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Prediction model of Piloted Ignition Time for Thermoplastic Material

Xudong Cheng, Yong Zhou, Kaiyuan Li, Hui Yang, Heping Zhang*

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China

Abstract

The objective of this paper was to develop a prediction model to determine the ignition time of the thermoplastic material. Two different heat transfer mechanisms in the condensed phase and melting phase were taken into account in the model. The duration of phase change was also calculated using the melting enthalpy. The commercial Polypropylene (PP) was selected as testing material to verify the developed model. In the cone calorimeter tests, the PP samples with four different thicknesses, were tested under three different external heat fluxes, i.e., 20, 35 and 50 kW/m². The calculated and measured ignition times were compared and reasonable agreements were obtained. The comparative results show that the developed model gives more reasonable predicted ignition time.

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1. Introduction

Thermoplastic materials are widely used in our daily environment, but most thermoplastic materials are flammable. Lots of studies [1] have been conducted on the ignition behavior of combustible materials, especially for wood and wood products. Some analytical equations [2-3] have been developed regarding the dependence of ignition time on the radiant heat flux for both thermally thick and thermally thin materials. However, the combustion of thermoplastic material is a more complex process which involves melting stage that has been given little attention so far. The limited previous studies [4-7] have shown that the melting of thermoplastic material plays an important role during the ignition process and significantly affect the ignition time. Therefore it is worth investigating the ignition mechanism of thermoplastic material based on the previous studies.

The objective of this work is to develop a prediction model to determine the piloted ignition time of melting thermoplastic material, in which different heat transfer mechanisms inside the sample during the ignition process will be analyzed. Polypropylene (PP), as one of the most commonly used materials, is used as the testing material to verify the model. The ignition time is predicted using the model and compared to the experimental results from the cone calorimeter tests.

2. Prediction model

To simplify the developing process of the model, some basic assumptions are made: 1) Piloted ignition occurs when the surface temperature achieves the pyrolysis temperature; 2) The length and width of the thermoplastic sample are much larger than the thickness; 3) Temperature distribution inside the sample is

* Corresponding author. Tel.: 0086 551 63601665, E-mail address: zhanghp@ustc.edu.cn
nearly uniform when the material is melted. For typical thermoplastic material, the ignition process could be divided into three steps. Firstly, the temperature increases to the melting temperature via solid phase. In the second step, the solid phase starts to change to the melt by absorbing heat, while the temperature keeps as the constant melting temperature. During the third step, the phase of thermoplastic material has already changed to melt completely, and the temperature continues to increase.

During the first step, the heat transfer in thermoplastic material is a one-dimensional conduction problem [8]. At the exposed surface of the sample, the heat losses include convective heat loss and radiative heat loss. The external radiant heat flux at the exposed surface is steady whereas the back surface is insulated. Using the heat transfer theory [3], the surface temperature of the sample is calculated as,

\[
T_s = T_{so} + \frac{2(\varepsilon q_s^* - (h_s + h_r)(T_s - T_{so}))}{k \rho c_p} \sqrt{\frac{t}{\pi}} \quad (1)
\]

\[
t_i = \frac{\pi k \rho c_p}{4} \left( \frac{T_m - T_s}{\varepsilon q_s^* - (h_s + h_r)(T_m - T_{so})} \right)^2 \quad (2)
\]

During the second step, both the solid phase and melt exist simultaneously. Although the radiation heat is absorbed by the sample, there is no temperature increase. The heat balance equation can be expressed as:

\[
\Delta H_m \rho \frac{dS}{dt} = \dot{q}_{net}^* \Delta t = [\varepsilon q_s^* - (h_s + h_r)(T_s - T_{so})] \Delta t \quad (3)
\]

\[
t_2 = \frac{\Delta H_m \rho d}{\varepsilon q_s^* - (h_s + h_r)(T_m - T_{so})} \quad (4)
\]

During the third step, the thermoplastic material melt completely. The temperature distribution inside is nearly uniform. Therefore, the governing equation and third step can be described as,

\[
\rho c_p \frac{dT}{dt} = \dot{q}_{net}^* = \varepsilon q_s^* - (h_s + h_r)(T_s - T_{so}) \quad (5)
\]

\[
t_3 = \rho c_p \frac{d}{dt} \left( \frac{p_m - T_m}{T_m - T_{so}} \right) = \rho c_p \frac{d}{dT} \left( \frac{T_m - T_{so}}{\varepsilon q_s^* - (h_s + h_r)(T_m - T_{so})} \right) \quad (6)
\]

