WIND-AIDED FLAME SPREAD ACROSS STREWN DEBRIS

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Design of a laboratory experiment, to support further development of an already initiated theoretical model of wind-aided flame spread through a fuel matrix of large porosity, is presented. The design goals include delineation of a well-defined fuel matrix, careful control of the combustion environment (air flow and radiation), capacity for varying parameters (including fuel element type, matrix geometries, and introduction of upslope), and provision for attaining steady-state rate of spread (if one exists). If the model, given initial credibility by the laboratory experiment, is corroborated by field-scale data, then the model may be used with more confidence for predicting the movement in time of a fire front (with current position specified), through a partially combustible debris field of known topographical and aerothermochemical properties, under given meteorological conditions.

INTRODUCTION

The spectacular urban fires of modern times have usually been associated with the occurrence of strong sustained winds (London, 1666; Lisbon, 1775; Moscow, 1812; Chicago, 1871; Boston, 1872; Baltimore, 1904; Tokyo/Yokohama, 1923; Bandon, Oregon, 1936; Tokyo, 1945). Many of the memorable wildlands fires also were consequences of wind-aided flame spread (Miramichi River Valley, New Brunswick, Canada, 1825; Peshtigo, Wisconsin, 1871; Hinkley, Minnesota, 1894; Cloquet, Minnesota, 1918; Tillamook, Oregon, 1933; Shoshone National Forest, Wyoming, 1937; Victoria, Australia, 1939; Maine, New Hampshire, 1977; Sundance Mountain, Idaho, 1967; Victoria, Australia, 1983). This list is hardly exhaustive. What it suggests is that ignition often occurs in heavily fuel-laden areas in times of drought, but it is the coincidence of persistent winds of appreciable speed that causes a "blow-up." The arising of strong winds precipitates a startling run that ends only when the wind subsides, combustible matter is exhausted, or precipitation arrives. Clearly it is the wind-aiding, not the mode of ignition, that is the key common factor in most fire catastrophes.

What is missing in analysis of urban-scale fires is the capacity to predict with confidence the rate of flame spread, given the vertical and horizontal distribution, size distribution, exothermicity, and moisture content of the fuel; the nature of the topography; and the wind magnitude and direction,† the temperature, and the relative humidity as a function of pressure of the ambient atmosphere. If information were available on how fast the fire front will advance in a direction normal to the local front, then tracking of

†The "residue" left behind the fire front can serve to retard and divert the on-coming wind, such that the wind within a city or forest is reduced from the wind at the leading edge. On the other hand, narrow streets can constrict available passageway, so the flow can speed. Thus, the low-level modification of winds within an urban area is a complicated issue. Still, the first step remains obtaining the rate of spread, given local values of the pertinent meteorological, topographical, and aerothermochemical parameters; then the problem may be addressed of estimating appropriate local parameters (so that the local advance in time, from current position, of a given fire front may be executed).

the expected fire position at future time (given its position at the current time) becomes a relatively simple exercise. What is limiting is not computer storage or graphical display. What is limiting to meaningful prediction is reliable quantitative formulation of the physical processes controlling spread. (Spread rate from ignition site is also key insight in structure fires.)

The need for spread-rate information becomes more crucial as the rate becomes faster: escape times and countermeasure times are reduced. The fastest spread is almost invariably associated with wind-aiding: upslope spread exceeds downslope spread, spread under a sustained breeze exceeds spread in a calm. The accelerated spread can be owing to several factors: hot product gases blown downwind preheat uninvolved fuel in the fire path; more-distant transport of lofted firebrands is likely; bent-over plumes may ignite downwind fuel by contact or by enhanced radiative transfer (better view factor).

Interest here concentrates on an urban environment blasted into disarray. The debris-strewn setting has a far more continuous distribution of combustible material than the fire-code-satisfying preblast city. It should also be noted that interiors of (possibly partially toppled) structures are likely to be opened. While the similarity certainly should not be carried too far, the urban setting attains some of the properties of a wildlands setting, with ground-level combustibles playing the role of understory fuel (slash, litter, grass, brush, down woody matter) and the still-standing structures playing the role of overstory fuel (tree crowns); however, whereas ladder fuels linking understory and overstory fuels in a wildlands setting are often limited (lichen, dead or low branches, young trees, smaller trees), there is no lack of ladder fuels in the urban setting (there is no third story without a first and second story). Now, in a forest setting, one usually envisions flame spread through the large-pore fuel matrix of the understory, with an occasional crown being taken; in extremely severe, high-wind conditions a "wall" of flame takes all the readily combustible fuel from understory to overstory in one tall front; only <u>very rarely</u> (if ever) does flame race from crown to crown, either in the absence of an understory fire or far in advance of the surface-level fire (<u>1</u>). Though the taking of a crown is spectacular, aside from radiative transfer the event may not be that much more significant than the exothermicity contributed by reaction of a comparable mass of understory fuel. One point very much worth noting is that it is the small-diameter, thin, leafy matter that is dried out and consumed as the fire front passes, and hence is pertinent to rate of front progression; the thicker fuels are dried out and consumed on a longer time span, and thus react after the front has passed (if ever consumed at all).

