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A Study of Flame Spread in Engineered Cardboard Fuelbeds Part II: Scaling Law Approach

Brittany A. Adam[(a)], Nelson K. Akafuah[(a) (*)], Mark Finney[(b)],
Jason Forthofer[(b)], and Kozo Saito[(a)]

[(a)] *Institute of Research for Technology Development, Univ. of Kentucky, Lexington, KY 40506*
[(b)] *USDA Fire Science Laboratory, Missoula, MT 59808*
[*] E-mail address: *nkakaf0@engr.uky.edu*

Abstract

In this second part of a two part exploration of dynamic behavior observed in wildland fires, time scales differentiating convective and radiative heat transfer is further explored. Scaling laws for the two different types of heat transfer considered: Radiation-driven fire spread, and convection-driven fire spread, which can both occur during wildland fires. A new interpretation of the inertial forces introduced a downstream, time-dependent frequency, ω, which captures the dynamic, vortex shedding behavior of flames due to the unstable nature of the turbulent flow created in the wake of the fire. Excelsior and paper strip experiments suggest wildland fire is a falls into the convection-driven spread regime.

Nomenclature

α	the fuel bed angle
$\Delta\theta_1$	temperature rise of air and gas
$\Delta\theta_2$	temperature rise of fuel
π	pi-number
ρ_1	gas density
ρ_f	fuel density
$\Delta\rho_1$	density change of air and gas
$\emptyset$	ratio of consumed fuel to the total available fuel
ω	downstream, shedding frequency
c_2	specific heat of fuel
c_p	specific heat of a gas at atmospheric pressure
E	irradiance received by radiometer
F_b	buoyancy force of air and gas
F_i	inertial force
F_i	inertial force of air and gas
g	acceleration due to gravity
H	fuel height
H_f	flame height
I	fire intensity
L_a	height of flame and fire plume
L_e	effective length over which the majority of heat transfer occurs (also effective length for vortex shedding)
L_w	flame zone thickness
l_2	fuel bed width
l_H	characteristic length, height of fuel
Q	heat generated
Q_{c1}	heat stored in the air and gas associated with the temperature rise
Q_{c2}	heat stored in the unburned fuel
Q_r	radiant heat received by the unburned fuel
Q_λ	the latent heat of fuel (heat value per unit mass of fuel)
q_f	heat value per unit mass of fuel
R	spread velocity of flame front
t	characteristic time
u	horizontal wind velocity

Introduction

Although significant progress has been made in wildland fire study over the last decade, it continues to present interesting academic challenges, as pointed by Pyne et al., in Introduction to Wildland Fires: "The fire phenomenon in the wildland setting, however, has not been and may never be explained to the level of first principles." [1] Spreading and ignition mechanisms are still poorly understood. Finney et al (2013) further detailed our main curiosity, "In the study of wildfire spread, heating and ignition of fuel particles by flame contact has been largely neglected in favor of quantifying heat transfer by radiation. This focus on only one method of heat transfer is unfortunate as research has recently suggested that radiant heating alone is frequently insufficient to ignite fine fuel elements at fluxes common to wildland fires." [2]

A study of wildland fires leading to a correct understanding of flame spread in wildland fire would find its foundation firmly situated on an understanding of the governing mechanisms, processes, and threshold of ignition. It is, therefore, very important for effective firefighting efforts and safety reasons to identify the roles of radiative and convective heating.

Over the years, the United States Department of Agriculture (USDA) Missoula Fire Sciences Laboratory has conducted a series of experiments in their unique wind tunnel fire experimental facility. This rich database provides years of numerical data and video from burns conducted under a wide range of well-specified conditions. After identifying the need to explore the roles of both convective heat transfer and radiative heat transfer in the ignition process, the USDA's well documented line fire data provided an opportunity to observe ignition and, subsequently fire spread phenomenon, through a uniform fuel bed of laser-cut cardboard combs under controlled conditions.

The USDA Missoula Fire Sciences Laboratory and University of Kentucky Institute of Research for Technology Development (IR4TD) teams conducted two explorations to further understand ignition on a wildland fuel bed. The team first began by identifying and exploring flame behaviors in the lab environment that were previously only observed in large scale wildland fires. [3] The first part of the study raised the importance of the dynamic behavior of diffusion flames; we believe the buoyancy instabilities causing time-dependent flickering behavior increases convective heat transfer and must be considered. The goal of the second paper of the two part study is to identify features distinguishing radiative heat transfer from convective heat transfer. The team worked to explain scaling laws, determine key parameters to support the development of scaling laws, and begin a comparison of the scaling law predictions with USDA data.

