Advances in Forest Fire Research

DOMINGOS XAVIER VIEGAS

EDITOR

2014

The Strouhal-Froude number scaling for wildland fire spread

Brittany A. Adam[a], Justin D. English[a], Nelson K. Akafuahb[a], Kozo Saito[a]
Mark Finney[b], Jason Forthofer[b], Jack Cohen[b]

Univ. of Kentucky, Lexington, KY 40506, brittany.adam@uky.edu
justin.english@uky.edu; nelson.akafuah@uky.edu; ksaito@uky.edu
[b]USDA Fire Science Laboratory, Missoula, MT 59808, mfinney@fs.fed.us;
jaforthofer@fs.fed.us; jcohen@fs.fed.us

Abstract
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 goal of our 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 validated, it would be reasonable to design medium scale prescription fire experiments, which fall between the USDA experiments and the full scale wildland fires. Our step-by-step approach using 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.

***Keywords**: Scale Modelling, Scaling Laws, Fire Spread, Fuel beds, Forest Fire, Wildland Fire, Fire Behaviour*

1. Introduction

A correct understanding of flame spread in wildland fire would be based on governing mechanisms, processes, and thresholds of ignition. Critically, the roles of radiative and convective heating must still be discerned (Finney, Cohen, et al. 2013). 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 behaviours in the lab environment that were previously only observed in large scale wildland fires (Finney, Forthofer, et al. 2013) (Adam, et al. 2013). The goal of our 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 validated, it would be reasonable to design medium scale prescription fire experiments, which fall in size between the USDA experiments and full scale wildland fires. The USDA – University of Kentucky collaboration already produced two recent articles (Finney, Forthofer, et al. 2013) (Adam, et al. 2013), and we made further progress on the above study. In this paper we report recent field burn tests, organized by USDA Forest Service and conducted in Texas. Our step-by-step approach using different size scale model experiments will eventually allow us to understand the governing physics that control the mechanism of flame spread through and ignition on the wildland fuel bed.

2. Scale Modelling and Scaling Laws

University of Kentucky and USDA Forest Service in Missoula Science Laboratory have developed mutually beneficial research program to understand the mechanism of fire spread through forest fuelbeds. This paper reports one of our current progresses in this effort, namely focusing on scaling laws and scaling aspects forest fire. We begin with an excellent book: The Use of Models in Fire Research (Bert 1961). This book is the collection of sixteen different papers presented at five different sessions of the International Symposium of the same title as the book held in 1959, and commentaries are provided at the end of each session. This is a book written more than a half century ago when no computer simulation was available, but researchers' wisdom and unique insights in fire phenomena with their attempts to extract the governing physical laws which can help develop simple practical models are still valuable in the age of high speed computation, and therefore serve as an excellent reference for our forest fire research efforts.

Figure 1. A high speed color photographic image of spreading flame over artificially made cardboard fuelbeds (Finney, Forthofer et al. 2013).

To continue the above book's philosophy, the USDA's Forest Service Fire Science Lab (Finney, Cohen, et al. 2013) (Finney, Forthofer, et al. 2013) made a series of unique observations on forest fires by high speed video photography and thermocouple temperature measurement techniques. These techniques are rather ordinary but their observation results are rather extra-ordinary. The following are except from Finney's observations (Finney, Cohen, et al. 2013). "A series of preliminary burns of the cardboard fuelbeds in the wind tunnel were used to refine the instrumentation. The fires were filmed with digital video cameras from the top, sides, front, back, and various oblique angles. This footage revealed two principal dynamic features of the flame zone. First the flame zone became divided in the transverse or span-wise direction into convective peaks and troughs at fairly regular spacing. The ignition interface (at the leading edge of the combustion zone) was convoluted in association with this flame structure, with a concave segment located directly beneath these peaks (Figure 1) and convex segments in the troughs. Second, the flame zone exhibited clear instabilities, which when viewed at an angle from behind and above the bed, appeared as patches originating near the rear of the burning zone…… After reaching the ignition interface at the leading edge of the burning zone, they impinged new fuels ahead. When the flame zone was viewed normal to the stream-wise direction, eddies appeared on the upper and lower flame edges which rotated in the opposite direction. Regardless of the local geometry of the fire edge, it progressed at the same rate across the fire front." (Finney, Forthofer, et al. 2013)

