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An experimental study of fire growth and suppression of roll paper at small scales

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ABSTRACT

This study investigates roll paper fire using laboratory-scale experiments, with emphasis on water transport on burning surfaces for sprinkler suppression. Freeburn, water transport and suppression experiments were conducted using different types of paper with various basis weight and water absorptivity. For fire suppression, the experimental results showed different water transport patterns that are sensitive to the burning surface conditions. This is in contrast to the water transport under no fire conditions in straight vertical rivulets exhibiting highly non-uniform distribution along the roll perimeter. For roll paper fire growth, both surface delamination and exfoliation play a crucial role, with the delamination length increasing either linearly or exponentially with time and the exfoliation rates strongly dependent on paper basis weight. Although the effects observed at the small scale in this work may have differences from those at large scales, the experimental results yield insights for better understanding of fire growth and suppression mechanisms and provide extensive data for numerical model development and validation.

1. Introduction

High storage of roll paper is one of the most challenging fire hazards. The major challenges include extremely fast fire growth rate, e.g., on the order of megawatts per second [1], and very high water demand for adequate protection such as 9000 lpm under 18.3-m ceiling [2]. Full-scale testing has traditionally been used to determine the recommendation for sprinkler protection. Recently, numerical modeling [3,4] has been applied to help design full-scale tests to reduce the cost of testing and to increase the capability of generalizing the test results. Note that roll paper can be stored in different configurations, such as on-end arrays, on-side arrays, tambour arrays and even rack storage. This work, as well as many other previous studies, focus on the on-end storage, which typically presents the most challenging scenario for fire protection.

To evaluate roll paper fire hazards and assist model development, several experimental studies have been conducted to investigate both freeburn and suppression behavior of roll paper fires [1,5,6]. An early work of Xin and Troup [1] demonstrated the severity of fire hazards through intermediate-scale tests, and revealed the effects of paper area density and ash content on fire growth rates. Zeng et al. [5] studied the delamination phenomenon in laboratory-scale experiments and developed a pyrolysis model with emphasis on the crucial role of surface breaking and shrinking. It should be pointed out that delamination and exfoliation are two unique and key phenomena to fire development on roll paper surfaces, to which standard pyrolysis models of geometrically stable fuels are not applicable. In this work, delamination is defined as the break-up of the outer layer of roll paper, mostly along the vertical direction, while the entire paper sheet is still attached to the roll. In contrast, exfoliation is the detachment of the entire sheet from the roll when the outer layer of paper is delaminated from the lower to the upper edge of the roll. These definitions are consistent with those used in Ref. [5]. The delamination is the result of a paper sheet losing its shear strength due to pyrolysis, i.e., burned through, while the exfoliation occurs when the friction between outer and inner sheets can no longer balance the weight of the paper. For sprinkler protection, Zhou [6] investigated the water transport phenomena on the vertical paper surface. The results from these studies are critical to the development and validation of numerical models [3,4] aimed at simulating large-scale roll paper fires with sprinkler protection.

As part of the ongoing research, the present work focuses on an experimental investigation of roll paper fire growth and suppression, especially the water flow on burning surfaces of the roll paper. Water transport on fuel surfaces plays a key role in sprinkler fire protection. Previous work [7–10] investigated water transport on corrugated cardboard surfaces. Xin et al. [7,8] studied water flows on corrugated cardboard boxes in a rack storage configuration under no fire conditions; de Vries et al. [9] and Thumuluru and Xin [10] investigated the pre-wetting effects on fire propagation along vertical surfaces using single-wall and parallel panel configurations, respectively. Results from

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these studies assisted the development of fire suppression models in FireFOAM [12,13]. Compared to previous work under no fire conditions or on the pre-wetting effects, water transport along burning surfaces of roll paper is much more difficult to study, due to the complex surface conditions. In contrast to the no-fire or pre-wetted surfaces, the burning paper surfaces are no longer smooth as a result of charring, delamination and exfoliation. Given the complexity of burning surface conditions, the present work takes the first step to explore the feasibility of characterizing water flows along burning surfaces of roll paper qualitatively using laboratory-scale experiments.

2. Experimental method

The experimental method was designed to include both baseline and suppression tests using different types of paper. The baseline tests were freeburn and water transport (cold flow without fire) experiments to characterize fire development and surface flow, respectively. Note that the present work was conducted at a significantly reduced scale compared to real warehouse storage. Therefore, current experiments can only generate qualitative insights for water flow along burning surfaces of roll paper in fire suppression processes. It is expected that these experiments together with observations from intermediate-scale and large-scale tests will lay the foundation for numerical model development and validation.

2.1. Roll paper

The roll paper used in this work included two types of Kraft paper of 65 g/m^2 (ULINE Model S-11417) and 122 g/m^2 (ULINE Model S-7051-15) and a Butcher paper of 65 g/m^2 (ULINE Model S-11459). The Kraft paper has brown color and relatively rough surface, while the Butcher paper is white and smooth. These paper types are labeled, respectively, as 25-lbK, 13-lbK and 13-lbB in Table 1, which also lists properties of other paper used in previous large-scale studies [1,3,5,6] for comparison. Note that the area density (g/m^2) is the most important variable affecting the fire growth, while the bulk density is loosely related to the paper absorptivity. In this work, the area density and absorptivity were varied via paper selection, while the scaling of bulk density was not considered explicitly. The three paper rolls, used in this work, had a nominal outside diameter of 21.6 cm, an empty core diameter of 7.6 cm, and a nominal length of 38.1 cm. These nominal dimensions are much smaller than those of rolls used in large-scale tests which are typically 1.2-m in diameter and 2.1-m in length. However, the bulk densities of the paper used in this work, i.e., 558–682 kg/m^3, are comparable to those in previous work (584–800 kg/m^3).