When the above scaling laws are completely validated, it would be reasonable to design medium scale prescription fire experiments, which fall between the USDA experiments and the full scale wildland fires. We believe that this step-by-step approach guided by the scaling analysis in corporation with different size scale model experiments eventually allow us to understand the governing physics that control the mechanism of flame spread through and ignition on the wildland fuel bed.

Scaling Laws

Williams' pioneering study on scaling mass fires, Williams 1969, our previous two studies introducing scaling laws for pool and crib fires, Emori & Saito 1983, and a study on flame spread, Emori et al. 1988, can all provide the guidance for development of scaling laws for flame spreading through wildland fuel bed [4] [5] [6]. Only a brief summary of these previous work are provided here. Assumptions were made as follows: flow pattern is generally turbulent suggesting the inertial force is dominant over the viscous force. Near and in the flame region, temperature of air and gaseous combustion by-products can easily exceed 1000K, creating a strong buoyancy effect which will interact with the inertia force of air and gaseous combustion by-products. Radiation and convection heat transfer may both play important roles in determining spread rate; as the relative significance of these two methods of heat transfer is not certain at this point, we assume both are significant. Conduction heat transfer is assumed negligible over radiation and convection. As a result, the following key forces and heats are identified: Buoyancy force of air and gas (F_b), inertial force of air and gas (F_i), heat generated (Q), heat stored in the air and gas associated with the temperature rise (Q_{c1}), heat stored in the unburned fuel (Q_{c2}), radiant heat received by the unburned fuel (Q_r), and the latent heat of fuel (Q_λ). Those two different forces and five heats can be written as follows using characteristic parameters [6]. They are:

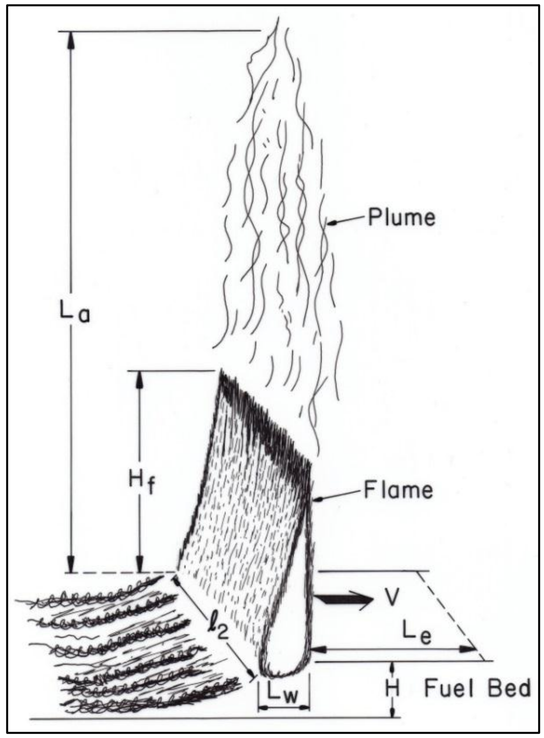

Figure 1. Schematic of flame spread over fuel bed and dimensions of flame height, plume height, and fuel bed. [6]

$$F_{i,up} = \rho_1 l_2 (L_a)^2 u\omega \qquad F_{i,down} = \rho_1 l_2 L_a u^2 \qquad F_b = \Delta\rho_1 l_2 L_w L_a g \qquad Q = \emptyset q_f \rho_f l_2 H L_w = I L_w t$$

$$Q_r = E l_2 L_e t \qquad Q_{c1} = c_p \rho_1 L_a l_2 L_e \Delta\theta_1 \qquad Q_{c2} = c_2 \rho_f l_2 H L_e \Delta\theta_2 \qquad Q_\lambda = \rho_f l_2 H L_e$$

Figure 1 provides schematic of flame spread over a typical fuel bed and dimensions of flame height, plume height, and fuel bed.

