Effects of wind velocity and slope on flame properties

David R. Weise and Gregory S. Biging

Abstract: The combined effects of wind velocity and percent slope on flame length and angle were measured in an open-topped, tilting wind tunnel by burning fuel beds composed of vertical birch sticks and aspen excelsior. Mean flame length ranged from 0.08 to 1.69 m; 0.25 m was the maximum observed flame length for most backing fires. Flame angle ranged from -46° to 50°. Observed flame angle and length data were compared with predictions from several models applicable to fires on a horizontal surface. Two equations based on the Froude number underestimated flame angle for most wind and slope combinations; however, the data support theory that flame angle is a function of the square root of the Froude number. Discrepancies between data and predictions were attributed to measurement difficulties and slope effects. An equation based on Byram's convection number accounted for nearly half of the observed variation in flame angle ($R^2 = 0.46$). Byram's original equation relating fireline intensity to flame length overestimated flame length. New parameter estimates were derived from the data. Testing of observed fire behavior under a wider range of conditions and at field scale is recommended.

Résumé : Les effects combinés de la vitesse du vent et du pourcentage de pente sur la longueur et l'angle des flammes ont été mesurés dans une soufflerie à ciel ouvert et inclinable, en y brulant des agencements de combustibles composés de frisons de peuplier et de bâtonnets de bouleau disposés à la verticale. La longueur moyenne des flammes a varié entre 0,08 et 1,69 m. Pour la majorité des feux brûlant à contrevent, la longueur maximale des flammes a été de 0,25 m. L'angle des flammes a varié entre −46° et 50°. Les données observées de longueur et d'angle des flammes ont été comparées avec les valeurs prédites par plusieurs modèles applicables aux incendies se propageant sur une surface horizontale. Deux équations fondées sur l'indice de Froude ont sous-estimé l'angle des flammes pour la majorité des combinaisons de vent et de pente. Cependant, les données observées se conforment à la théorie stipulant que l'angle des flammes est une fonction de la racine carrée de l'indice de Froude. Les divergences entre les données observées et les valeurs prédites ont été attribuées aux difficultés de mesurage et aux effets de la pente. Une équation utilisant l'indice de convection de Byram a expliqué près de la moitié de la variation observée de l'angle des flammes ($R^2 = 0{,}46$). L'équation originale de Byram, reliant l'intensité frontale du feu à la longueur des flammes, a surestimé la longueur des flammes. De nouveaux estimateurs des paramètres de l'équation ont été dérivés des données. L'évaluation du comportement du feu observé dans un gamme plus vaste de conditions et à l'échelle du terrain est recommandée.

[Traduit par la Rédaction]

Introduction

Properties of wildland fire flames have been examined in some detail (Putman 1965; Albini 1981; Nelson and Adkins 1986). Flame angle and flame length are two critical factors that determine heat transfer from a flame via radiation. These two quantities play critical roles in determining the rate of spread of fires for which radiation is the primary method of heat transfer to the unburnt fuel. Additionally, flame properties play a dominant role in heat transfer to the soil surface for fires burning in fuel types that contain little or no organic material on the soil surface (Pafford et al. 1991). Flame length has been used to predict foliage scorch height caused by a fire burning under a forest canopy (Van Wagner 1973); the BEHAVE fire prediction system utilizes Byram's (1959) empirical relationship between fire intensity and flame length to predict this scorch height (Andrews and Chase 1989).

The action of horizontal wind on a flame may deflect the flame at some angle from the vertical (Drysdale 1985). This angle (or its complement) is commonly referred to as flame angle. Numerous authors have derived theory and (or) correlations relating flame angle to the ratio of a fire's buoyant force and the force of horizontal wind (i.e., Putnam 1965; Rothermel and Anderson 1966; Fang 1969; Nelson 1980; Albini 1981; Nelson and Adkins 1986). Nelson (1980) extended Fang's (1969) model and presented formulas for flame length and angle for wind-driven fires. A model for calm-air and backfire flame length was also presented. The model results were compared with field data from several southern U.S. fuel types.

Albini (1981) developed a physical model of the structure of the wind-blown flame of a turbulent wind-driven line fire. Chemical reactions were included in the model.

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A rough approximation for flame angle was derived tan2€),= $(3/2)U^2/gH$ (see Appendix for definition of variables) (Albini 1981, eq. 35). The ratio (U^2/gH) is dimensionless and is called the Froude number. Predictions from this rough approximation matched observed data from laboratory fires somewhat better than existing empirical relations.

Nelson and Adkins (1986) examined flame length and angle data from 22 laboratory and 8 field-scale fires. New coefficients for Byram's (1959) empirical relation relating flame length and fire intensity were estimated. The resulting empirical relation was found to predict flame lengths that were 70–80% of those predicted by Byram's original relation. Albini's flame angle model was examined also, but the model did not fit the data. The presence of the wind tunnel ceiling was identified as one potential cause for disagreement.

Two terms that have recently reappeared in the wildland fire community, "power of the fire" (P_f) and "power of the wind" (P_w), describe the rate of conversion of thermal energy to kinetic energy and the rate of flow of kinetic energy in the atmosphere due to the wind field (Nelson 1993). When this energy criterion is expressed as the ratio P_f/P_w, a dimensionless group $(2gh_cwR)/(pc_pT(U - R)^3)$ sometimes called the convection number (N_c) is formed. Assuming that $(2g/pc_pT)$ is constant, U is much larger than R, and using eq. 1 (byram 1959), the relationship $N_c \alpha (I_B/U^3)$ results. Albini (1981) first demonstrated the equivalence of the convection number and a Froude number based on flame height by (1) showing that the tangent of flame angle was proportional to the square root of a Froude number based on flame height and (2) stating that the tangent of flame angle should be proportional to the square root of $(U^3/(pwD)_o)$.[2] Martin et al. (1991) examined the relationship between N_c and flame angle by observing flames from burning pools of alcohol. No numerical relationship was presented; however, a scatterplot of the data indicated that flame angle could be modelled as a power function of N_c, the power being between 0 and 1.

