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Research Note

Dimensional Analysis on Forest Fuel Bed Fire Spread[1]

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Abstract

A dimensional analysis was performed to correlate the fuel bed fire rate of spread data previously reported in the literature. Under wind condition, six pertinent dimensionless groups were identified, namely dimensionless fire spread rate, dimensionless fuel particle size, fuel moisture content, dimensionless fuel bed depth or dimensionless fuel loading density, dimensionless wind speed, and angle of inclination of fuel bed. Under no-wind condition, five similar dimensionless groups resulted. Given the uncertainties associated with some of the parameters used to estimate the dimensionless groups, the dimensionless correlations using the resulting dimensionless groups correlate the fire rates of spread reasonably well under wind and no-wind conditions.

Key words: data correlation, dimensional analysis, flame spread, forest fuel, wildfires

Introduction

Research interest in fire spread along fuel beds has its origin in the study of wildland fire behavior since the early 40s. In his pioneering work at the U.S. Forest Service, Fons (1946) examined the effect of forest fuel size and type, fuel bed compactness, fuel moisture content, wind velocity, and slope on fire spread, provided a detailed analytical framework to understand the mechanism of fire spread, and lay down a sound foundation for subsequent studies on fire spread along a forest fuel bed. Many studies from around the world has since been conducted and appeared in the literature (Beaufait 1965; Rothermel and Anderson 1966; Anderson and Rothermel 1966; Anderson 1969; Fang and Steward 1969; Pagni and Peterson 1973; Nelson and Adkins 1986, 1988; Weise and Biging 1994; Dupuy 1995; Simeoni et al. 2001; Morandini et al. 2001; Viegas 2004a, 2004b; Weise et al. 2005, 2016; Zhou et al. 2005a, 2005b, 2005c, 2007; Morvan 2007, 2013, 2015; Boboulos and Purvis 2009; Silvani and Morandini 2009; Anderson et al. 2010; Viegas et al. 2010; Dupuy et al. 2011; Dupuy and Maréchal 2011; Pérez et al. 2011; Marino et al. 2012; Liu et al. 2014; Nelson 2015; Rossa et al. 2016; and Mulvaney et al. 2016). The reference list is by no means exhaustive. Most of the studies fall into one of the two major categories: (1) development of empirical fire spread models using experimental data obtained in laboratories or in situ fuel complexes in the field under various test conditions or (2) comparisons of predicted rate of spread using developed analytical or numerical models with experimental fire spread data. The availability of experimental data in the literature, especially the extensive tabulated data set with detailed experimental conditions in the recent work by Anderson et al. (2010) and the comprehensive database made available online by Weise et al. (2015), give impetus to the work presented here.

Dimensional analysis is a very powerful tool for correlating experimental data in a compact and concise way. In addition, important dimensionless groups could be identified and used for scaling to reduce experimental efforts. The importance and the application of the theory of similitude to fire spread were mentioned in passing in Fons (1946). Pagni and Peterson (1973) obtained a nondimensional flame spread rate as a function of nondimensional fuel, flame, and ambient flow properties. Dimensional analysis on the spread of wind-driven fires was carried out by Nelson and Adkins (1988) to correlate the experimental data from their own studies and previous investigators with some success. Pérez et al. (2011) used dimensional analysis in an attempt to develop scaling laws for the effect of wind and slope on the fuel bed fire spread rate. The approach presented in this paper differs from Nelson and Adkins (1988) and Pérez et al. (2011) in that the primary variables used in the dimensional analysis to correlate fire spread rate are the initial conditions, thermo-physical properties of the fuel, configuration of the fuel bed, and the wind conditions. Flame properties were not included as primary variables in this analysis because they could, in principle, be correlated with fuel properties, fuel bed structure, and ambient conditions.

Dimensional Analysis

Fig. 1 is an illustration of the configuration considered in the analysis. Based on the experimental results reported in the literature, the fuel bed properties and geometry and ambient conditions were found to affect the rate of spread (ROS). To use dimensional analysis to correlate the data, we start by expressing the rate of spread as a function of the following relevant parameters, which characterize the fuel bed and ambient conditions.

