



Prediction of properties and modeling fire behavior of polyethylene using cone calorimeter



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ABSTRACT

Fire behavior of pure polyethylene has been investigated by performing flammability analysis using a standard cone calorimeter. Specifications of polyethylene samples were 100 ± 1 mm long, 100 ± 1 mm wide and 5 mm thick, with mass of 25.0 ± 0.1 g. Sample surface area exposed to the external heat flux was limited to 94 mm in length, 94 mm in width due to use of edge lip sample holder frame. The values of external heat flux used were ranging from 40 to 55 kW m^{-2} with an incremental step of 5 kW m^{-2} . Three sets of experiments were performed for each value of external heat flux. The results obtained were recorded and fitted to a set of mathematical equations to determine the thermal inertia, critical heat flux and the peak heat release rate. Study shows that thermal inertia value obtained from experimental data was $0.86 \text{ kJ}^2 \text{ m}^{-4} \text{ K}^{-2} \text{ s}^{-1}$ and from well-known correlations was $0.83 \text{ kJ}^2 \text{ m}^{-4} \text{ K}^{-2} \text{ s}^{-1}$ with a difference of 3.49%. The factors to relate the observed critical heat flux with the actual critical heat flux were determined as 0.77 and 0.64. The peak heat release rate for each test was determined using the model equation based on oxygen depletion index and concentrations of gaseous species such as oxygen, carbon monoxide, carbon dioxide and water. The values observed experimentally and the ones calculated had a standard deviation of $\pm 4.56\%$. Thus, this work serves as basis for transformation of qualitative understanding of polyethylene fire behavior into systematic quantification, which can be generalized for other polymers and their composites.

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1. Introduction

It is observed that construction and manufacturing industries are favoring polymers over other materials due to their machinability, raw material cost, easy processing, availability and their structural & chemical stability. Apart from these attractive properties, their easy availability and a reliable supply at competitive prices are constantly out casting the conventional materials. This has resulted in transition with steady increase in the share of polymers in manufacturing industry. In the times when polymers are being accepted as a feasible and reliable replacement we also have to be cautious about the risks associated with them, specifically fire hazard. As we all know most of the conventional polymers are based on hydrocarbon backbone, which pose a fire hazard. Thus it is of prime importance to understand the fire behavior of polymers.

Efforts are ongoing to study the fire behavior of the polymers and their nanocomposites as promising flame retardants (Wang,

2013). Fire behavior of black polymethyl methacrylate (PMMA) was studied and its property characterization has been demonstrated (Luche et al., 2011). Similarly flammability analysis has been performed to investigate fire behavior of polystyrene (PS), polyethylene terephthalate (PET), polypropylene (PP) and polyvinyl chloride (PVC) (Shi and Chew, 2013). Fire behaviors of polycarbonates (PC) and polyvinyl chloride (PVC) have been investigated (Stoliarov et al., 2010). They have demonstrated the relation among cone calorimeter results with model equations using a computational framework called ThermaKin (Lyon and Stoliarov, 2009; Stoliarov et al., 2010). Generalized pyrolysis model for combustible solids using Gpyro model for polymethyl methacrylate (PMMA) and polyurethane foam have been developed (Lautenberger and Fernandez-Pello, 2009). Most of this research has yielded a general idea about how a polymer degrades under pyrolysis conditions, what are the different stages involved and the external factors governing the process. Thus a sound qualitative interpretation has been developed with an insight that the fire behavior can be modeled and hence quantified. As such pyrolysis models have been reviewed and published (Di Blasi, 1993;

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Kashiwagi, 1994; Fernandez-Pello, 1995; Moghtaderi, 2006; Fernandez-Pello and Lautenberger, 2008). Current research work is an effort to bridge this gap and create a platform for quantitative comparison of polymer fire behavior.

Enhancing the fire behavior of polymer means to reduce the generation of smoke and noxious gases, to prevent the entire polymer from getting burnt and increase the time until when polymer retains its mechanical strength so as to allow effective egress time in case of emergency fire scenarios. This calls for a quantitative understanding of the polymer fire behavior. This paper talks about the flammability analysis of pure polyethylene (PE) using cone calorimeter and validating a set of mathematical models to predict the polymer thermal inertia, critical heat flux and peak heat release rate. To conclude the paper, external heat flux and HRR have been correlated with thermal inertia of PE and exhaust gas composition resulting in quantitative interpretation of PE thermal degradation.

2. Experimental

2.1. Material specimen

Material used for this study was white non-charring Polyethylene (PE), supplied by SIGMA-ALDRICH. Being a laboratory grade polymer, it was assumed that sample contains negligible quantities of chlorine and sulfur impurities. Its molecular weight and molecular weight distribution were obtained using Gel Permeation Chromatography (GPC) (Sigma Aldrich Safety datasheet, 2014). PE employed in this work was in form of small granules with an average particle size of 1 mm. Number average molecular weight (Mn) for the sample is 7700 g mol⁻¹ and molecular weight is 35,000 g mol⁻¹ with melt index of 2250 g·(10 min)⁻¹. Polymers being employed in construction industry as support structures, separators, moisture containment and in other applications have density of 0.92–0.94 g cm⁻³, which corresponds to molecular weight of the order of >10,000 g mol⁻¹. Thus, polyethylene with molecular weight of 35,000 g mol⁻¹ was selected for the current study.