Fendell et al. (1990) examined flame angle of wind-driven fiies in a wind tunnel that did not impose an artificial boundary on buoyancy (Fleeter et al. 1984). Flame angle was plotted against the ratio of fuel loading and wind speed. No numerical relationships were derived; however, powers of the ratio ranging from 0.15 to 0.25 fit the shape of the data well (Fendell et al. 1990).

To date, all of the above studies have examined the relationship between wind speed and flame angle on level ground. While it is fairly well accepted that tilting a fuel bed upslope increases a fire's intensity and thus it's buoyant force, the concurrent effects of wind and slope on flame angle have not been examined. Most models of flame length and angle were developed for wind-driven fires on level ground. This paper describes a comparison of several models of flame properties, both theoretical and empirical, with observed flame data for laboratory heading and no-wind fires burning upslope, downslope, and on level ground. In many cases, the models are being tested outside of the conditions they were developed to represent. Data for laboratory backing fires are also presented; however, these data are outside the scope of the models.

Methods

Experimental

Wind and slope interaction effects on flame properties were examined by burning fuel beds in an open-topped tilting wind tunnel with an adjustable roof and a 2.5 m long by 0.9-m test section (Fig. 1) (Weise 1993). An open-topped wind tunnel was used to remove any effects that a ceiling may have on the buoyancy of the flame (Fleeter et al. 1984). Wind velocities of −1.1, −0.4, 0, 0.4, and 1.1 m/s were combined with slope percentages of −30, −15, 0, 15, and 30%. Velocities and slope percentages <0 indicate backing fire and downslope fire spread, respectively. Similarly, positive velocities and slope percentages indicate heading fire and upslope fire spread, respectively. Ambient environment was not controlled. Wind was induced by a commercially available three-blade, 0.75 m diameter, free-standing, rotary fan that was placed at either end of the wind tunnel depending on the type of fire spread desired (upslope–downslope, heading–backing). The adjustable roof was gradually extended behind the flame during each experimental fire to insure a relatively constant wind velocity without impeding buoyancy.

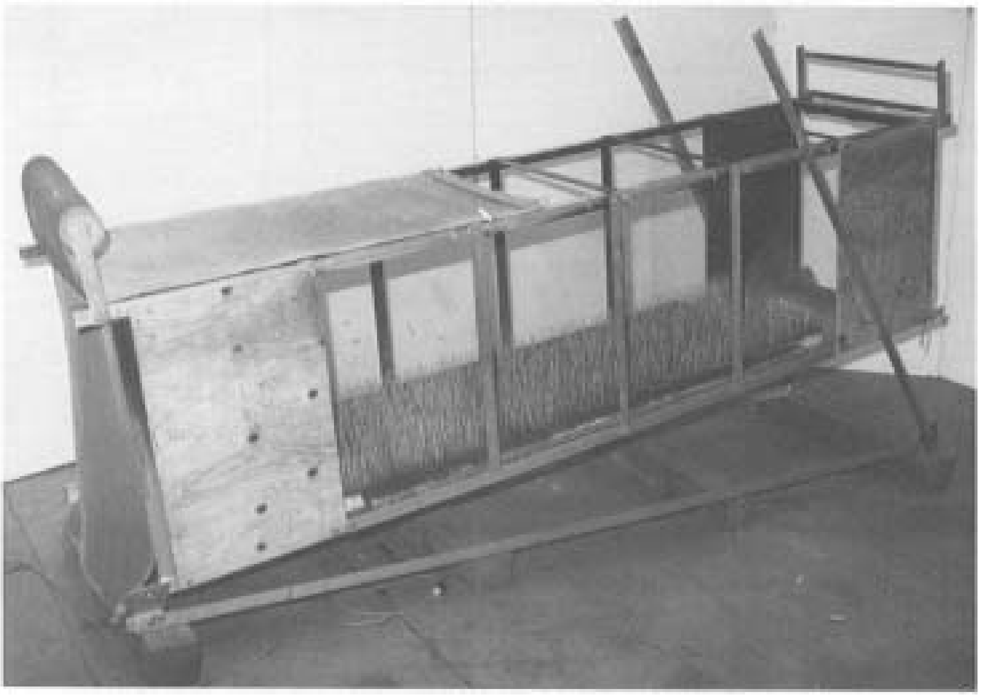
The vertical velocity profiles for both wind velocities were relatively uniform with the exception of the −30% downslope setting. There was some indication of an inverted velocity profile (velocity decreased with increasing height) for this setting. Velocity profiles for the high-wind setting for the 15 and 30% slopes indicated increasing velocity with height as might be expected with formation of a boundary layer near the brick base. The average turbulence level was about 15% of mean wind velocity (Weise 1994).

Fuelbeds consisted of vertical paper birch *(Betulu papyrifera* Marsh.) sticks (13.97 × 0.455 × 0.110 cm) and quaking aspen *(Populus tremuloides* Michx.) excelsior. Mean fuel loadings were 0.13 and 0.43 kg/m^2 for the excelsior and stick components of the fuel bed, respectively. Mean surface area to volume ratios for the sticks and excelsior were 22.75 and 24.90 cm^2/cm^3, respectively. Mean fuel moisture contents of the sticks and excelsior in 60 fires were 11 and 12%, respectively. Five additional fuelbeds had stick fuel moisture content of approximately 35%.

Ten flame length (L_f) and angle (0_f) observations were randomly sampled after quasi-steady-state spread was achieved from video images of 62 of the 65 experimental fires using the Fire Image Analysis System (Adkins 1987; Adkins et al. 1994). The remaining three fires were not used because of equipment malfunction. Flame length was defined to be the distance from the middle of the flame base to the flame tip (Fig. 2); flame angle and flame height were then computed using the horizontal and vertical reference lines (broken lines in Fig. 2) and the geometric properties

[2] Making the assumption that fireline intensity *(I)* is proportional to $h_c(pwD)$, (Albini 1981, p. 164) results in the statement that flame-angle tangent should be proportional to the square root of U^3/I_B The equivalence of a Froude number based on flame height and the convection number follows since both are proportional to the square of the tangent of flame angle. The authors acknowledge the assistance of Dr. Ralph Nelson, USDA Forest Service, in illustrating this equivalence.