(1) $$S_p = f_1(A_b, \delta_b, \alpha_s, \beta_s, M_s, M_w, U, \theta)$$

Note that dimensional analysis does not provide specific nature of the function. The fuel volume-to-surface ratio β_s could be considered as a characteristic dimension of the fuel particle. Following the systematic matrix operation described in Langhaar (1951) on the dimensional matrix obtained from eq. 1, an application of the Buckingham π-theorem (Buckingham 1914) results in the following dimensionless groups.

$$\pi_1 = \frac{S_p \sqrt{A_b}}{\alpha_s} \tag{2}$$

$$\pi_2 = \frac{\beta_s}{\sqrt{A_b}} \tag{3}$$

$$\pi_3 = \frac{M_w}{M_s} \tag{4}$$

$$\pi_4 = \frac{\delta_b}{\sqrt{A_b}} \tag{5}$$

$$\pi_5 = \frac{U \sqrt{A_b}}{\alpha_s} \tag{6}$$

$$\pi_6 = \cos\theta \tag{7}$$

The variable θ needs not appear in the formal matrix operation because it is considered dimensionless (Langhaar, 1951), and we express π_6 in terms of cosθ instead of simply θ to avoid the trivial (unrealistic) situation of $S_p \equiv 0$ when $\theta = 0$ (i.e., horizontal fuel bed) in the functional forms for the dimensionless correlations given below. The dimensionless group π_3 is, by definition, the moisture content (MC) (wet basis) of the fuel. The dimensionless group π_4 is a dimensionless fuel bed depth. The dimensionless group π_4 can also be expressed in terms of F_{ld}, $\sqrt{A_b}$, ρ_s, and ε_b. Since $V_b = A_b \delta_b$, $F_{ld} \equiv \frac{M_s}{A_b}$, and $\varepsilon_b \equiv 1 - \frac{V_s}{V_b}$,

(8) $$\pi_4 = \frac{\delta_b}{\sqrt{A_b}} = \frac{V_b}{A_b\sqrt{A_b}} = \frac{F_{ld} V_b}{M_s \sqrt{A_b}} = \frac{F_{ld} V_s}{V_s \rho_s \sqrt{A_b}} \frac{V_b}{V_s} = \frac{F_{ld}}{\rho_s \sqrt{A_b}} \frac{1}{(1-\varepsilon_b)}$$

The dimensionless group π_4 can also be considered as a dimensionless fuel loading density. The functional form in eq. 1 can now be expressed in terms of the six dimensionless groups as $\pi_1 = g(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6)$. If we assume the following functional form for the dimensionless correlation,

(9) $$\pi_1 = a_1 [\pi_2]^{b_1} [\pi_3]^{b_2} [\pi_4]^{b_3} [\pi_5]^{b_4} [\pi_6]^{b_5}$$

or

(10)

$$\frac{S_p \sqrt{A_b}}{\alpha_s} = a_1 \left[\frac{\beta_s}{\sqrt{A_b}} \right]^{b_1} \left[\frac{M_w}{M_s} \right]^{b_2} \left[\frac{F_{ld}}{\rho_s \sqrt{A_b}} \frac{1}{(1-\varepsilon_b)} \right]^{b_3} \left[\frac{U \sqrt{A_b}}{\alpha_s} \right]^{b_4} [\cos\theta]^{b_5}$$

Although other convenient functional form can be assumed to correlate the dimensionless variables, the form expressed in eq. 9 is less complex and amenable to simple statistical analysis. Using the experimental data, the coefficients a_1, and b_1 to b_5 can be determined by performing a multiple linear regression analysis on the logarithmic form of eq. 10.

