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ABSTRACT

In this paper the effect of the dimensions of the polymer sheets upon the downward flame spread is studied by theoretical and experimental methods. In the theoretical method, the effect of the solid fuel dimensions on the energy balance in the solid phase is studied by the order of magnitude of parameters. In the experimental method a sample of polymethyl methacrylate (PMMA) sheets with various thicknesses (1.75 – 7mm) and width (10 – 150mm) is examined in a big room with quiescent air. A slit burner, a camera, a load cell and a thermocouple are used to ignite, videotape the movement of surface, record the mass of the specimen and measure the temperature during the process, respectively. In this study, theoretical model shows for a large value of the ratio of the width of the sample to its thickness, can be the processes considered by one-dimensional model. So that the temperature distribution and consequently the flame spread rate are functions of thickness and physical properties of sheet. Also, the experimental results confirm the result of theoretical model. The experimental result shows the flame spread rate is independent of the width of the sample if the ratio is bigger than ten.

Keywords: Combustion; Downward flame spread; PMMA; Solid fuel.

INTRODUCTION

Synthetic polymers are pervasive parts of society. They can be found in every commercial building, residential house, transportation vehicle, etc. The precise reasons for using polymers are many, although two prominent designs have been considered as follows: - mass reduction of systems that causes increased efficiency of them - reduced manufacturing costs. However, one weak aspect of synthetic polymer materials compared to the traditional materials is their combustibility under certain conditions. Therefore, it is important to understand how polymers burn and how they are modified and made less flammable. Thus, majority of polymers containing end products must pass some type of regulatory test to help assure public safety from risk of 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. Kashani and Esfahani (2008) and Esfahani and Kashani (2006) studied a transient one dimensional model to formulate a substantial role of polymer gasification. The purpose of the study was to investigate the interaction between the oxygen diffusion and related volatiles on the rate of polymer degradation. Also, Esfahani and Abdolahadi (2007) studied the effect of char layer on the unsteady thermal oxidative degradation of polyethylene (PE). Numerical simulation of thermal oxidative degradation of PE and effect of oxygen concentration on gasification, absorptivity and reflectivity of PE was the purpose of this work.

Esfahani et al. (2005) studied a transient two dimensional model of thermal and oxidation degradation of PMMA subjected to a monochromatic, radiation heat flux. The purpose was to improve a degradation model to analyze the effect of oxygen on the route of thermal degradation mechanism. Fujita et al. (2003) 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 increase in oxygen concentration or pressure. Lin and Chen (2000) developed an unsteady two-dimensional combustion model, which includes radiative ignition and the subsequent transition to the flame spread over a vertical thermally thick solid fuel under a normal gravity. In the first heating stage, the maximum temperature increases with time but the rate of increase slows down due to pyrolysis reaction. In the second stage, the flame is formed and propagates over the solid.

Bhattacharjee et al. (2003) studied a general opposed flow flame spread in a quiescent microgravity environment which uses the novel time scale analysis. The purpose was to bring together various sub regimes of fundamental topic by examining the characteristic times of participating processes. Several experiments (Niioka et al. 1981, Brehob and Kulkarni 1998, Magee and Mcalevy 1971, Perrins and Petett 1974) have investigated the effect of the temperature of the opposed flow on a flame behavior. It was found that ignition delay time decreases and flame spread rate increases with the increasing temperature of the opposed flow.

Lefebvre et al. (2004) 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 showed that a high density
leads to a lower flame spread and to a longer step of melting of the foam. Di Blasi (1995) and Lin (1999) investigated how the thickness of the solid fuel influenced the behavior of downward flame spread, 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 the solid fuel. Finally, in the third regime, the flame spread rate becomes almost constant when the fuel thickness increases over a certain amount. Higaera (1999) studied the steady two dimensional downward flame spread on a vertical surface of a thermally thick solid fuel and showed that the flame moved into the gas immediately upon inception. Wu et al. (2003) studied downward flame spread over a thick PMMA slab in a mixed convection environment by experimental and unsteady numerical modeling. They showed that the flame spread rates increase by decreasing the velocity or increasing the temperature of free stream in the opposed flow. Ayani et al. (2007, 2006) studied downward flame spread over PMMA sheets and showed that the flame spread rate decreases with increasing the thickness of the sheets. They studied the spread rate for the various solid thicknesses with constant width samples. Mamourian et al. (2009) studied downward flame spread over vertical PMMA sheets and obtained an equation for the flame spread rate based on the thermal properties and the thicknesses of the sheet by scale up method. They measured the temperature within the solid and gas phases and showed that the gradient temperature in the solid phase decreases by increasing the thicknesses of the sample. They also show the preheating length of the sample is proportional to its thickness.

