Takahashi, J., Ito, K., Proceeding of the Combustion Institute, Vol. 28, Pittsburgh, p. 2761-2767, 2000.

4- Niioka, T., Takahassi, M., Izumikawa, M., "Gas –phase ignition of a splid fuel in a hot stagnation point flow," 18th Symposium (International) on Combustion, pp. 741-747, 1981.

5- Brehob, E. G., Kulkarni, A. K., "Experimental measurement of upward flame spread on vertical wall with external radiation," Fire Safety J. Vol. 31, pp. 181-200, 1998.

6- Magee, R. S., Mcalevy, R. F., "The mechanism of flame spread," J. of Fire and Flammability, Vol. 2, pp. 271-282, 1971.

7- Perrins, L. E., Pettett, K., "Measurement of flame spread velocities," J. of Fire and Flammability, Vol. 5, pp. 85-96, 1974.

8- Lin, P. H., Chen, C.H., "Numerical analysis for radiative auto ignition and transition to flame spread over a vertically oriented solid fuel in gravitional field," Combust. Sci. Technol, Vol. 151, pp. 157-187, 2000.

9- Higuera, F. J., "downward flame spread along a vertical surface of thick solid in the thermal regime," Combustion Theory Modeling, Vol. 3, pp. 147-158, 1999.

10- Wu, K. K., Fan, W.F., Chen, C. H., Liou, T. M., Pan, I.J., "Downward flame spread over a thick PMMA slab in an opposed flow environment: Experiment and modeling," Combustion and Flame, Vol. 132, pp. 697-707, 2003.

11- Di Blasi, C., "Influences of sample thickness on the early transient stage of concurrent flame spread and solid burning," Fire safety J. Vol. 25, pp. 287-304, 1995.

12- Lin, P. H., "Numerical analysis for downward flame spread over a thin and thick fuels in a gravitation field," Combustion Flame, Vol. 118, pp. 744-746, 1999.

13- Ayani, M. B., Esfahani, J. A., Mehrabian, R., "Downward flame spread over PMMA sheets in quiescent air: Experimental and theoretical studied," Fire Safety, Vol. 41, pp. 164-169, 2006.

14- Mita, I., Effects of Structure on Degradation and Stability of Polymers, in Aspects of Degradation and Stabilization of Polymers, Chap. 6, (H. H. G.) Jellink, Ed., Elsevier Scientific, Amsterdam, 1978.

15- Kelen, T., Polymer Degradation, Van Nostrand, New York, 1983.

16- Hamins, A., Klassen, M. E., Gore, J. P., Fischer, S. J., and Kashiwagi, T., "Heat Feedback to the Fuel surface in pool Fires," Combustion Sci. Technol. Vol. 97, pp. 37-62, 1994.

17- Choi, M. Y., Hamins, A., Rushmeier, H., and Kashiwagi, T., "Simultaneous optical measurement of soot volume fraction, temperature and CO_2 in heptan pool fire," 25th Symposium (International) on Combustion, Vol. 1, pp. 1471-1480, 1994.

18- Kashiwagi, T., "Radiation ignition mechanism of solid fuels," Fire Safety J. Vol. 3, pp. 185-200, 1981.

19- Finlayson, E. U., Aung. W., and Kashiwagi, T., "Theoretical Models for Combined Radiation-Conduction in Polymeric Solids Heat by External Radiative Flux," Proceedings of the ASME/JSME Thermal Engineering Joint Conference, pp. 525-536, 1987.

20- Manohar, S. S., Kulkarni, A. K., and Thynell, S. T., "In Depth Absorption of Externally Incident Radiation in Non-Gray Media," Heat and Mass Transfer, Vol. 21, pp. 236-244, 1995

21- Incropera, F. P., and De Witt, D. p., Introduction to Heat Transfer 4th ed., John Wiley & Sons, 2002.

22- Michael, M. F., Heat Radiation and Absorption, New York, McGraw-Hill, 1993.

23- Glassman, I., Combustion 3th ed., Academic Press, 1996.

24- Esfahani, J. A., Sousa, A. C. M., "Ignition of epoxy by a high radiation source : A numerical study," Int. J. Thermal Sci. Vol. 38, pp. 315-323, 1999.

25- Esfahani JA., "Oxygen sensitive thermal degradation of PMMA: A numerical study," Combustion Sci. and Tech. Vol. 174, pp. 183-198, 2002.

26- Sousa, A. C. M., Esfahani JA., "Numerical modeling of PMMA ignition induced by monochromatic radiation," 17th UIT national heat transfer conference, pp. 409-420, 1999.

27- Suzuki, M., Dobashi, R., Hirano, T., "Behavior of fires spreading downward over a thick paper'" Proceeding of the 25th Symposium on Combustion, pp. 1439-1446, 1994.

28- Drysdale, D., An introduction to fire dynamics 2nd ed., J Wiley, 1999 [Chapter 6 & 7].

29- Test methods, specification and standards, vol. 2, fire safety aspects of polymeric materials, Technomic, 1979.

30- Troitzsch, J., International plastics flammability handbook, Hanser, 1983.

31- Janssens, M., SFPE handbook of fire protection engineering, NFPA, 1995.

32- Kashiwagi, T., "Polymer combustion and flammability-role of the condensed phase," Proceeding of the 25th symposium (International) on combustion, pp. 1423-1437, 1994.

33- Fernandez-Pello, A. C., Williams, F. A., "Laminar flame spread over PMMA surfaces," Proceedings of the 15th symposium (International) on combustion, pp. 217-231, 1975.