The complexity of wind-aided fire spread through a porous, vertically extensive fuel bed lies partly in the fact that the reactants are initially in different phase, and partly in the fact that the intensively burning zone (separating the downwind preheat zone from the upwind burn-up zone) involves strongly buoyant convection. Thus, one must keep track of heat lost to drying out and gasification that may not be recovered, but one must also discard one-dimensionality for two-dimensionality. In fact, the buoyant updraft forms a barrier to the oncoming flow in two dimensions, and at least forms an obstacle about which oncoming flow is diverted in three-dimensional situations. Now, if the oncoming wind is strong enough, it should be able to blow over the convective column, whereas for not so strong a wind the column should remain fairly vertical.* Since the strength of the updraft is related to the rate of fuel consumption, and since the rate of fuel consumption increases with the crosswind, the plume posture is a complicated matter. However, if the entrainment from the downwind side is overwhelmed by the crosswind strength (2), the plume should be blown over such that the fire is confined to the surface-layer fuels only, as far as burning at the front is concerned. Trying to state more than this soon becomes so convoluted that the need for experiment should be manifest.

MODEL ACCREDITATION BY LABORATORY EXPERIMENT

It is suggested that laboratory-scale experimentation should precede field-scale tests. The laboratory-scale experimentation permits attaining much data relatively quickly and relatively inexpensively, so appreciable parametric variation and considerable repetition (to check for error) is possible. There is likely to be better environmental definition, and more extensive and sophisticated diagnostic instrumentation, and better isolation of constituent components, in the laboratory than in some remote, possibly hostile, field environment. Conversely, relatively few data points are furnished by large-scale field tests, and these are obtained sometimes with long-time intervals; there is always a temptation to change too many parameters from one test to another, and there is almost never adequate redundancy, so field tests are in danger of becoming anecdotes (isolated events of uncertain reproducibility).

An oft-quoted argument against laboratory experimentation in fire science is that sometimes relatively few parameters can be assigned the values that they have in the field. Thus, one usually cannot carry out an experiment on laboratory scale, and by use of dimensional analyses, predict definitively what would occur in the field. However, if one could demonstrate, by comparison against a wide range of experimental data, that the theoretical model could predict (as accurately as required for the user's needs) physical events from boundary/initial conditions, then the model is given credibility. The wider the range, the greater the credibility. Of course, if the range of experimental data is not great enough to encompass the actual field situation of ultimate interest, the corroboration of the model remains incomplete: the model could still fail in the field. Thus, in the practical world of highly

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*The wind is constant neither in magnitude nor in direction. Hence, use of the fire-front-propagation insight gained here will probably entail invoking a (well-justified) quasisteady approximation. That is, the propagation of flame normal to the front depends only on the component of wind instantaneously normal to the front, even though that wind is varying in magnitude and direction. During calms the fire may diminish in intensity, such that fire is confined to the understory. In fact, for the elliptical, preferred-axis shape of a wind-aided front, the fire at the flanks tends to have a weak aiding wind normal to the front, and "crowning" is less likely than at the head (3). As the wind freshens beyond some minimum, the fire may again enter the overstory along most of the front. Thus, as the front passes, it is quite likely that some tall structures may be left unconsumed because of wind variability and fuel combustibility--though these structures may be consumed later, well behind the front.

complicated, interdisciplinary phenomena, there remains an important role for engineering judgment.

This discussion would not be complete without reference to the desirability of ultimately utilizing results from the periodic burns on 500 X 500 ft. sections of coniferous stands carried out in the Canadian National Forest over the past decade by Brian Stocks of the Great Lakes Forest Research Center, Canadian Department of the Interior, Sault Sainte Marie, Ontario, Canada. These burns in heavily fuel-laden sectors provide an apparently unique opportunity to study large-scale wind-aided flame spread under relatively well characterized conditions, although motion-picture photography is presently the major mode of documentation.#

DESIGN OF LABORATORY EXPERIMENT

Since a model for wind-aided flame spread has been fairly well outlined (4), but even the most closely related experiments (5 - 9) are not appropriate for present needs, attention is limited to the design of a suitable, well-defined, easily repeatable experiment.