Under no-wind condition, we could similarly express the fire spread rate as

$$S_p = f_2(A_b, \delta_b, \alpha_s, \beta_s, M_s, M_w, \theta) \tag{11}$$

Following similar procedure, the resulting dimensionless groups are π_1, π_2, π_3, π_4, and π_6. We will also use a functional form similar to eq. 10 to correlate the experimental data reported in the literature.

$$\frac{S_p\sqrt{A_b}}{\alpha_s} = a_2\left[\frac{\beta_s}{\sqrt{A_b}}\right]^{c_1}\left[\frac{M_w}{M_s}\right]^{c_2}\left[\frac{F_{ld}}{\rho_s\sqrt{A_b}}\frac{1}{(1-\varepsilon_b)}\right]^{c_3}\left[\cos\theta\right]^{c_4} \tag{12}$$

Results and discussion

Table 1 summarizes the data sources used to correlate the fire spread rate using eq. 10 or eq. 12 depending on the wind conditions. The data sources cover wide ranges of homogenous fuel species, fuel loading densities, fuel moisture contents and wind speeds. The sources were selected solely based on the completeness of the experimental data provided in the published works by the author(s) of the sources so that all dimensionless groups for the dimensionless correlations could be estimated readily from the available data. However, there is one caveat. Since the thermal diffusivities of most of the fuels used in the studies were not given or known, a nominal thermal diffusivity α_s of 1.6×10^{-7} m^2/s (Glass et al. 2010) was used for all the fuel species in the calculations of the dimensionless groups π_1 and π_5.

Whenever the experimental data were not given in tabulated forms in the papers by the author(s) of the data sources, the data were extracted from the figures using the following procedure. The figures were first digitally scanned and followed by measuring the relative coordinates of the data points on the scanned figures with respect to the origin of each figure using a computer-aided design (CAD) software. The actual coordinates of the data point were derived using a scale factor based on the distance of the two adjacent tick marks on the two axes of the scanned figure and their corresponding values associated with the tick marks.

Note that moisture content expressed in fraction (not in percent) was used in the dimensionless variable, π_3 and was based on moist fuel (wet-basis). If the MC data reported in the literature were based on dry fuel, the wet-basis moisture content (in fraction) can be easily obtained using the following equation.

(13) $$\mathrm{MC}_{\textit{wet-basis}} = \frac{\mathrm{MC}_{\textit{dry-basis}}}{1 + \mathrm{MC}_{\textit{dry-basis}}}$$

If δ_b was given, eq. 5 was used to calculate the dimensionless group π_4, whereas eq. 8 was used if F_{ld}, ρ_s, and ε_b were available.

Field data from Table 6 of Rothermel and Anderson (1966) and from Table 2 of Nelson and Adkins (1986), laboratory data of needles plus palmetto fronds from Table 1 of Nelson and Adkins (1986) and scrub oak data from Weise et al. (2015) were excluded in the correlations because the information needed to estimate some of the dimensionless groups was not available or given.

In some cases, as discussed below, informed and educated estimates were used for the parameters in the dimensionless groups. When only a range of the experimental parameter values associated with the test series was given, the average value was used, as a nominal value for that particular parameter, to calculate the dimensionless variables for that test series.

In the work of Anderson (1969), the fuel loading density and fuel bed surface area were not specified in each fire spread test, and only a range of values was given; (0.612 kg/m^2 – 1.223 kg/m^2) for fuel loading density and (0.0465 m^2 – 0.0929 m^2) for fuel bed surface area. A nominal fuel loading density of 0.917 kg/m^2 and fuel bed surface area of 0.0697 m^2 were used to correlate the experimental data from Anderson (1969).

Since β_s was not given in Nelson and Adkins (1986) for needles of pinus elliottii engelm, the needles were assumed to have a nominal length of 0.2 m and 2 mm in diameter. These values were used to estimate β_s in π_2.

In the experimental studies of Dupuy (1995), tests were separately conducted in 1991 and 1993, and the results were given without reference to which year a specific test series was conducted; the fuel bed area was varied from 1 m^2 to 1.5 m^2 and moisture content from 1 % to 3 % in 1991 and 1.5 % to 3.5 % in 1993. Respective nominal values of 1.25 m^2 for fuel load density and 2.25 % for moisture content were assumed and used to correlate the data. In addition, only the median fire spread rates were used in the correlations because individual data points were aggregated together in the plot making them very difficult to extract.