These identified two different forces and five different heats constitute the following seven independent pi numbers.

$$\pi_1 = \frac{F_{i,down}}{F_b} = \frac{\rho_1 u^2}{\Delta\rho_1 L_w g} \qquad \pi_2 = \frac{F_{i,down}}{F_{i,up}} = \frac{L_e \omega}{u} \qquad \pi_3 = \frac{Q_r}{Q} = \frac{E l_2 L_e}{I L_w}$$

$$\pi_4 = \frac{Q_{c1}}{Q} = \frac{c_p \rho_1 L_a R \Delta\theta_1 l_2}{I L_w} \qquad \pi_5 = \frac{Q_{c2}}{Q} = \frac{L_e}{L_w} \qquad \pi_6 = \frac{Q_\lambda}{Q} = \frac{\lambda L_e}{\emptyset q_f L_w}$$

$$\pi_7 = \frac{F_i u t}{Q} = \frac{\rho_1 L_a u^3 l_2}{I L_w}$$

For the equations

$$V = \frac{L_e}{t} \qquad I = \frac{\emptyset q_f \rho_f l_2 H}{t}$$

The scaling criteria demand: $\pi_i = \pi_i'$ for similarity, where $i = 1$ to 7, the left hand π_i represents a full scale scenario, and the right hand π_i' represents a corresponding scale model. Note that π_2, is the ratio of the inertial force causing vortex shedding behind a flame, $F_{i,down}$, to the inertia force of wind, $F_{i,up}$, is unique to the current wildland fire problem, where a flame acts like a vertical solid cylinder to generate a wake in the downstream against an upcoming horizontal flow [7]. Finney et al. [2] suggested the St-Fr correlation, which is equivalent with the (π_2 - π_1) correlation, based on their careful observations on the engineered cardboard fuelbed experiments. Using the same fuels for both the full scale and the model and assuming the same temperature at the corresponding points, π_5 and π_6 can be automatically satisfied, and the above scaling criteria yields the following, Equation (1):

$$\phi\left[\frac{u^2}{L_w}, \frac{L_e\omega}{u}, \frac{E l_2}{I}, \frac{L_a R}{I}, \frac{L_a u^3}{I}\right] = 0 \qquad (1)$$

Based on previous studies [5] [6], there are two different types of fire: radiation-driven and convection-driven. Scaling laws for each type of fires were developed separately; these scaling laws can be applied to the current flame spread study, since the governing forces and heat balances described in the above references also can be applied to the current problem. The following provides summary of relevant scaling studies [5] [6].

(1) Radiation-driven type fire

There is little effect of the fluid dynamics on the overall heat balance, and radiation is the main source of the solid fuel evaporation and ignition leading to the flame to spread. For this type of fire, Equation (1) can yield the specific scaling relationships seen in Equation (2).

$$\frac{u}{u'} = \sqrt{\frac{L_w}{L'_w}} \qquad \frac{R}{R'} = \frac{E}{E'} \tag{2}$$

$$t = t' \tag{3}$$

Note that the fire intensity, I, was set to satisfy $I/I' = (L_w/L_w')^2$, and π_7 has no effect on this angle.

(2) Convection-driven type fire

For this type of fire, contrary to the radiation-driven type, fluid dynamics influences the heart transfer mechanism as the form of heat convection, creating a coupling between the force and heat balances, and leading to the following Equation (3).

$$\frac{u}{u'} = \frac{R}{R'} = \frac{E}{E'} = \sqrt{\frac{L_w}{L'_w}} \tag{4}$$

Time scale also can be obtained as:

$$\frac{t}{t'} = \sqrt{\frac{L_w}{L'_w}} \tag{5}$$

(3) Consideration for ignition time scaling

It would be reasonable to assume that the diameter of fuel particles, d, is much smaller when compared to other characteristic lengths, yielding scale separation to occur when d<<L. Under this condition, the inner and surface temperature of the fuel particles can achieve steady state temperature across the particle diameter within a very short time after they are exposed to an external heat, either radiation or convection heat whichever it might be. This assumption can simplify the ignition time scaling, which to follow equation (3) under a radiation heating and equation (5) under a convection heating.

(4) Distinguishing between convective and radiative heat transfer

To test the scaling laws, a condensed-phase characteristic length (the fuel depth, l_H) of several burns was plotted against the recorded spread rate, R, as fire spread along fuel bed of paper combs at four various inclinations. The inclinations ranged from a horizontal bed (α=0°) to a bed with a positive slope of 45°. The paper strips were coated in wax so that they burned at a moderate speed and released enough heat to create turbulent flames. [6] Figure 2 is a plot of the different spread rates with respect to that characteristic length, the fuel depth, l_H.

