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Entrainment regimes and flame characteristics of wildland fires

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Herein we report details of the derivation of two supplementary flame characteristic models and a discussion of flame tilt angle in the laboratory and field for which space was not available in the published text.

Background

In the published text, equations for entrainment parameters and flame characteristics of steadily burning 2-D head fires in uniform wildland fuels are derived. The text suggests three separate regimes of flow above such fires, with two of these regimes delineated by a critical value of the Byram convection number $N_c = 10$. The starting point for the flame characteristic derivations is a simplified version of the Albini (1981) flame model. The model equations are tested with fire behaviour data from laboratory wind tunnel burns in slash pine litter fuels (Nelson and Adkins 1986) and field data reported in Appendix A of the text. It is shown that flame characteristics derived from the Albini model are descriptive of flame tilt angle only in the laboratory fires and, as expected, only when $N_c < 10$. The authors wish to present alternative flame angle models for the $N_c > 10$ regime to give the reader a complete report of our work and provide modeling approaches that bring the models into agreement with the experimental data.

tan*A* in laboratory and field fires for $N_c > 10$

The sketch in Fig. 1 of the text depicts a time-averaged visible flame of height H tilted at mean angle A from vertical; the flame shape approximates a rectangular solid with flow area A_f (thickness $D_o\cos A$ by unit width L of fireline into the page) and length $H\sec A$. A mixture of burning volatiles and combustion-zone air flows steadily along the flame axis with a velocity whose 'whole fire' mean vertical component (rather than vertical velocity w at z) is the characteristic velocity w_c (Eqn 18 of the text). The mean flame temperature of 750 K ((1000 +

500)/2) is computed from previously assumed values for T_o and T_t. We assume that viscous forces are negligible and the fluid is incompressible (mean density $\rho_c = 0.48$ kg m^{-3}); thus, the integrated form of the Euler equation (Lay 1964) may be used to write the vertical buoyant force as

$$F_B = -A_f \Delta p = g D_o \cos A(\rho_a - \rho_c) HL \sec A = \left(\frac{\rho_c w_c^2}{2} \right) HL \quad \text{(A1)}$$

where Δp is the pressure drop in the flame due to buoyancy. The horizontal drag force on the flame, using Eqn 19 of the text, is

$$F_D = \frac{C_D \rho_a u_e^2 A_p}{2} = \frac{C_D}{2} \rho_a \eta^2 u_a^2 HL \quad \text{(A2)}$$

where C_D is the drag coefficient for the inclined flame and A_p is the projected area (the area normal to the direction of air flow). The balance of transverse forces that determines angle A is $F_B \sin A = F_D \cos A$ and leads to

$$\tan A = \frac{F_D}{F_B} = \frac{C_D \rho_a \eta^2 u_a^2}{\rho_c w_c^2} = 3.85 \eta^2 N_c^{-2/3} \quad \text{(A3)}$$

where $C_D = 1.54$ (Fang 1969).

Differences in tan*A* data for laboratory and field fires

Fig. 2 of the text indicates that tan$A$ relationships for the laboratory and field fires differ significantly. For the laboratory fires, tan$A$ is proportional to either $N_c^{-1/2}$ or $N_c^{-1/3}$ when $N_c < 10$, and follows Eqn A3 when $N_c > 10$. In the field, tan$A$ is constant for all N_c. These differing results may be related to hindered *v.* freely moving combustion products in and above the flame for the laboratory and field fires respectively. We expect smaller tilt angles and reciprocal N_c values in field measurements than would be observed for the same fire in a wind tunnel. In the field, the reduced influence of wind speed and tilt angle should combine with generally greater fuel loads and an increased rate of spread due to greater fireline length (Cheney and Sullivan 1997) to drive tan$A$ toward a constant value. The dependence of tan$A$ on powers of N_c close to $-1/3$ seems associated with fires in wind tunnels with fixed ceilings (Taylor 1961; Nelson and Adkins 1986); an exception is the study of Weise and Biging (1996) who found a dependence close to $N_c^{-1/3}$ even though their relatively small tunnel was operated with a moving ceiling. However, a tendency toward N_c independence, or at most a weak dependence, seems to occur in relatively large wind tunnels (Anderson *et al.* 2006) and in tunnels that allow free convection (Fendell *et al.* 1990).

tan*A* in the field fires based on kinetic energy flux

We assume the flame tilt angle is determined by a balance between the transverse components of the kinetic energy flux of ambient air approaching the flame and the vertical flame fluid kinetic energy flux due to buoyancy. This balance is given by:

$$(\mathrm{d}W/\mathrm{d}t)_{\mathrm{drag}} = (\mathrm{d}W/\mathrm{d}t)_{\mathrm{buoyancy}} = F_D u_e \cos A = F_B w_c \sin A$$

where W is work done and t is time. With this interpretation, rates at which parcels of air and flame fluid do work apparently govern flame tilt angle for moderate winds in the field, whereas a mass flux balance is operative in wind tunnels such as the SFFL tunnel in which the steady winds are more unidirectional because convection is confined. Use of Eqns 20 of the text and A1 and A2 above leads to

$$\tan A = C_D \rho_a \alpha^3 / \rho_c = 3.85\alpha^3 \quad \text{(A4)}$$

This equation gives an estimate of entrainment constant α identical to that derived for the lab fires from Eqn 23 of the text.

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