Fires in Porous Media: Natural and Urban Canopies

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1. INTRODUCTION

Uncontrolled fires and their associated smoke have been part of mankind's hazard environment since prehistoric times. Fires caused by lightening or volcanic activity moved across the earliest vegetative landscape whether grassland or forest scourging away all life before its path. Later, as man collected into groups and tribes, villages, towns and cities were routinely wiped away as natural, accidental, war or arson sources provided ignition. Most cities were not burned to the ground once, but multiple times. Even today massive wild fires in forests occur every year all over the world, and the threat of mass fires in cities haunt the minds of those concerned by large petrochemical accidents, wars or terrorism.

Large fires (or mass fires) occur at infrequent intervals, but are capable of causing immense loss of life and property. Mass fires occur where heavy fuel loadings exist over extensive areas; hence, they are observed in both wildland and urban areas. Given the distribution of trees, vegetation and buildings within these regions, the flow regime is essentially over and within a porous canopy. "Natural" urban or forest fires occur at widely spaced intervals, and the costs are such that it is not appropriate to cause them deliberately in order to study their physics. Most reports of such fires tend to be anecdotal in nature, and very little quantitative information is generated. Their infrequency has made it difficult to generate the public awareness and support for long term research. Nonetheless, concerns about the results from war such as Fire Storms and Nuclear Winter, terrorism, as well as the increased incidence of rural/urban wildfires as the public penetrates previously unsettled regions makes the situation urgent.

Given the cost and difficulty of studying mass fires analytic, physical and numerical models of fire and flow behavior in such situations are necessary. Unfortunately, fire itself is an extremely complicated phenomenon, and when combined with the almost infinite range of combinations of fuel type, fuel size, geometry of needles, leaves, vegetation and dwelling shape, atmospheric condition (wind, temperature, humidity), terrain variations and ignition source (lightning, cigarettes, explosives, etc.) the problem begins to look untenable. Nonetheless, a great deal has been learned by studying the individual components of fire scenarios, and conclusions have been reached that guide strategies to mitigate, contain and reduce the impact of massive fires. This chapter will examine the historic character of mass fires, the nature of fire spread, the character of fire whirls as a significant aggravating component of such fires, full-scale field and scaled physical model studies, and the use of numerical models to investigate fire and fluid physics systematically.

2. FOREST AND WILDLAND FIRE STATISTICS

Throughout the world it is more and more common to see homes and other types of structures in wildland environments. This trend is creating an expansion of wildland/urban interface areas where structures are located next to large amounts of vegetation. Because of their location, these structures are extremely vulnerable to fire should a wildland fire occur in the surrounding area. For example, the wildland fires in southern California, U.S.A., burned 2,985 sq km, killed 22 people, and destroyed some 4,810 structures. The most costly fire in California history occurred in October 1991 in the Oakland Hills firestorm in which there were US$2.3 bn in insured property losses. Applying a simple least-squares logarithmic curve fitting to the inflation-adjusted California wildfire loss data (annual aggregates) yields an estimated return period of five years for US$ 100 m, ten years for US$ 650 m, and 25 years for an aggregate loss of US$ 2bn. (Munich Re, 2004).

Recent publication of world fire statistics reveals that costs of fires currently runs around 1% of GDP in most advanced countries. Deaths and losses in the United States tend to be the most extreme with annual losses of $10bn/year (Geneva Assoc., 2001). The annual review performed by Munich Re of world disaster losses reveals that world-wide forest fire losses alone exceeded US$5.5bn and insured losses exceeded US$2.5bn during 2003. Such losses exceed the sum of all losses from volcanic eruptions, hailstones, flash floods, Tsunamis, landslides, avalanches, water drainage, frost, and local and winter storms combined! (Of course the Baran earthquake, the European heat wave, floods, and severe and tropical storms individually exceeded forest fire losses.) (Munich Re, 2004).

The most catastrophic US fire disaster was the Peshtigo, WI, wildfire in October 1871 in which 1,500 lives were lost and 3,780,000 acres (15,300 sq km) burned. The death toll was four times higher than the famous Great Chicago Fire, which ignited the same day. (Pernin, 1971) The second most significant US fire was probably the Big Blowup of August, 1910 in Idaho and Montana during which 78 fire fighters lost their lives and 3,000,000 acres (121,100 sq km) burned. This fire led to a century long policy in the U.S. to put out all fires in all situations regardless of the long-term consequences. (Pyne, 2001) An average of 140,000 wildfires per year took place in the United States from 1916 to 1996. The number of acres burned each year fell from a peak of 52.3 million in 1930 to 3.6 million in 1958 (212,000 to 14,600 sq km). Since then, the number of acres burned each year by wildfires has remained fairly steady between 1.6 to 7.4 million (6,500 to 30,000 sq km). Historical wildland fire statistics compiled by the US National Interagency Fire Center indicates the number and acreage burned of wild fires has decreased since the1920s, and remained more or less constant since 1960, but total loses and suppression costs have nearly doubled. The long-term decline in the area burned reflects fire suppression policies after the Big Blowup of 1910 aimed at suppressing all wildfires quickly, but one unintended consequence has been that brush and litter have accumulated increasing the potential for higher intensity fires. Meanwhile population shifts have moved more people and greater building infrastructure into heavily vegetated areas where wildland meet urban development. Today there are fires outside of homes every 38 seconds in the United States. (Karter, 2003; ISO, 1997; NCFPC, 1973, 1987)

3. HISTORIC LARGE URBAN FIRES

Literature and history record many famous forest and urban fires (Brode and Small, 1986; VIC, 2000). Urban fires also exist in myth and legend. Stories about the Fall (burning) of Troy about

1200 BC were told orally for several hundred years before Homer composed his brilliant epics, the *Iliad* and the *Odyssey*, about the Greek heroes who conquered Troy and the Trojan heroes who attempted to defend it.

The Roman historian Tacticus in his book *Anals* reported that during the night of July 18, 64 AD, fire broke out in the merchant area of the city of Rome. Fanned by summer winds, the flames quickly spread through the dry, wooden structures of the Imperial City. Soon the fire took on a life of its own consuming all in its path for six days and seven nights. When the conflagration finally ran its course it left seventy percent of the city in smoldering ruins. (Eyewitness to history, 1999; Halsall, 1998)

The Great London Fire of September 1666 was one of the world's worst urban conflagrations until the twentieth century. It lasted for five days and nights destroying five-sixths of the city, 13,000 homes were burned, 100,000 were left homeless, and most business and public buildings were destroyed. Incredibly, the death toll included only four to six people by fire, while falling walls, fright or exertion killed others, but many of the homeless froze, starved or died of disease. (Cannon, 1977)

Another great fire occurred in Moscow, Russia, in 1812 when Napoleon entered the city after the battle of Borodino. Shortly after Napoleon entered Moscow, the Russians set fires across the entire city. Both soldiers of Napoleon's Great Army and Russian criminals and looters complicated fighting of the fire. (Mozak, N. and Mozak, H., 2004)

In the United States one can identify at least thirteen major fires between 1835 and 1991 during which between 400 and 28,000 buildings were destroyed and up to 2,300 lives were lost. On Sunday, 8 October 1871 the Great Fire of Chicago and the Peshtigo forest fire (which started the same day) killed 3,600 and burnt over an area of 5,900 square miles (15,300 square kilometers). In Chicago burning planks were lifted by fire whirls and dropped as far as three-eights of a mile (~ 1km) ahead of the main fire. Musham (1941) attributes a large part of the destruction of the city to burning material carried by the fire whirlwinds**.**

The San Francisco earthquake of 1905 caused fires, which destroyed 28,000 buildings and killed 1,200. More recently, the Oakland Hills Tunnel Fire during 1991 shocked California with its economic impact (US$ 3 bn), and the Cerro Grande, New Mexico, fire near Los Alamos in 2000 displayed how a prescribed fire set to mitigate fire loads can quickly get out of control. (Parker, 1992; Routley, 1991; Cohen, 2000)

The 1923 Kanto earthquake in the Yokohama/Tokyo area produced mass fires that killed over 100,000, injured over 40,000 more and destroyed property up into the Hakone Mountains. One gigantic fire whirl killed 38,000 in fifteen minutes in the Hifukusho-Ato region of Tokyo. (Jagger, 1922)