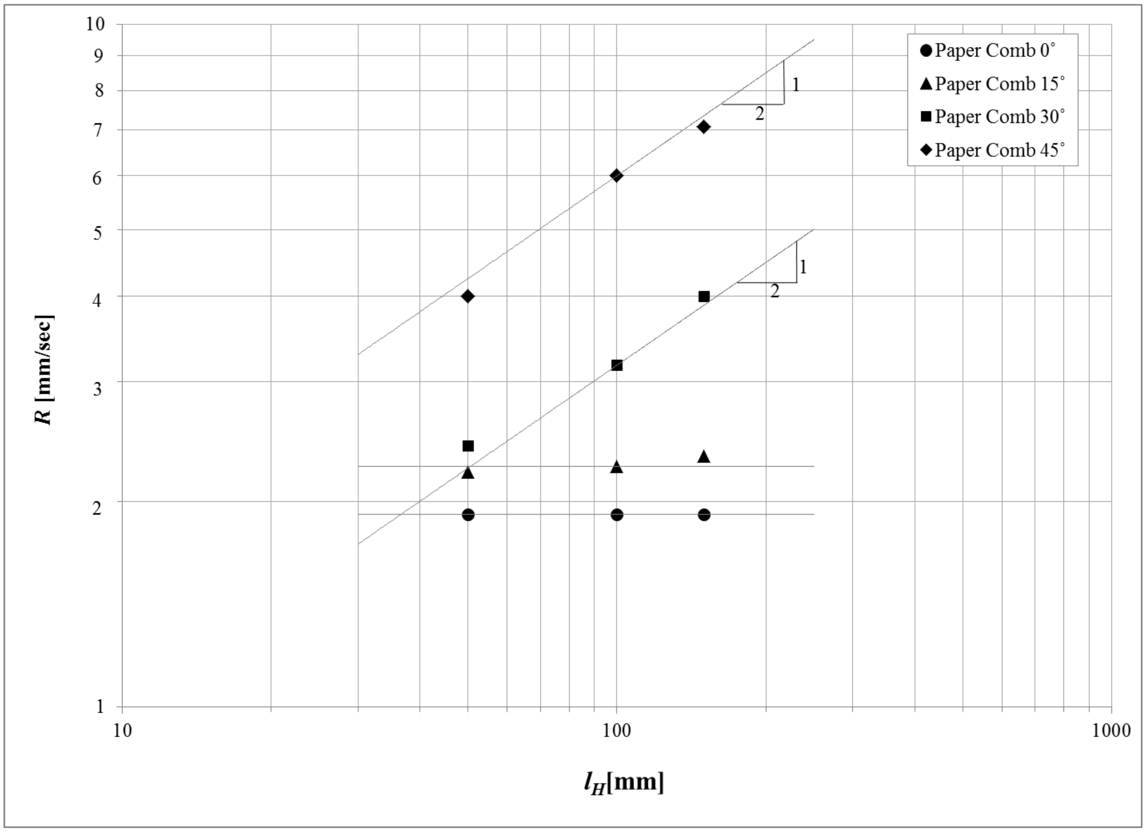

Figure 2. Convection-dominated fire spread and radiation-dominated fire spread abide by different power law relationships to a characteristic length of the fires. The relationship between flame height (l_H) and spread rate (R) for the burns on horizontal beds ($\alpha = 0°$) and beds at an inclination of 15°, corroborates the proposed radiation-driven scaling law suggesting that the rate of spread is proportional to a condensed-phase characteristic length. The relationship between flame height (l_H) and spread rate (R) for the burns on beds at an inclinations of 30° and 45°, corroborates the proposed convection-driven scaling law suggesting that the rate of spread is proportional to the square root of a condensed-phase characteristic length. [5]

Flame spread behavior during exploratory paper comb burns on both a horizontal bed (α=0°) and a bed with a slope of 15° best fit the radiation-driven spread profile identified by the scaling law given in equation (3). Flame spread behavior during paper comb burns on a slope of 30° and a slope of 45° best fit the convection-driven spread profile identified by the scaling law given in equation (5).

Excelsior trials yielded surprising results. Spread rates recorded for excelsior burns on both a horizontal bed (α = 0°) and a bed with a slope of 25° fit identified convection spread profile, with the ½ slope spread pattern as shown in Figure 3. This suggests that flame spread over excelsior fuel beds is convective driven, irrespective of fuel bed slope indicating that full scale wildland fire spread is convection driven. Excelsior better mimics litter and duff of the actual wildland fuelbed than paper comb. However, studies have found that excelsior experiments demonstrate poor reproducibility because excelsior's packing density and material properties are not uniform like paper combs.

