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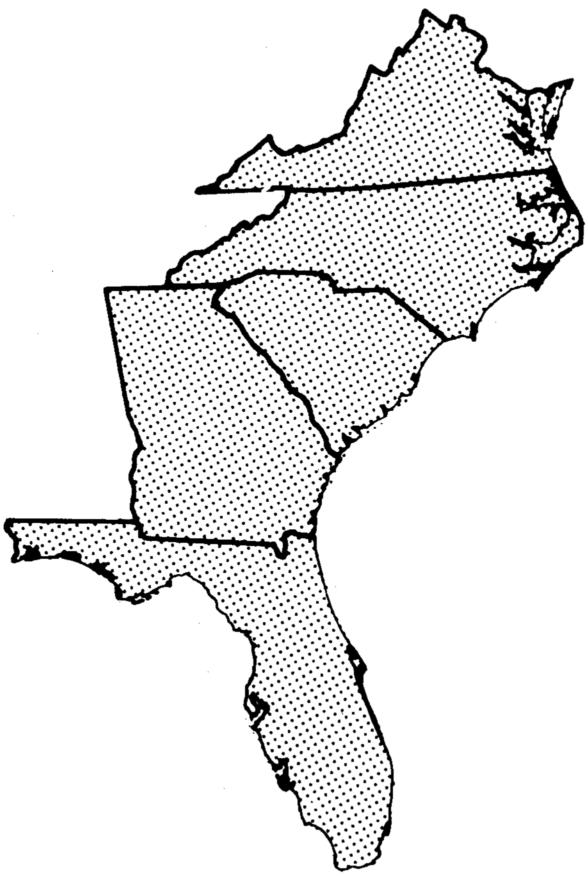
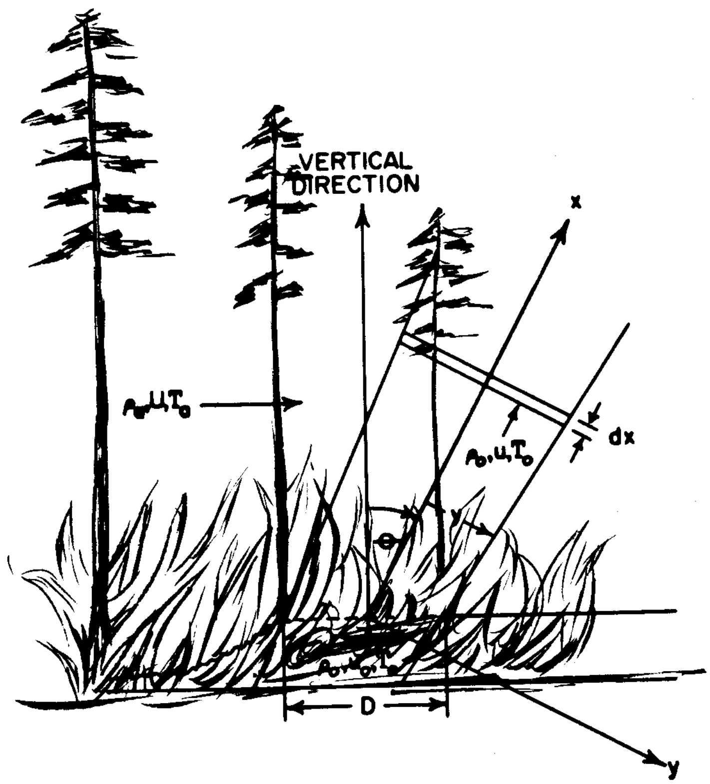
Flame Characteristics for Fires in Southern Fuels

by Ralph M. Nelson, Jr.





English units are still commonly used in forestry in the United States, and therefore are used in this paper. Conversion factors from English to metric units are:

From English	*Abbreviation*	*To metric*	*Multiply by*
Btu/pound	Btu/lb	joule/gram	2.3263
Btu/second/foot	Btu/ft-sec	kilowatt/meter	3.4613
Btu/second/foot^2	Btu/ft^2-sec	kilowatt/meter^2	11.3559
foot	ft	meter	.3048
foot^2	ft^2	meter^2	.0929
foot/second	ft/sec	meter/second	.3048
¼ milacre	—	meter^2	1.0117
pound	lb	kilogram	.4536
pound/foot^2	lb/ft^2	kilogram/meter^2	4.8818

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Flame Characteristics for Fires in Southern Fuels

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ABSTRACT.—Equations describing flow in buoyant turbulent jets have been applied to the derivation of characteristics for forest fire flames. Approximate solutions are used to develop relationships for flame lengths, angles, heights, and tip velocities for fires heading with the wind and burning in calm air as functions of Byram's fire intensity, I (Btu/ft-sec). Flame length and velocity relationships are tested with data taken during controlled burns in southern fuels and with data from the literature. Backfire data are described by the equations for calm-air conditions. Both theoretical and experimental results show that flame lengths for backfires and headfires vary as $I^{2/3}$ and $I^{1/2}$, respectively; flame tip velocities vary as $I^{1/3}$ and $I^{1/2}$.

Keywords: Flame length, flame velocity, flame tilt, fire intensity, buoyant flames.

Through concentrated research during recent years, the U.S. Forest Service has developed a capability for predicting burning rates of surface fires in representative forest fuel types throughout the Nation. During these same years, there has been a growing demand from Federal and State land management agencies for better predictions of wild land fire behavior which would contribute to improved fire and smoke management planning. Thus, burning-rate predictions need to be used in the consideration of such problems as description of spotting, crowning, convection column rise, and fire effects. Because of increasing interest in such problems, research is becoming more sharply focused on flame characteristics and their role in fire behavior phenomena.

A few studies of flame characteristics in real fuels have been reported. Research has been carried out in southern fuels by Byram (1959), in logging slash of western fuels by Anderson and others (1966), and in western grasses by Sneeuwjagt and Frandsen (1977). Thomas (1971) and Van Wagner (1968) also have made flame measurements in field experiments.

Much past research on flame characteristics has been associated with analytical work and modeling efforts in the laboratory. Among the variables studied are flame length, flame tip velocity, and angle of flame tilt. However, prediction models of these and other characteristics have not been firmly established with field experiments.

Flame lengths for line fires have been studied by Thomas (1963), Fons and others (1962), and Steward (1964) from theoretical and experimental points of view. For line fires in calm air, Thomas (1963) and Rothermel and Anderson (1966) have obtained empirical flame-length correlations of the form

$$L/D = K\left[\frac{m''}{\rho_o\sqrt{gD}}\right]^n$$

with the exponent n taking on values close to two-thirds. In this relation L is flame length, D is flame depth, m'' is rate of fuel consumption per unit area, ρ_0 is mass density of the ambient air, g is acceleration due to gravity and K is a constant that differs among fuel species. The data of Rothermel and Anderson (1966) for fires in calm air and wind were analyzed in a different way and reported by Anderson and Rothermel (1965). The general form of the correlation equation was retained, but values of n were approximately equal to unity. In other experiments, Thomas (1971) has applied $n = 2/3$ to wind-driven fires in the field with reasonable success.