Fires started by bombing during World War II caused incredible damage and hardship and damage in urban regions. During the fires storm caused by bombing in Dresden, Germany, in 1943, some 250,000 were believed to have died (which exceeds the death toll at Hiroshima, Japan, by a factor of three). Fires in Dresden, Hamburg, Hiroshima, and Tokyo would be classified as mass fires, whose size were sufficient to generate their own wind fields associated with massive thermal updrafts of air. (Bond, 1946; Kerr, 1971; Carrier, 1985)

Post WW II concerns about the impact of mass fires led to studies in Europe and the United States of the physics and behavior of very large fires. A joint research effort called Project Flambeau by Australian, Canadian and United States foresters and civil defense agencies examined fire development over simulated urban regions in the late 1960s. They created simulated housing areas by creating 10 ft (2 m) high piles of pine and juniper wild-land fuels distributed in checkerboard patterns. Measurements were made of wind speeds, temperature, and fuel consumption rates. Fire whirls and fire tornadoes were observed to frequently occur. (Countryman, 1965; Meroney, 2003)

During the mid 1980s studies of large fires were renewed due to the concern that the insertion of large amounts of ash and debris into the stratosphere from large fire or nuclear explosion might bring about a "Nuclear Winter." (Carrier, 1985) Predictions were primarily based on atmospheric computational models, and some scientists argued these models were inadequate since they did not reflect the observed physics seen in large fire experiments such as Project Flambeau. The January 1994 fires in Sydney, N.S.W., Australia exemplify how wildfires can invade urban and suburban areas imbedded in forested hilly terrain. These fires demonstrated how fires in urban and forest canopies can produce unexpected explosive spread conditions. (Trevitt, 1995)

An almost infinite set of case examples both old and recent could be provided; however, this selection should provide an introduction to the nature and extent of fires in the wild land-forest/urban interface. The causes of these fires range from accidental to arson, and artificial to natural (lightning). The extent of the fires can be assigned to unfavorable meteorological conditions, multiple arson and terrorist actions, inadequate city planning, failure to recognize or understand the physical mechanisms of fire moving through vegetative or urban canopies, or even fire-fighting inexperience or ineptitude. The challenge here is to focus on the fluid mechanics of fires in order to predict and plan for future conflagrations.

4. FIRE CLASSIFICATION

Fires are often classified by materials burnt or their size. Composition categories include Class A: Ordinary combustibles like wood, cloth, or paper; Class B: Flammable or combustible liquids, gases, or greases; Class C: Energized electrical equipment; and Class D: Combustible metals like magnesium, phosphorous or sodium. A large body of research exists which has studied how the composition of the fuel bed limits fire growth. These studies include the fire chemistry or pyrolysis, ignition sources, ignition susceptibility, and influence of radiation. (Quintiere, 1998) These concepts will not be discussed further in this paper. Large or mass fire sizes are classified as conflagrations, fire storms, or moving fire storms. The large mass fires initiated by nuclear war are feared to contribute to possibilities of "Nuclear Winter."

4.1 Mass Fires

There is no precise definition of a "mass fire", but it is generally accepted to be a flaming region at least 100 m in diameter in which the flame heights are small compared to the diameter. Such fires can produce storm like winds and a rotating cloud column. Very large-scale or mass fires are classified by their burning characteristics. A *conflagration* is a fire that develops moving fronts under the influence of wind or topography, and the hot, burning area is usually confined to a relatively narrow depth. A *firestorm* is defined as a fire in which many parts of the entire fire area are burning simultaneously. Conditions for firestorm genesis are generally accepted to include a fuel loading of > 4 g/cm^2 , a building density of > 20 to 30 percent, a fire area of > 3 km^2 , initial fires in > 20 percent of the buildings, and ambient winds of < 10 km/h. Such a fire is essentially stationary, with little outward spread, and can be identified by a towering convection column extending up to several kilometers. A *moving firestorm* is a firestorm that spreads under the influence of wind or topography. This latter type is often observed in wild-land fires that produce firebrands, which can be carried by fire-whirls further downwind to ignite additional regions. Moving firestorms and associated fire-whirls were present in the Great Fires of London, Chicago, Peshtigo, and at Hifukusho-Ato. (Lee, 1974)

4.2 Nuclear Winter

Although large-fire research in a war and wildland context has been going on for many years, a popularized study of the supposed effects of large fires, directed toward support of the anti-nuclear weapons movement, was written and first published in Europe as *"The atmosphere after a nuclear war: Twilight at noon*," by Crutzen and Birks (1982). The idea was subsequently reworked, a new computer model was developed, and the results were published in the U.S. by Turco et. al. (1983). In 1985 the U.S. National Academy Press published a summary report (Carrier, 1985). The report did not consider the radioactive or biological implications of a Nuclear Winter, only the extent to which the atmosphere would be modified by a major exchange of nuclear weapons. They concluded a major nuclear exchange would insert significant amounts of smoke, fine dust and undesirable chemical species into the troposphere, but they were uncertain as to the amount that would reach the stratosphere. They emphasized the high level of uncertainty in available models, and recommended further research. The report includes a chapter on large fires and an excellent summary of the observations of large fire plume heights and smoke characteristics (Fendell, 1985).

5. MODELING METHODOLOGIES

Predicting smoke and flame behavior can be based on full-scale field experience, analytic integral approximations that capture the gross flow behavior, fine-scale numerical modeling and/or physical modeling at reduced scale...these methods are typically called full-scale, zone, field (numerical), and physical modeling, respectively.

5.1 Full Scale Fire Tests

Full-scale modeling tends to be prohibitively expense, and other than a few post-disaster studies of actual fires is not frequently utilized. During the 1960s and 70s a joint agency program called Project Flambeau studied large fires set among piles of forest slash. The slash was set into piles approximating the geometry of suburban housing areas. Measurements were made of fire temperatures, velocities, radiation, and fire load burning rates. Movie film and photographic sequences were collected for each test. (Countryman, 1965; Palmer, 1981) Some qualitative evidence from the Flambeau series does exist. Fire whirls were observed in every test burn carried out during the Flambeau fire tests. Fire whirls tended to form on the lee side of these fires. This is the position of strong vortex activity due to fire-blocking effects on the ambient wind. Often two fire whirls of opposite rotation were observed. Fire whirls are more likely for fires where the convection column is leaning due to the presence of ambient wind. (Countryman, 1969)

In Operation Euroka, based at Langley in Queensland, Australia, two square kilometers of scrub was flattened by two bulldozers towing a giant ball on a chain. The uprooted trees (approximately 6000 tonnes) were then pushed into rows in a 50-acre area to simulate the fuel loading and pattern of an urban environment. This area was then set alight. Scientists studied the patterns of winds induced by a large fire, assessed the rate of burning, analyzed the effects of large fires on electromagnetic communications and identified the degree of protection needed for human survival. (Williams et al., 1970)

Another significant field test was the Canadian Mass Fire Experiment of 1989 (Quintiere, 1993). The U.S. Defense Nuclear Agency worked with Forestry Canada and the Ontario Ministry of Natural Resources to instrument a large prescribed burn in forest debris near Hill Township, Ontario. The fire covered about 480 ha in area (4.8 sq km). Measurements included estimations of energy release rate, emission factors for smoke particulates and species, ground level winds and temperatures, and some aspects of cloud dynamics. The fire caused a capping cloud to form up to 6.5 km. Rain, snow, hail and lightning were reported along with ground level fire whirls and water spouts.

5.2 Zone Modeling:

This method predicts the vertical and horizontal motions of a well-mixed smoke layer continuously supplied from a fire plume. The method assumes there is a large volume available in which turbulence and relatively small lateral velocities distribute the heated gases into a homogeneous mixture. The analytic relations used are based on laboratory and field scale fires for a limited range of volume configurations. They are popular as a means to perform smoke management inside of building structures, and for calculating simple isolated plume behavior. Many factors can make a zone model prediction unrealistic. Special consideration must be given to situations where irregular boundaries, inhomogeneous materials, and secondary flows occur (like in urban street canyons). (Palmer, 1981; Klote and Milke, 2002c)

5.3 Field Modeling

Computational fluid dynamics (CFD) provides a design technique to examine the relative merits of various fire suppression strategies. Such programs can inherently consider irregular building and terrain geometry, heat transfer due to variable properties and radiation, time varying fire strength, fire chemistry, affect of fire suppression operation, and variations in weather phenomena. While CFD represents a significant improvement in the predictive capability of smoke control modeling, uncertainties in the predictions remain. The smoke layer boundaries suggested by CFD simulations, just like those of the zone models, are best estimates, and as such have no conservativeness or “safety factor” built in. It is prudent to examine solutions to ensure that they are robust, that is that the flow patterns predicted are insensitive to small changes in boundary conditions such as external wind environment, fire strength, and even fire location. (Klote and Milke, 2002b) In Section 7.3 several idealized calculations of fire behavior are considered for both two and three-dimensional fires ignited in porous canopies immersed in a deep atmospheric shear layer.