Table 1 also compares three key quantities for fire growth and suppression of roll paper, i.e., heat of combustion ΔH_c, ash content and water absorptiveness. The heat of combustion was measured using the oxygen bomb method; the ash content was measured by long-time oxidation in ovens; and water absorptiveness was quantified using 2-min Cobb tests [11]. The test results show that the ΔH_c values are similar among the three papers. The two Kraft papers had a moderate amount of ash content (~3%) compared to the Butcher paper which had very little ash (< 1%). On the other hand, the Butcher paper had a much lower water absorptiveness than either Kraft paper, especially the 13-lbK paper. These paper types were selected to provide a range of area densities and water absorptivities, while maintaining similar bulk densities as those used in large-scale tests. It was expected that the study of the three different papers could provide reasonably representative burning and suppression behaviors similar to those in large-scale roll paper fires.

Table 1
Material properties of paper.

Paper type	Bulk density (kg/m^3)	ΔH_c(kJ/g, dry)	Ash content(wt %, dry)	Water absorptivenessg/m^2 (2 min)
Kraft, 25-lbK	558	18.7	3.2	36.6 ± 12.5
Kraft, 13-lbK	558	16.7	3.5	96.2 ± 10.6
Butcher, 13-lbB	682	17.6	0.06	24.8 ± 4.4
Newsprint, 9-lb	584	15.7	3.6	77 ± 3.5
Coated, 12-lb	660	18.3	11.1	104 ± 5.6
Coated, 17-lb	800	14.8	8.6	34.6 ± 7.2
Kraft, 26-lb	689	16.6	1.4	33.7 ± 8.1
Coated, 37-lb	798	14.5	8.5	75.7 ± 2.3

2.2. Experimental setup

Suppression experiments are the main focus of this work. Fig. 1 shows a schematic of the fire suppression tests. Two fuel columns were placed on a platform with a 5-cm separation distance (flue space) in the Small Burn Lab (SBL) of the FM Global Research Campus in West Glocester, RI, USA. The two-fuel-column setup was particularly selected to facilitate ignition and heat transfer between the rolls, as well as observation of surface delamination, exfoliation and water flow. Each column contained three rolls stacked on end, with a total height of 114.3 cm. The top surface of the top roll in each column was covered by aluminum tape and sealed with a gasket and stainless steel plate (20-cm diameter). The aluminum tape extended downward by approximately 1.3 cm, essentially banding the top roll at the upper edge.

The platform supporting the fuel was made of heavy-duty metal grid that could be reused in multiple tests. Load cells were placed under the platform to monitor the fuel mass loss rate. The estimated convective heat release rate was less than 300 kW; therefore, the fuel columns were placed under the 1-MW calorimeter in the SBL. A scaled-down igniter (5-cm dia. ×1.3 cm cellulosic cotton soaked with 20 ml gasoline) was placed at the center of the flue space flush with the lower edge of the bottom roll for ignition. After ignition, the fire was allowed to develop to a predetermined condition before applying water.

The water was discharged from a full-cone water spray nozzle (Spray System Co., Model 1/8GG2.8 W) at a range of flow rates between 0.8 and 2.3 lpm. The nozzle was installed 20-cm above the top surface of a splash ring. The splash ring was 5-cm high and 20-cm in diameter and placed on top of each fuel column. There was a 0.6-cm gap between the bottom of the splash ring and the top surface of the roll paper. When the full-cone nozzles discharge water, the splashing rings collect and guide the water to flow out to the side and down along the surface of the roll. This creates a relatively simple initial condition for simulating the water transport. It should be pointed out that, as the applied water flow rate increased, the spray patterns also changed, resulting in different fractions of discharged water impinging on the splash ring.

In order to create well controlled water delivery, water was supplied to the nozzle to achieve steady state before the start of each suppression test. A water shield was placed between the nozzle and the splash ring to block water discharge to the roll paper. The use of the water shield generated a step function in the water application process. The shield consisted of a pan 5-cm tall, 50-cm square with a 1.3-cm drain hole. At the time selected for the start of water application, the shield was removed to allow water discharge to the roll paper. The water application time was controlled so that water was delivered at either an early or late stage in fire development and at three water fluxes (0.8, 1.5 or 2.3 lpm). The two burning stages corresponded to the initiation of exfoliation at either the bottom or middle roll of paper, respectively.

To quantify the water transport, two collection pans were placed below the metal-grid platform directly under the fuel columns. A pressure transduced was installed in each pan and calibrated to measure accumulated water volume. Two high-definition (HD) video cameras and one infrared (IR) camera (FLIR SC655, 7–13 µm, 18°×25° view angle) were placed 3 m away from the fuel to observe