The information now available indicates that different equations describe the variation in flame lengths, depending on the range in experimental data and other factors. Albini (1976) has pointed out that experimental flame-length data seem to be well described by an equation formulated by Byram (1959) (which corresponds approximately to $n = 1$), although there is more theoretical justification for Thomas' equation (for $n = 2/3$). The experimental studies of Sneeuwjagt and Frandsen (1977) also show that Byram's equation applies over a greater range of fire intensity than Thomas' equation.

In experiments on alcohol pool fires, Thomas (1965) found that flame tip velocities were proportional to the square root of the height of the flame zone. Theoretical flame velocities were reported by Byram and Nelson (1974). Flame tilt angles have been studied theoretically and in the laboratory by Anderson and Rothermel (1965), Welker and Sliepcevich (1966), and Fang (1969). Flame height—the perpendicular distance from the flame tip to the ground—has been discussed by Thomas and others (1963). The work on velocities, angles, and heights described above has produced several relationships among flame, fuel, and weather variables, none of which has been verified with field experiments in a convincing manner.

More field data are needed for testing current theories. Furthermore, a general analysis is needed from which information on flame characteristics of forest fires can be derived. To my knowledge, the only treatment of this kind is by Fang (1969) who derived flame length and tilt angle relationships from the theory of buoyant turbulent jets applied to a headfire in wind. However, he did not consider backfires and calm-air fires. The present paper is an attempt to extend this work. The flame model and analytical methods of Fang, modified in places, are used to derive flame lengths, heights, tip velocities, and angles of tilt for heading and calm-air fires. Expressions are obtained for flame lengths and velocities as functions of Byram's (1959) fire intensity by considering all other factors appearing in these expressions to be constant. Flame characteristics are written in terms of fire intensity for the purpose of providing a basis of comparison between the results of this paper and the existing models of Byram (1959) and Thomas (1963). Results of the analysis are used to develop relationships between lengths and velocities for headfires and backfires. The equations are compared with experimental data from fires of low intensity in southern fuels and with data in the literature. Expressions for flame tilt angle and flame height are developed also, but no comparisons with experimental data are made.

THEORETICAL CONSIDERATIONS

Equations for flame characteristics are derived for both headfires and calm-air fires. It is argued that flame lengths and velocities of backfires can be represented with the calm-air analysis.

Headfires

Following Fang (1969), we assume that combustion in the flame is controlled by the rate at which air mixes with volatilized fuel through the process of entrainment. In the case of headfires, possible accretion of horizontally moving air in the flame is not considered. The magnitude of the error built into the model through omission of terms accounting for this air is not known, but probably is small unless windspeed exceeds 15 to 20 miles per hour. The flame geometry is shown in figure 1, which depicts the cross section of a fire of infinite length (into the page) burning on flat ground. The x axis, an axis of symmetry through the center of the flame, makes an angle, Θ, with the vertical direction. This angle, which does not

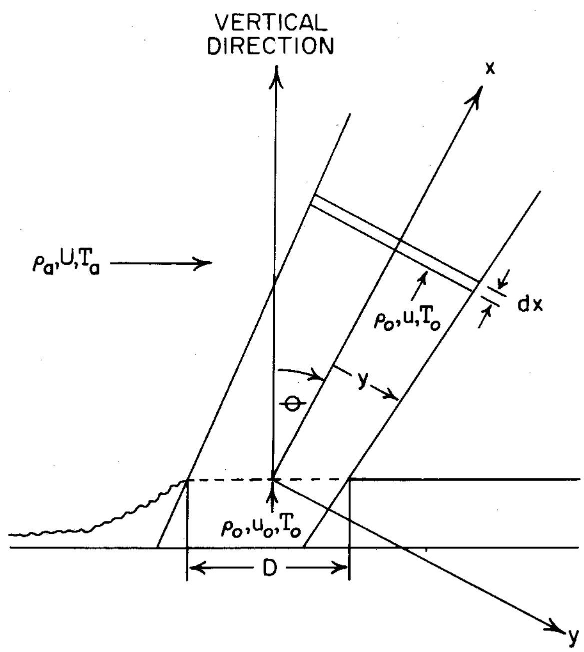

Figure 1.—Geometrical model of a line fire burning in wind.

change with changing x, is caused by a mean wind of speed U, blowing from left to right. The quantities Θ and U are known to vary, but are taken as constants in accordance with Fang (1969). Such a formulation simplifies the mathematical solution and seems to be a reasonable first approach. Though in a fluctuating turbulent flow, the flame is considered to be in a quasi-steady state in surroundings of constant density, ρ_a, and absolute temperature, T_a. The quantities u and y vary with axial distance, x. They represent local axial velocity and half the transverse dimension, respectively. Thus, y at a given x is half the flame thickness in a direction perpendicular to the x axis. Flame depth, D, is defined as the distance from front to rear of the flame, measured at the fuel surface. Fuel pyrolysis and partial combustion occur beneath the surface due to heat feedback from the flame and entrainment of some air into the fuel layer. This air is completely utilized in combustion. Thus, a mixture of volatilized fuel and combustion products of density, ρ_o, and absolute temperature, T_o, flow perpendicularly through the surface at a mean velocity, u_o. The density and temperature are considered constant with x, which results in a simpler analysis than that of Fang's for variable density. At the visible flame tip, combustion is completed in the sense that the reacting gases pass from a flaming to nonflaming state. It is assumed that because of imperfect mixing, the air entrained into the visible flame exceeds the amount required for stoichiometric combustion. The entrainment process is taken to be independent of fire size, type, and behavior. Radiation loss is accounted for with a reduced heat of combustion. In addition, the following assumptions are taken from Fang (1969):

a. Turbulent flow is fully developed and molecular transport processes are insignificant.

b. The flame behaves as a buoyant turbulent jet in which the rate of air entrainment is proportional to the local axial velocity.

c. The distribution of velocity is constant across the jet axis.

d. All flame components obey the ideal gas law and possess thermal properties that equal those of air and are independent of temperature.

e. Upon mixing, the volatilized fuel and entrained air react instantaneously in stoichiometric proportions.