Fig. 1. Tilting wind tunnel and sample fuel bed used to test effects of wind velocity and slope angle on flame length and angle.



of a digitized video. In this study, flame height (H_f)is $L_f \sin^{-1}(\theta_f)$. A sample size of 10 was selected based on time, budget, and equipment availability restrictions. This sample size was generally larger than the sample size used by Nelson and Adkins (1986). Flame angle was defined in this study as the angle between the flame axis and a vertical line as has been done in many studies. This differs, however, from the study by Martin et al. (1991) in which flame angle was defined as the angle between the flame axis and a horizontal line. Mean flame length and flame angle were estimated for each fire. Byram's (1959) fireline intensity (I_B) was estimated for each fire:

$$[1] \quad I_B = h_c w R$$

Fuel consumption (w) of 0.56 kg/m^2 and heat of combustion (h_c) for paper birch of 20 934 kJ/kg were assumed (Musselman and Hocker 1981). If the heat of combustion is reduced for radiation loss (2791 kJ/kg) and heat associated with water loss (1628 kJ/kg), a low heat of combustion of 16 515 kJ/kg results (Brown and Davis 1973, p. 162).

Rate of spread (was measured for each fire using nine pairs of chromel–alumel (type K) thermocouples spaced equidistantly along the fuel bed. Of the 65 fires in this experiment, nine failed to spread the entire length of the fuel bed. Fuel consumption was virtually complete for all fires that spread the length of the fuel bed and was assumed complete for computation of I_B. Further details of the experiment and wind tunnel can be found elsewhere (Weise 1993, 1994; Weise and Biging 1994, 1997).

Flame angle models

Predicted flame angles from four models were compared with observed data. Albini's (1981) eq. 35, a rough approximation of the relationship between θ_f and the Froude number for a uniform wind field, can be algebraically solved for $\tan(\theta_f)$ per Nelson and Adkins (1986):

$$[2] \quad \theta_f = \tan^{-1}(1.22(U^2/gH)^{0.5})$$

Fig. 2. Flame geometry of a line fire. Flame angle (θ_f) is measured from the vertical in the direction of fire spread: positive values indicate that the flame is tilted in the direction of fire spread, and negative values indicate that the flame is tilted away from the direction of fire spread. Slope angle (θ_s) is measured relative to a horizontal line.

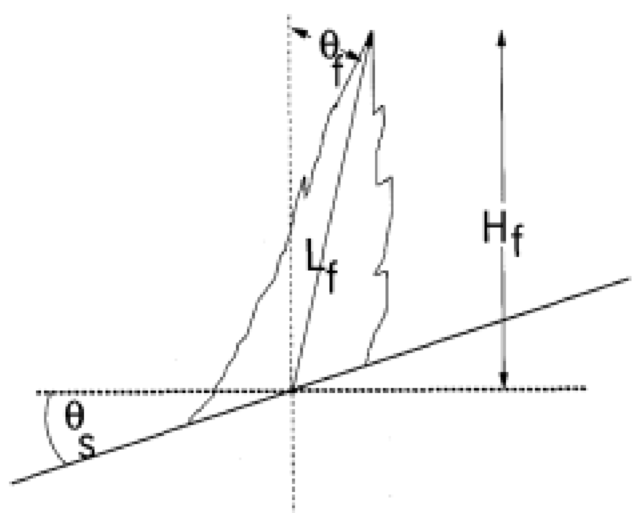


Table 1. Mean flame angle and flame length for experimental laboratory fires by wind velocity and percent slope.

Wind velocity[a]	Percent slope				
	−30	−15	0	15	30
Flame angle (θ_f)[b]					
HB	−41.0 (17.3)	-40.5 (21.9)	−46.0 (2.8)	−25.5 (12.0)	−32.7 (5.8)
LB	−38.5 (16.3)	−36.5 (6.4)	−20.0 (4.2)	−2.0 (28.3)	13.0 (.)
0	−39.5 (9.2)	−7.5 (0.1)	2.3 (1.3)	5.0 (0.0)	13.5 (5.0)
LH	25.0 (5.7)	32.0 (7.1)	13.5 (0.7)	18.0 (4.2)	12.5 (2.1)
HH	43.0 (2.1)	32.0 (1.4)	32.5 (7.8)	41.5 (2.1)	49.5 (4.0)
Flame length (L_f)[c]					
HB	0.09 (0.008)	0.09 (0.013)	0.12 (0.035)	0.11 (0.000)	0.13 (0.007)
LB	0.08 (0.011)	0.11 (0.015)	0.15 (0.005)	0.22 (0.060)	0.53 (.)
0	0.09 (0.012)	0.27 (0.079)	0.26 (0.013)	0.25 (0.015)	0.70 (0.066)
LH	0.30 (0.033)	0.23 (0.013)	0.41 (0.129)	0.57 (0.115)	0.57 (0.101)
HH	0.78 (0.039)	0.84 (0.006)	1.07 (0.020)	1.18 (0.028)	1.69 (0.126)

[a]Wind velocity (m/s) and direction. HH, 1.1 m/s (high velocity) heading; LH, 0.4 m/s [low velocity) heading; 0, no wind, no slope; LB, 0.4 m/s backing; HB, 1.1 m/s backing. (.) indicates SD could not be calculated because of too few values.

[b]Mean flame angle (degrees) measured from the vertical, with SD given in parentheses.

[c]Mean flame length in meters, with SD given in parentheses.

Parameters for Putnam's (1965) theoretical model were determined from experimental data for natural gas flames:

[3] $\theta_f = \tan^{-1} 1.4(U^2/gL_f)^{0.5})$

As noted above, these models assumed horizontal wind flow and no slope. Pagni and Peterson (1973) stated that Putnam's model was valid when slope angle (θ_s) was small, Under the assumption that wind flow in this experiment was parallel to slope, using $U\cos(\theta_s)$ to compute the horizontal wind component resulted in reductions of 2 and 5% for the low and high slope angles, respectively. Given this small reduction, U was used in the models without adjustment.

