How dripping flames ignite a thin fuel

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1 Introduction

Dripping flame refers to the burning and melting solid fuel whose gravity can overcome its surface tension and then produce dripping phenomenon. At the early stage, the drips from ignited fuel are always accompanied with the flame during the dripping process. This phenomenon is widely observed in the burning of thermoplastics such as polyethylene (PE), polyethylene chloride (PVC), polypropylene (PP) and expanded polystyrene (EPS) [1]. Today, these thermoplastics have been widely used as the wire insulation [2,3] and a thermal insulation layer for the building façade, thus increasing the potential fire hazards of building fire [4], as shown in Fig. 1.

Figure 1. The dripping phenomenon in (a) electrical wire fire, and (b) façade fire.

Unfortunately, to the best of authors' knowledge, very few researches in the literature have investigated the phenomenon of dripping flame and the corresponding ignition process of other fuels. Wang *et al*. [5] studied the dripping behavior of different thermoplastic materials via the UL94 standard test [6]. The results

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show that there are two types of dripping group, small-size dripping with spherical appearances, such as low-density polyethylene (LDPE), and larger drip size. Later, the dripping process in the UL94 test was successfully simulated by Kempel *et al*. [7]. Kobayashi *et al*. [2] revealed that the dripping flow would control and increase the downward fire spread. He *et al*. [3] found that overload currents play an important role in promoting the wire fire spread, and the dripping frequency increases with the current. Kim *et al*. [8] simulated the melting, deformation and dripping behaviors of the phase change material (PCM), but the gas-phase flame was not modeled. In short, most past studies focused on the generation of dripping and its influence on the fire source. However, very few studies have investigated how the dripping flames ignite other fuels and start a new fire. In our previous study [1], the ignitability of PE drip is found to depend on whether the drip can carry a flame. When a PE drip is larger then 2.3 mm, it can carry a flame during the free fall for at least 2.6 m and ignite a 0.02-mm thick tissue paper. However, whether a single drip or how many drips are needed to ignite other fuels is still unclear, so there is a big knowledge gap.

In this work, we study how these dripping flames ignite the thin fuel. Well-controlled experiments are designed and conducted to investigate the ignition probability of printer paper with different thicknesses by PE drips. The size and number of drips are controlled to find the limiting ignition conditions.

2 Experiment setups

The experimental setup is upgraded from the previous work [1], and the schematic diagram is shown in Fig. 2(a). The drips are produced from a burning PE tube which is placed horizontally. A metal tube is inserted into the PE tube, and then fixed to the sample holder. To control the size and frequency of drips, PE tubes and metal tubes with different wall thicknesses are used. The metal tube can alter the cooling rate as well as the surface tension of molten PE, because the surface tension decreases significantly with the increasing temperature [9]. Therefore, PE tube with a thicker metal tube generally generates a bigger drip.

In this experiment, four kinds of drips of different mass (Types A-D) and a similar dripping frequency of about 1 Hz are produced. The mass of drip (M_{dr}) is measured by a precision balance (±0.1 mg), i.e., between 2 and 6 mg, as listed in Table 1. The random uncertainty of drip mass is less than 10% for multiple repeating tests. Video imaging process reveals that during the fall, the shape is not a perfect sphere but an ellipsoid, and the drip is porous as there are many small bubbles inside the drip. This strong bubbling process implies that the temperature of drip must be higher than the pyrolysis point of about 400 ℃. For simplicity, their equivalent diameter of a preface spherical drip (D_{dr}) is calculated by assuming a bulk density of the porous PE drip as ρ_{dr} = 640 kg/m^3, as listed in Table 1.