Under no-wind condition, the fuel bed length varied from 4 m to 7.5 m was stated in Anderson et al. (2010) and was not identified for each test. A nominal value of 5.75 m was used to calculate A_b for all the no-wind test data taken from Anderson et al. (2010).

If the void fractions of the fuel beds were not given, they were estimated using the following equation.

(14) $$\varepsilon_b \equiv 1 - \frac{1}{\sigma\lambda + 1}$$

where $\sigma \equiv 1/\beta_s$ and λ is defined in Anderson (1969) as

(15) $$\lambda \equiv \frac{V_b - V_s}{\sigma V_s}$$

Eq. 14 can be easily derived using the definition of ε_b and eq. 15. If fuel bed porosity is not available, it can be estimated using the following formulae from Anderson (1969) with known σ, ρ_s and $\rho_b \equiv M_s / V_b$.

$$\sigma\lambda + 1 = \frac{\rho_s}{\rho_b} \qquad (16)$$

The ratio ρ_s / ρ_b is sometimes termed the packing ratio of the fuel bed in the literature. Substituting eq. 16 into eq. 14, the void fraction can be expressed in terms of ρ_s / ρ_b.

$$\varepsilon_b \equiv 1 - \frac{\rho_b}{\rho_s} \qquad (17)$$

The dimensional groups in eq. 10 and eq. 12 were calculated using the data sources listed in Table 1. Taking logarithm of both sides of the two equations and performing multiple linear regression analysis using the least-squares method result in the following dimensionless correlations for wind and no-wind conditions.

(18)

$$\frac{S_p\sqrt{A_b}}{\alpha_s}=1.03\times10^{-7}\left[\frac{\beta_s}{\sqrt{A_b}}\right]^{-0.41}\left[\frac{M_w}{M_s}\right]^{-0.82}\left[\frac{\delta_b}{\sqrt{A_b}}\right]^{-0.29}\left[\frac{U\sqrt{A_b}}{\alpha_s}\right]^{1.32}\left[\cos\theta\right]^{-13.98}$$

(19) $$\frac{S_p\sqrt{A_b}}{\alpha_s}=0.169\left[\frac{\beta_s}{\sqrt{A_b}}\right]^{-1.27}\left[\frac{M_w}{M_s}\right]^{-0.068}\left[\frac{\delta_b}{\sqrt{A_b}}\right]^{-0.158}\left[\cos\theta\right]^{-6.249}$$

Table 2 shows the regression coefficients for the correlations and their respective standard errors under wind and no-wind conditions. Figs. 2 and 3 show the dimensionless correlations using eq. 18 and eq. 19 respectively. A total of 334 data points for wind condition and 319 data for no-wind conditions were extracted from the sources in Table 1 and used in the regression analysis. The coefficient of correlations (R^2) for eq. 18 and eq. 19 are 0.83 and 0.66, respectively. The correlation under wind condition correlate the experimental data slightly better than the no-wind condition; this could be due to the fact that less data information needed to evaluate the dimensionless groups was given or available in the studies with no-wind and more nominal values and informed estimates had to be used for some of the parameters in the calculations.

Conclusions

A dimensional analysis was performed to correlate the fuel bed fire rate of spread data previously reported in the literature. Under wind condition, six pertinent dimensionless groups were identified, namely dimensionless fire rate of spread, dimensionless fuel particle size, fuel moisture content, dimensionless fuel bed depth or dimensionless fuel loading density, dimensionless wind speed, and angle of inclination of fuel bed. Under no-wind condition, five similar dimensionless groups resulted. The dimensionless correlations using the resulting dimensionless groups correlate the fire rates of spread reasonably well in light of the wide range of uncertainties associated with some of the parameters used for the calculations.