The convection number N_c was also examined as an alternative Froude number-based predictor of θ_f. N_c applies only to wind-driven fires. Applying this relationship to Nelson and Adkins (1986) eq. 10 yields a result similar to

[4] $\theta_f = \tan^{-1}(2.58 N_c^{-0.29})$

except for the multiplier (2.58). The parameters of eq. 4, which Nelson and Adkins (1986) estimated (2.58, -0.29), were estimated statistically using the data from the present experiment. It should be noted that N_c, which is a function of Froude^{-1}, has several features that make it desirable as an empirical relation. As U approaches 0, the following happens: θ_f approaches 0°, $\tan(\theta_f)$ approaches 0, N_c approaches infinity, and N_c^{-1} approaches 0. Similarly, when U is much greater than I_B, θ_f approaches 90°, $\tan(\theta_f)$ approaches infinity, N_c approaches 0 and N_c^{-1} approaches infinity. $\tan(\theta_f)$ and N_c^{-1} appear to have the same limits. N_c was estimated using the $2gh_c wR/\rho c_p T(U - R)^3$ formulation.

Flame length model

Byram (1959) developed an empirical relationship between flame length and fireline intensity:

[5] $L_f = 0.0775\, I_B^{0.46}$

This relationship is currently used in the BEHAVE fire behavior system to predict L_f Parameters of the general nonlinear regression model for Byram's model can be estimated by linear regression of the log–log transformed version of the following model:

[6] $L_f = B_0 I_B^{B1}$

Nelson and Adkins (1986) used this approach and estimated $\beta_0 = 0.0475$ and $\beta_1 = 0.493$ for wind tunnel fires with fuel beds of loblolly pine (*Pinus taedu* L.) needles and saw-palmetto (*Serenoa repends*) fronds.

Statistical analysis

The relationships between I_B, L_f, N_c, and θ_f were examined statistically. A general form of the model relating flame angle to the Froude number is

[7] $\tan(\theta_f) = \beta_2(\text{Fr})\beta_3$

The parameters for Albini's formulation (based on flame height) and Putnam's formulation (based on flame length) were compared with estimated parameters derived by fitting eq. 7 using the appropriate Froude number. Coefficient estimates derived from the data in this study for the flame length model (eq. 6) were compared with Byram's (1959) and Nelson and Adkins (1986) coefficient estimates. Since eqs. 6 and 7 are nonlinear statistical models, log–log transformations of the models were computed resulting in linear models. Parameter estimates for $\log(\beta_0)$, β_1, $\log(\beta_2)$ and β_3 were estimated using linear regression. Thus all statistical tests presented pertain to the linearized forms of eqs. 6 and 7.

To determine if slope affected model performance, analysis of variance (ANOVA) was used. In this analysis, model predictions were treated as data. The effects of slope, wind velocity and their interaction on predicted flame angles

Fig. 3. Flame angles predicted by Putnam's flame length based Froude model (eq. 3) versus actual flame angles for several wind velocities and slopes.

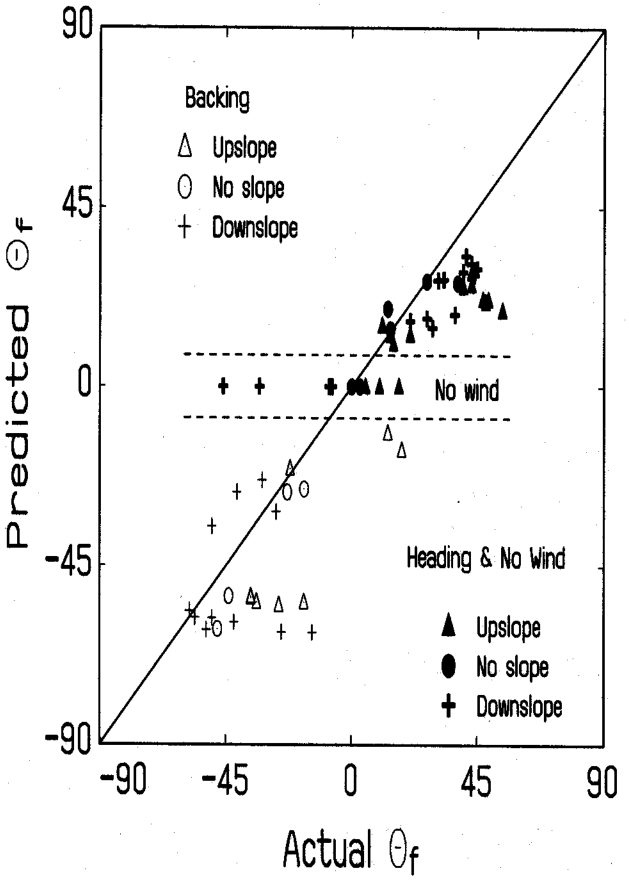
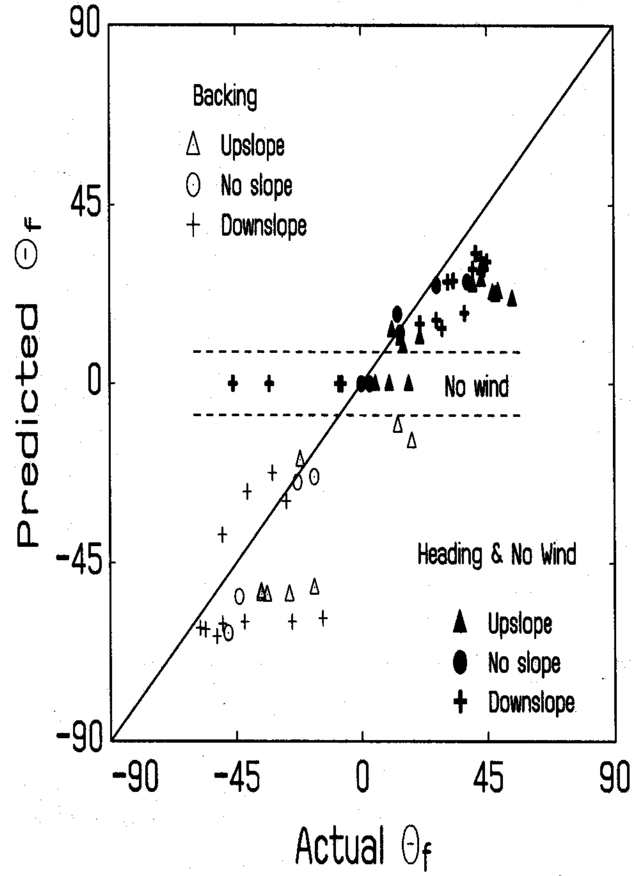


Fig. 4. Flame angles predicted by Albini's flame height based Froude model (eq. 2) versus actual flame angles for several wind velocities and slopes.



were tested using ANOVA. Since wind velocity was used to predict flame angles, the effect of wind velocity had to be included in the analysis. By isolating the wind effect statistically, the remaining variation is attributed to slope, wind and slope interaction, and experimental error.