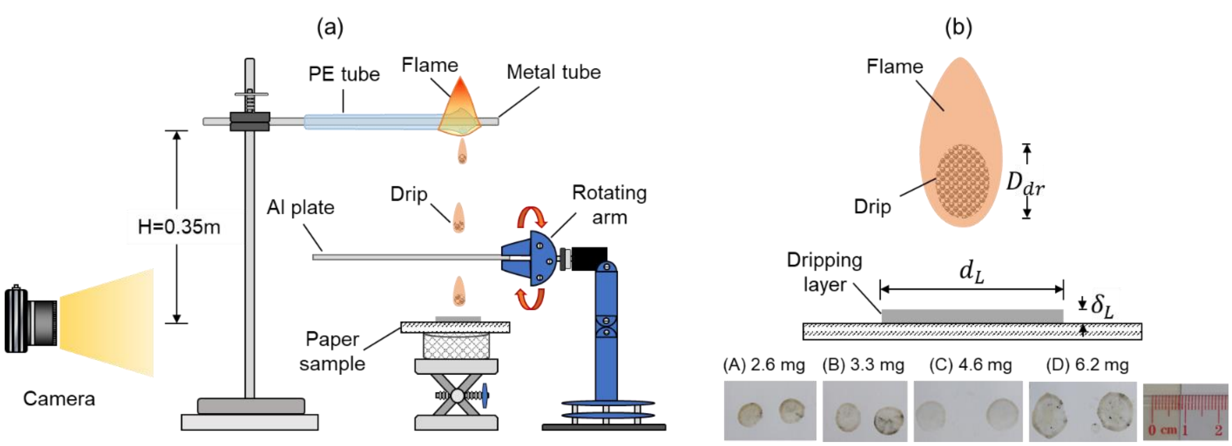

Figure 2. Schematic diagrams of (a) experiment apparatus for the printer paper sample ignited by PE drips with flames, and (b) the formation of dripping layers on the paper surface.

Once the drip lands on the surface of tested fuel, the PE drip will break and self-compress into a thin layer of PE, which can be equivalent to the thin cylinder, as illustrated in Fig. 2(b). Although a small amount of molten PE is splashed into tiny drips that flies away, the majority mass will stay, and the area of the landing drip is measured via the imaging process. The average equivalent landing diameter (d_L) of multiple drips are measured, and the layer thickness (δ_L) is calculated based on volume conservation. Both parameters are listed in Table 1, and their random uncertainty is less than 10%.

Table 1. Characteristics of drips tested in experiments.

Drip Type	**A**	**B**	**C**	**D**
Mass of drip, M_{dr} (mg)	2.6	3.3	4.6	6.2
Dripping frequency, f_{dr} (Hz)	1.5	1.2	0.7	0.7
Drip diameter, D_{dr} (mm)	2.0	2.1	2.4	2.6
Landing diameter, d_L (mm)	6.7	7.7	9.6	11.3
Landing thickness, δ_L (mm)	0.12	0.11	0.10	0.10
Thermal energy of drip, E_{dr} (J)	4.03	5.11	7.12	9.60
Energy flux, E''_{dr} (J/mm^2)	0.11	0.11	0.10	0.10

In this work, three different printer papers (Type I-III) as the characteristic thin fuel are tested. Their surface densities (ρ_p) are 75 g/m^2, 140 g/m^2 and 300 g/m^2. Their equivalent thickness (0.07 ~ 0.32 mm) is proportional to their surface density, as calculated and listed in Table 2. Note these paper samples are much thicker and less porous than previously tested tissue paper [1], so that they cannot be ignited by a single drip. The dimension of all paper samples is fixed as 10 cm × 7 cm (i.e., 1/9 of the A4 paper). The tested paper is placed horizontally on the top of a tubular mesh, so that the bottom of the paper is exposed to air. The distance between burning PE tube and the paper sample is fixed to be 0.35 m, and the flame will always attach to the drip until it lands on the paper surface.

Table 2. Characteristics of paper tested in experiments where the density of paper is 930 kg/m^3.

Paper Type	**I**	**II**	**III**
Surface density, ρ_p (g/m^2)	75	140	300
Calculated thickness, δ_p (mm)	0.07	0.15	0.32

In prior to the dripping ignition test, the PE tube is first ignited by a lighter, and the flame is allowed to develop and spread until drips are produced in a table manner. The ignition intensity is controlled by the number of drips (N). To better control the number of drips landing on the paper, a control system including the alumina (Al) plate, robot arm, and a PC is introduced. The mechanical arm is controlled by the PC to rotate the Al plate, which either blocks the drips or allows drips to land on the paper, as illustrated in Fig. 1(a). The testing process is recording by a camera (Sony D10 III) with a shooting speed up to 960 fps. Because the size and frequency of drips cannot be perfectly controlled and the ignition process is complex, a large experimental uncertainty is expected. Thus, more than 100 repeated tests are conducted for each type of drip and paper sample to estimate the ignition probability.

3 Results and discussions

Figure 3 shows the snapshots by a high-speed camera capturing the moment when the drip lands on the paper surface. For the first a few drips (Fig. 3a), the flame attaches to the drip to the paper and tends to form a small pool flame, but quickly extinguishes due to the cooling from the paper and its own weakness, i.e., a *weak flame*. Small flamelets also fly away with splashing tiny droplets. For the last a few drips before ignition (Fig. 3b), the dripping flame also ignites the flammable mixture above the landed drips like a small explosion, and the following blue flame propagation above the paper can also be observed, i.e., a *strong flame*. These strong flashes are expected to help drips ignite the paper and sustain the flame.