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List of symbols

a_1, a_2	regression coefficients
b_1, b_2, b_3 b_4, b_5	regression coefficients
c_1, c_2, c_3, c_4	regression coefficients
A_b	fuel bed surface area (m^2)
F_{ld}	fuel loading density (kg/m^2)
M_s	moist fuel mass (kg)
M_w	water content of fuel (kg)
S_p	fire spread rate (m/s)
U	wind speed (m/s)
V_b	fuel bed volume (m^3)
V_s	fuel volume (m^3)
α_s	fuel thermal diffusivity (m^2/s)
β_s	fuel volume-to-surface ratio (m)
δ_b	fuel bed thickness (m)
ε_b	fuel bed void fraction
θ	inclined angle of fuel bed (^{o})
λ	fuel bed porosity (m)
ρ_b	fuel bed bulk density (kg/m^3)

ρ_s fuel density (kg/m^3)

σ fuel surface-to-volume ratio (m^{-1})

Table 1. Data sources used for the dimensionless correlations.

Data sources	Wind	No wind	Slope
Tables 1-2 (Fons 1946)	✓		
Figure 1 (Beaufait 1965)	✓	✓	
Tables 2-5 (Rothermel and Anderson 1966)	✓	✓	
Tables 1-2 (Anderson 1969)		✓	
Figures 2-5 (Fang and Steward 1969)		✓	
Table 1 (Nelson and Adkins 1986)	✓		
Figure 2 (Dupuy 1995)		✓	✓[a]
Figures 6, 8, and 9 (Simeoni et al. 2001)	✓	✓	✓[b]
Appendix table (Anderson et al. 2010)	✓	✓	
Tables 1 and 3 (Dupuy and Maréchal 2011)		✓	✓[c]
Weise et al. (2015)	✓	✓	✓[d]

[a] $-30° \leq \theta \leq 20°$; [b] $0° \leq \theta \leq 10°$; [c] $0° \leq \theta \leq 30°$; [d] $-30° \leq \theta \leq 35°$

Table2. Regression coefficients and their standard errors

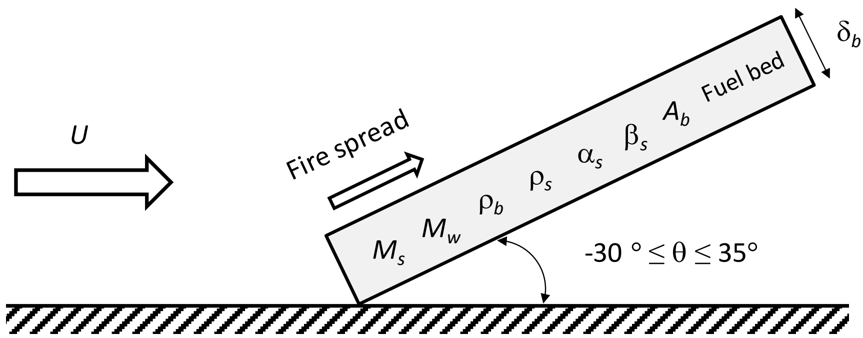
b_1	b_2	b_3	b_4	b_5	c_1	c_2	c_3	c_4
-0.41 (0.045)	-0.82 (0.052)	-0.29 (0.048)	1.32 (0.046)	-13.98 (5.344)	-1.27 (0.074)	-0.07 (0.057)	-0.16 (0.058)	-6.25 (0.713)

Figure captions

Fig. 1. A schematic showing the pertinent parameters used in the dimensional analysis.

Fig. 2. Dimensionless correlation for fuel bed fire spread under wind condition (334 data points).

Fig. 3. Dimensionless correlation for fuel bed fire spread under no-wind condition (319 data points).