Combining Equations (4), (6) and (8), the piloted ignition time of thermoplastic material is obtained,

\[
t_{ig} = t_1 + t_2 + t_3 = \frac{\pi k \rho c_p}{4} \left( \frac{T_m - T_{so}}{\varepsilon q_s^* - (h_s + h_r)(T_m - T_{so})} \right)^2 + \frac{\rho d \Delta H_m}{\varepsilon q_s^* - (h_s + h_r)(T_m - T_{so})} + \frac{\rho d c_p (p_m - T_m)}{\varepsilon q_s^* - (h_s + h_r)(T_m - T_{so})} \quad (7)
\]

3. Results and discussion

Equation (7) could be used to calculate the piloted ignition time of thermoplastic material theoretically, which is affected not only by the thickness of sample, but also by the net external heat flux. For the thermoplastic material with a certain thickness, the ignition time is the quadratic function of the net heat flux at the sample surface; for the thermoplastic material exposed a certain external heat flux, the ignition time is directly proportional to the sample thickness.

Figure 1 compares the calculated and measured piloted ignition times with respect to the external heat flux. For a certain thickness, the ignition time decreases with the increasing of the external heat flux, and a parabolic relation is clearly indicated. Reasonable agreements are obtained between the calculated and measured ignition times. As shown in Figure 1, the calculated time is slightly higher than the measured time at a lower heat flux, and the discrepancy is reducing gradually as the external heat flux increases. The maximum error occurs at the 20kW/m² case where the calculated ignition time is approximately 54 s longer than the measured result. When the external heat flux increases to 50kW/m², the error between calculated and measured ignition time is rather small, which is less than 18 s. One possible reason for this outcome is likely to be the assumption of a uniform temperature distribution in the melt during the second step. For higher external heat flux, the temperature of sample increases rapidly which makes the assumption to be relatively reasonable. However, at lower external heat flux, the temperature increase slowly and the inside temperature distribution may be not uniform.

The piloted ignition time according to thermally thick model is also shown in Figure 1 and compared with the measured results. It can be found that the calculated piloted ignition time using the thermally thick model is independent with the sample thickness, which is obviously different from the experimental results. The ignition times determined by the thermally thick model are 184 s, 41 s and 18 s, respectively. Therefore, the thermally thick model could not reasonably describe the ignition behavior of thermoplastic material with different thickness.
Figure 1. Comparisons of calculated and measured ignition time for a certain thickness

Figure 2 shows the calculated and measured ignition times with respect to the sample thickness. It is clearly shown that for a certain external heat flux, both the calculated and measured ignition times are linearly proportional to the sample thickness. The error between the calculated and measured ignition times increases with the increasing of sample thickness. The ignition time from thermally thin model is also plotted in Figure 2. Although the trend is similar, the results are much higher than the measured results, indicating that the thermally thin model is not suitable for the thermoplastic material.
Figure 2. Comparisons of calculated and measured ignition time exposed to a certain external heat flux.

4. Conclusion
A prediction model was developed to calculate the piloted ignition time of thermoplastic material under external heat flux. In the model the ignition process was divided into three steps with different heat transfer mechanisms. The heat loss at the sample surface and the melting enthalpy of the thermoplastic material were taken into account. The calculated piloted ignition time of the PP sample using the developed prediction model was compared to the measured results, which were obtained from the previous cone calorimeter tests. Both the calculated and measured results show that for the thermoplastic material with a certain thickness, the ignition time is the quadratic function of the external heat flux; for the thermoplastic material exposed to a certain external heat flux, the ignition time is linearly proportional to the sample thickness. The discrepancy between calculated and measured ignition times is relatively small for short ignition times, but gradually noticeable for the thicker PP sample exposed to lower external heat flux, resulting in long ignition times. The ignition times calculated by the traditional thermally thick and thermally thin models are also involved for comparison and the results show that the developed model gives better predictions to the ignition times compared to the traditional models.

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References