In the present work, the flame spread over the solid fuel is studied by theoretical analysis and the effects of the dimension of the solid fuel on the flame spread rate are investigated. Also the downward flame spread over PMMA sheets is studied experimentally. Comparison of experimental results with the theoretical estimates shows good agreement.

**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. Fire initiation is influenced by the 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 solid fuels, the simplest case of fire initiation is one-dimensional. Fire initiation on the sheet of materials subjected to the thermal source may thus be visualized as 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 may be complex. Combustion of synthetic polymer materials is characterized by a complex interaction between condensed and gas phases. Furthermore, each phase consists 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 dimensions 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 begins and evolves small gaseous degradation products. There are several books and articles that describe thermal degradation chemistry in details (Mita 1978, Kelen 1983). 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 (Ito and Kashiwagi 1986, Fernandez-Pello and Hirano 1983, Williams 1977).

A schematic of the physical model of the sample sheet and its dimensions is shown in Fig.1. A sheet of PMMA is exposed to a high heat source (burner) from its top surface and is held in the quiescent air in an open space. Heat is input from gas to the solid phase by diffusion, transferred by radiation from the top of the solid fuel to the surrounding with temperature \( T_\infty \), advected by volatiles, consumed by thermal degradation and stored in the solid fuel.

In Fig. 1, \( q''_e \), \( q''_g \), and \( q''_a \) are the heat flux emitted from the solid surface (\( w/m^2 \)), the diffusion of heat flux from gas to the solid phase (\( w/m^2 \)), the advection heat flux that transferred by volatiles (\( w/m^2 \)), respectively and \( S \) is the rate of degradation of the solid fuel (\( kg/m^2.s \)).
Fig. 1. The physical model and the coordinate system fixed on the sample sheet

MATHEMATICAL MODEL

As the solid surface is exposed to the heat source, heat is penetrated in the solid along its depth and causes the temperature in the solid to increase, so that the thermal degradation is begun in the solid. The rate of degradation of the solid fuel can be represented by Arrhenius law (Glassman 1996):

\[ S = -A_0 \exp\left(-\frac{E}{RT}\right) \rho \]  

(1)
where $A_0$, $E$, $R$, $T$, and $\rho$ are the zero order pre-exponential factor (1/s), 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 can be determined as follows:

$$q = q_p.S$$  \hspace{1cm} (2)

where $q_p$ is the heat of degradation per unit mass (J/kg).

The advection heat flux transferred by volatiles is formulated as:

$$q''_a = m''.h$$  \hspace{1cm} (3)

where $h = C_p\rho T$ and $m'' = \int_0^\infty A_0 \exp(-E/RT) \cdot \rho dy$  \hspace{1cm} (4)

In view of the complexity of the physical situation, and to simplify the modeling approach the following assumptions were made:

- steady state process.
- all thermal properties of the fuel sample are constant.
- no thermal contraction or expansion is considered as time elapse.
- melting and dynamics of bubble movement are neglected.
- thermal radiation from the flame to the sample is negligible.
- gravitational forces are negligible compared to the inertia forces.
- constant pyrolysis temperature.
- constant pressure condition.
- The volatiles within the solid moves only in the y direction.

By use of Eqs. (1-4) and the above assumptions, the first law of thermodynamics for the control volume in the solid phase is obtained as follow (Ayani et al. 2007):

$$k(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2) - A_0 \rho q_p \exp(-E/RT) + \partial(m'' h)/\partial y = 0$$  \hspace{1cm} (5)

The coordinate systems fixed at the leading edge of the sample sheet (Fig. 1). W, b and $\delta$ are the width of the sample in the x direction (mm), the length of the pyrolysis region ahead of the flame in the y direction (mm), and the thickness of the sample in the z direction (mm), respectively. With the following dimensionless definition of the parameters:

$$\bar{x} = x/W, \bar{y} = y/b, \bar{z} = z/\delta, \bar{m} = m''/m_{ref}, \bar{T} = (T - T_\infty)/(T_p - T_\infty) = \theta/\theta_p$$  \hspace{1cm} (6)
equation 5 is being non-dimensionalized as follow:

$$(\delta/W)^2 \frac{\partial^2 T}{\partial x^2} + (\delta/b)^2 \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - C_2 \exp\left\{-E/[R(T_0 + T_\infty)]\right\}$$

$$+ C_1 \frac{\partial(\bar{T} \bar{m})}{\partial \bar{y}} + C_1 (T_\infty/\theta_p) \frac{\partial \bar{m}}{\partial \bar{y}} = 0$$