The equations describing the system are written by considering conservation of mass and momentum for the elemental flame volume of thickness, dx, in figure 1. These equations are:

$$\frac{d(uy)}{dx} = \left(\frac{\rho_a}{\rho_o}\right)E'u \tag{1}$$

$$\frac{d(u^2y)}{dx} = \frac{C_F}{4}\left(\frac{\rho_a}{\rho_o}\right)U^2\cot\Theta \tag{2}$$

where C_F is a flame drag coefficient and E' is a constant associated with entrainment of ambient air into one side of the flame. A transverse force balance applied to the elemental flame volume gives

$$\frac{\tan\Theta}{\cos\Theta} = \frac{C_F\rho_a U^2}{4gy(\rho_a - \rho_o)} \tag{3}$$

in which g is acceleration due to gravity and Θ is constant. Equation (3), according to the assumptions of the model, is not strictly valid because it contains only one variable, y. In a thorough analysis, ρ_o and Θ would be replaced by variable quantities and the equation would be correct. It is assumed further that changes of y with x are sufficiently small that, to the level of accuracy required here, the equation $2y = D\cos\Theta$ can be regarded as roughly valid—not only at $x = 0$, but for all x. Thus, Equation (3) can be written approximately as

$$\tan\Theta = \frac{C_F\rho_a U^2}{2gD(\rho_a - \rho_o)}. \tag{4}$$

Dimensionless variables are defined as

$$x' = \frac{x}{D},\ y' = \frac{2y}{D} = \cos\Theta,\ u' = \frac{u}{u_o}.$$

Equations (1) and (2) now can be written as

$$\frac{d(u'y')}{dx'} = Au' \tag{5}$$

$$\frac{d(u'^2y')}{dx'} = B \tag{6}$$

where the constants A and B are obtained from Equations (1), (2), and (4) as

$$A = E\left(\frac{\rho_a}{\rho_o}\right) \qquad B = \frac{gD(\rho_a - \rho_o)}{\rho_o u_o^2} \tag{7}$$

and $E = 2E'$ is an entrainment constant for the entire flame.

Equations (5) to (7) can be used to develop expressions for flame length and other characteristics for headfires. Details of these derivations are presented in Appendix I. The final equations are:

Flame length:

$$L = \frac{(r^2 + 6r + 5)}{5\rho_a H}\left[\frac{I_R}{Eg(1 - \rho_o/\rho_a)}\right]^{1/2} I^{1/2} \tag{8}$$

Flame tilt angle:

$$\tan \Theta = \frac{C_F U^2 I_R}{2gI(1 - \rho_o/\rho_a)} \qquad (9)$$

Flame height:

$$h = L[1 + \tan^2\Theta]^{-1/2} \qquad (10)$$

Flame tip velocity:

$$u_L = \left[\frac{g}{EI_R}(1 - \rho_o/\rho_a)\right]^{1/2} I^{1/2} \qquad (11)$$

In Equation (10), L and tan Θ are obtained from Equations (8) and (9). The previously undefined quantities in Equations (8) to (11) are:

- r = mass of air entrained into the visible flame per mass of fuel burned, lb/lb
- H = heat yield of the combustion process, Btu/lb
- I_R = reaction intensity[1], Btu/ft²-sec
- I = fire intensity[2], Btu/ft-sec.

Equations (8) and (11) imply a relationship between u_L and L. Elimination of $I^{1/2}$ yields

$$u_L = \left[\frac{5\rho_a Hg(1 - \rho_o/\rho_a)}{(r^2 + 6r + 5)I_R}\right]L. \qquad (12)$$

If the factors multiplying L are roughly constant, u_L and L should be proportional. Of primary interest is the variability of I_R. The extent to which I_R changes for field burns in a given fuel or from one fuel type to another is unknown. The field data of Sneeuwjagt and Frandsen (1977) for headfires in grass indicate that I_R is a variable quantity. On the other hand, observations of wind- and slope-driven fires in the laboratory by Byram and others (1966) suggest that I_R may be affected by changes in windspeed and slope angle only to the extent that fuel consumption changes from one fire to another. For the sake of simplicity, I_R is considered constant from fire to fire within and among fuel types. This assumption is an oversimplification of the actual variation, and is believed to be a meaningful hypothesis only for fuel types in which unit area fuel consumption, fuel particle surface-to-volume ratio, and fuel moisture are not widely different. The experimental fires discussed later in this paper seem to satisfy these conditions reasonably well.

Calm-Air Fires

Forest fires burning on flat ground in very light winds or calm air exhibit vertical flames. Thus, in figure 1 the flame must be visualized as standing vertically with the y axis coincident with the fuel surface and $\Theta = 0$. Spread rates and flame depths are smaller than for headfires because the primary mechanism of heat transfer is radiation rather than the combined effects of radiation and convection present in headfires. The assumptions discussed previously for headfires also apply to the mathematical description of calm-air fires. Because Θ is zero, Equation (4) is no longer required for description of the problem. Also, Equation (2) must be replaced by

$$\frac{d(u^2y)}{dx} = gy\,\frac{(\rho_a - \rho_o)}{\rho_o}. \qquad (13)$$

The equations to be solved are expressed in dimensionless form as:

$$\frac{d(u'y')}{dx'} = Au' \qquad (14)$$

$$\frac{d(u'^2y')}{dx'} = By' \qquad (15)$$

where A and B are given by Equations (7). The analytical procedures used to obtain flame characteristics are the same as for headfires, and are given in Appendix II. Only flame length and tip velocity are considered, however, because Θ is known and flame length equals flame height for fires in calm air. Equations for these variables are:

Flame length: L =

$$\left\{\frac{9(r^2 + 10r + 25)\,[(r + 1)^{2/3} - 1]^3}{50H^2E^2\rho_a^{\,2}g(\rho_a/\rho_o - 1)}\right\}^{1/3} I^{2/3} \qquad (16)$$

Flame tip velocity: u_L =

$$\left[\frac{3(r^2 + 6r + 5)g(1 - \rho_o/\rho_a)}{20EH\rho_o}\right]^{1/3} I^{1/3} \qquad (17)$$

A relationship between u_L and L can be obtained with elimination of $I^{2/3}$ between Equation

[1]Reaction intensity is the rate of heat release per unit area of ground below the combustion zone of a fire.

[2]Fire intensity, as defined by Byram (1959), for a spreading fire is the rate of heat release per unit length of fire front.

(16) and the square of Equation (17). Thus, u_L can be written in terms of L as

$$u_L = \left[\frac{17(r^2 + 6r + 5)}{48(r^2 + 10r + 25)^{1/2}}\right]^{1/3} \left\{\frac{g(\rho_a/\rho_o - 1)}{[(r+1)^{2/3} - 1]}\right\}^{1/2} L^{1/2} \quad (18)$$

for calm-air fires.