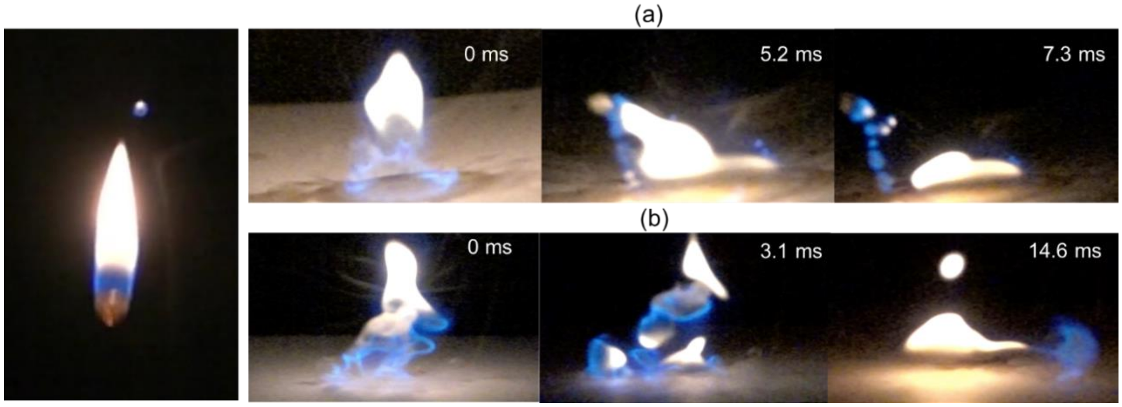

Figure 3. Ignition situations (a) weak ignition without explosion; (b) strong ignition with an explosion.

A successful dripping ignition of the thin paper is defined if a stable flame can be sustained and burn the entire paper, which also excludes smoldering ignition. The ignition probability, correlating the critical number and mass of drips and the density of the paper, is measured through the statistical analysis of repeating experiments. Referring to the past study on the hot-particle ignition [10,11], the ignition probability (P_{ig}) is defined as the ratio of the number of successful ignitions (N_{ig}) to the number of repetition (N_{tot}), as

$$P_{ig} = \frac{N_{ig}}{N_{tot}} \times 100\% \tag{1}$$

The ignition probability for three types of paper (I-III) as a function of the total mass of drips (M_{ig}) and the number of drips (N) with the mass of a drip (M_{dr}) are plotted in Fig. 4. P_{ig}= 50% is defined as the dripping ignition limit to compare the ignition intensity of each drip type and paper type.

Experiment results in Fig. 4(left) show that as the surface density (or the thickness) of paper is increased, both the required number of drips and total mass of ignition are increased. This is as expected, because with the paper becomes thicker, its thermal inertia increases, and more heat energy is required for the paper to reach the critical ignition condition. In other words, the dripping ignition process of paper also satisfies the classical Thermally-Thin Theory, that is, the required ignition energy or the difficult of ignition increases with the fuel thickness.

More interestingly, the required number of drips (N) for ignition is almost insensitive to the mass of a single drip (M_{dr}), as shown in Fig. 4(right). Specifically, Paper I needs about 4 drips to ignite; Paper II needs 7 drips; and Paper III needs 11 drips, where the number of drips is almost proportional to the thickness of the paper. Therefore, the required total mass of drips will increase almost linearly with the mass of a single drip. This result is unexpected, because a large total mass of drips means a large amount of ignition energy.

Nevertheless, scrutiny of the deformation process of drip reveals that for a larger drip, the size of landed drip on the paper is also larger, as visualized in Fig. 2(b) and summarized in Table 1. Meanwhile, the thickness of PE layer is almost the same (about 0.1 mm). In other words, the energy flux of each drip is almost the same (about 0.1 J/m^2). Although after many drips the size and thickness of landed drips will increase, the total energy flux (E''_{dr}) to the paper may still be the same. Considering the continuous dripping is like a pulsating heat flux, the equivalent heat flux ($\dot{q}''_{dr}$) is

$$\dot{q}''_{dr} = f_{dr} E''_{dr} \tag{2}$$

Thus, under a similar dripping frequency (f_{dr}), the equivalent heat flux is the similar for different drips.