(7)

where

$$C_1 = m_{m0}C_m \delta^2 / (bk) \quad \text{and} \quad C_2 = A \rho \sigma \delta^2 / (k \theta_p)$$

The major part of heat transfer through the pyrolysis region takes place in the critical zone (in the first 2mm distance ahead of the flame) in the vicinity of the flame foot (Ito and Kashiwagi 1986, Esfahani 2002, Sousa and Esfahani 1999, Suzuki et al. 1994). Then the order of $\delta$ and the order of $b$ ($b\approx 2 \text{ mm}$) are the same. If $\delta << W$, the first term at the left hand side of Eq. 7 is much smaller than the second term and can be neglected. When the thickness of the solid is very thin compared to its width, the temperature gradient in the z direction is much smaller than the y direction and hence can be neglected. Thus, the temperature distribution becomes one-dimensional (y direction) as follow:

$$(\delta/b)^2 \frac{\partial^2 T}{\partial y^2} - C_2 \exp\left\{-E/[R(T_0 + T_\infty)]\right\} + C_1 \frac{\partial(\bar{T} \bar{m})}{\partial \bar{y}}$$

$$+ C_1 (T_\infty/\theta_p) \frac{\partial \bar{m}}{\partial \bar{y}} = 0$$

(8)

Therefore, the theoretical model shows the temperature distribution for large widths and small thicknesses is one-dimensional in y direction. The extent value of $W/\delta$ is determined by the experimental data that is explained in the following section.

**EXPERIMENTAL APPARATUS AND CONDITIONS**

The factors which affect the rate of flame spread across a surface are listed by Drysdale (1999). These factors include the time and magnitude of an imposed heat flux, the composition of the atmosphere, the surface orientation, the direction of flame propagation, air velocity, surface roughness, geometry, sample thickness, 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 mentioned that in a real fire, many of these parameters are always changing (such as temperature, imposed heat flux, oxygen concentration). For simplicity,
Fig. 3. The variation of the burned height of PMMA sheet versus time ($\delta = 1.75\, mm$)

Fig. 4. A zoom of the variation of the burned height of PMMA sheet at steady regime ($\delta = 1.75\, mm$)
RESULTS AND DISCUSSION

The burned height of the sample sheets is obtained by two methods as follows:

- the instantaneous mass of the sample that is measured by the load cell. The burned height of the sample at each time can be determined by transforming the load cell data using the following relation:

\[ Y = \frac{(m_0 - m)}{(p \cdot A)} \]  \hspace{1cm} (9)

where \( Y, m_0, m \) and \( A \) are the burned height of the sample sheet, the initial and the instantaneous mass of the sample and the cross section area of the sample, respectively.

- the specified distance which is pen lines marked on the sample (\( \Delta Y = 10 \text{mm} \)).

The variation of burned height of PMMA sheet with respect to time for different thicknesses based upon the load cell data is shown in Figs. (3-7), which show that the burning of the solid fuels consists of two regimes. First are the unsteady regimes, where the slope of the curves depends upon time (approximately the burning of the first 20 mm of the solid fuel). This regime occurs because of the initial effects such as: the movement of the pilot over the surface, the angle of the pilot with the surface, ignition times and the heat flux consumed for beginning of degradation. Second are the steady-state regimes, where the slopes of the curves are independent of time.
in this study, all these factors are assumed to be constant except the dimension of the sheets.

Testing methodology

There are a variety of tests which have been developed to establish the manner in which materials will behave in fires (Drysdale 1999, Test methods 1979). These are principally small scale standard tests (Troitzsch 1983), full scale tests and finally newer tests which examine a material reaction to fire, such as the cone calorimeter (Janssens 1995). 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 scales are arbitrary, and therefore, results from one test do not necessarily agree with another one (Kashiwagi 1994), 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 in well-defined conditions and the results used as inputs to fire growth models are analyzed using theories of combustion to drive values of critical parameters that determine flammability properties (Kashiwagi 1994).