2.2. Cone calorimeter

Cone calorimeter is a sophisticated and a significant bench scale instrument employed to conduct flammability analysis of PE. Cone calorimeter has been accepted by the International Organization for Standardization (ISO) 5660-1 for measuring heat release rate of a sample (ISO 5660-1, 2002). It has been observed and recorded in the literature that approximately ~13.1 MJ of heat is liberated per unit kg of oxygen consumed in the combustion reaction. Thus based on the observed consumption of oxygen we can determine the amount of heat released for a sample under consideration. The instrument used for the current work is supplied by Fire Testing Technology Limited. Following were some of the important calibration parameters of cone calorimeter for current work in line with standard recommended practice by Fire Testing Technology Limited:

- Ambient pressure = 97.688 kPa
- Ambient temperature = 24 °C
- Relative humidity = 63%
- Exhaust duct volumetric flow rate = 24 ± 3 l s⁻¹ = 0.024 ± 0.003 m³ s⁻¹
- Baseline oxygen concentration = 20.95% (v/v)
- Baseline carbon dioxide concentration = 0.067% (v/v)
- Incident heat flux from cone heater (four tests) = 40, 45, 50, 55 kW m⁻²
- Surface area exposed to the incident heat flux = 88.36 cm²

2.3. Sample preparation

As the polyethylene sample was in granule form, it was precisely weighed into 12 equal samples of 25 gm each with an accuracy of ±0.1 gm. The temporary sample holder was created using aluminum foil. The sample was evenly spread through the sample holder having dimensions 100 × 100 mm ± 1 mm². Though the surface area exposed to incident heat flux is limited to 94 × 94 mm², due to use of edge lip sample holder frame. Thickness of the sample for all the tests was maintained uniformly as 5 mm. A practical spectrum of heat fluxes was employed ranging from 40 kW m⁻² to 55 kW m⁻² in step of 5 kW m⁻². Heat flux range was selected so as to make each test last over duration of 10–15 min, allowing sufficient time to record the data and properly spread profiles to identify different regions of polymer degradation. Three sets of tests were performed at each heat flux.

All polymer samples were mounted horizontally, using a specimen holder with edge frame. The bottom of the specimen holder was supported with two layers of insulating material with effective thickness of 30 mm. Each specimen was allowed to attain its autoignition temperature before getting ignited. No external ignition source or pilot flame was employed during the experiments. Following Fig. 1, a, b, c, d, e, f, g, h, i, j, k, l and m exhibit various stages of sample preparation and instances captured during a cone test. Also, the final remains obtained at the end of the test are demonstrated in part l and m.

2.4. Data collection

Various events were recorded during the timeline of each test such as start of test, ignition time, flame out time and end of test time. Here, start of tests corresponds to the instance when sample is first exposed to external heat flux. Ignition time corresponds to the instance when sample starts burning. Flame out time corresponds to the instance when the flame is almost about to extinguish. And test stop time corresponds to the instance when the external heat flux is stopped. Table 1 shows observations for ignition time and flame out time for each test.

3. Results and discussion

3.1. Thermal inertia

While studying the PE thermal degradation under autoignition condition (Shi and Chew, 2013), the only heat source available was cone. From the first principles of heat transfer (Rhodes and Quintiere, 1996; Hopkins Jr., 1996; Tewarson, 2002) following relations to relate external heat flux and ignition time with the basic properties of a polymer:

$$\dot{q}_{ext} = \frac{1}{\epsilon} \left[h_c (T_{ig} - T_0) + \epsilon \sigma T_{ig}^4 \right] \quad (1)$$

$$t_{ig} = \frac{2}{3} k \rho C_p \left(\frac{T_{ig} - T_0}{\dot{q}_{ext}} \right)^2 \quad (2)$$

$$\frac{1}{\sqrt{t_{ig}}} = \left[\frac{\epsilon}{\sqrt{\frac{2}{3} k \rho C_p (T_{ig} - T_0)}} \right] \dot{q}_{ext} - \left[\frac{h_c (T_{ig} - T_0) + \epsilon \sigma T_{ig}^4}{\sqrt{\frac{2}{3} k \rho C_p (T_{ig} - T_0)}} \right] \quad (3)$$

Here, \dot{q}_{ext} (kW m⁻²) is the set value of external heat flux being supplied by cone heater which remains constant through each test. t_{ig} (sec) is the recorded ignition time during each test. ϵ is the emissivity of PE which has a constant value of ~0.92. k

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