Backfires

A separate analysis for flame characteristics of backfires is not made because the results of previous analysis can be applied to these fires. Backfires on flat ground spread against the wind, and one might expect a modified form of the analysis for headfires to apply. However, in the section describing experimental measurements of flame lengths and velocities, it can be observed that this is not the case. This result suggests that factors determining flame characteristics are related to the fuel layer burning zone rather than the flame zone above the fuel. A plausible interpretation based on the different models of momentum conservation expressed by Equations (2) and (13) is now offered. For headfires, the momentum change per unit distance along the flame axis involves a number of variables. The drag force on the flame, flame tilt angle, flame depth, and burning rate are strong functions of windspeed, but for any given fire they adjust themselves so that the change in momentum with respect to axial distance is roughly constant. However, the momentum change, which affects flame characteristics, may vary greatly from fire to fire in a given fuel type through changes in D and u_o^2 in Equations (7) for A and B. On the other hand, axial momentum for calm-air fires in similar fuels changes primarily in response to changes in burning rate or flame depth from fire to fire. If wind has but a small effect on burning rates and flame depths of backfires, changes in axial momentum per unit length of flame, and hence flame characteristics, for such fires should correspond to those of fires in calm air even though the flames are tilted. The values of A and B in Equations (7) would tend to be more constant from fire to fire than for headfires. As indicated above, such behavior agrees with experiments reported in this paper. It is consistent also with experimental observations that rates of fuel consumption, rates of spread, and flame depths for headfires are strongly affected by wind but only weakly affected in backfires. On this basis, backfire flame lengths and tip velocities should be described by Equations (16), (17), and (18).

Exceptions to this argument are backfire flame tilt angles and flame heights whose values differ from values for the calm-air case due to their dependence on windspeed. Because backfires have not been analyzed separately, it is assumed that Equation (9) gives flame angles and that Equation (10) with L given by Equation (16) describes flame height. These assumptions should be tested with experimental data.

EXPERIMENTAL DATA

In tests of the theoretical relationships presented in this paper, Equations (8), (12), (16), (17), and (18) will be compared with experimental data on flame lengths and velocities. No tests of flame heights or angles are made because of incomplete data.

Procedures

Information on fire behavior and flame characteristics was collected from field burns of operational size (roughly 15 to 200 acres burned) conducted during February and March 1975. The fires were burned in southern fuels such as pine litter under plantations, mixtures of litter and grass, and the palmetto-gallberry stands of Georgia and northern Florida. The data are presented in table 1. All fires but two (Leesville, La., and Pierson, Fla.) were burned as backfires, but some data were taken on three of the backfires during periods when the fires had been switched to a headfire mode of spread by variable winds. The reported fire behavior measurements are averages and do not correspond to specific time intervals during which flame measurements were made.

Fire-spread rates were measured by using reference stakes a known distance apart along several lines perpendicular to the expected direction of spread. A team of observers timed the fire front as it passed each stake. Later, the movement of the entire front was mapped, and an average rate of spread determined for the burn.

Vegetation and litter weights were obtained with a double-sampling technique. Fuel information on 100 equidistant ¼-milacre plots within the main plot was recorded by an observer who walked along transect lines and estimated weights by species, condition (living or dead), and size

Table 1.—Fire behavior measurements for 1975 field burns in southern fuels[1]

Fire location	Fuel type	Mode of spread	No. film segments	Fuel consumption (W_a)	Rate of spread (R)	Flame length (L)	Flame tip velocity (u_L)	Byram's fire intensity[2] (I)
				lb/ft²	*ft/sec*	*ft*	*ft/sec*	*Btu/ft-sec*
Waycross, Ga.	pal-gal	B[3]	16	0.36	0.022	2.3 ± 0.2	11.4 ± 0.8	48
Waycross, Ga.	pal-gal	B	5	.28	.042	3.0 ± .4	9.3 ± 1.3	71
Macon, Ga.	pine-hdwd	B	13	.10	.050	.90 ± .14	7.3 ± .9	29
Macon, Ga.	pine-hdwd	H[4]	5	.10	—	1.1 ± .3	11.5 ± 1.7	—
Barberville, Fla.	pal-gal	B	10	.30	.022	2.5 ± .4	11.7 ± .8	40
Pierson, Fla.	pal-gal	H	3	.11	.170	1.5 ± .2	12.4 ± 1.1	112
Macon, Ga.	lit-grass	B	10	.13	.018	.73 ± .15	7.0 ± .6	14
Leesville, La.	lit-grass	H	10	.09	.072	.85 ± .10	8.2 ± .8	38
Kirbyville, Tex.	pine-hdwd	B	5	.10	.012	.46 ± .05	3.5 ± .5	7
Kirbyville, Tex.	pine-hdwd	B	5	.06	.021	.51 ± .13	7.2 ± 2.4	8
Kirbyville, Tex.	pine-hdwd	H	2	.06	—	2.1 ± .7	24.0 ± 11.8	—
Macon, Ga.	pine-hdwd	B	8	.12	.044	.83 ± .12	7.0 ± 1.3	32
Macon, Ga.	pine-hdwd	H	2	.12	—	3.7 ± .26	34.7 ± 9.3	—
Macon, Ga.	pine-hdwd	B	10	.08	.012	.51 ± .13	5.9 ± .8	6
New Bern, N.C.	lit-shrubs	B	12	.10	.051	1.6 ± .3	9.1 ± 1.1	31

[1]All measurements made by Fuels and Fire Behavior Team of the Smoke Management Research and Development Program, Southern Forest Fire Laboratory, Macon, Georgia, under leadership of W. A. Hough.

[2]Heat yield is 6,000 Btu/lb for computation of I.

[3]B = backfire mode.

[4]H = headfire mode.

class. Approximately 10 percent of these plots were also physically sampled by species, condition, and size class. The measurements were used to devise a method for correcting the visual estimates. This sampling procedure was followed before and after the burn to determine fuel consumption.

Flame characteristics were recorded with a movie camera mounted on a tripod and operated at 64 frames per second. Filming was parallel to the fireline. Short segments of film (usually about 5 to 10 seconds each) were used to make exposures of the flame as the fire burned into the camera's field of view. Flame lengths, velocities, and angles were determined later from the flame images displayed on a screen. A standard length was included in each frame to provide a reference for distance measurements. Velocities were estimated by selecting a small parcel of flame and noting its change in location from frame to frame on the screen. Frame speed was then used to obtain velocity. These measurements were usually made near the image of the flame tip. Flame tilt angles (and hence the corresponding heights) were obtained also, but are not discussed further in this paper because windspeeds are not known with sufficient accuracy to allow meaningful tests of Equations (9) and (10).

RESULTS AND DISCUSSION

The flame characteristics data of table 1 are averages from a number of segments filmed during a given fire, and are presented with corresponding standard errors of the mean. Suitable film segments for fires in the headfire mode of spread were usually fewer than for fires in the backfire mode of spread. Though flame characteristics continually fluctuated due to variations in wind direction, turbulence, and differences in fuel consumption, it was expected that meaningful relationships could be obtained without use of a statistical design and analysis because of guidelines from the theoretical results. Table 1 also gives fire intensities, which were computed from averaged measurements of fuel consumption and spread rate when available.