5.3 Physical Modeling

Another option to simulate smoke movement is physical modeling at reduced scale. The concept of similitude is basically simple. Two systems at different geometric scales will exhibit similitude if a one-to-one correspondence exists in space and time between fluid particle kinematics (locations, velocities, accelerations and rotations) caused by fluid particle dynamics (pressures, gravity, viscous forces, etc.), when properly scaled by characteristics scales of fluid properties, force, length and time. To achieve this similarity, however, is not trivial. The specification of dimensionless parameters, which guarantee similarity, has historically been the subject of much discussion and debate. (Snyder, 1972; Meroney, 1988; Meroney, 1990)

Williams (1969, 1992) identified twenty-nine dimensionless groups required to simulate large fires based on normalization of the governing equations of motion, energy and concentration. A subset of eleven dimensionless groups were considered important, and seven were designated as critical for even partial simulation:

- Geometrical similarity,
- Convection (Reynolds number),
- Radiation groups (2) (Ratio of L to radiation absorption length and blackbody radiation flux to enthalpy convection),
- Gas-phase heat release (enthalpy of formation to ambient enthalpy),
- Fuel gasification energy (total heat required to gasify a unit mass of fuel to ambient enthalpy), and
- Fuel loading or burning rate group (Time average mass burn rate to convective mass flux);

Of lesser importance were listed dimensionless ambient velocity, vorticity, and atmospheric lapse rates. These dimensional considerations lead to several possible strategies for simulating mass fires.

<u>Standard scaling:</u> Keep some groups constant. Usually Froude number and Mass burning rate are chosen which leads to distortions in radiation, convection, turbulence and fuel bed geometry. Basically one is just looking at a buoyant plume.

<u>Pressure adjustment</u>: Varying pressure might preserve scaling of all but radiation parameters. Unfortunately to scale a 1 mile fire to 50 feet would requires use of 1000 atm pressure.

<u>Pressure and body force adjustment</u>: Varying pressure and G (centrifuge) simultaneously allows consideration of all core variables except blackbody radiation.

<u>Adjustment of composition and temperature of ambient atmosphere</u>: Varying pressure and temperature could permit scaling of all core variables except absorptive radiation.

<u>Adjust pressure, temperature & body force</u>: All core variables satisfied, but maximum LSR variation probably limited to about 10.

The conclusion must be that satisfactory physical model scaling of all aspects of mass fires is not likely.

Froude modeling (Fr) using either air or saltwater is probably the most common kind of physical modeling for hot smoke transport. Smoke movement away from the vicinity of a flame can be reproduced, but chemical kinetics, flame dynamics, and heat transfer scaling is not preserved. Unfortunately, due to scaling constraints it is difficult to simultaneously simulate buoyant plume movement and wind induced pressure distributions about the external urban building envelope. Nonetheless, physical modeling has been successfully used to study flow through forest and urban canopies in the absence of fires, and with fires for flow and fire movement through ground litter, idealized ignition concepts, fire whirl dynamics and compartment fires. Quintierre (1989) provides a variety of examples of how physical modeling has been used to model various aspects of fires including simple fire plumes, ceiling jets, burning (pyrolysis) rate, flame spread, and enclosure fires. Heskestad (1975) includes cases of sprinklered fires. (Gani and Williams, 1992; Quintierre, 1989; Klote and Milke, 2002a; Heskestad, 1975)

6. FOREST AND URBAN CLIMATE METEOROLOGY

The dynamics of fire growth is strongly influenced by the kinematics of flow through porous vegetation and urban structures (the canopy). The local wind and turbulence environment at the source determines the initial spread of a fire. Wind profiles vary depending upon the density (porosity) of the surrounding objects, their distribution vertically or laterally, the presence of below canopy open regions, and the distance from the canopy edge. (Meroney, 1968; Neff and Meroney, 1998) Wind approaching across less obstructed surfaces initially penetrate the upstream edge of the porous region, but subsequently the flow is deflected upward and flows within the media diminish. This process is reversed as flows move out of a canopy into clear areas.

Thus, fires starting near the edge of a canopy see larger horizontal crosswinds and turbulence which produces plumes that lie close to the ground; whereas, fires that ignite within the center of a canopy tend to rise vertically until deflected by winds at the upper edge or roof of the porous region. Fire and smoke spread within the forest or urban canopy is subsequently strongly influenced by canopy composition, density and distribution. These parameters are the proper subject of further research by analytic, physical and numerical modeling.

Once a hot smoke plume rises above the underlying canopy the buoyant force of a large fire leads to significant plume rise. The plume rise trajectory and the dispersion of its materials can be predicted. The effect of small-scale atmospheric turbulence, initial plume cross-sectional aspect ratio is minimal on plume trajectory, but the magnitude of atmospheric turbulence, atmospheric stratification, and ground terrain on rate of dispersion can be significant. (Lee, 1974; VIC, 2000)

6.1 Agricultural/Forest Canopy Behavior

Previous chapters in this monograph have considered the physics of easily penetrable flow (EPF) within vegetative canopies in some detail. Hence, only those aspects that relate to further understanding of the development and spread of fire and smoke within plant canopies will be repeated here emphasizing those features related to the author's personal experience using wind tunnel modeling. Arrangements of pegs, flexible strips, artificial trees and vegetation over hills studied are shown schematically in Figure 1.

6.1.1 <u>Flow Within and Downwind of an Individual Tree</u>

Even a single tree can significantly reduce wind speeds and increase turbulence downwind of its stem and crown. Gross (1987) used a three-dimensional nonhydrostatic numerical model to investigate the airflow and turbulence around a single tree. For turbulence closure he used the Prandtl-Kolmogorov exchange coefficient and the Blackadar mixing length relation. The presence of the tree was simulated by an additional drag coefficient associated with tree foliage density or leaf area density. Cone and ball shaped crown tree regions, with and without elevating trunks, neutral and stable air stratification, and a tree porosity of 0.934 was assumed based on field measurements. Calculations produce the anticipated wake deficits, turbulence excess, and a drag coefficient of ~1.0, which are similar to individual tree values measured by Meroney (1968, 1970). All simulations show a reduction of wind speed inside the tree foliage, an accelerated flow over and around the tree and a wake region in the lee. The geometry of the crown seems to be the dominant factor. In a stable stratified atmosphere, the flow around the canopy is enhanced, while vertical motion is suppressed, and the strength and length of the reverse flow region behind the tree increases.

The superposition of individual tree wakes results in the under-forest and above-forest velocity features found in extensive areas of forests or woods. The initial growth of wake deficits and the subsequent decay at greater downwind distances are characteristics of both individual tree and forest measurements. Yano (1966) developed a concept of momentum defect superposition in the wakes of an array of roughness elements to reproduce velocity, turbulence and shear distributions within and above canopies.

6.1.2 Under-Canopy Forest Flow Field

The presence of tree trunks, branches, stems and leaves (or needles) in a forest produces a barrier to air flow caused by form drag and skin friction which reduces the under-forest flow velocities substantially compared with wind speeds which occur above the canopy. Surface layer streamlines are displaced vertically, flow beneath the canopy is driven by shear from the flow above the canopy, and maximum winds occur at the top of the average height of the vegetation. Mean wind speeds typically decrease within the canopy as one approaches the ground to about 20% of the treetop wind values. Turbulence levels beneath the canopy may be similar to those found at ground level over small roughness surfaces (5-15%), but are significantly less than those which can occur in the strong shear which occurs above the canopy roof (20-40%). Meroney (1993) summarizes field measurements, and fluid model and numerical estimates of flows through vegetative canopies.