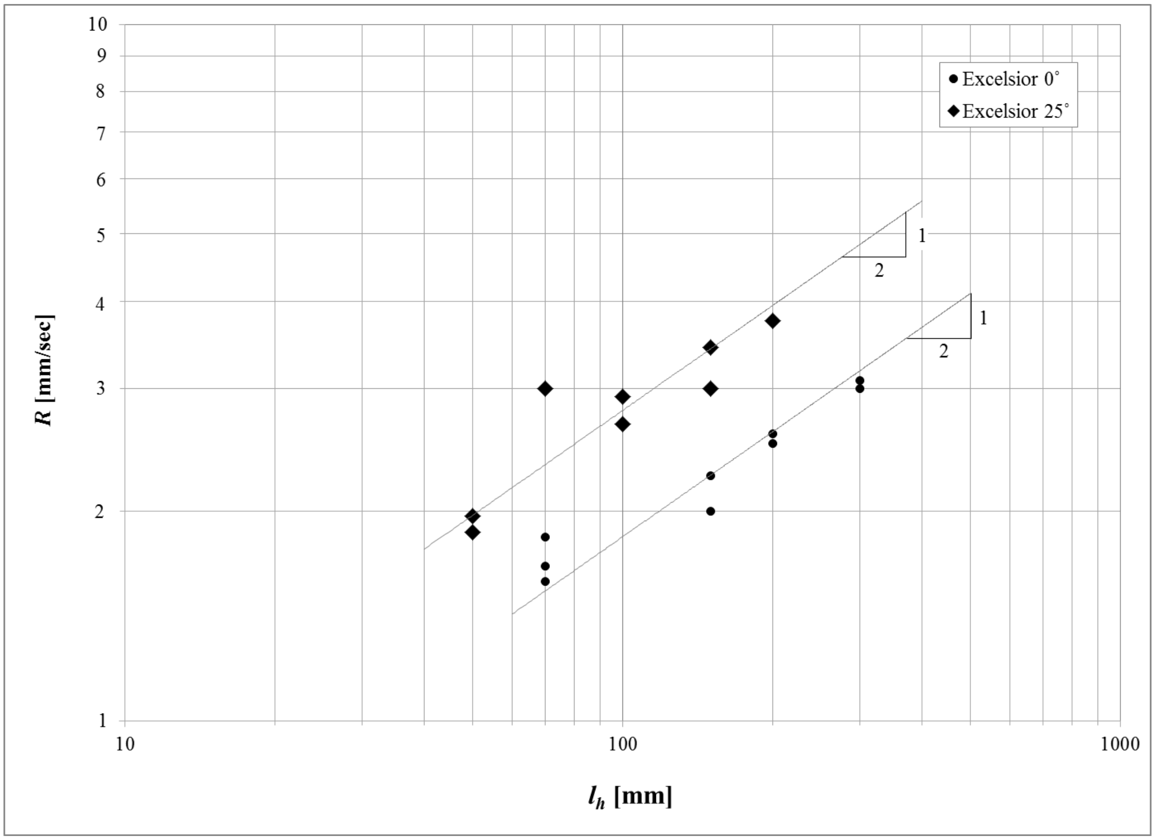

Figure 3. Excelsior trials at two different slopes fit identified convection spread profile.

Discussion

It is understood that wildland fire flames are inherently dynamic. Time dependent flame behavior like flickering, pulsing, and vortex shedding have all been observed in diffusion flames, though studies noting these behaviors have been primarily focused on buoyant diffusion flames originating from circular nozzles or jets [8] [9] [10]. Wildland fire flames exhibit these behaviors as well [11] [12] [13]. Time-averaged analyses of these fires, while more mathematically palatable, [14] disregard key time-dependent mechanisms, like vortex shedding, which is a behavior that has been found to significantly increase convective heat transfer in a variety of applications. [15] [16] It is a reasonable assumption that a time-average, static analyses would not capture the entirety of convective heating, and thus not accurately predict ignition.

A preliminary set of assumptions for a typical flame-spreading pattern (i.e., flame spreading through pine forest under relatively moderate wind speed condition over rather moderate terrain geometry) is considered. At this point, no consideration is given to whether the fuel is alive or dead; rather, the fuel is treated as an average wildland fuel with typical thermo-physical properties. It is understood that later this analysis would be modified when applied to specific scenarios and fuels.