The data of table 1 are presented in figures 2 and 3. Figure 2 shows backfire flame lengths and velocities as functions of fire intensity. For headfires, such plots are omitted because of inadequate rate of spread data. The slopes of the lines in figure 2 have been plotted according to predictions of Equations (16) and (17). Intercepts have been determined visually. The experimental values fall close to these lines with a reasonable amount of scatter. In figure 3, headfire and back-

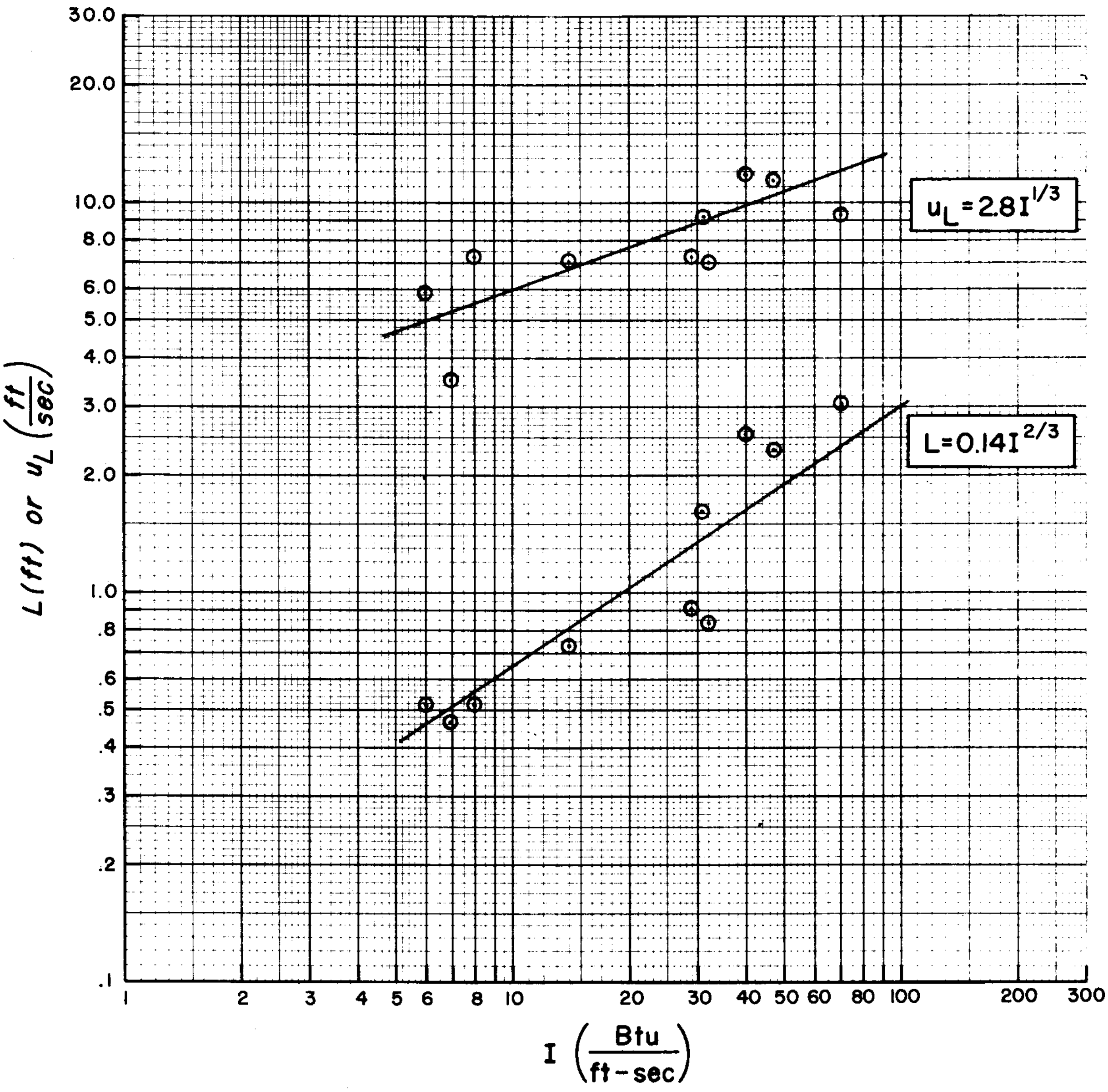

Figure 2.—Flame length and flame tip velocity data for backfires in southern fuels. The equations shown are visual fits of the data constructed with theoretical slopes from Equations (16) and (17).

fire flame velocities are related to flame lengths. The slopes of the lines have been constructed in accordance with Equations (12) and (18). As before, intercepts have been located visually. Although some scatter is present, the agreement between theory and experiment is good.

Another test of Equations (12), (16), (17), and (18) is to assign "reasonable" values to the multiplying factors and predict the constants obtained empirically in figures 2 and 3. The quantities E and r in these equations are not as well known as the other factors, and are assigned values based on estimates of previous investigators. For flames above line fires in cribs, Thomas (1963) has used an entrainment constant given, in the notation of this paper, by

$$E' = 0.16\left(\frac{\rho_o}{\rho_a}\right)^{1/2}$$

for a one-sided flame. To account for both sides of the flame, E′ must be doubled. It is believed that a realistic value of ρ_o/ρ_a for fires in southern fuels is 0.25. Thus, we obtain