Different profiles have been proposed using first order closure models which specify a simple eddy diffusivity, K, and a drag coefficient, C_d, to describe that portion of the mean wind profile which exists beneath the forest ceiling for constant foliage distribution:

$u/u_h = [(\sinh \$>)/\sinh \$]^{1/2}$ ....(Cowan, 1968), [1]

$u/u_h = \exp[-\$(1 - >)/2]$ ....(Inoue, 1963; Cionco, 1965), and [2]

$u/u_h = [(\cosh \$>)/\cosh \$]^{1/2}$ ....(Massman, 1987), [3] where $>$ = z/h, u_h = is the mean horizontal wind speed at the top of the canopy, h; and $\$$ is a maximum value of the foliage area density and the extinction coefficient given by:

$$\$ = [2\ C_d\ LAI\ (F:)]^{½} \qquad [4]$$

which is a combination of the drag coefficient, C_d, the leaf-area-index, LAI, a measure of foliage distribution, F, and a normalized eddy diffusivity, : = K_h/hu_h. Only the expression proposed by Massman is consistent with the frequently observed zero wind gradient within the lower region of the canopy. Other authors have produced velocity profiles for non-constant foliage distributions and using higher order turbulence closure. Once a velocity distribution model is specified it is possible to solve by iteration for shear stand drag coefficient, $C_f = 2(u_*/u_h)^2$, displacement height, d and surface roughness, z_o, parameters useful to characterize above canopy flow dynamics as functions of C_d LAI and foliage structure. Massman (1987) concluded that C_dLAI values from 0.25 to 0.5 characterize most full foliage canopies. Over this range almost any under-canopy model gives results very close to the following expressions:

$$0.10 < z_o/h < 0.13,$$

$$0.67 < d/h < 0.75, \text{ and} \qquad [5]$$

$$0.17 < C_f < 0.20.$$

6.1.3 Above-canopy Forest Flow Field

The atmospheric boundary layer (ABL) is that portion of the atmosphere where surface drag due to the motion of the air relative to the ground modifies synoptic-scale motions caused by horizontal pressure gradients, Coriolis forces, and buoyancy. The depth of the ABL is highly variable (50 to 2000 m), but it generally increases with proximity to the equator, with wind speed, and as the earth surface roughness, but it decreases at night, and is strongly modified by thermal winds, inversions, and stratification. The lowest 10 % of the atmospheric boundary layer is called the surface layer. It is characterized by the sharpest variations of wind speed, temperature, humidity, and turbulence characteristics with height. Counihan (1975) concluded the surface (or constant flux) layer would be about 100 m deep during adiabatic conditions. In diabetic (stratified) situations the surface layer depth is about equal to the absolute value of the Monin Obuknov length, $L_{mo} = Tu_*^3/(6\ g\ \ w't')$.. For a summary of surface layer behavior for both neutral and stratified flows combined with both smooth and rough surfaces see Meroney (1986, 1992).

Within the surface layer the mean wind-speed profile is commonly described by logarithmic expressions. For situations when stratification has only a minor influence a modified logarithmic law has been proposed:

$$u(z) = (u_*/6)\ \ln_e [(z - d + z_o)/z_o] \qquad [6]$$

where $u_* = (J/D)^{½}$ is the surface friction velocity, d is the zero-plane displacement, 6 is Von Karman's shear layer constant, and z_o is the surface roughness. The displacement thickness, d, is important for tall roughness elements such as agricultural crops, forest and cities. When the roughness elements are short, such that $z_o < 0.2$ m, one can set $d = 0$. The parameters can be determined from representative field measurements; however, fitting an expression that permits three free parameters to field measurements of wind speed in/above agricultural canopies is not trivial. It is not uncommon for some least-square fitting routines to produce negative displacement heights–which is, of course, inappropriate.

No exact definition of high roughness has been offered, but roughness of a height exceeding 10% of the surface layer is generally viewed as high roughness. Generally, the von Karaman universal constant κ is assumed equal to 0.4 based on extensive experimental study of fully developed turbulent flow through pipes and its relationship to the Kolmogorov dissipation constant. Some experiment alist treat the constant as another free parameter to improve curve fit to data; hence, values ranging from 0.15 to 0.5 have been recorded.

Jaeger (1965) recorded wind speed measurements over a ten-year period over stands of Scotch pine located in southern Germany as they grew from 3 to 8 m height. He made estimates of the variation in u_*, z_o, d, β (Deacon parameter), and Richardson number, Ri, from wind and temperature data collected from meteorological towers placed within the forest stand. He found that the following correlations described the measurements:

$d = 0.63\,h$ ....regression coefficient, r = 0.73-0.93; [7]

$z_o = 0.174\,h + 0.227$ ....regression coefficient, r = 0.44; and [8]

$u_* = (0.027\,h + 0.062)\,U_{10} + b$ ....regression coefficient, r = 0.84 [9]

The expressions are functionally similar to those derived from under canopy flow.

Artificial plastic trees were selected by Meroney (1968) to reproduce the median behavior of measurements made about live trees (Colorado Blue Spruce, Juniper, Pine, and Spruce). These model trees were randomly positioned on support boards with approximately one tree per 36 cm^2. (See Figure 2 and 3) The total canopy was 2 m wide and 11 m long when installed in the Meteorological Wind Tunnel at Colorado State University Figures 4 and 5 display typical mean velocity and turbulence profiles found within and above the model plastic tree forest canopies. Notice the initial intrusion of the approach flow into the trunk space within the canopy at the upwind edge that diminishes with distance until the flow reaches an equilibrium state. Then as the flow approaches the down wind edge of the forest, the streamlines dip down into the canopy again and accelerate the air closer to the ground. (Meroney, 1970)

6.1.4 Wind Flow Near Clearings, Clear-cut and Forest Edges

When airflow passes from a cleared area into a forest, winds initially penetrate into the canopy space, but then the streamlines are lifted upward to the canopy roof. The penetration distance among the trunks space in the canopy under story may persist for 5 to 10 tree heights. Subsequently the wind rises above a recirculation region and re-enters the forest about 20 h from the windward forest edge. Figure 6 from Meroney (1968) displays the effect of such initial wind penetration at the windward forest edge and the subsequent flow acceleration before the downstream forest edge on canopy drag. Thus, embers carried from fires at ground level near the upwind of a forest will have a strong tendency to rise into the upper canopy and initiate crown fires; whereas embers released by ground fires near the windward edge of a forest will be deflected downward. If a crown fire exists near the windward edge of a forest, the embers may be immediately deflected down into yet unburnt ground cover downwind of the forest.

Eimern (1964) considered the aerodynamics of shelter belts and summarized the influence of density, shape, surface roughness, thermal stratification, wind angle and tree arrangement on downstream wind speed, turbulence, soil moisture, etc. The micrometeorology of shelterbelts and forest edges are reviewed by McNaughton (1989). There are similarities as well as differences between flow downstream of thin shelterbelts and forest edges. The foliage density of the forest canopy replaces the porosity used for narrow shelterbelts. Upwind profiles must be characterized by the upwind forest roughness, displacement height, forest friction velocity, and foliage density. McNaughton sought a comparison to the flow over a forest canopy edge and the flow that occurs when a boundary layer passes over a solid backward facing step. For solid steps a recirculating eddy occurs of downwind extent of about 6-7 h. But permeability often allows the wind to penetrate the forest upwind of the forest edge. In coniferous forests researchers detect upwind penetration over several heights upwind, but in denser foliage other researchers see little penetration at all. Nonetheless, little evidence exists to support the presence of a recirculating eddy downwind of the forest edge. The flow velocities and surface shear appear to adjust to the immediate absence of the forest edge by 20 h; however, the wind continues to accelerate over a longer distance as a deeper layer of the atmosphere adjusts to the change of surface roughness.

Fowler et.a. (1987) examined the effects of shelter wood cutting (30-percent canopy removal) and clear cutting clearings from 0.8 to 8.5 ha on climatic variables of the High Ridge Evaluation Area within the Umatilla National Forest in northeastern Oregon. Areas were harvested in 1976 after nine years of pre-logging calibration. The wind speeds increased substantially in all classes of clearings.

6.1.5 Homogeneous Surface Roughness Over Hills/Mountains

Complex hilly terrain may exist with a variety of vegetative surface cover. For example the approach terrain and a hill itself may be either bare or vegetation covered. Alternatively then, the upwind surface may be smooth (farmed plains or meadows) and the hills may be rough (tree covered, or the upwind surface may be rough (tree covered) and the hill bare. In some cases only portions of the hill may be bare due to selective shelter woodcutting or clear cutting. The presence or absence of high roughness may lead to lower/higher wind speeds, higher/lower turbulence, or attached/separated streamline flow. Such open regions are often deliberately provided in forested regions as “fire breaks.” The distance fires can propagate across such open areas is of primary interest to fire engineers.

