

Numerical modeling of melting and dripping process of polymeric material subjected to moving heat flux: Prediction of drop time

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Abstract

Numerical simulations are carried out in order to predict drop-size and -time of molten polymer during fire. Mass, momentum and energy conservation equations are solved in a 2-D system based on a fixed grid by means of a finite volume method. The Volume of Fluid (VOF) method and the Enthalpy-Porosity method are applied to model the deformable polymer–air interface and the melting processes, respectively. Results successfully show the dynamic behavior of the molten polymer and the effect of the deformation on the melting process. It is found that the total heat flux at the melting front which directly controls melting speed is linearly correlated with the length of the melting front during frequent accumulation and dripping of molten polymer even if the inclination angle is varied. Drop-size and -time can be estimated by a simple force balance equation at the polymer–air interface, and show a linear correlation with a modified inverse Bond number and with a combined Capillary number and modified Bond number, respectively.
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1. Introduction

From a fire safety point of view, one of distinct features of polymeric material is its melting and dripping process during fires. When polymers whose pyrolysis mechanism is random scission (i.e., PE, PP) are heated up, their molecular weight is dramatically reduced during the decomposition processes, and they soften to undergo a melting

and dripping process. The melting and flaming drops can then remove the burning polymer and reducing heat release from the sustained-main polymer, whereas flaming drops possibly ignite other materials and promote fire growth on the ground. Therefore, attention is recently being paid to characterize the fire hazard caused by melting and dripping of the molten polymeric material.

Zhang et al. [1] found that the glass transition temperature plays a role in flaming drops, and claimed that the effect of the melting behavior should be considered in modeling the flame spread and burning rate for polymers. Butler et al. [2] and Oñate et al. [3] developed a numerical model for melting and dripping polymer objects in fires by

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using the Particle Finite Element Method (PFEM), and revealed that PFEM can calculate both melting and dynamic motion of polymers. However, although the temperature-dependent viscosity noted in experiment is used to define the motion of the molten polymer, the surface tension effect was excluded. Ohlemiller and Butler [4] conducted burning tests by using thermoplastic. They expected that when polymers whose pyrolysis mechanism is random scission (i.e., PE, PP) are burning, surface tension may play a role due to the fact that molten polymer tends to result in small size dripping. Kandola et al. [5] developed a methodology to quantitatively record the real-time melt and burn dripping behavior of vertically hanging small-size thermoplastic polymers, showing the limitation of measuring the number and size of drips. Authors et al. [6] simulated the melting and subsequent dripping processes in a simplified geometry which provides an analogy with the combustion over polymer suspended from a metal plate. Results show that the deformable polymer–air interface enhances the melting from the time of deformation to that of dripping as compared with the case that of a non-deformable polymer–air interface. In real fires, the flame is formed over the molten polymer and deforms as the shape of molten polymer varies so that the heat flux transferred from it to the unburned fuel also varies in time. In our previous research [6], however, we only considered a fixed heat source at a certain location for simplicity, and the melting front moves away from it as the time goes by and the melting speed becomes accordingly gentle. Therefore, this approach is insufficient to explain the role of the melting and deformation in the process in fire growth.

In this work we follow up previous research [6] by numerical investigations carried out to predict drop-size and -time of molten polymers during fire. To investigate this, we choose constant flame size, intensity and spread rate which are generally accepted range under fire condition, and ignore the gasification and chemical processes. Then, the flame is simplified as a fixed-size moving heat flux with constant speed traveling on the flat copper plate, which is located over the melting polymer. Consequently, the problem can be simplified as a melting and subsequent dropping process subjected to a moving heat flux. Figure 1 illustrates those simplifications. Where, red and blue¹ arrow represents the pass of heat and mass transfer, respectively. The governing equations can only consist of the fundamental conservation equations (for mass, momentum and energy) under a multi-phase framework. Here, we use the Enthalpy-Porosity [7] and Volume of Fluid

methods (VOF) [8] in order to model the melting and dynamic motion of molten matter suspended from a metal plate. Although the combustion process in the gas phase is not included on purpose for simplification, the fundamental heat transfer process governing the combustion of polymeric material should be satisfactorily captured in the present model. This study is done with commercial software (FLUENT 12.0) based on the finite volume method [9].

2. Mathematical and numerical model

Our numerical model calculates the time-dependent melting, deforming and dripping processes of polymeric materials subjected to moving heat flux to enable the investigation of drop-size and -time. This study involves two phase interface, namely, the melting front driven by energy absorption and the polymer-gas interface driven by momentum balance. The melting process is solved by the Enthalpy-Porosity method (for details, see [7]) and the motion of the molten polymer–air interface is calculated by the Volume of Fluid (VOF) method (for details, see [8]). By exploiting a combination of these methods, melting combined with a three-phase problem was properly considered. In order to reduce the numerical difficulty in calculating the transport properties, a piecewise polynomial approximation was applied that takes into account jumps of material properties at the melting front as well as at the polymer–air interface. Note that the polymer represents the universal expression of any meltable material, and the transient range between the solid and liquid (melting front) has the same physical meaning as the mushy zone in metallic alloy [6].

The complete process of melting, deforming and dripping of polymeric material is governed by a set of balance equations with a jump conditions implemented as volumetric source terms. Here, we assumed that velocity in the bulk of the polymer is the same with that along the surface between polymer and air. We restrict our treatment to constant material properties in each phase, assuming Newtonian fluid behavior, and neglect the effect of compressibility, viscous dissipation and the temperature effect in the bulk phases. The interface between the gas and other materials is assumed to be sharp enough to take account of the singular characteristics of the problem [10] under the assumption that the representative volume element is small enough to resolve the interface topology. Generally, the interface between the gas and other materials occupies only 2 grid cells. However, due to the characteristics of the mushy region between the solid and liquid, this region is modeled by assuming a thick interface. Although mushy region between the solid and liquid is determined by critical temperature

¹ For interpretation of color in Figs. 1 and 3, the reader is referred to the web version of this article.

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