$$E = 2E' = 0.16$$

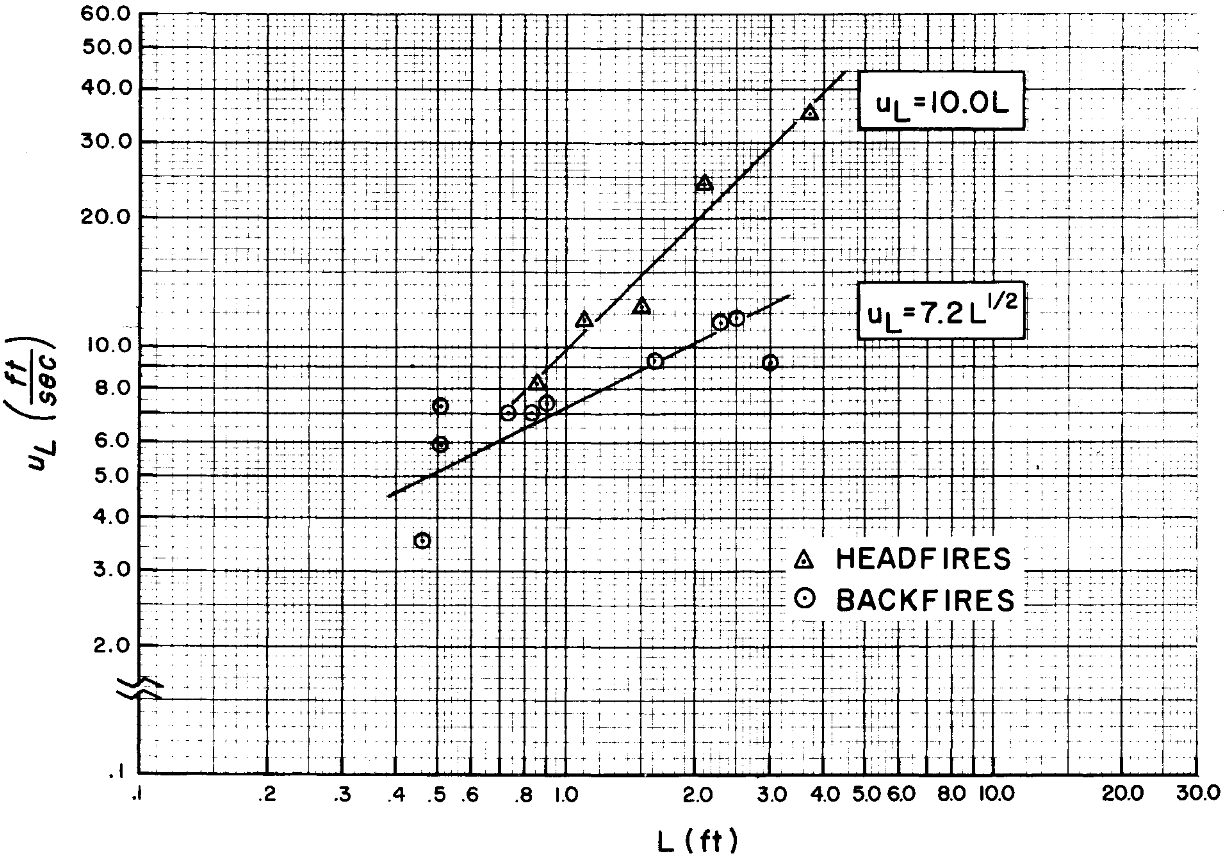

Figure 3.—Flame length–flame tip velocity relationships for headfires and backfires in southern fuels. The equations shown are visual fits of data constructed with theoretical slopes from Equations (12) and (18).

with E assumed independent of all other fire and weather variables. A constant value of r is used, although r probably varies from fire to fire. The stoichiometric air-fuel requirement on a mass basis depends on fuel composition, and is approximately 6 lb/lb. It is also unclear how much air in excess of the stoichiometric amount is involved in free-burning fires. Thomas (1965) has measured the horizontal air flow toward a burning crib 3 feet in diameter, and reports an r value of 60. He points out, however, that a large fraction of this air does not enter the flame zone. Steward (1964) compared experimental and theoretical flame heights for burning liquid fuels and found good agreement when 200 percent excess air was assumed for r. Van Wagner (1974) has used 100 percent excess air in his studies on crown fires. For purposes of this paper, 100 percent excess air is assumed, resulting in r = 12 lb/lb. The remaining quantities are g, ρ_o/ρ_a, ρ_a, H, and I_R; they are assigned the values 32 ft/sec², 0.25, 0.075 lb/ft³, 6,000 Btu/lb, and 30 Btu/ft²-sec, respectively.

Substitution of the proper numbers into Equations (16) and (17) for backfires results in

$$L = 0.21\, I^{2/3} \tag{19}$$

$$u_L = 3.5\, I^{1/3} \tag{20}$$

which will overestimate L and u_L according to the relationships given in figure 2. The agreement is well within a factor of 2, however, and seems reasonable in view of the many approximations made in deriving Equations (19) and (20).

Flame velocity–flame length relationships can be tested by substitution of the above numbers into Equations (12) and (18). The results are given by

$$u_L = 8.1\, L \tag{21}$$

for headfires and by

$$u_L = 7.7\, L^{1/2} \tag{22}$$

for backfires. Agreement is within 20 percent of the experimental results in figure 3.

Also of interest is a comparison of Equation (8) for headfire flame lengths with the empirical flame length equation given by Byram (1959). This equation is $L = 0.45\ I^{0.46}$. If it is assumed that 30 Btu/ft²-sec adequately represents the I_R values associated with Byram's experimental fires, substitution of the appropriate numbers into Equation (8) gives

$$L = 0.27\ I^{1/2}. \tag{23}$$

Within the range of fire intensity of interest for prescribed fires in the South ($I < 200$ Btu/ft-sec), Equation (23) yields flame lengths that are smaller than those predicted by Byram by a factor of 30 percent or less.

Sneeuwjagt and Frandsen (1977) reported experimental measurements of flame length, fuel loading, rate of spread, and flame depth for headfires in grass fuels. The fire intensity and reaction intensity based on a heat yield of 6,000 Btu/lb were computed from these observations. A plot was constructed of L versus I (with the exception of fires CF-3C and CWF-2) and is presented in figure 4 with groups of data identified according to the associated values of I_R. These values ranged from about 5 to 180 Btu/ft²-sec, based on the reported ocular observations of flame depth. The relationship in figure 4, with slope constructed in accordance with Equation (23), is in good agreement with the data and thus supports the notion that headfire flame lengths are proportional to the square root of fire intensity. The four data points for $I < 4$ Btu/ft-sec seem unusually far removed from the remaining data. The reasons for this result are unclear. One explanation could be given in terms of errors in visual estimates, which probably increased as I_R decreased. Another possibility is that flow of gases in the flame tends to become nonturbulent for small values of I_R, causing a change in the relationship between L and I. In any case, the dependence of L on I_R at constant I is not in accordance with predictions of Equation (8). Further studies of the effect of I_R are needed.

