Brand Lofting in Large Fire Plumes

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Urban/wildland intermix conflagrations occur when dry vegetative fuels of the wild areas combine with structural fuels from houses to produce a combustible environment that, once ignited, easily becomes uncontrollable. The dominant mechanism for propagation of these fires is the copious fire brands these fuels produce. This research is a first step in the development of a modular model for fire growth in the urban/wildland intermix. The goal is to predict the area that is at risk from brand-induced fire spread during a large conflagration. Our work expands that performed by Tarifa, et al.[2,3], substituting a more realistic plume velocity field based on the Baum and McCaffrey plume model[4] for the constant plume velocity assumed there.

The problem of fire spread by brands consists of two major parts: lofting above and propagation downwind of the fire. The emphasis here is on lofting. The height to which a firebrand will ascend is a function of two forces: the drag induced by the gas velocity relative to the brand, and gravity. A preliminary assumption is that during the lofting process the brand does not change size, shape, or mass. This allows us to focus on the dynamics of the problem; e.g. finding the maximum height to which a firebrand will ascend before the drag and gravity forces balance, as well as calculate the particle velocity, with respect to ground, as a function of height. The latter is determined by numerical integration of the dimensionless vertical force balance on the particle.

$$V^*(dV^*/dz^*) = (3BC_d/4d^*)(U^*_{bm} - V^*)^2 - 1 \qquad (1)$$

where the symbols are defined in the notation and B is a weighted air-to-particle density ratio, $B = (\rho_a/\rho_s)(z_c U_c/\nu)$. $C_d(Re)$ is given in Fig. 1 for spherical brands [5] in the range of Reynolds numbers relevant to fire plumes with $Re = d^*(U^* - V^*)$ since the normalizing diameter is defined as $d_c = \nu/U_c$. From Baum and McCaffrey [4], the dimensionless centerline plume velocity is

$$U^*_{bm} = \begin{cases} 2.13\, z^{*0.5} & z^* \le 1.32 \quad (2a) \\ 2.45 & 1.32 \le z^* \le 3.3 \quad (2b) \\ 3.64\, z^{*-0.33} & z^* \ge 3.3 \quad (2c) \end{cases}$$

This double-valued velocity, shown in Fig. 3, dictates the existence of both a maximum height to which a brand of a given dimensionless diameter can be lofted and a minimum height below which the plume velocity is not sufficient to lift the brand. At both of these extremes, the plume is moving past the brand at its terminal velocity (i.e., the brand velocity relative to the ground is zero). Setting $V^*=0$ and using Eq (2c) in Eq (1) gives $z^*_{max} = 31.3(BC_d/d^*)^{1.5}$. Similarly, using Eq (2a), we obtain $z^*_{min} = 0.294 d^*/BC_d$. These limits are shown in Fig. 2 as functions of dimensionless diameter and parameterized in B. The implication of Fig. 2 that the smallest brands achieve the greatest loft in the plume is misleading; the smallest brands will burn up before they reach z^*_{max}.

To determine the time each brand takes to reach its maximum height, we need to solve Eq (1) for $V^*(z^*)$, as shown by the solid lines in Figs. 3 and 4. Fig. 3 has been parameterized in d^* for B=7600, typical of pine brands in a plume from a 50 MW house fire. Fig. 4 has d^*= 5000 and a range of B that is pertinent to brands in urban/wildland intermix fires. The dotted lines in both figures indicate the local relative velocity past the brand, $U^*_{bm} - V^*$. The initial condition required by Eq (1) is $V^*(z^*_{min}) = 0$. From Figs. 3 or 4 the brand height can be easily found as a function of time. The next step is to introduce brand consumption as $d^*(t^*)$, e.g., from Tarifa's data[6]. The net effect will be to eliminate the smallest diameters in Fig. 2 and to produce an extremum in z^*_{max} near d^* of order one.

Notation

d^*	dimensionless brand diameter, $d/(\nu/U_c)$	z^*	dimensionless brand height, z/z_c
g	9.8 m/s^2	U_c	characteristic velocity, $(g^2\dot{Q}_o/(\rho c T)_\infty)^{0.2}$
$\dot{Q}_o$	fire heat release rate in Watts	ν	kinematic viscosity
V^*	dimensionless brand velocity, V/U_c	z_c	characteristic height, $(\dot{Q}_o/(\rho c T)_\infty g^{0.5})^{0.4}$
U^*_{bm}	dimensionless centerline plume velocity, U_{bm}/U_c	ρ	density of air

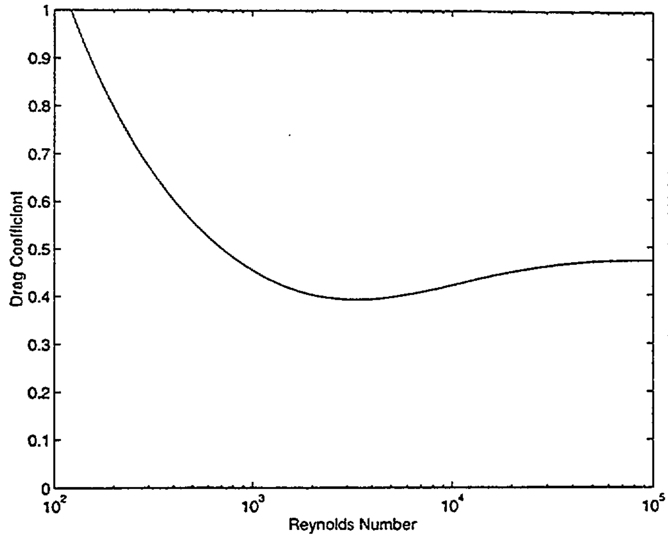

Fig. 1 Drag coefficient for an assumed spherical brand as a function of Reynolds number, Haider and Levenspiel. All variables in these four figures are dimensionless.