The linear-perturbation theory approach to predict effects of sudden roughness changes of airflow over 2-dimensional hills can be reduced to a few simple algebraic algorithms. These equations can be used to estimate the effect of forest clear cutting on winds above hills and ridges. Jensen (1978) proposed that perturbations in mean wind velocities induced by surface roughness change could be calculated from:

$$Du(z)_{roughness} = (u_{*1}/j)\ \ln[z_{o2}/z_{o1}]\{\ln[z/z_{o1}]/\ln[l_{zr}/z_{o1}] - 1\} \quad [13]$$

where $l_{zr} \ln[l_{zr}/z_{o1}] = 2\, j^2 x$. Jensen and Petersen (1978) recommended perturbations induced by surface elevation change for triangular shaped hills could be calculated from:

$$Du(z)_{hill} = (u_{*1}/j)\, [1 + (h_{hill}/L)(\ln[L/z_{o1}]/\ln[l_{zh}/z_{o1}])^2 \ln[z/z_{o1}] \quad \text{[14]}$$

where $l_{zh} \ln[l_{zh}/z_{o1}] = 2\, j^2 L$. Since the solutions are separately linear their perturbations should be additive; thus,

$$u(z)_{hill\ \&\ roughness} = u_o(z) + Du(z)_{roughness} + Du(z)_{hill} \quad \text{[15]}$$

These expressions are sufficient to calculate wind speeds over hills for different clear-cut options over alternative slope triangular hills. Meroney (1993) presented figures based using the above relations for effects of various size forest clear-cuts on hill top flow fields. These measurements were subsequently compared with wind tunnel measurements of wind fields over various two-dimensional hill shapes covered with model forest canopies simulated by different depths of plastic indoor-outdoor carpeting. (Meroney, et.al., 1993)

6.1.6 Change in Roughness Effects

It has long been observed that when the wind flows from one surface texture to another a transition takes place in wind speed and turbulence within an inner boundary layer that grows in depth with downstream distance from the surface change. When the surface change is associated with roughness height, and downstream wind profiles are plotted semi-logarithmically with height, then a distinct "kink" in the slope of the plot is observed which can be associated with this inner-boundary-layer depth, l_z. The wind profile near the ground will adjust to surface roughness changes as it moves downwind from the ground cover transition. Above l_z the profiles will correspond to the wind profile for the roughness before the change in cover. Various field measurement programs over smooth-to-rough and rough-to-smooth roughness transitions provide justification for empirical plots of the sort proposed by Park and Schwind (1977).

More elegant analytic and numerical models exist to predict the resultant variation in wind profiles that exist at different fetch distances downstream of a transition of roughness. The subject is extensive enough that a literature review has been prepared on the topic by Hunt and Simpson (1982). Unfortunately, little data exists for roughness variations as large as the abrupt change that occurs from a forest edge to a meadow or from rural to urban areas.

Wu and Meroney (1995) measured flow field responses over modeled roughness changes of smooth, rough and very rough boundaries (equilibrium power law coefficients of " = 0.12, 0.16 and 0.34, respectively) for smooth-to-rough and rough-to-smooth transitions in the Meteorological Wind Tunnel at Colorado State University. Separate internal boundary layer depths were defined based on mean velocity, turbulent intensity and shear stress profiles. Flow predictions from several first-order turbulence closure schemes were compared to the wind-tunnel data. Since the log velocity profile was not found to exist in the transition region at all, the assumption that local eddy diffusivity varies as K = 6z is not acceptable. Similarly mixing assumptions associated with mixing length theory and J/E = const are not valid. On the other hand, mixing assumptions that $K = c_o 6 z E^{1/2}$ or $(u^2 - w^2)\, dU/dx = 0$ seem justified. (Wu, 1992).

6.2 Urban Canopy Behavior

Again the reader is referred to earlier chapters in this monograph related to air movement within urban canopy layers. Only those details related to the growth and spread of mass fires within a suburban, urban or wildland/urban interface will be discussed below.

A good summary of urban behavior is contained in the recent book edited by Moussiopoulos (2003) titled *Air Quality in Cities*. This book summarizes some of the results of Project SATURN a European Union effort under EUROTRAC-2. Although the book emphasizes air pollution meteorology over cities, several chapters consider details of air flow over and within cities based on field, windtunnel and numerical models. Researchers considered airflow in geometrically simple cases (arrangements of 2-d rectangles, blocks and cubes) as well as data from actual city streets geometries. Some 20 local, urban scale and meso scale models were evaluated and compared to field and laboratory measurements of wind speed and concentration.

The authors concluded that both wind tunnel and numerical models could reproduce field conditions, but the numerical models were very sensitive to alternative specifications of grid resolution, wall boundary conditions, source size and turbulence model. Indeed, one author noted during one comparison "*this example shows how easily model results can be manipulated by merely varying the choice of parameters which are accessible to the user.*" In another case four experienced user groups predicted the dispersion of dense gas releases around simply shaped building by using the same commercially available CFD code. The concluded "*the variability between different modeller's results was shown to be substantial*."

6.2.1 Urban Flow Styles: Classification

Plate (1995) provides a review of flow over uniformly rough boundaries, with special applications to urban areas. For neutral stratification in the absence of elevated inversions the flow is found to be very similar in character to vegetative canopy flows. Many of the same characteristics of porosity, permeability, displacement height, and effective surface roughness are used to describe the boundary layer over the suburbs and city center. But a critical difference between uniform and homogeneous canopies and the typical city is that wind blowing from open country onto a city complex meets different types of building formations. These range from the open rural and usually uncluttered country at the edge of the city, to suburb regions with single family and one or two story houses, to light industry regions, to high rise buildings in the city center. At the same time there is often an increase in building density, closed street canyons and quite irregular building heights. Thus, the urban boundary layer grows as a superposition of inner boundary layer flows driven by roughness changes occurring in the windward direction.

A very comprehensive study of urban boundary layer characteristics was made by Theurer (1992) to summarize what is know about these parameters and to correlate them with building dimensions. Theurer used two parameters to describe the distribution of roughness elements:

8_{ar} = 3 of areas covered by buildings/total urban area, and

8_{fa} = 3 of average building areas normal to the wind/total urban area.

These two parameters combined with a pictorial description of the roughness pattern are sufficient to classify the roughness height, z_o, and the displacement height, d, for each configuration.

The lower part of the urban boundary layer has its own flow field driven by the shear from the boundary layer above the structures. It is extremely difficult to parameterize the flow beneath the building height, H, since it is strongly driven by local arrangement of the streets, the building density, trees and vegetation, parks, lakes, hills and even traffic. Nonetheless, it is in this "penetrable" region that fires ignite, flames spread, plumes grow and eventually large "mass" fires can develop. Once the fire's buoyant plume penetrates into the boundary layer above the city structures, then the "aerodynamic" boundary layer described by earlier can deflect and transport the smoke, flames and embers downwind.

Oke (1978, 1988) differentiated the flows within urban street canyons based on the street width to building height ratio (B/H). The flow was classified as skimming flow (0 < B/H < 1.2), wake interference flow (1.25 < B/H < 5.0), or isolated roughness flow (B/H > 5.0). Wind tunnel simulations provide an opportunity to examine the linear and nonlinear effects of various parameters individually and/or in combination. The case of an isolated 2-d street canyon in open country was examined by Meroney et al. (1996). Similarly, the case of arrays of 3-d street canyons made of rectangular blocks was examined by Chang & Meroney (2003a, 2003b). The same street canyon geometries were subsequently studied in an urban environment, i.e., with additional canyons of similar geometry upstream and downstream of the test section. In each case various street canyon aspect ratios, (B/H), were tested under different wind conditions.

For the open country case visualization using smoke and a vertical light sheet revealed that clean air is sucked into the canyon by an intermittent eddy circulating down into the canyon. These smoke eddies change character with canyon aspect ratio as proposed by Oke (See Figures 7-8). This eddy circulates upwind at street level. A roof top eddy that begins at the upwind upstream building roof corner sucks canyon gases onto the roof. In the open country case, the first building alters the flow locally quite dramatically, promoting separation from the floor. On the other hand, in the urban roughness case the surrounding buildings raise the displacement height to the urban canopy level, almost to the roof of the buildings. The shear zone thus formed at the ceiling of the canyon induces a permanent eddy recirculating inside the canyon. As a result, vertical mixing across this shear layer is suppressed and pollution is trapped inside for longer times, until upstream turbulence in the main flow may cause sufficient disturbance to break down the recirculating eddy. The flow inside the canyon in open country is much more nonstationary than in the urban canyon case. A recirculating eddy forms only intermittently in the former, whereas it is clearly much more stable amidst urban roughness.