Using those assumptions, a new idea is proposed to describe this dynamic system. It is assumed that the wind-driven wildland fire spread is a "Strouhal number" controlled dynamic system where instabilities break the spreading fire front flame structure into several turbulent fire columns. The instability which generates smaller stable fire columns is controlled by the buoyancy force acting in the flame and the pressure difference created inside the flame [17].

Each fire column generates a strong upward buoyant flow and acts like a solid wall against the horizontal wind [18] [19] [20]. The columns are then similar to a pool fire. When the wind flows around the column, it picks up heat from the flame. It is also well known that when the wind passes around the column, it sheds a von Karman vortex street in the down-stream direction [7]. This combination of the heated air/combustion gas and von Karman vortices can effectively transfer the convective heat to the unburned fuel.

To simplify this concept, a flame column could be treated as a liquid pool fire governed by its Froude number [5], defined as the ratio of the inertia force of air to the buoyancy force of hot combustion by-products in the flame. When this oscillating flame interacts with the inertia force of wind, it forms a St-Fr^{-1} number controlled dynamic system. Figure 4

The Strouhal number is typically defined as the ratio of the kinetic force of the flame column to the inertia force of wind. For wildland fires, however, we replace kinetic force with pressure force, since the pressure force acts like the kinetic force in wildland fire systems to create dynamic instability.

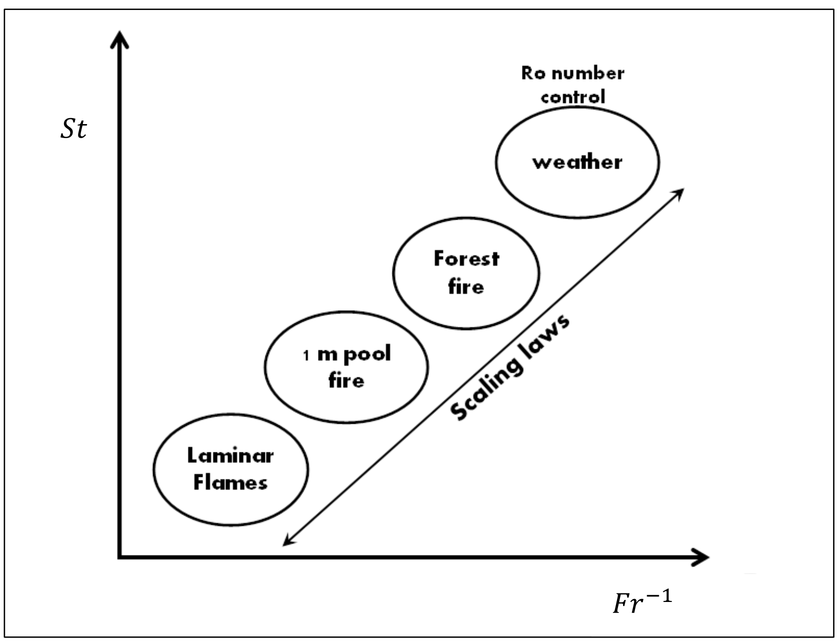

Figure 4. Proposed St - Fr^{-1} number relation map, including relations of small-scale laminar diffusion flames, large-scale wildland fires, and global-scale weather phenomena.

The idea of the St-Fr number dynamic system also can help connect seemingly disparate phenomena for the benefit of wildland fire research. Figure 4 shows a possible scaling correlation that requires for validation. If this correlation works, then we should be able to correlate various size scale phenomena, which include flame sizes as small as a 1cm diameter candle-like laminar flame and a laminar spreading flame over a few cm wide paper strip, a medium scale 1m diameter turbulent liquid pool fire, a typical wildland fire with a fire front length on the order of 10m to 100m, and up to as large as atmospheric weather, which is governed by the Rossby number.

Conclusion

In the pioneering work by Emori and Saito [5], scaling laws for both radiation-driven pool fire and convective-driven crib fires were developed. Later, Emori and Iguchi applied those scaling laws to flame spread over paper combs and excelsior, and identified six pi numbers. [6] In this paper, we have built upon their work to establish a seventh pi number based on a new interpretation of the role of the inertial force. This interpretation introduces a downstream, time-dependent frequency, ω, which captures the dynamic, vortex shedding behavior of flames due to the unstable nature of the turbulent flow created in the wake of the fire. This downstream inertial term is in addition to the already accepted upstream inertial force due to the wind's initial flow.

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