What is sought is a propagating one-dimensional wind-aided fire front in a basically two-dimensional flow through a precisely defined fuel matrix of large "porosity". There is to be relatively little constraint on air motion within the matrix, pyrolyzing to yield the combustible hydrocarbon vapors that burn exothermically with oxygen. (Only in later, more complicated versions would one consider initiating the experiment such that a two-dimensional fire front exists.)

The fuel bed is to consist of vertically suspended strips of thin combustible material (e.g., strips of paper); the separation between strips may be taken to be constant initially, such that the rows and columns of strips define a rectangular checkerboard (the number of rows is not in general equal to the number of columns). One may alter the "porosity" by (say) halving the separation between strips. However, if one homogeneously added more fuel loading to elements of the rarer matrix such that the total fuel loading equaled that of the denser matrix, the anticipation here is that the difference in flame spread rates might not be very large: details of the porosity are not believed to be crucial. The ability to incline the entire matrix at a constant angle to the horizontal, for purposes of adding upslope effects, would be desirable.

All the strips in the first row are to be ignited simultaneously by use of gas-jet-type diffusion flames. (For a two-dimensional experiment, one would ignite just the central few strips in the first row.) The key

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#In the experiments conducted to date, the entire leading edge of the section perpendicular (more or less) to the wind direction is ignited simultaneously. It is suggested that only the (say) right half of the leading edge be ignited in at least one future test, for purposes of checking lateral-edge effects during wind-aided spread.

information sought is the rate at which the (hopefully) one-dimensional front moves from row to row. The number of rows should be enough to permit the initial transient to decay and a steady rate of flame propagation to be achieved, if a stable steady rate exists--there is no guarantee. But certainly the number of rows must be at the very least half again as many as are involved in the moving-front structure, from preheating through vigorous burning to residual burn-out. How many rows this is must be found empirically, but provision for hundreds of rows is advisable. The other key information sought is at what (constant) wind the flames of the vigorously burning zone are blown flat so no front can be defined.

It should be appreciated that much information about suitable properties for the test matrix can be obtained only by trial and error. Also, one must consider the fuel-loading in terms of the air flux past the matrix: one should be aware if the experimental conditions approach an oxygen-starved burning.

Space prevents listing of parameters, but two final issues are noted--topics deferred because they require particular attention. The first issue is achieving a uniform wind across the rows and down the columns (aside from perturbations owing to the fuel matrix itself and the burning thereof). If one employs just any nozzle to produce a wind, then the jet expands and slows (to conserve momentum flux) with distance from the nozzle exit, such that the speed experienced (say) half-way down the matrix may be reduced appreciably from that experienced by the leading row (independently of any perturbation caused by the matrix). Hence, achievement of a steady fire-front propagation is precluded. A response is to enclose the experiment in a duct. The floor always produces a boundary layer--probably an effect one wants to retain because of its relevance to the practical situation. The ceiling would restrain the buoyant gases, and possibly interfere with the downwind portion of the experiment--so the ceiling should be in place only upwind of the fire front. Sidewalls would restrain the spreading of the stream and thus serve the useful purpose of preserving the cross-sectional area; one should allow for the turbulent boundary-layer growth on these (nearly) parallel sidewalls. Most of the matrix elements should not lie in the sidewall boundary layer, even at the trailing row of the matrix.

The other issue concerns the radiation, the role of which in transport of heat increases with spatial scale, such that radiative transfer may be appreciably more important in the urban-scale fire than it would be in the small laboratory apparatus. However, it is well worth noting that it is quite feasible to add radiative heat input via an external source to examine the nature and magnitude of the laboratory-flow response.

This discussion of wind-aided flame spread through a uniform fuel matrix is concluded with the following two observations. First, perhaps not enough emphasis has been placed on the possibly highly variable thickness of the flame structure, the streamwise length spanning the domains of (1) preheating and thermal degradation; (2) pyrolysis and vigorous flaming with buoyant ascent; and (3) burn-up of the char residue left after pyrolysis is complete. For close spacing in a high wind, there may be only partial burn-up as the flame front passes, and burn-out occurs only long after flame passage; conversely for widely spaced elements in a modest wind, the fuel elements may burn almost individually and the "wave structure" is smaller. Second, since only a fraction of the debris is combustible in a blasted urban environment, the other inert portion perhaps serving as a heat sink-source repository, perhaps the homogeneous addition of such inert mass to the fuel matrix ought to be considered ultimately.

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