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Short communication

A dimensional analysis on firebrand penetration through a mesh screen ☆

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HIGHLIGHTS

- We examined firebrand penetration through a mesh screen.
- A dimensional analysis was performed.
- The resulting dimensionless parameters correlate the experimental data well.

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ABSTRACT

A dimensional analysis on firebrand penetration through a mesh screen was carried out to correlate the experimental data previously reported in the literature. Three dimensionless variables, one dimensionless time and two dimensionless lengths, were obtained. The resulting dimensionless parameters correlated the data well and may provide a useful framework to assess firebrand penetration through mesh screens, a significant problem associated with the ignition of interior contents of built structures in wildland–urban interface fires.

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1. Introduction

The "wildland–urban interface (WUI)" is a term commonly used to describe a geographical area where built structures and other human development have the potential to interact or intermingle with wildland or vegetative fuels. The urban sprawl in the U.S. has increasingly encroached on the wildland and put a growing number of communities at risk to WUI fires originating from wildland fuels. In 2007, the Southern California WUI fires alone displaced nearly 300,000 people, destroyed over 1000 structures, and resulted in US$1 billion paid by insurers [1]. WUI fires are also a growing problem in the world [2]. As vegetation and structures burn in WUI fires, pieces of burning material, known as firebrands, are generated, become lofted and get carried by the prevailing wind resulting in structures being bombarded by firebrands during these fires. Anecdotal evidence and post-fire damage assessment studies suggests that wind-driven firebrand attack is responsible for the majority of structure ignitions in WUI fires [3,4]. Firebrands may find their way to enter the structure interior via vents, which are used in houses for attic ventilation to ensure proper thermal management and help prevent humidity build-up, molding, and rotting. Once firebrand penetration through vents is materialized, the combustibles inside the structures are exposed to potential ignition by firebrands. One way to prevent firebrands from entering through vents is to have the vent openings screened. Screens are used to prevent the intrusion of vermin. No technical or theoretical basis exists to determine the proper mesh sizes to prevent firebrand penetration. Recently, a standard test method for evaluating the ability of exterior vents to resist the entry of firebrands and direct flame impingement was developed by the American Society for Testing and Materials (ASTM) [5]. However, the ability of such vents to completely exclude entry of flames or firebrands is not evaluated in the standard. Quantitative assessment of building vent vulnerability to firebrand attack in a WUI fire is needed for standard and code development [6].

Firebrand penetration through a mesh screen has been experimentally studied using a small-scale wind-tunnel coupled with the NIST firebrand generator by Manzello et al. [7]. In that work, a generic building vent design, consisting of only a frame fitted

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with a metal mesh, was used since the purpose of the experiments was to assess the proposed test methods and not specific proprietary vent technology. A section of screen was mounted perpendicular to the flow in the test section of the wind-tunnel, and firebrands from the firebrand generator were directed toward the screen. The entire firebrand penetration process was tracked. Measurements included feed and penetrated firebrand sizes and the firebrand retention (burning) times on the screen before penetration. Details on the experimental set-up and procedure can be found in Manzello et al. [7].

2. Dimensional analysis

Fig. 1 illustrates the pertinent parameters describing the physical process of firebrand penetration through a screen. A firebrand with a projected area (perpendicular to the vent) of A_e entrained by a uniform wind with speed of V lands on the screen with a characteristic mesh size L_s. Interest focuses on a firebrand that cannot penetrate the screen initially. The firebrand captured by the screen is assumed to continue to burn with aid from the imposed wind until it can penetrate through the screen with a projected area of A_L ($<A_e$) due to its size reduction. The retention time t_r of the firebrand on the screen is defined as the duration between the firebrand arrival (t_1) at the screen and penetration (t_2) through the screen and is directly related to the burning time of the firebrand on the screen before penetration.

Based on the experimental conditions used in Manzello et al. [7], the following assumptions are applied to the dimensional analysis:

1. The burning characteristics of individual firebrands arriving at the screen are similar; the firebrands are glowing.
2. The firebrand loading is low in the feed stream; no two firebrands will land on the same area of the screen, and there is no interaction among glowing firebrands on the screen.
3. As the firebrand reduces its size due to burning, accumulation of ash on the firebrand does not prevent it from penetrating the screen; ash is blown away by the imposed wind.
4. The screen material is non-combustible (stainless steel) and does not vary; only the screen mesh size varies.
5. The imposed wind speed does not cause blow-off of the glowing firebrands on the screen.

The screen penetration process can be characterized by the five governing parameters, A_e, A_L, L_s, t_r, and V. The size of the firebrand penetrating through the screen with a retention time t_r can be expressed as

$$A_L = f(A_e, L_s, V, t_r) \tag{1}$$

Application of the Buckingham π theorem [8] results in the following three dimensionless groups.

$$\pi_1 = \frac{L_s}{\sqrt{A_e}} \quad \pi_2 = \frac{Vt_r}{\sqrt{A_e}} \quad \pi_3 = \frac{A_L}{A_e}$$

The resulting general functional form that describes the firebrand penetration through the screen can be expressed as

$$\pi_3 = a\pi_1^b \pi_2^c \tag{2}$$

where a, b, and c can be determined by correlating the experimental data using multiple linear regression analysis.