Almost 30 years prior to Finney's observations, F.A. Albini (Albini 1984) made a comprehensive review on wildland fires addressing Rothermel's steady-spread model (Rothermel 1972) to predict the rate of spread of surface fire as a successful example, while describing wildland fires as poorly understood phenomena. As of today, many of the unknowns pointed out by Albini (who believed radiation as the key heat transfer mechanism for flame spread) in 1984 still remain to be unknown (for example, the role of live fuels in fire spread and the effect of wind on fire spreading behaviour). As to the wind effect, some progress has been made on fire whirl studies (Emori and Saito 1982; Chuah *et al*. 2011), while an important progress was made recently on the mechanism of fire spread (Finney, Cohen, et al. 2013) (Finney, Forthofer, et al. 2013) based on a serious of unique observations mentioned. This paper mainly focuses on the latter development (Finney, Cohen *et al*. 2013; Finney, Forthofer *et al*. 2013; Finney *et al*. 2014) which establishes a high correlation between Strouhal (St) – Froude (Fr) number based on a series of careful observations over a variety of fuel types and a wide range of size including full scale crown fires, grassland control burn experiments, large scale wood crib fires, and wind tunnel laboratory-scale fire experiments using artificial cardboard fuelbeds. In the following, we provide governing physical laws responsible for the above St-Fr correlation and possible scaling laws on fire spread.

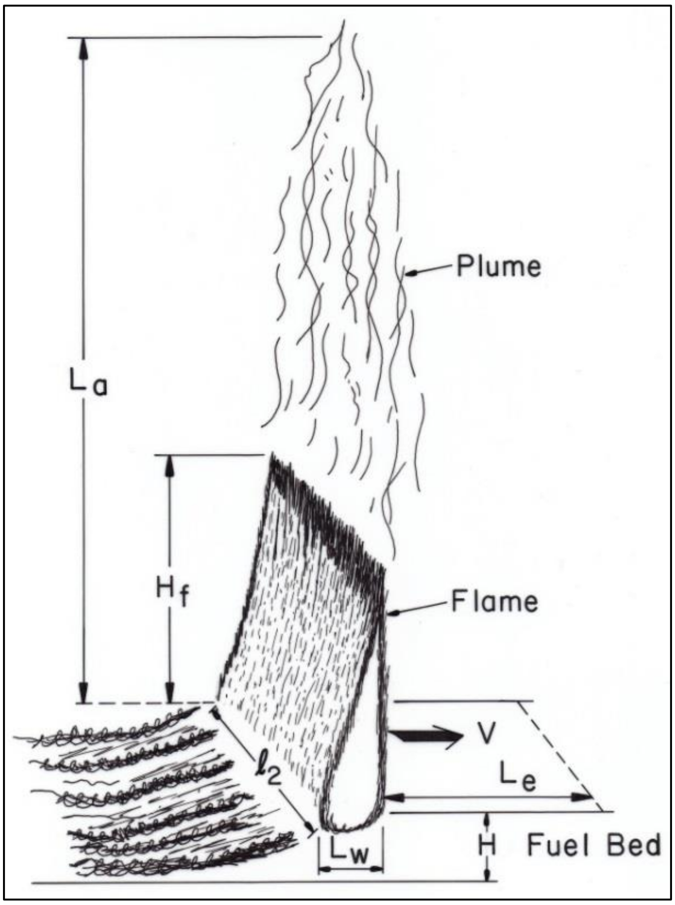

Figure 2. Schematic of one-D flame spread over fuel bed and dimensions of flame height, plume height, and fuel bed (Emori, Iguchi et al. 1988)

Here we use the law approach whose details are provided in refs (Emori and Saito 1985; Emori, Saito and Sekimoto 2000) to obtain seven independent pi-numbers from the above three different forces and five different heats. 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 the ratio of the inertial force causing vortex shedding behind a flame, $F_{i,down}$, to the inertial force of the 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 (Kuwana, et al. 2007), and pi-number constituting between heat and work done by fluid motion can be ignored. Finney *et al*. (Finney, Cohen, et al. 2013) obtained a reasonably strong St-Fr correlation, which is equivalent with the (π_2 - π_1) correlation, over wide range of experimental data including the wind tunnel fire spread experiments on cardboard fuelbeds, a full scale crown fire data, and outdoor large scale wood crib fire experiments. Using the same fuels both for the full scale and the model and assuming the same temperature at the corresponding points, the law approach can produce the following, Equation (1):

$$\phi\left[\frac{u^2}{L_w},\frac{L_e\omega}{u},\frac{El_2}{I},\frac{L_aR}{I},\frac{L_au^3}{I}\right]=0 \qquad (1)$$