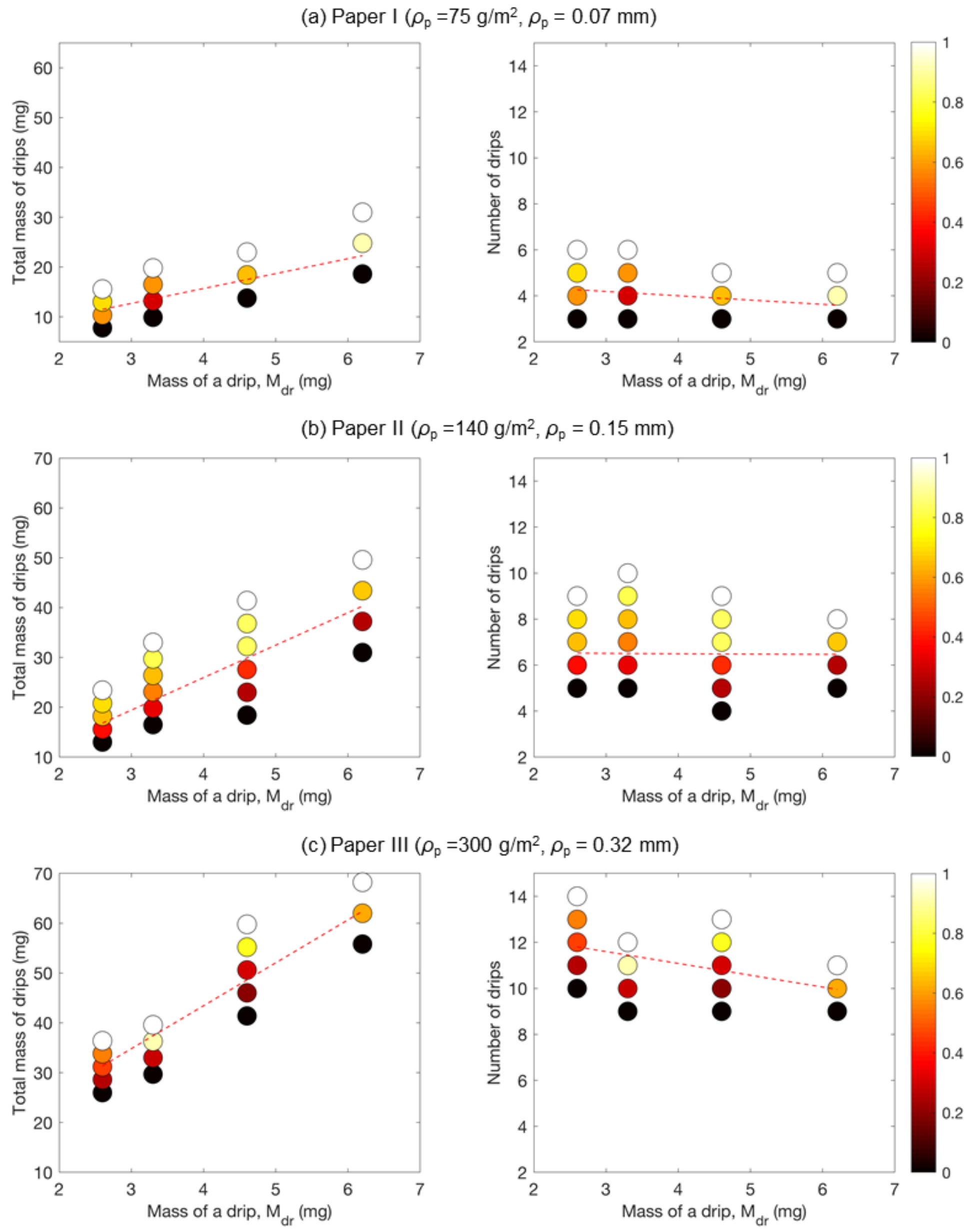

Figure 4. Dripping ignition limit as a function of total mass of drips (M_{ig}) and number of drips (N) with the mass of a drip (M_{dr}) for (a) Type I paper (ρ_p = 75 g/m^2), (b) Type II paper (ρ_p = 140 g/m^2), and (c) Type III paper (ρ_p = 300 g/m^2), where the ignition probability (P_{ig}) is scaled by the color bar.

In future work, more detailed ignition process will be studied with IR camera to measure the temperature of paper, and other fuels with different material and thickness will also be investigated for comparison. Due to the complexity of the dripping ignition process, several issues need to be considered when analyzing the ignition process. Firstly, the ignition is a collaborative result of heat transfer, mass transfer and chemical process at the surface. The phase change of the drips will affect the heat and mass transfer between the drips and the surface. If the drips accumulate on the surface of the material, a liquid pool fire may be sustained. As a result, the continuous heat transfer from multiple drips to the cold material may eventually bring the material, if flammable, to its pyrolysis point. Secondly, the surface temperature is considered as the criterion to characterize the fire point for the solid exposed to the constant heat flux. But for dripping fire ignition, this method may be not satisfied because the ignition heat flux is varied for dripping fire. Additionally, the explosion and flame shedding during the dripping process may induce a different ignition behavior. New criteria are needed to judge the ignition by dripping flame. Finally, some materials like PE can be absorbed by the paper to consist of a new type of fuel which has different physical property.

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