Results

Flame angle (θ_f) was defined as the angle between a line running from the middle of the flame base to flame tip and a vertical line (Fig. 2.) Positive angles indicate that the flame is tilted in the direction of fire spread, negative angles indicate that the flame is tilted away from the direction of fire spread. 8, was difficult to determine for backing fires because of (1) small flame size and (2) curvature of the flame front. Mean flame length ranged from a minimum of 0.08 m for downslope backing fires to a maximum of 1.69 m for upslope heading fires,(Table 1). Similarly, mean flame angle ranged from -46 to 50°. The standard deviation associated with mean flame angle ranged considerably. The absolute value of 8, for backing fire was more variable than for heading fire. This variability was attributed to measurement error due to the small flames.

A confidence interval (95%) was calculated for mean 8, for each treatment combination ($t = 2.262$, df =9), These confidence intervals did not contain 0 for 8 of 10 backing fires (rows HB, LB in Table 1) indicating that mean 8, was less than 0 for all backing fires except the 15 and 30% slope treatments. Mean 8, for the no-wind fires behaved as expected. 8, was less than 0 for the two downslope treatments, near 0 for the no-wind, no-slope fires, and greater than 0 for the upslope fires. Mean 8, for the heading fires (HH, LH in Table 1) was greater than 0 for all slope treatments indicating that wind velocity was sufficient to cause the flames to tilt in the direction of spread. For upslope fires, wind contributed to the tendency of the flame to lean into the slope; for downslope fires, wind velocity was sufficient to overcome the tendency of a flame to lean into the slope as well as the buoyant force of the flame.

Flame angle models

Albini's and Putnam's Froude number based models (eqs. 2 and 3) performed nearly identically though based on flame height and flame length, respectively (Figs. 3 and 4). All data are plotted in the figures, not just the means presented in Table 1. As one would expect, the agreement between predicted flame angles for these two models was very close (Figs. 3 and 4). However, observed flame angles generally fell beneath the line of perfect agreement (Figs. 3 and 4). The models underpredicted 8, for upslope backing fires and for most headfires. Flame angles for most headfires fell below this line. Note, however, that agreement

Table 2. Analysis of variance table for wind velocity and slope angle effects on predictions from several flame angle models based on forms of the Froude number.

Source	df	Partial SS		P >F
Albini's model (eq. 2)				
Block"	2	10.5	1.05	0.3601
Wind velocity (*U*)	4	51 728.2	2582.32	0.0001
Slope (SP)	4	147.9	7.38	0.0002
U × SP interaction	16	802.4	10.01	0.0001
Error	3	175.3		
Total	61	62 108.2		
Putnam's model (eq. 3)				
Block	2	16.4	1.81	0.1786
Wind velocity (*U*)	4	52 477.9	2901.37	0.0001
Slope (SP)	4	82.7	4.57	0.0045
U × SP interaction	16	669.8	9.26	0.0001
Error	36	158.3		
Total	61	62 002.7		
Convection number model (eq. 4)[b]				
Block	2	0.25	3.75	0.0335
Wind velocity (*U*)	4	24.82	185.97	0.0001
Slope (SP)	4	0.76	5.67	0.0013
U × SP interaction	16	2.07	3.88	0.0004
Error	36	1.17		
Total	61	35.07		

[a]Block effects contain effects of stick orientation and fuel moisture.
[b]Byram's convection number (Byram et al. 1964). Also known as power of fire to power of wind ratio.

between observed and predicted flame angles for the no-slope fires was good.

ANOVA indicated that wind velocity, slope angle, and wind velocity × slope angle interaction significantly affected predictions from eqs. 2 and 3 (Table 2). Wind velocity by far affected predictions as would be expected given that wind velocity is a predictor variable. The effect of slope can be seen by examining the no-wind data in Table 1. Predicted flame angle for the no-wind fires is 0°; however, observed mean flame angle ranged from -39.5° for downslope fires to 13.5° for upslope no-wind fires (Table 1.) Mean flame angle for the 30% downslope fires was --35.9°; mean flame angles for the other no-wind fires were much closer to 0°. As stated previously, flame angle was difficult to measure for fires with very short flame lengths. Mean flame length and standard deviation of flame angle for the 30% downslope fires were 0.09 m and 9.2°, respectively. Stick length was 0.11 m. The observed value of --39.5° should be viewed with caution given the observed variation and potential for measurement error. For the --15, 15, and 30% slopes, mean flame angles indicated a tendency for the flame to attach to (or lean into) the slope. This phenomenon may be due to upslope entrainment.

Heading fire data were used to estimate the parameters for both forms of the Froude model (eq. 7). The regression model based on flame height was significant and accounted for 61% of the variation in heading fire flame angle (Table 3). Approximate 95% confidence intervals for estimates of β_2 (2.35) and β_3 (0.573) are (1.32, 4.17) and (0.35, 0.80), respectively:

$$[8] \quad \theta_f = \tan^{-1}(2.35(U^2/gH)^{0.57}), \qquad R^2 = 0.61$$

Parameter estimates for eq. 8 were highly correlated (r = 0.95). The regression model based on flame length only accounted for 48% of the variation:

$$[9] \quad \theta_f = \tan^{-1}(2.67(U^2/gL_f)^{0.57}), \qquad R^2 = 0.48$$

Both Putnam's and Albini's models generally underpredicted the data (Fig. 5). The estimated exponent β_3 for both Froude numbers was 0.57, close to the 0.5 derived by Albini and Putnam. The primary cause for disagreement between the data and the Froude models are the intercept (β_2) estimates. The β_2 term in Putnam's model was estimated from data collected from natural gas flames; the term was analytically derived in Albini's model.