Experimental set up

Figure 2 schematically depicts the experimental set up. Sample of PMMA sheets are made of various thicknesses from 1.75 to 7 mm with various widths from 10 to 150 mm. The sheets are made by Acrylic Enterprise Co., Ltd. in Taiwan. A sample sheet is clamped between pairs of metal straps suspended in a big room, therefore the walls temperature of the room doesn’t effect on the processes and air on faraway of the test apparatus is quiescent. A slit burner is used to ignite the sample along its top edge and is removed after ignition. To observe spreading behavior, the surface of the sheet is videotaped during the flame spread. The test samples are mounted on the load cell (GF series 400/GF from A&D Company with 1 mg minimum display and ± 0.5 mg accuracy) which records the mass of the specimen during the process every second. A 25μm wire diameter k-type thermocouple is mounted, approximately 30 mm below the surface of the virgin solid, for measuring the history of interior temperature of the sample.

The rate of flame spread is measured by the videotape for the time required to propagate the flame through the specified distance (10mm), or by the mass reduction rate from the load cell. For each thickness and width, the test is repeated 5 times to minimize experimental errors.
Fig. 5. The variation of the burned height of PMMA sheet versus time ($\delta = 4\ mm$)

Fig. 6. The variation of the burned height of PMMA sheet versus time ($\delta = 5.7\ mm$)
In the present work, the flame spread rate is determined by two methods as follows:

- from the slope of the best fit lines in Figs. (3-7). Since \( Y = Vt + a \), the slopes of the curves in the steady-state regime show the flame spread rate.

- from videotape, the flame spread rate is calculated from the time required that flame to spread between the pen lines marked beforehand, then using \( V = \Delta Y/t \).

Figure 3 shows the burned height of PMMA sheet versus time based on the load cell data for different widths and fuel thickness of 1.75 mm at both unsteady and steady-state regimes. The dispersion of data from the best fit curves in Fig. 3 shows that uncertainty for \( W/\delta < 10 \) and \( W/\delta > 10 \) at steady-state are about \( \pm 1.1 \) mm and \( \pm 0.65 \) mm, respectively. Figure 4 displays the burned height of PMMA sheet versus time for different widths and fuel thickness of 1.75 mm at steady-state regime. The flame spread rate is determined from the slope of the best fit line that is sketched in this figure. The flame spread rate increases from 0.089 to 0.097 mm/s with increasing \( W/\delta \) from five to ten, and for \( W/\delta \) between ten and fifteen it is 0.098 ± 0.011 mm/s and independent of \( W/\delta \). In Figs. (3-7) the same results are shown for fuel thicknesses of 4, 5.7 and 7 mm, respectively. They also show that the flame spread rate increases with increasing \( W/\delta \) when \( W/\delta < 10 \) and remains almost constant when \( W/\delta > 10 \). The flame spread rate for fuel thicknesses of 4, 5.7 and 7 mm obtained from slop
of curves at steady-state regime are $0.058 \pm 0.006$, $0.051 \pm 0.005$ and $0.049 \pm 0.005$ mm/s, respectively.

The experimental results show that the slope of the burned height curves reach to a constant value if $W/\delta > 10$. In other words, if $W/\delta > 10$ then the flame spread rate is constant, and the analysis can be considered one-dimensional. This can occur since edge effects and the problem must be considered two-dimensional at lower widths. The experimental result confirms the criteria value for $W/\delta$ that is obtained in the analytical analysis in section 3.

The variation of the flame spread rate with respect to sheet thickness for PMMA is shown in Fig. 8. The results obtained from both methods are compared with data obtained from experimental results of Fernandez-Pello and Williams (1975), and experimental results of Ayani et al. (2006):

$$V = 0.1038(1/\delta) + 0.03471 \quad (10)$$

![Graph](image)

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

This figure shows that the downward flame spread over the PMMA sheet decreases and approaches to a constant value as the sample thickness is increased.

The temperature distribution in the solid phase that is measured by a thermocouple for five different experiments for PMMA sheet with $\delta = 1.75$ is shown in Fig. 9. It shows that, the solid temperature decreases sharply at about
2 mm ahead of the foot flame and becomes smooth afterwards. In other words, the temperature gradient of distances longer than 2 mm is much smaller than shorter ones. Therefore, the major part of heat transfer takes place in the first 2 mm distance ahead of the flame. This result supports \( b \approx 2 \text{ mm} \) which was used previously in the scale analysis (\( \delta \approx b \)).