Previously Emori and Saito (1983) showed liquid pool fires to be radiation-driven and wood crib fires to be convection-driven, each governed by a different set of scaling laws. Later Emori and Iguchi *et al*. (1988) conducted flame spread experiments using two different types of fuel bed: vertically oriented allay of paraffin-coated paper strips and packed excelsior mats. They found that the above two different scaling laws also can be applied to flame spread identifying two different types of spreading mode, radiation-driven and convection-driven. Recently Finney's group in Missoula and the University of Kentucky's group are collaborating to develop scaling laws for flame spread through actual full scale forest fuelbeds (Adam, et al. 2013), which are significantly complex in nature consisting of live and dead fuels of different fuel types and geometry. This work is still in progress. The following provides summary of the above scaling studies (Emori and Saito 1983; Emori, Iguchi *et al*. 1988) and one of recent findings on St-Fr correlations (Finney, Forthofer *et al*. 2013; Finney *et al*. 2014).

Radiation-driven Fire Type: 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).

$$\frac{u}{u'}=\sqrt{\frac{L_w}{L'_w}} \qquad \frac{R}{R'}=\frac{E}{E'} \qquad t=t' \qquad (2)$$

(2) Convection-driven Fire Type: 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.

$$\boldsymbol{\frac{u}{u'}=\frac{R}{R'}=\frac{E}{E'}=\frac{t}{t'}=\sqrt{\frac{L_w}{L'_w}}} \qquad (3)$$

The St – Fr Number Correlation

Figure 3 shows St-Fr correlation over the wide range of scale of fires. Data consist of a full scale crown fire (10m; 100m-1,000m), controlled grassland fires (3 m; 10m-100m), large scale wood crib fires (2m; 3m-10m), and wind tunnel laboratory-scale fire experiments (0.5m; 2m – 5m). The first number in parenthesis indicates a typical flame height, and the second number indicates a typical fuel bed dimension, width x length. There are two important practical implications of the St-Fr correlation that have not been previously known. First, time-varying convective heating derives from buoyant instabilities, explaining the origin of the frequency scaling from laboratory to field-scale wildfires. Second, with frequency related inversely to flame size, it suggests a negative feedback on wildfire spread rate. In other words, as fires move faster (with increasing wind for example) and release more energy, flame size increases but convective frequency decreases (according to St-Fr) and slows the convective heat transfer.

The Figure 3 correlation can provide an approximate correlation: $St \sim Fr^{-0.5}$, which indicates $F_\omega/F_i \sim (F_g/F_i)^{0.5}$, i.e., $F_\omega/(F_iF_g)^{0.5} \sim$ const. Using characteristic parameters, this relationship can yield: $(L^{1.5}\omega^2)/Ug^{0.5} \sim$ const.