Slope was found to be a statistically significant variable; however, its effect is not readily visible (Fig. 5). Downslope and no-slope heading fires generally fell close to the equations. The upslope heading fires fell into two distinct groups. Low wind speed fires had Froude numbers <0.04 while the high wind speed fires exhibited Froude numbers >0.08. Corresponding flame angles were tilted appreciably from the vertical resulting in large values of $\tan(\theta_f)$. The cause of separation of the upslope, high wind speed fires into two groups is not known. If these particular fires did not achieve quasi-steady-state spread, then L, may not have achieved a quasi-steady state with a fairly constant buoyancy (Weise 1993).

The relationship between θ_f and N_c exhibited two distinct forms (Fig. 6). Backing fires are indicated by open circles, heading fires by solid circles. There was little evidence of

Table 3. Analysis of variance for various empirical regression models developed from laboratory-scale data.

Source	df	Sequential SS[a]	F	$P > F$
Flame angle – Froude number (eq. 8)				
Model	1	5.0232	37.862	0.0001
Error	24	3.1841		
Total	25	8.2073		
Flame angle – Froude number (eq. 9)				
Model	1	3.9002	21.733	0.0001
Error	24	4.3071		
Total	25	8.2073		
Flame angle – Convection number (eq. 10)				
Model	1	3.8084	20.778	0.0001
Error	24	4.3989		
Total	25	8.2073		
Flame length – fireline intensity (eq. 11)				
Model	1	51.3298	853.855	0.0001
Error	57	3.4266		
Total	58	54.7564		

Note: Sums of squares are calculated for log-transformed models.

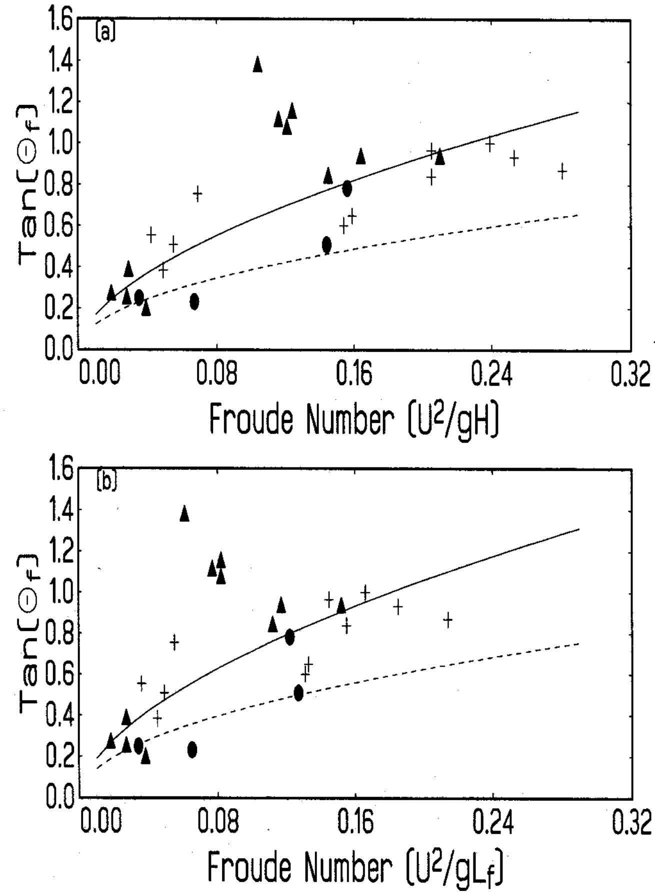
a relationship between θ_f and N_c for backing fires. This is due largely to the relatively constant rate of spread and fireline intensity of backing fires. To date, no theory exists relating the Froude number to θ_f for backing fires. The data supported the previously noted similarity in the limiting values for 8, and N, As the power of the fire increased relative to the power of the wind (N_c increased), flame angle approached 0° and the flame approached vertical. ANOVA indicated that wind velocity, slope angle, and their interaction affected N_c (Table 2).

Coefficients of eq. 4 were estimated for the log-transformed regression model using heading fire data only. N_c is equal to ∞ for no wind fires (Byram et al. 1964). The regression model was statistically significant and explained 46% of the variation in $\ln(\theta_f)$ (Table 3). The estimated model is

[10] $\theta_f = \tan^{-1}(3.08 N_c^{-0.383})$, $R^2 = 0.46$

Approximate 95% confidence intervals for estimates of β_2 (3.08) and β_3 (--0.383) are (1.46, 6.53) and (−0.56, --0.21), respectively. The range of $\tan(\theta_f)$ was greater for upslope fires than for downslope fires (Fig. 7). Upslope fires clustered into two distinct groups that were associated with the two wind speed settings. Low wind speeds resulted in $N_c > 240$ and the high wind speed group resulted in $N_c < 60$. Downslope and no-slope fires were similarly clustered. Low wind speed fires for these two groups yielded $120 \leq N_c \leq 240$ and high wind speed fires exhibited $N_c < 30$ for the downslope and no slope orientations. The solid line in Fig. 7 is the fitted regression model (eq. 10). The estimated parameters in this study (3.08, −0.383) are similar to those reported by Nelson and Adkins (1986) in eq. 4.

Fig. 5. Comparison of observed flame angles ($\tan(\theta_f)$) with statistically derived models based on the Froude number for head fires on several different slopes.
(a) Albini's model: short dashed line, flame height based Froude (eq. 2); solid line, regression model (eq. 8).
(b) Putnam's model: short dashed line, flame length based Froude (eq. 3). solid line, regression model (eq. 9).
(▲) upslope heading, (●) no slope heading, (+) downslope heading.



Flame length

The relationship between L_f and I_B can be seen in Fig. 8. The parameters in eq. 6 were estimated using all data; $R^2 = 0.94$ for the log-transformed data. The regression model was highly significant (Table 3). The fitted regression model for the present study is

[11] $L_f = 0.016 I_B^{0.70}$, $R^2 = 0.94$

The β_0 estimate in this study was smaller than Byram's (0.0775) and Nelson's (0.0475). The β_1 estimate was larger than Byram's β_1 (0.46) and Nelson's β_1 (0.493). In the present study, parameter estimates were highly correlated ($r = -0.95$). A second regression model in which β_1 was set equal to 0.46 was fit. The model was of the form of eq. 11 so linear regression was used and the intercept forced through 0. The slope estimate (β_0) of 0.065 with an $R^2 = 0.88$ fell midway between Byram's and Nelson's coefficient estimates. A third regression model was fit and the intercept term was not suppressed. For this model,

Fig. 6. Relationship between Byram's convection number (N_c) and flame angle (θ_f) for heading (solid circles) and backing fires (open circles).