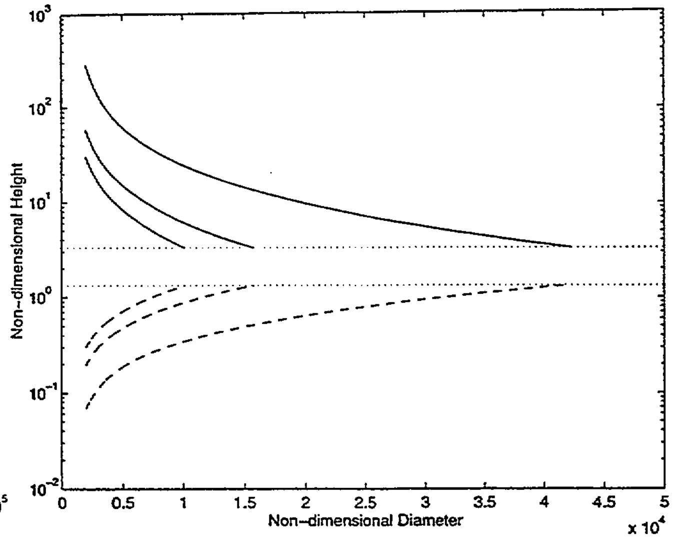

Fig. 2 Solid lines indicate the maximum height to which a spherical brand can ascend along the centerline in an axisymmetric, steady-state, Baum and McCaffrey plume as a function of diameter and the weighted density ratio, B. B = 5000, 7600, and 20000 from left to right. Dashed lines indicate the minimum height required for a brand to move, with the same parameterization. Dotted lines show the limits of the intermittent-flame region in the Baum and McCaffrey plume.

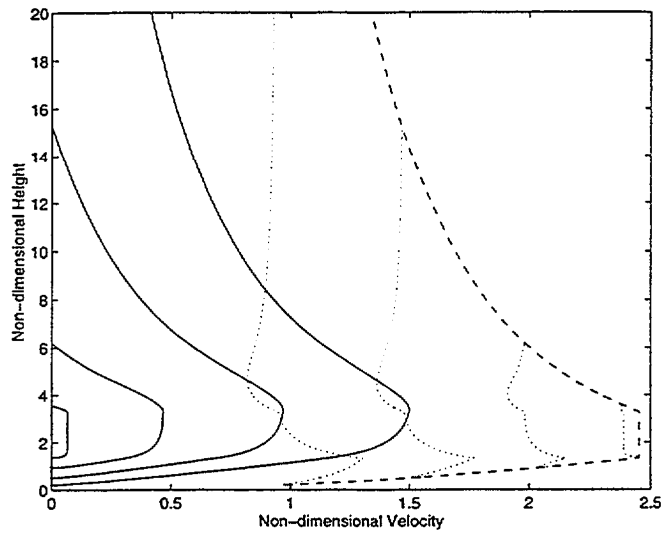

Fig. 3 The dashed line gives the centerline velocity for the Baum and McCaffrey plume. Solid lines show the particle velocity, with respect to ground, as a function of height for a weighted density ratio, B = 7600; d* = 2000, 5000, 10000, and 15000, from right to left. Dotted lines indicate the relative velocity as seen by the particle for the same values of B and d*, which increases from left to right.

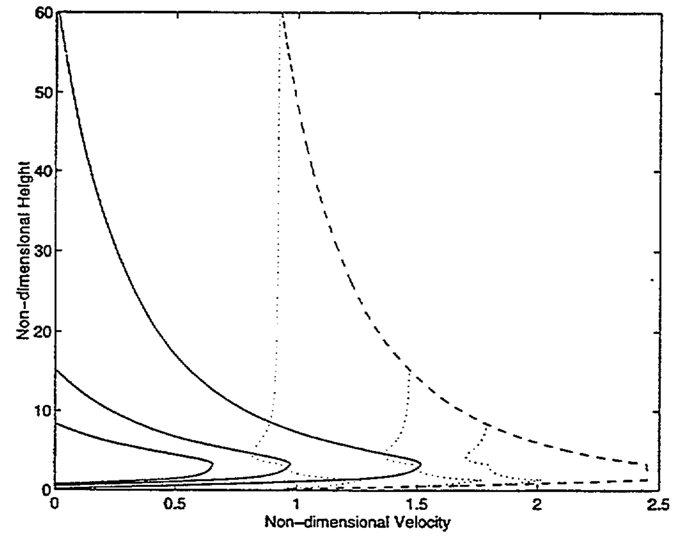

Fig. 4 The dashed line gives the centerline velocity for the Baum and McCaffrey plume. Solid lines show the particle velocity as a function of height for a diameter of 5000; B = 5000, 7600, and 20000 from left to right. Dotted lines indicate the relative velocity as seen by the particle for the same values of B and d*; B increases from right to left.

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Acknowledgments

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