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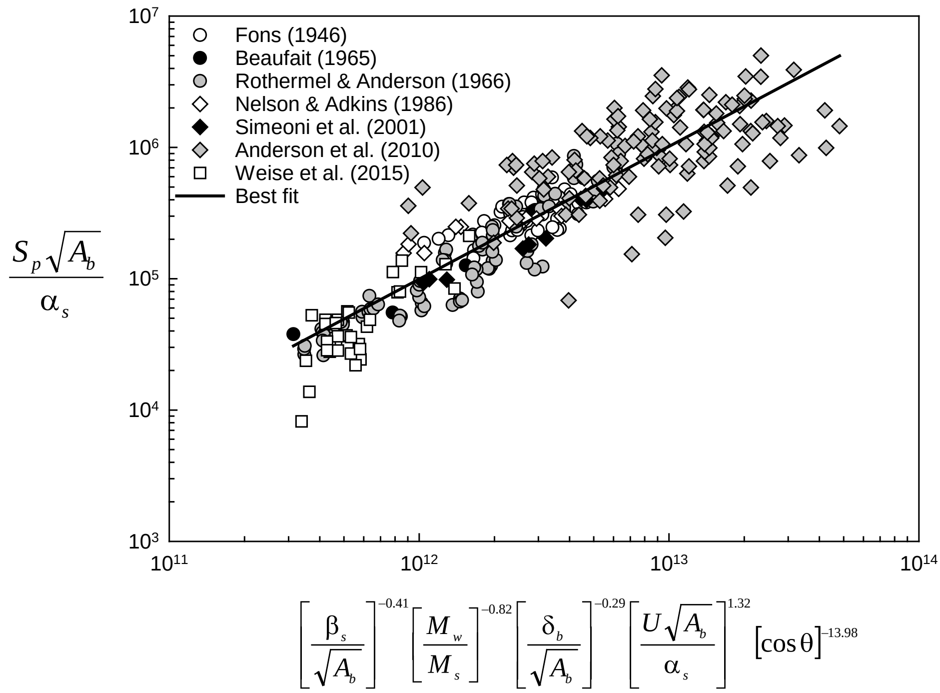

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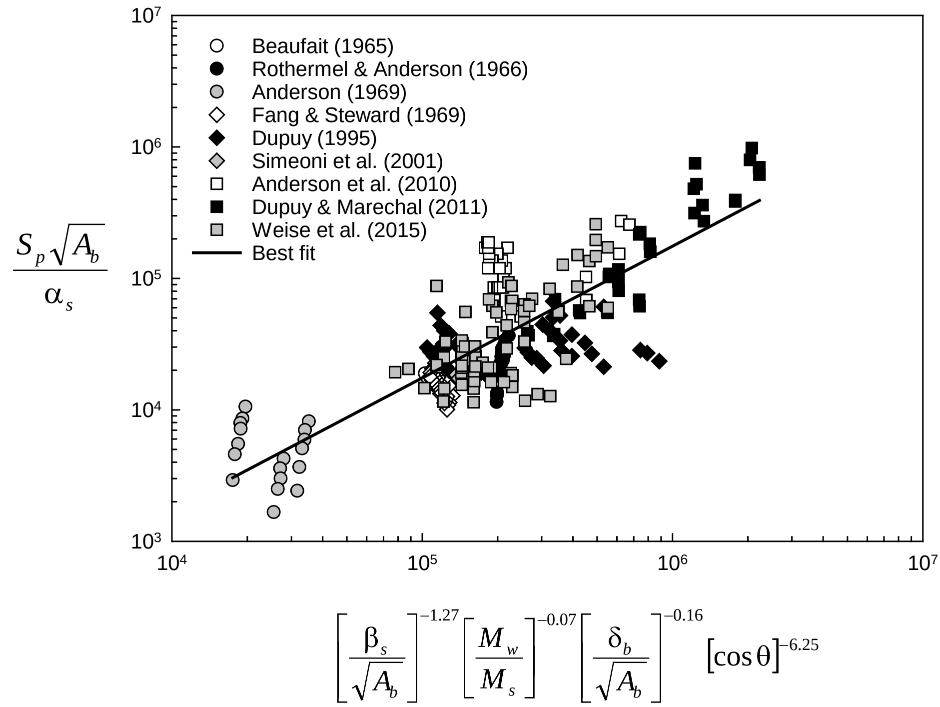

Fig. 3. Dimensionless correlation for fuel bed fire spread under no-wind condition (319 data points).