Smoke and fire from sources ignited within a street canyon at ground level will tend to follow streamline trajectory patterns. Thus, smoke will be drawn against the upwind wall side of a canyon oriented normal to the wind to roof levels. Smoke and fire may even propagate upwind along the roof for situations where separation occurs on the upwind corner of a building. Similarly rooftop or upper level fires will tend to travel along recirculating street canyon eddies to impact the upwind faces of downwind buildings.

Typical smoke propagation scenarios seen during visualization are shown in Figures 9 to12. Rural or open country building (N=1) complexes tend to produce an extended separation zone from the upwind corner of the upwind building, resulting in upwind roof contamination and more energetic canyon breathing. (Figure 9) Urban building complexes (N>1) tend to produce less frequent canyon breathing, and stronger canyon vortex circulations. Building orientations with approach winds directed perpendicular to a building face or street canyon axis produce flows with augmented lateral growth but no shift in the plume axis (Figure 10). Building orientations with approach winds oblique to a building face or street canyon axis produce flows with augmented lateral growth and significant shift in the plume axis (Figure 11).

Canyon breathing plays an important role in street canyon dispersion. Vortices establish within the street canyons and are maintained by the shear flow over the street canyon top at roof level, but occasionally the turbulent flow above the building roofs penetrate downward into the canyon and lift or wash the vortex out of the canyon. Subsequently, a new vortex appears and is sustained until the canyon breathes again (Figure 12).

Numerical models show that for steady-state type calculations although general flow field behavior is reproduced, predicted concentrations are often too large. This is believed to be caused by the fact that the "average" flow and transport predicted by a steady-state calculation did not realistically reproduce the combined dispersion and diffusion effects of an intermittently fumigating street canyon.

6.2.2 Urban Flow Characteristics

A limitation of direct field measurements of atmospheric phenomena is that all possible governing parameters are simultaneously operative; thus, it is not simple to determine which are governing, which are secondary or which are insignificant. In addition if nonlinear interactions occur their role may not be clear. Thus, independent influences of building geometry (building height, width, roof shape), street dimensions (breadth, width, intersection location), thermal stratification (solar insolation and orientation, building and street thermal capacitance), vehicular movement (size, number, frequency), plume buoyancy, vegetation or landscaping, and surface roughness are all intertwined. Consequently, many of the qualitative and most of the quantitative conclusions about urban canopy flow result from systematic physical and numerical model studies.

Kastner-Klein and Rotach (2004) investigated a detailed 1:200 scale model of a portion of the city of Nantes, France in a neutral boundary-layer wind tunnel at the University of Karlsruhe, Germany. They used laser-doppler anemometry to measure all components of velocity, turbulence intensity, and turbulent shear at different locations within the city. Subsequently, they compared their data with various parameterization schemes and concluded that in the roughness sub-layer (RSL),

$$u_{RSL}(z) = u_*/(0.6\ 6)[1 - 0.6 \ln(0.12) - \exp\{0.6 - 0.072[(z - d_o)/z_o]\}], \quad \text{[16]}$$

whereas above the canopy layer,

$$u(z) = u_*/6 \ln [(z - d_o)/z_o, \quad \text{[17]}$$

where u_* = friction velocity, d_o = displacement height, z_o = roughness length, just as for forest canopies. Consequently, they propose parameters for these relations that depend on local building geometry:

$d_o/H = 1 + 4.43^{-8p} (8_P - 1)$, and .... [18]

$z_o/H = 0.12\ (z_s - d_o) = 0.072(z_s - d_o)$ .... [19]

where H = average building height, where the plan areal fraction $8_P = A_P/A_T$ is the ratio of average frontal plan area of roughness elements to total surface area, and where z_s = height of the maximum shear stress. Similarly, turbulent shear stress scales as:

$(u'w')/(u'w')_s = F(Z/Z_s)$ .... [20]

Where $(u'w')_s \sim (u'w')_{max}$,
Where $Z = (z - d_s)$ and $Z_s = (z_s - d_s)$,
Where z_s = height of max shear stress, and
Where d_s = height of region inside canyon with nearly zero shear stress $= 8_p$

Hence, an empirical fit gives:

$(u'w')/(u'w')_s = (Z/Z_s)^2 \exp[2(1 - Z/Z_s)]$. .... [21]

From the review provided in Sections 6.1 and 6.2 it is apparent that the average flow characteristics over forest canopies and urban canopies are very similar. Almost identical expressions are found to correlate profiles of velocity, turbulence and shear stress. Nonetheless, structural differences inside canopy elements are expected to strongly affect the propagation of fire and smoke, since urban structures have large regions of impenetrable wall; whereas, the resistance of trees and vegetation is spread more uniformly through the canopy volume as many small elements of leaves, twigs, needles and boughs.

6.2.3 Joint Wildland/Urban Configurations

Tree windbreaks have long been known to modify the wind field downwind, and they have frequently been used to mitigate extreme winds and modify the flow around groups of buildings. Sometimes the trees are arranged to modify snowdrift patterns, in other cases they are intended to reduce wind forces or reduce heating or air-conditioning loads. Recently, Rehm et al. (2002) proposed a grid-free way to model individual trees for study of flow over a wooded building complex. Their proposal is to represent the trunk and branches of each tree by a collection of spherical particles strung together like beads on a string. The drag from the tree, determined as the sum of the drags of the component particles, produces an oscillatory, spreading wake of slower fluid.

The authors tested their concept through a CFD simulation of the flow around an eleven story target building made up of a cluster of ten buildings, surrounding buildings and trees on the NIST (National Institute of Standards and Technology) campus near Gathersburg, Maryland. They used a large eddy simulation (LES) turbulent model over a grid made of ~ 600,000 cells using the FDS (Fire Dynamics Simulator) code which can be downloaded free from the URL:

http://fire.nist.gov . Time dependent simulations produced realistic looking velocity fields and unsteady pressure spectra for probes placed on target buildings. One case examined a typical result for a row of 20 m high trees located upwind of the 49 m tall building. The wakes of the trees oscillate and spread laterally and produce fluctuations at low levels on the target building.

7. FLUID MECHANICS OF FIRES AND POROUS CANOPIES

When a solid or liquid fuel burns, the molecular structure of the fuel is modified by the action of the heat resulting in the production of a combustible vapor. This process, called *pyrolysis*, precedes the actual burning of fuel like a wave moving ahead of the flame. Once pyrolysis has occurred ignition is possible. Ignition usually depends on the presence of an ignition source (spark, cigarette, lightning, existing fire) that has a sufficiently high temperature to initiate combustion in the fuel vapors. The process of the spread of fire through a fuel canopy is then a multi step process:

- Preheating and out gassing region (pyrolysis),
- Intermittent deflagration (ignition),
- Flame attachment region, and
- Steady burning region.

Spontaneous or self-ignition is also possible if external heating is sufficient to raise the vapor temperatures above critical levels (eg. In wood pyrolysis occurs between 65-340 ^{o}C, piloted ignition between 200- 350 ^{o}C and self ignition can occur between 250-600 ^{o}C depending on wood species, humidity, and exposure time.) (Lee, 1972; Lee and Hellman, 1974; Pitts, 1991). Pyrolysis and ignition can occur even without a flame present if radiation is sufficiently large. By proper forest thinning and building structure separation radiation intensity levels can be reduced low enough to limit the propagation of fires.

One dominant source of ignition in wildland/urban fires is due to firebrand activity. This method is most effective when wind speed is great. Showers of large numbers of burning embers ignite spots in areas ahead of the primary burning region. These areas coalesce and add to the forward movement of the fire front. The wind also tilts the convective column generated by the fire and brings it closer to downwind and unburnt fuels; thus, increasing radiation intensities and initiating pyrolysis ahead of the moving fire front.

Most forest fires begin at ground level among layers of dead leaves, needles and other litter. The propagation of the fire through this porous fire bed (or canopy) has been extensively studied in fire wind tunnels. Many studies use actual forest litter; whereas, others use idealized porous structures including arrays of match sticks, circular rods of rolled paper, incenses sticks, vertically supported index cards, wooden dowels, Popsicle sticks, strips of cardboard, strips of paper, beds of torn newsprint, wooden teepee arrangements, and even computer card punching (chad). (Vogel and Williams, 1970; Prahl and Tien, 1973; Lee and Hellman, 1974).