![Graph showing temperature variation](image)

**Fig. 9.** The variation of temperature in the solid fuel with respect to the distance from the surface of solid (\( \delta = 1.75 \text{ mm} \))

### CONCLUSIONS

This study investigated downward flame spread over a thin polymethyl methacrylate (PMMA) sheets in the quiescent air in an open space, both experimentally and theoretically. The parametric study is done based on the conservation of the energy and the scale up model, and results in the following concluding remarks:

- The theoretical consideration shows the temperature distribution and consequently the downward flame spread over the sheet for large width and small thickness is one dimensional.

- The experimental results show that if the ratio of the width to the thickness of the sheet is bigger than ten, the spread rate is constant and the analysis can be considered one dimensional.

- The theoretical results and measurements give identical qualitative trends for the flame spread rate if \( W/\delta > 10 \).
NOMENCLATURE

\( A \)  Heat transfer area (\( m^2 \))
\( A_0 \)  Zero order pre-exponential factor (\( s^{-1} \))
\( b \)  Length of ahead of pyrolysis region (\( mm \))
\( C_{pr} \)  Specific heat of gases at constant pressure (\( J.kg^{-1}.K^{-1} \))
\( E \)  Activation energy (\( J.kg^{-1} \))
\( h \)  Enthalpy of volatiles (\( J.kg^{-1} \))
\( k \)  Thermal conductivity of solid (\( W.m^{-1}.K^{-1} \))
\( m \)  Instantaneous mass (\( g \))
\( m^* \)  Rate of mass loss (\( kg.m^{-2}.s^{-1} \))
\( m_0 \)  Initial mass (\( g \))
\( q \)  Rate of heat (\( W \))
\( q_a^* \)  Advection heat flux (\( W.m^{-2} \))
\( q_e^* \)  Emitted heat flux (\( W.m^{-2} \))
\( q_p \)  Heat of degradation per unit mass (\( J.kg^{-1} \))
\( R \)  Gas constant (\( J.kg^{-1}.K^{-1} \))
\( S \)  Rate of degradation (\( kg.m^{-3}.s^{-1} \))
\( T \)  Temperature (\( K \))
\( t \)  Time (\( s \))
\( T_\infty \)  Ambient temperature (\( K \))
\( T_p \)  Pyrolysis temperature (\( K \))
\( V \)  Flame spread rate (\( mm.s^{-1} \))
\( W \)  Width of the sample (\( mm \))
\( Y \)  Burned height of the sample (\( mm \))

Greek symbols

\( \rho \)  Solid density (\( kg.m^{-3} \))
\( \delta \)  Thickness of the sample (\( mm \))

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التحقيق التجريبي لتأثير أبعاد الوقود الصلب على انتشار اللعب النحتي

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خلاصة

في هذه الورقة تم دراسة تأثير أبعاد صاحف البوليمر على انتشار اللعب النحتي بالطرق النظرية والتجريبية. في الدراسة النظرية، تم دراسة تأثير أبعاد الوقود الصلب على توافر الطاقة في الحالة الصلبة بواسطة ربط العناصر. أما في الدراسة التجريبية فقد تم اختبار عينة من صبقة PMMA بمسمك مختلف (0.75 مليمتر) وعرض (10-150 مليمتر) في حجرة كبيرة ذات هواء ساكن. وتم استخدام مشعل صغير، كاميرا، وخلية حمل ومزودة حرارية للاشتعال، تصوير حركة السطح، تسجيل كتلة العينة وقياس درجة الحرارة خلال العملية. في هذه الدراسة، أظهر النموذج النظري أن القيمة الكبيرة لتسرب عرض العينة لمسكها، من الممكن أن تكون العملية المعبرة عن النموذج أحدى البقاء. لذا، فإن توزيع درجة الحرارة، وبالتالي معدل انتشار اللعب هما عاملان للسمك والخصائص الطبيعية للصاحف. إضافةً، أظهر النتائج التجريبية نتائج النموذج النظري. كما أظهرت النتائج التجريبيّة أن معدل انتشار اللعب لا يعتمد على عرض العينة إذا كانت النسبة أكبر من 10.
التحقيق التجريبي لتأثير أبعاد الوقود الصلب على انتشار اللهب التحتي

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