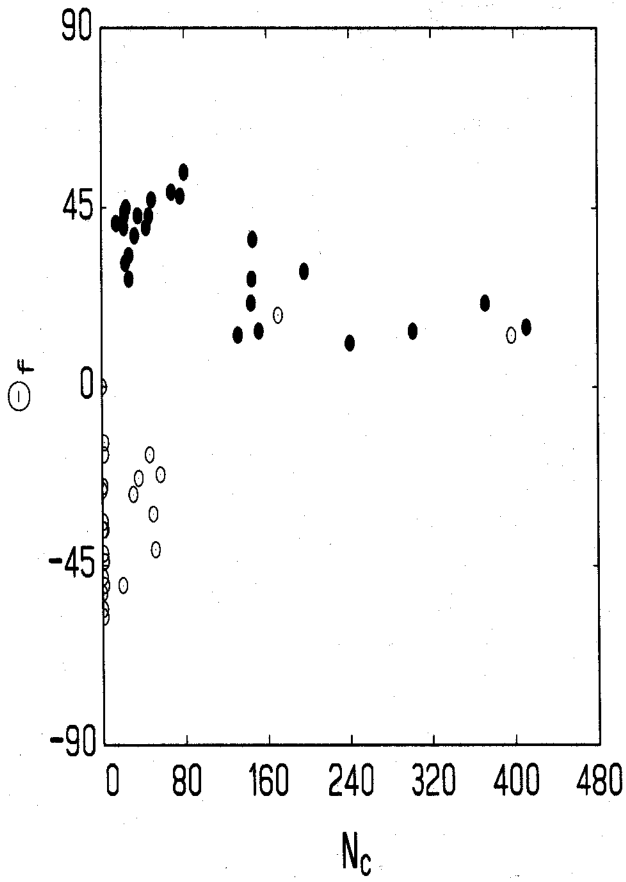
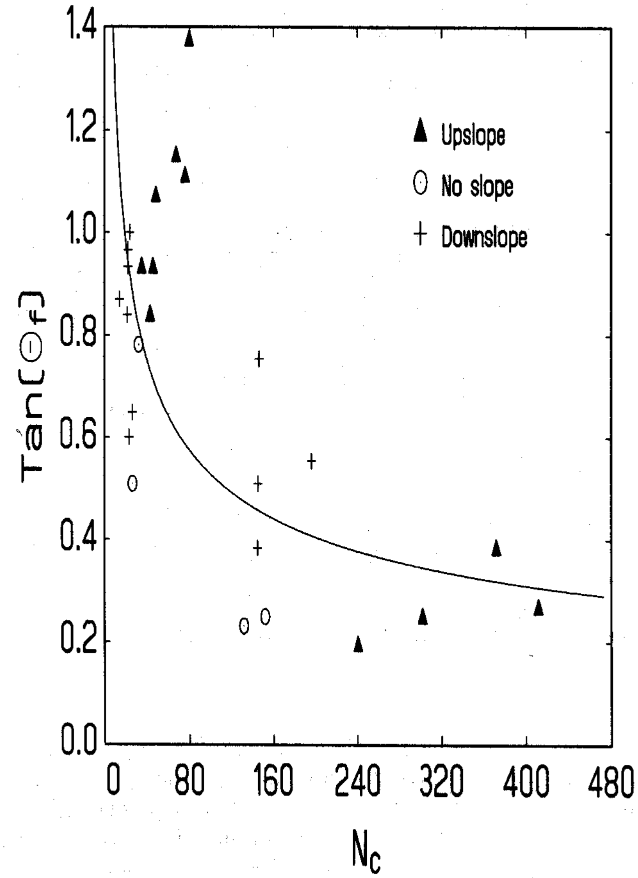


Fig. 7. Comparison of predictions from flame angle ($\tan(\theta_f)$) regression model (eq. 10) based on Byram's convection number (N_c)with actual $\tan(\theta_f)$ for heading fires spreading on several slope angles.



$R^2 = 0.95$, but negative flame length was predicted for $I_B = 0$. While this model statistically fit the data well, the model was rejected because negative L_f did not physically make sense. This third model was also rejected. The parameters for eq. 7 were also estimated when I_B was calculated using the low heat of combustion (16 515 kJ/kg). The estimate of β_0 increased to 0.019, but the β_1 estimate was unchanged. This is to be expected as using the low heat of combustion reduces I_B uniformly across the data shifting the data downward, thus changing the intercept (β_0) of the log-transformed data but not the slope (β_1).

The wind speeds in the present study were generally less than those in the Nelson and Adkins (1986) study. Fuel consumption in the present study was assumed to be virtually complete. A fuel consumption of 0.56 kg/m^2 was assumed for all fires that spread the length
This value is within the range reported by Nelson and Adkins (1986). The ranges of flame length and I_B in the present study, however, were larger than ranges in Nelson and Adkins' wind tunnel study. Maximum I_B in that study was 492 kW/m; this is approximately 60% of the maximum I_B (819 kW/m) for the present study.

The regression models developed by Byram (1959) and Nelson and Adkins (1986) are also plotted in Fig. 8. Note the close agreement between these two regression models. Most of the data from the present study were bounded by the Byram and Nelson models for $I_B < 400$ kW/m. For $I_B > 400$, two of six data points fell outside the area bounded by the models. On the assumption that the high-heading, high-upslope fires did not achieve steady-state spread and flame length was inaccurate, these observations were removed from the data set and the coefficients for eq. 6 were estimated again. The β_0 estimate did not change, $\beta_1 = 0.71$, and R^2 decreased to 0.91. Thus, the presence of the high-heading, high-upslope fires tended to reduce the estimate of β_1.Equation 10 may be a conservative prediction model.