Unfortunately, these ground fires can extend up into the crown regions of trees if dry dead branches extend beneath the living crown along the trunks down to the ground. The fires are said to "jump" into the crown region. Once crown fires exist forest fires tend to grow almost explosively with flames leaping from tree-to-tree top, embers become lofted to great heights ahead of the fire, and fire whirls develop among the strong crown fire updrafts.

Finally a column of buoyant combustion products, ash, embers, and smoke are produced which rise above the flames. This often spectacularly visible plume of exhaust products can itself be very hazardous since it contributes to pyrolysis, firebrands, suffocation, and loss of visibility. The behavior of this plume has been the subject of extensive analysis and research, but in most cases the plume is presumed to rise independent of any surrounding terrain, structures or porous surroundings. Little attention has been given to the motion of the plume in the immediate vicinity of a fire as it is modified by surrounding forest or building structures. Once the plume penetrates the surface layer above the canopy it is presumed to follow conventional plume/jet mixing, trajectory, and kinematic under the influence of buoyancy and cross flow winds. (Lee and Hellman, 1974; Fendell, 1985; Brode and Small, 1986; Pitts, 1991; Viegas, 1998)

7.1 Field Scale Experiments

This section provides some additional information about a few of the field scale experiments introduced in Section 5.1 under Modeling Methodologies: Full Scale Fire Tests.

Probably the most extensive and ambitious mass fire experiments were performed during the Flambeau project between 1964 and 1975. Approximately 25 separate large-scale field experiments were performed of sizes ranging from 2 to 20 ha on both flat and inclined slopes to examine the behavior of very large fires. (Palmer, 1981; Countryman, 1964, 1967) During Test Fire Number 5(1966) 240 piles of pinyon pine and juniper tree debris approximately 15 m square were arranged in 15 x 16 rows, 7.5 m apart, and 1.5-2 m tall. The region covered was approximately 350 m square (~12.5 ha). The test region was instrumented with heat-protected anemometers, radiometers, aspirated thermocouples and fuel bed weighing platforms. Outside the fire perimeter were mounted pulsed-Doppler radars, smoke visibility measurement equipment, infra-red spectral scanners, and still and cine photographic equipment.

The lower 100 to 200 m of the Project Flambeau convection columns contracted because of the inflow of the air to the fire. This inflow was horizontal at ground level, but contained a considerable downward component. Winds typically occurred as single line spiraling columns or dual vortex fire whirls. Maximum measured winds were 56 m/s. This fire had a maximum energy release rate of 500 kW/m^2. Given the limited height of the fuel beds and the simultaneous ignition of the entire region few conclusions are possible with respect to fire spread through a porous canopy.

During 1970 Operation Euroka was performed in Queensland, Australia. (Williams et al., 1970). This fire was principally of brigelow, a heavy dense hardwood. The slash was arranged by bulldozers into fire beds that had very little fine material; hence the peak combustion rates were considerably later and lower than those of the U.S.A. fires. The fire had peak energy release rates of about 120 kW/m^2. During Operation Euroka maximum winds were 20 m/s, and after 30 minutes a fire whirl developed. Winds tended to spiral inward from around the fire which covered an area of about 2 ha.

7.2 Laboratory Scale Experiments

As noted earlier there have been extensive studies in fire wind tunnels of fire propagation through porous fire beds made of a variety of different depths of natural and artifical materials. Unfortunately, little of this work is directly applicable to the simulation within urban fires or forests including crown fires. One minor exception is the limited work of Lee and Otto (1975).

In urban areas, buildings of various shapes and heights are grouped together to form city blocks separated from each other by the open streets. Consequently, fire propagation is strongly affected by the unique relationship of the buildings. Lee and Otto (1975) chose to simulate how fires develop about just two rectangular buildings simulated by identical woodpiles of length L, width L/2 and height L/3 with the long sides parallel to each other. These fuel piles were separted by a distance L/2 with an overlap of equal magnitude. The wood cribs were set afire at the same time, and velocity, temperature, and heat flux measurements were made, while ordinary and infrared photography were used to monitor the flames. The fire developed in five stages related to heat flux levels as noted below:

- During Stage 1 both piles burned independently, ambient indrafts were controlled by each pile separately with no evidence of gross vortex activity.
- During Stage 2 the heat flux became strong enough to produce weak interaction between the induced airflow about the two fuel piles. Discretely separate multiple fire whirls extended from each corner. Individual fire whirls strengthened and heat flux increased.
- During Stage 3 the individual whirls of each pile coalesce almost instantaneously into one single flame leaning towards the open street with a single strong vortex column.
- During Stage 4 the vortex becomes so strong that flames are actually drawn out from the openings on the opposing sides of the piles facing the streets towards the vortex column. Heating no longer occurs primarily in the vertical, but lateral and horizontal heating causes fire to move along the model building. Secondary vortices appear.
- During Stage 5 the fuel is exhausted, the piles start to collapse, the main vortex column dissipates, and vortex shedding into a wake region predominates. The vortices shed so frequently and violently that this may indicate a primary period of fire spread to other structures.

The interaction of the fire between the two structures that resulted during fire whirl formation and subsequent sucking of flames out of openings (windows and doors) is similar to that assumed by the Himmoto and Tanaka (2002) fire propagation model.

As noted earlier a number of wind tunnel studies have examined flow within arrays of building like blocks placed in arrays to simulate generic and actual urban districts. Cermak (1995) concluded that the general nature of above city flow including distributed roughness and the effects of the heat island can be simulated when Richardson number similarity exists and for sufficiently large model Reynolds numbers. Plate (1995) and Theuer (1995) demonstrated that similarity of flow exists for a wide range of roughness arrangements including actual city geometries. Quintela and Viegas (1995) and Meroney (1978) concluded that even thermal effects to buildings can be simulated given equality of the parameter $Re/(Gr)^{1/2}$. Finally, dispersion of neutrally buoyant scalar plumes from point or line sources, which might represent the dispersion of cool smoke, was studied by Theurer (1995), Meroney et al. (1996), Chang and Meroney (2003a), among many others.

No additional examples of intense heat sources or actual fires released within model forest or simulated urban environments are known to this author.

7.3 Numerical Experiments

Fortunately, numerical modeling despite its many limitations associated with grid resolution, choice of turbulence model, or assignment of boundary conditions is not intrinsically limited by similitude or scale constraints. Thus, in principle, it should be possible to numerically simulate all aspects of fires within canopies for which realistic models exist for combustion, radiation, fluid properties, ignition sources, pyrolysis, etc. In addition it should be possible to examine all interactions of fire properties individually, sequentially and combined to evaluate nonlinear effects. Thus, computational fluid dynamics may well provide a greater understanding of the behavior of small, medium, and mass fires in the future.

Realistically, however, many of our computational submodules for combustion, radiation, pyrolysis, etc. are still primitive, and even inclusion of all models within a computation becomes cumbersome to calculate, and excessive in use of computational resources and time. Continued verification and validation is required at almost every level of CFD prediction. These caveats notwithstanding, there does exist exciting progress in the use and interpretation of numerical predictions of fire behavior.

7.3.1 Zone Model Based Fire Spread Model

Himoto and Tanaka (2002) describe calculations of fire spread in a simulated urban district by combining a modified zone model and a model for pyrolysis and ignition. Once a fire is ignited in a room, the combustibles inside the building burn filling the room uniformly with combustion products, heat and radiation; then the conditions in the first room communicate to surrounding rooms or buildings through convection plumes and radiation. Once the new space heats to a sufficient temperature, it also ignites, and the process proceeds.

The model was supplied with an idealized urban district of 49 identical buildings arrayed at a uniform separation distance of 3 m. The buildings chosen were assumed to be light weight concrete two-story houses composed of ten rooms. Some openings were open, others closed by window glass. The simulation was carried out for two wind speeds, 0.0 and 6.0 m/s. For no-wind the fire spreads in a symmetric pattern, but with a prevailing wind to the north the fire induced plumes were blown down by the wind and ignited downstream buildings earlier. For both cases the growth rates of fire in the 2nd floor compartments were faster than that of the 1st floor due to a) effects of plume buoyancy and b) 2nd floor compartments were closer to the external fire plume centerline and exposed to more outside heating.