SUMMARY

Equations describing forest fire flames in terms of turbulent jets have been solved and relationships derived for flame lengths, angles,

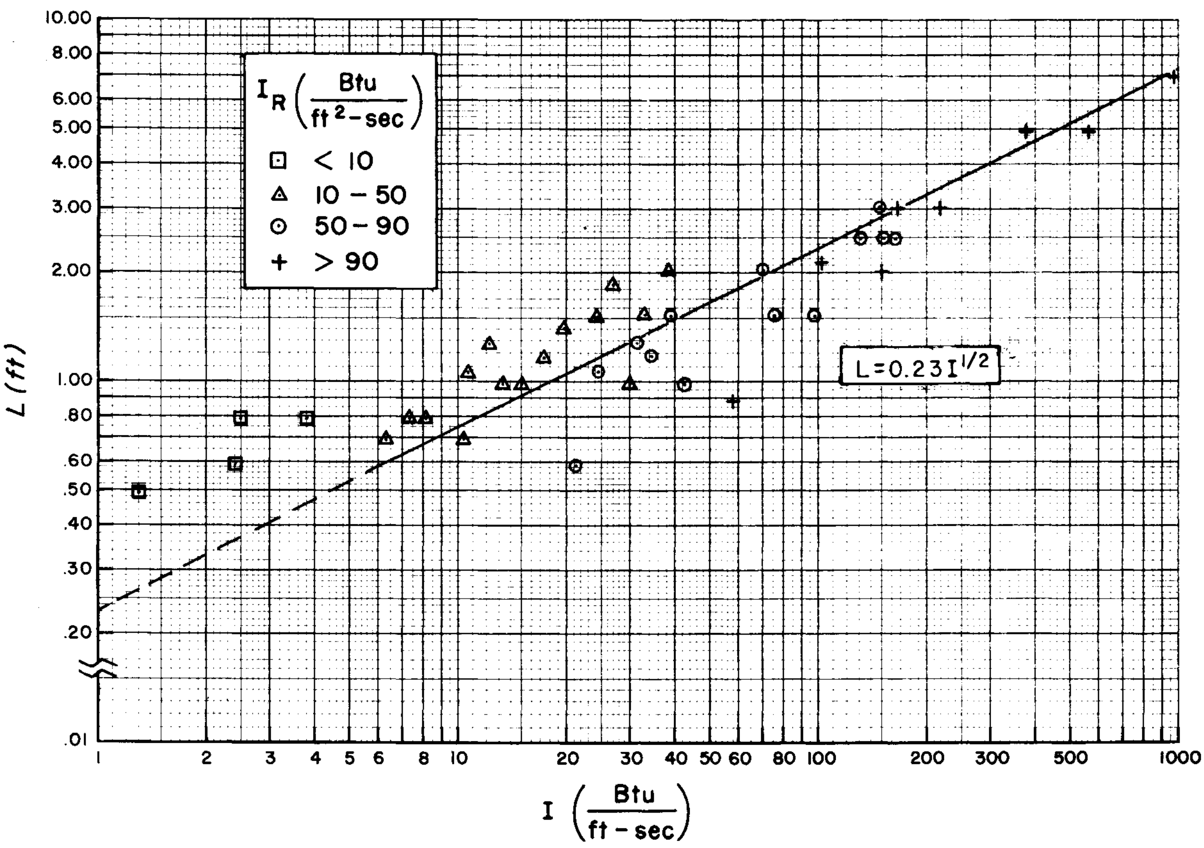

Figure 4.—Flame length data of Sneeuwjagt and Frandsen (1977) for headfires in grass fuels grouped according to values of I_R. The equation shown is a visual fit of the data constructed with the theoretical slope from Equation (23).

heights, and tip velocities for flames in wind and in calm air. Flame length and velocity data from low-intensity fires (less than 120 Btu/ft-sec) in southern fuels were used to test the theoretical relationships. It was found that backfire data were described by the equations for calm-air conditions.

Contingent on the assumption that I_R is nearly constant from fire to fire, the most significant results of this paper can be summarized as follows:

(1) Theoretical considerations and experimental work in the literature suggest that headfire flame lengths vary as the square root of Byram's fire intensity.

(2) Thomas' relationship expressing flame length as proportional to the ⅔ power of fire intensity apparently applies to backfires and fires in calm air.

(3) Relationships between flame lengths and flame velocities differ for headfires and backfires in southern fuels.

As is true of most mathematical models, this particular attempt to describe flame characteristics involves many approximations made in the model itself, in the solutions of the equations, and in the data used to test some of the relationships. Nevertheless, the theory agrees with experiment—both in form and in prediction of constant multipliers (well within a factor of 2). More work is needed with fires burned over a greater range of fire intensity and in a variety of fuel and weather conditions to further verify these results.

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APPENDIX I

DERIVATION OF HEADFIRE FLAME CHARACTERISTICS

Equations (4) to (7) of the text are used to derive headfire flame lengths, angles, heights, and tip velocities. We begin by defining the variables a and b as

$$a = u'y'$$

$$b = u'^2y'$$

so that $u' = b/a$ and $y' = a^2/b$. Thus, Equations (5) and (6) become

$$(da/dx') = Au' = A(b/a) \qquad \text{(I-1)}$$

$$(db/dx') = B. \qquad \text{(I-2)}$$

Integration of Equation (I-2) with the condition that $b = \cos\Theta = y'$ when $x' = 0$ gives

$$b = Bx' + \cos\Theta. \qquad \text{(I-3)}$$

Integration of Equation (I-1) with Equation (I-3) substituted for b and the condition that $a = \cos\Theta$ when $x' = 0$ results in

$$a = [ABx'^2 + 2A\cos\Theta\, x' + \cos^2\Theta]^{1/2}. \qquad \text{(I-4)}$$

Flame Length

Flame length, L, is defined as the distance along x' at which an amount of air, r pounds per pound of unburned fuel flowing through the surface, has been entrained into the flame zone. At the flame tip,

$$(2\rho_0 uy/\rho_0 u_0 D) = u'y' = a = r + 1. \qquad \text{(I-5)}$$

Thus, at $x' = L/D$, $(r + 1)$ pounds of combustion products flow through the flame tip for every pound of fuel-products mixture flowing through the burning surface layer of depth D. It can be shown that, except when $L \ll D$ which is not of interest here, the quantity ABx'^2 in Equation (I-4) greatly exceeds the quantity $[2A\cos\Theta\, x' + \cos^2\Theta]$. Therefore, Equations (I-4), (I-5), and (7) from the text can be combined into the approximate form

$$L = \left[\frac{(r+1)^2\rho_0^2 u_0^2 D^2}{E\rho_a gD(\rho_a - \rho_0)}\right]^{1/2}. \qquad \text{(I-6)}$$

The quantity $\rho_0 u_0 D$ is evaluated through the assumption that air is supplied to the combustion zone at a rate equal to r/5 times the mass burning rate per unit length of fireline and is involved in combustion below the fuel surface. This figure is an arbitrary one, and probably varies with fire size and intensity. However, the occurrence of flaming combustion below the surface clearly indicates that some oxygen is flowing into that region of the combustion zone. Thus,

$$\rho_0 u_0 D = \left(\frac{r+5}{5}\right)RW_a = \left(\frac{r+5}{5}\right)\frac{I}{H} \qquad \text{(I-7)}$$

where R is the rate of fire spread, W_a is the weight of fuel consumed per unit area,[3] H is heat yield, and I is fire intensity as defined by Byram (1959). Substitution of Equation (I-7) into Equation (I-6) and use of the relation between fire intensity and reaction intensity

$$I_R = I/D \qquad \text{(I-8)}$$

results in the expression

$$L = \frac{(r^2 + 6r + 5)}{5\rho_a H}\left[\frac{I_R}{Eg(1 - \rho_0/\rho_a)}\right]^{1/2} I^{1/2} \qquad \text{(I-9)}$$

which reduces to a form nearly identical to Byram's empirical result ($L = 0.45\ I^{0.46}$) for a series of fires in which multipliers of $I^{1/2}$ do not change appreciably.