Discussion

Flame length is commonly estimated using Byram's empirical model (eq. 5) and is readily available in the BEHAVE system of fire models (Andrews 1986). Flame length is then used to estimate fire effects such as crown scorch. Results from this experiment indicate that the coefficients in Byram's original model overestimated flame length for the experimental fires for fireline intensities <750 kW/m Rothermel (1991) stated that, based on personal observation and discussions with fire behavior analysts, Byram's model underestimated flame length for crown fires. Byram

(1959) stated this very fact and further stated that the relationship was better suited for low-intensity fires. If this overestimation in fact exists for low-intensity prescribed fires, then caution should be exercised when estimating fire effects. Fire damage may in fact be less severe than estimated. Nelson and Adkins (1986) concluded that further study of the relationships among flame angle, flame length, and wind speed were needed under field conditions. The fact that neither Byram's original model nor Nelson and Adkins model fit the data in this experiment well further indicates the need for field testing of empirical flame length models as well as other models. Both of these empirical models were developed with data for fires on flat surfaces.

The two Froude number based models underestimated flame angle for most wind and slope combinations. This can be attributed to several factors: (1) the measurement difficulties identified previously and conditions of the wind tunnel experiment and (2) differences in the coefficient β_2 in this study). The heading fire data reported here generally support the theory that flame angle is a function of the square root of the Froude number. Slope effects, while statistically significant, were not readily visible in the data. It is possible that the relatively shallow angles used in this study did not significantly affect flame properties. Byram et al. (1966) suggest that spread rate may not be affected until slope angle approaches 20°; the slope angles in the present study were approximately 7 and 14°.

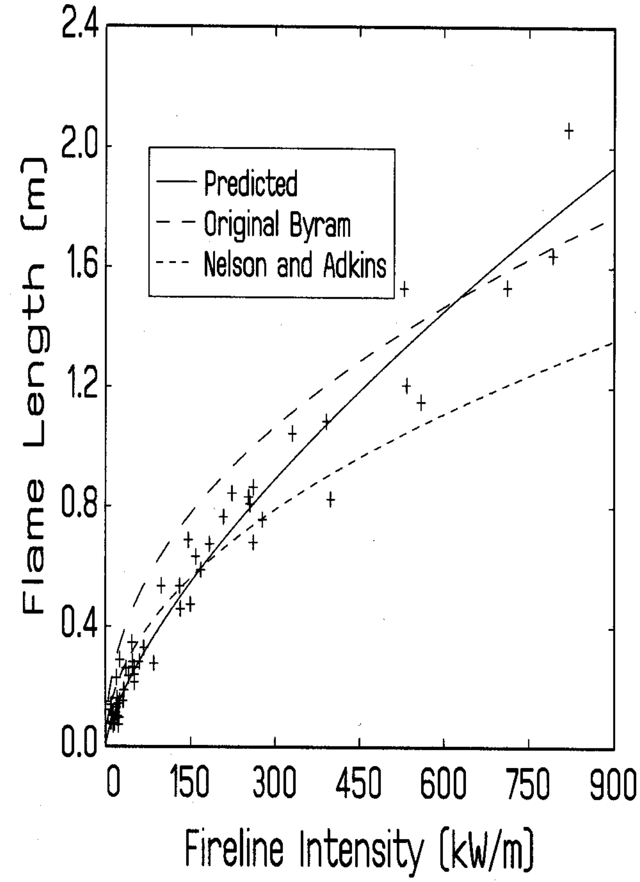
Byram et al. (1966) further stated that, while the slope component of buoyancy and inertial force of wind for a horizontal fire affect rate of spread similarly, the slope component of buoyancy increases with increasing fire intensity while inertial force of wind remains constant. The presence of slope also affects heat transfer from the flame to the unburnt fuel. The effect of wind alone is to tilt the flame relative to the fuel and to affect radiant and convective heat transfer. Inclusion of slope potentially changes the view factor between the flame and the fuel and further changes radiant heat transfer. The relative importance of radiant heat transfer compared with convective heat transfer is dependent on flame size among other factors. Flame length ranged by an order of magnitude in this experiment. Thus the dominant heat transfer mechanisms potentially varied.

The relationship between N_c and θ_f visually differs from the results of Martin et al. (1991). In that study, flame angle was measured from the horizontal. Thus, for small values of N_f (wind dominant region), θ_f, as defined by Martin et al. (1991) will be close to 0°. Flame angle as defined in the present study would be closer to 90°. When flame angle is defined consistently, the data of Martin et al. (1991) are similar to that observed in the present study. The heading fire data in the present study were also in general agreement with the results of Nelson and Adkins (1986).

Conclusions

Results from this experiment indicated that theoretical flame angle models based on the Froude number underestimated flame angle for fires spreading on slopes; however, the results support the relationship between flame angle and square root of the Froude number. These models were developed for horizontal spreading fires and do not include a slope component of buoyancy. Existing flame models based on the Froude number (including N_c) need to be extended to fires on sloping surfaces.

Fig. 8. Observed flame length (+) as a function of Byram's fireline intensity. Byram (1959) and Nelson and Adkins (1986) regression models are compared with eq. 11 (denoted predicted).



The flame length, fire intensity model developed by Byram that is extensively used overestimated flame lengths for fireline intensities <750 kW/m in the small-scale wind tunnel fires in this experiment. The present study examined a wider range of flame length and fire intensity than previous studies; however, the model is still limited because of its empirical nature.

Based on this study, slope appears to significantly affect flame angle; however, slope is not incorporated into existing flame models. Further detailed study in both laboratory and field settings and theory development is needed. Field tests of the relationships must be undertaken to determine if the effect of slope is scale dependent and to determine which, if any, of the several flame property models are accurate and appropriate.

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Appendix

The variables are defined as follows:

U	wind velocity (m/s)
g	gravitational acceleration (m/s^2)
H	flame height (m)
L_f	flame length (m)
ρ	ambient air density (kg/m^3)
c_p	specific heat capacity (kJ/kg K)
T	absolute temperature (K)
R	rate of spread (m/s)
h_c	fuel heat of combustion (kJkg)
w	fuel loading (kg/m^2)
θ_f	flame angle (degrees)