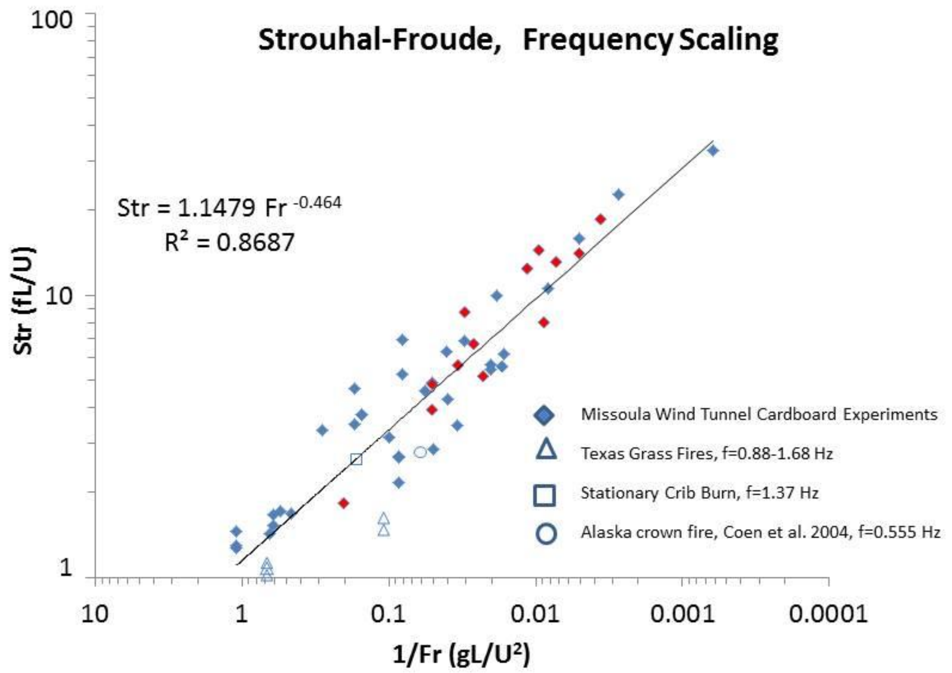

Figure 3. Strouhal (St) – Froude (Fr) number correlation for various size and type of fires including a full scale crown fire (10m; 100m-1,000m), controlled grassland fires (3 m; 10m-100m), large scale wood crib fires (2m; 3m-10m), and wind tunnel laboratory-scale fire experiments (0.5m; 2m – 5m). The first number in parenthesis indicates a typical flame height, and the second number indicates a typical fuel bed dimension (width x length) [32].

3. Summary

We provided background for the need to study spreading mechanism of actual forest fuelbeds. This study is one of our collaborative studies between USDA Forest service and University of Kentucky to achieve that goal with the scale modeling approach. We used the law approach to provide the major governing physical laws on the St-Fr correlation which have been established over a wide range of scale of fires and different types of fuels. The results indicate that previously developed scaling laws on stationary (pool and wood crib) fires and flame spreading can be extended to the current problem with possible some modifications which will be studied in the future.

4. References:

Adam, B.A., N.K. Akafuah, K. Saito, M.A. Finney, J. Forthofer, and I.C. Grenfell. 2013. "A Study of Flame Spread in Engineered Cardboard Fuelbeds, Part II: Scaling law approach." Proc. the Seventh International Symposium on Scale Modeling (ISSM7) Hirosaki, Japan 2013, and to appear in Progress in Scale Modeling volume 2, Springer 2014.

Albini, F. A. 1984. "Wildland Fires: Predicting the behavior of wildland fires—among nature's most potent forces—can save lives, money, and natural resources." American Scientist 590-597.

Bert, W.G., 1961. International Symposium on The Use of Models in Fire Research, National Academy of Science - National research Council, Washington, D.C.

Chuah, K. H., K. Kuwana, K. Saito, and F.A. Williams. 2011. "Inclined fire whirls." Proc. The Combustion Institute 33 (2): 2417-2424.

Emori, R. I., and K. Saito. 1983. "A study of scaling laws in pool and crib fires." Combustion Science and Technology 31: 217-230.

Emori, R. I., and K. Saito. 1985. "A unified view of scaling laws in fires (First report): Scaling laws in stationary fires." Transactions of JSME, Series B 29: 1892-1898.

Emori, R. I., and K. Saito. 1982. "Model experiment of hazardous forest fire whirl." Fire Technology 18: 319-327.

Emori, R.I., K. Saito, and K. Sekimoto. 2000. Scale Models in Engineering (Mokei Jikken no Riron to Ohyou). Third Edition, Gihodo Publishing Co. Tokyo, Japan, in Japanese.

Emori, R.I., Y. Iguchi, K. Saito, and I.S. Wichman. 1988. "Simplified scale modeling of turbulent flame spread with implication to wildland fires." Fire Safety Science – Proc. the Second International Symposium 263-273.

Finney, M.A., J. Forthofer, B.A. Adam, N.K. Akafuah, and K. Saito. 2013. "A Study of Flame Spread in Engineered Cardboard Fuelbeds, Part I: Correlations and Observations." Proc. the Seventh International Symposium on Scale Modeling (ISSM7) Hirosaki, Japan 2013, and to appear in Progress in Scale Modeling volume 2, Springer 2014.

Finney, M.A., J.D. Cohen, S.S. McAllister, and W.M. Jolly. 2013. "On the need for a theory of wildland fire spread." Intl. J. Wildl. Fire. 25-36.

Finney, M.A., *et al*. 2014, this conference.

Kuwana, K., K. Sekimoto, K. Saito, F.A. Williams, Y. Hayashi, and H. Masuda. 2007. "Can we predict the occurrence of extreme fire whirls?" AIAA Journal 45 (1): 16-19.

Rothermel, R.C. 1972. "A mathematical model for predicting fire spread in wildland fuels." USDA Forest Service Research Paper, INT-115.