Flame Tilt Angle

Flame tilt angle, Θ, defined as the tilt of the flame axis from the vertical direction, is determined from Equation (4) of the text and Equation (I-8) as

$$\tan\Theta = \frac{C_F U^2}{2gD(1 - \rho_0/\rho_a)} = \frac{C_F U^2 I_R}{2gI(1 - \rho_0/\rho_a)} \qquad \text{(I-10)}$$

[3]A distinction is not made between total fuel consumed and fuel available for flaming combustion, which strictly applies here.

which implies that $\tan\Theta$ is proportional to U^2/I for headfires with constant I_R, C_F, and ρ_o.

Flame Height

Flame height, h, is the perpendicular distance from the flame tip to the ground. Equation (I-10) can be used to write h as

$$h = L\cos\Theta = L\left\{1 + \left[\frac{C_F U^2 I_R}{2gI(1-\rho_o/\rho_a)}\right]^2\right\}^{-1/2} \tag{I-11}$$

Substitution of Equation (I-9) for L yields

$$h = \frac{(r^2+6r+5)}{5\rho_a H}\left[\frac{I_R I}{Eg(1-\rho_o/\rho_a)}\right]^{1/2} \times\left\{1 + \left[\frac{C_F U^2 I_R}{2gI(1-\rho_o/\rho_a)}\right]^2\right\}^{-1/2} \tag{I-12}$$

If winds are strong and $(C_F U^2/2) >> gD(1-\rho_o/\rho_a)$, h can be written approximately as

$$h = \frac{(r^2+6r+5)}{5\rho_a H}\left[\frac{4g(1-\rho_o/\rho_a)}{C_F{}^2 U^4 I_R E}\right]^{1/2} I^{3/2} \tag{I-13}$$

None of the above equations for h is valid at very small values of U and Θ because Equation (I-9) does not apply when U and Θ approach zero.

Flame Tip Velocity

Flame tip velocity is the rate of movement of flame gases in the axial direction near the tip of the visible flame. An equation for u′ can be written, from definitions of a and b and Equations (I-3) and (I-4), as

$$u' = \frac{u}{u_o} = \frac{b}{a} = \frac{Bx' + \cos\Theta}{[ABx'^2 + 2A\cos\Theta x' + \cos^2\Theta]^{1/2}}.$$

We evaluate u′ by retaining only the first terms in the numerator and square of the denominator. This simplification would be most valid for strong winds when $\cos\Theta$ is small, or when $x' >> 1$; that is, for tall, narrow flames. Thus, as x′ approaches L/D, u approaches the flame tip velocity, u_L, and

$$u_L = u_o\left(\frac{B}{A}\right)^{1/2} = \left[\frac{gD}{E}(1-\rho_o/\rho_a)\right]^{1/2}$$

from Equations (7) of the text. Using Equation (I-8), we obtain

$$u_L = \left[\frac{g}{EI_R}(1-\rho_o/\rho_a)\right]^{1/2} I^{1/2} \tag{I-14}$$

which implies that u_L is proportional to $I^{1/2}$ if multipliers of $I^{1/2}$ are constant.

APPENDIX II

DERIVATION OF CALM-AIR FLAME CHARACTERISTICS

Equations (14) and (15) of the text are used to derive flame lengths and tip velocities. The variables a and b are defined as in Appendix I. Thus, Equations (14) and (15) can be written as

$$(da/dx') = A(b/a) \qquad \text{(II-1)}$$

$$(db/dx') = B(a^2/b) \,. \qquad \text{(II-2)}$$

Division of these two equations gives

$$(db/da) = (B/A)a^3/b^2$$

and integration subject to the condition that b = 1 when a = 1 results in

$$b = [(3/4)(B/A)(a^4 - 1) + 1]^{1/3}$$

which can be approximated by

$$b = [(3/4)(B/A)a]^{1/3}a \qquad \text{(II-3)}$$

because (B/A) >> 1 and we consider applications in which a > 1. Substitution of Equation (II-3) into Equation (II-1) and integration with the condition that a = 1 when x' = 0 yields

$$a^{2/3} = 2/3\,[(3/4)(A^2B)]^{1/3}x' + 1. \qquad \text{(II-4)}$$

Flame Length

Substitution of Equation (I-5) and Equations (7) of the text into Equation (II-4) when x' = L/D gives

$$L = \left[\frac{9[(r+1)^{2/3} - 1]^3\rho_o^2u_o^2D^2}{2\rho_a^2E^2g(\rho_a/\rho_o - 1)}\right]^{1/3} . \qquad \text{(II-5)}$$

Equation (I-7) used in this equation gives

$$L = \left[\frac{9(r^2+10r+25)\,[(r+1)^{2/3} - 1]^3}{50H^2E^2\rho_a^2g(\rho_a/\rho_o - 1)}\right]^{1/3} I^{2/3} \qquad \text{(II-6)}$$

which agrees with the dimensional considerations of Thomas (1963) for strip sources of infinite length in calm air when the factors multiplying $I^{2/3}$ are constant.

Flame Tip Velocity

The gas velocity at the flame tip is obtained from Equation (II-3) which can be written as

$$u' = \frac{u}{u_o} = \frac{b}{a} = \left[\frac{3gD(1-\rho_o/\rho_a)a}{4Eu_o^2}\right]^{1/3}$$

using Equations (7) of the text. Because $u = u_L$ and a = r + 1 at the flame tip, Equation (I-7) may be used to express u_L as

$$u_L = \left[\frac{3(r^2+6r+5)g(1-\rho_o/\rho_a)}{20EH\rho_o}\right]^{1/3} I^{1/3} \qquad \text{(II-7)}$$

which also conforms to a well-known scaling law for turbulent flow above line sources (Taylor 1961) when r, ρ_o, and E are constant.

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Nelson, Ralph M., Jr.
1980. Flame characteristics for fires in southern fuels. USDA For. Serv., Res. Pap. SE-205, 14 p. Southeast For. Exp. Stn., Asheville, N.C.

A flame model and analytical method are used to derive forest fire flame characteristics. Approximate solutions are used to express flame lengths, angles, heights, and tip velocities of headfires and calm-air fires in terms of fire intensity. Equations are compared with data from low-intensity controlled burns in southern fuels and with data from the literature.

KEYWORDS: Flame length, flame velocity, flame angle, fire intensity, buoyant flames.

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