3. Results and discussion

The firebrand sizes in the feed and at penetration and retention time data from Figure 15 in Manzello et al. [7] were used for the dimensional analysis. In the experiments, V was fixed at 7 m/s, while the screen opening size L_s was varied from 1.04 mm to 5.72 mm. The projected areas A_e ($\approx$ 45 mm^2) of six initially similar size firebrands were tracked and measured as a function of time burning on a screen until the firebrand penetrated through the screen. Additional retention times of firebrands with projected areas other than the aforementioned six could be derived from the experimental data as follows. If the firebrand burning characteristic on the screen is assumed to be independent of firebrand size and burning histories on the screen, then the tracked firebrand with the projected area at a specific time t_s after landing and burning on the screen could be perceived as if it were a brand new firebrand with a smaller projected area landing on the screen at t_s with a retention time of $t_r - t_s$. Over the range of the experimental parameters used, the resulting multiple linear regression is

$$\frac{A_L}{A_e} = 2.7183\left(\frac{L_s}{\sqrt{A_e}}\right)^{0.154}\left(\frac{Vt_r}{\sqrt{A_e}}\right)^{-0.156} \tag{3}$$

If we approximate $b \approx c \approx 5/32$, Eq. (3) can be simplified.

$$\frac{A_L}{A_e} = 2.7183\left(\frac{L_s}{Vt_r}\right)^{5/32} \tag{4}$$

Then $\frac{A_L}{A_e}$ can be scaled approximately as

$$\frac{A_L}{A_e} \sim \left(\frac{L_s}{Vt_r}\right)^{5/32} \tag{5}$$

Fig. 2 shows the experimental data plotted in terms of the three dimensionless parameters. Note that the correlation is only

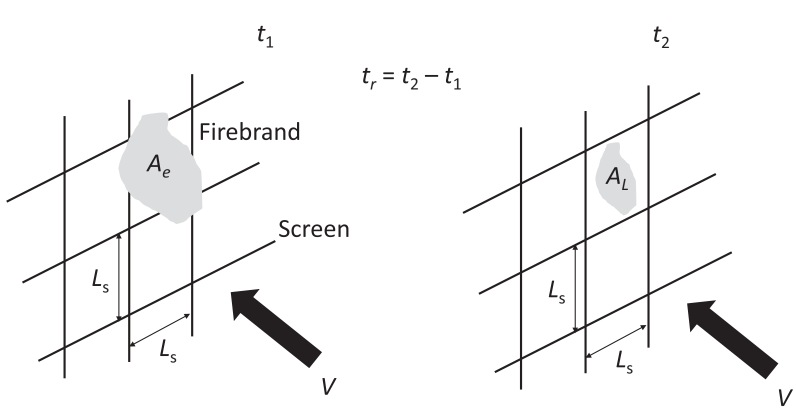

Fig. 1. Illustration of firebrand penetration through screen.

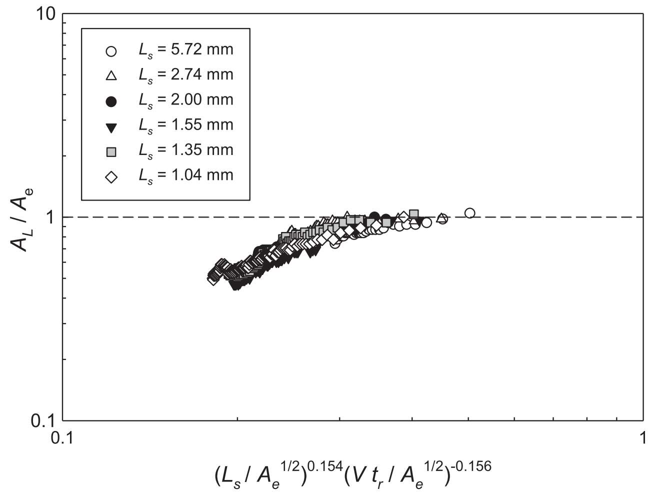

Fig. 2. Dimensionless correlation for firebrand penetration through screen (relative uncertainty in the measurements is ±10%).

applicable under the condition of $A_L < A_e$. The data points with values of A_L/A_e greater than unity in the figure are not physically possible and are due to measurement uncertainties in the firebrand projected areas. The asymptotic trend in the experimental data indicates that as $t_r \to 0$, $A_L/A_e \to 1$, which reaffirms the fact that if the retention time of the firebrand on the screen is zero, the firebrand simply passes through the screen. The dimensional analysis correlates this limited set of experimental data well; however, additional experiments need to be performed using a wide range of values for V, L_s, and A_e to extend the range of the dimensionless parameters in order to test the general applicability of the correlation.

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