7.3.2 Field Model Based Fire Spread Models

Baum and McGrattan (1999) considered a fire growing from the exposed top of an oil storage tank in a 3 x 3 matrix of large cylindrical tanks. Each tank was 84 m diameter and 27 m high. The geometry was chosen to represent a portion of the oil storage facility of the Japan National Oil Corporation at Tomakomai. A approach velocity profile with a power law distribution of 0.15 and a wind speed at tank height of 6 m/s was stipulated. They used the LES program FDS to calculate time dependent combustion, plume rise and radiation exposure of the nearby tanks. The model included the effects of radiation from smoke particle back to tank surfaces.

Morvan and Dupuy (2001) predicted fire propagation in Mediterranean shrub land by representing the vegetation as a collection of solid fuel particles distributed with appropriate size, moisture content, density, etc.. Separate layers were created to represent ground cover, crown canopy regions, thinning, and fire breaks. The model captures the degradation processes (dryng, pyrolysis, char combustion) and ignition. Calculations were performed over a domain 5 m tall by 20 m long. The authors considered different cell sizes (5, 10 and 20 cm) and compared rate of spread, mass fluxes, contributions of radiation and convection. The model predicted the temperature and velocity field for fires with canopy top wind speeds of 1 and 5 m/s. Their model is intended for incorporation in the EU FIRESTAR system forest fire prediction tool.

Researchers are beginning to add complex terrain into their predictions of fire-spread behavior. Viegas (1998) calculated fire spread rates over a simplified canyon geometry consisting of a horizontal plane and two inclined planes that intersect each other along a line that exists in the vertical plane. Canyon centerline slopes varied from 16.1^{o} to 30^{o}. A constant heat flux over a small area represented a fire at the base of the canyon. A fire propagation algorithm was incorporated in the flow field to estimate the movement away from the ignition point at the base of the canyon. It was found that fire driven convection processes modified the shape of the thermal plume depending on the ambient wind speed and fire intensity.

Coen and Clark (2001) has coupled a fire model into a three-dimensional non-hydrostatic terrain- following numerical mesoscale model developed at the US National Center for Atmospheric Research, Boulder, CO. The model includes rain and cloud physics. Calculations predict the growth and spread of a fire line moving across a two dimensional small Gaussian hill (height 200 m, half-width 300 m) for a wind speed of 3m/s, and a stable atmospheric lapse rate (10^{o} C/km). The head of the fire propagated quickly uphill in the direction of the environmental wind. Once the fire reaches the top of the hill, the updrafts tend to inhibit the forward movement of the fire front, and the fire spreads faster laterally in the lee of the hill.

7.3.3 Hot Plume Behavior in Generic Porous Canopies

One of the features of the forest fire problem making rigorous analysis difficult is the presence of individual trees, shrubs, bushes, trunks, branches, leaves and occasional human structure. To simulate these elements in detail with sufficient accuracy to replicate individual vortical motions would be intractable. Over a region of even a few acres there must be thousands of individual unequally sized and spaced objects.

A number of authors, however, have represented forest or urban canopy layers by porous regions of distributed force (or drag) (Garzan\ et al., 1998; Jeram et al., 1995, Shaw and Schumann, 1992; Yamada, 1982) The advantage of such an approach is that it permits inclusion of a canopy sublayer without the use of excessive and costly grid resolution. Yamada (1982) and Shaw and Schumann (1992) introduced the approach in order to add vegetation to meso-scale models of complex terrain. Jeram et al. (1995) used the concept in 2-d calculations for inviscid flow and constant eddy diffusivity flow estimates of the up and downwind penetration of flow within simple urban areas.

Garzan et al. (1998) treated a 2-d forest as a highly inhomogeneous and very permeable porous medium. The heat generated in the burning part of the forest was simulated through the addition of an area source term to the equation of thermal energy. The resulting velocity field was then used to estimate the position and velocity of firebrands. They simulated an atmospheric region 800 m high and 1000 m long with a 20 m high porous forest region also 1000 m in extent along the ground boundary. A constant heat flux of 50 kW/m^2 was imposed over a 20 m high and 100 m long region some 100 m downwind of the domain inlet. Turbulence was modeled by the standard k-, model. The plume height is deflected downward and the firebrands ae blown further downwind at the higher wind speed.

Numerical model calculations using the CFD code FLUENT 6.1 were performed to evaluate the time dependent behavior of fires ignited within a homogeneous porous canopy. These were compared with flow behavior from a similar fire in the absence of the canopy. Consideration was given to the effects of grid resolution, turbulence model (6-, RANS versus LES), wind speed (U_h = 0, 1, 2, 5 m/s), fire intensity (Q = 20, 50, 100 kW/m^3), and inlet velocity profile (" = 0 or 0.14). The development of velocities, turbulence intensity, static pressure, and temperature fields were examined for such examples. Typical results are discussed below.

7.3.3.1 *Fire in 2-d Porous Canopies*

Calculations considered a fire domain 60 m tall and 300 m long including a porous canopy 100 m from the entrance along the ground 6 m high and 100 m long. The associated computational grid consisted of 9000 rectangular cells. A buoyancy source was placed 10 m inside the canopy 2 m tall and 4 m long that dissipated 100 kW/m^3. A power law velocity profile approached the canopy with a power-law exponent of 0.14 and a velocity at canopy height of 1 m/s. Inlet turbulence levels were 10 %. Calculations were completed for fires with a) no canopy present and b) a canopy present with porous material having inertial resistance coefficients of 1 m^{-1} in both coordinate directions.

For the case of a fire ignited along a smooth ground surface, the thermal plume calculated by a transient LES turbulent model tended to grow downwind in time, creeping along the surface occasionally releasing unstable buoyant puffs of heated air upwards from the downwind tongue of the plume into an ascending turbulent thermal plume. The thermal plume along the ground was instantaneously rather shallow but mixed into regions above intermittently. (Figure 13) The thermal plume calculated by a steady state 6-, RANS model produced a ground level plume of greater depth but which decayed exponentially in the vertical and downwind directions in a Gaussian manner. For the no-canopy fire plume situation, the laid over behavior of the plume resembles the visualizations of line source plumes photographed by Maruyama and Tanaka (2002) during their study of the high temperature field behind a flame in a turbulent boundary layer. Measurements of downwind velocity profiles also produced similar wall-jet behavior near the ground.

For the case of a fire ignited within a porous canopy region, the thermal plume calculated by a transient LES turbulent model was initially laid over slightly by the approach winds, but then separated from the wall and accelerated upward in the low speed regions within the canopy. When the plume reached the canopy ceiling it had substantial vertical velocity and lofted above the canopy in a conventional bent-over turbulent plume. (See Figure 14) The plume calculated by a steady state 6-, RANS model also lofted from within the canopy, but the RANS average plumes were broader since they represented the average character of the intermittent plume observed during the transient calculations. These results resemble the behavior of a fire ignited within a deep canopy that quickly moves from the ground fire bed into the canopy region.

7.3.3.2 *Fire in 3-d Porous Canopies*

Calculations considered a fire domain 60 m tall, 300 m wide and 300 m long including a porous canopy that existed along the wall 6 m high, 100 m wide and 100 m long. The computational grid consisted of 185,000 hexagonal cells. A buoyancy source was placed 10 m inside the canopy 2 m tall, 80 m wide and 4 m long that dissipated 100 kW/m^3. A power law velocity profile approached the canopy with a power-law exponent of 0.14 and a velocity at canopy height of 2 m/s. Inlet turbulence levels were 10 %. Calculations were completed for fires with a) no canopy present and b) a canopy present with porous material inertial resistance coefficients of 1 m^{-1} in all three coordinate directions.

During the 3-d calculations the fire line produced very similar patterns to those observed for the 2-d model. For a fire ignited along a smooth wall the transient plume also spread (creeped) along the ground surface releasing intermittent puffs of heated air from the tip of the plume tongue. However, given a finite lateral extent there was evidence of end effects where air descended from above, and converged laterally inward toward the center of the fire line. Surface temperatures remained high for long distances downwind. (See Figure 15)

For a fire ignited within the porous canopy the 3-d fire line again produced similar patterns to those observed for the 2-d model. The heated plume rose upwards irregularly along the fire line to the canopy ceiling. When the plume penetrated through the shear zone into the higher wind speed above the canopy it was bent over, but continued to ascend upwards. There was considerably more evidence of lateral convergence downwind of the fire line however, and within the canopy there was an extensive region of reverse flow downstream of the fire line that fed air into the rising heated plume. (Figure 16)

The consistent and physically realistic behavior of these virtual plume calculations is very encouraging. Future calculations should consider the effects of forest canopy inhomogeneities (ground cover versus crown vegetation), alternative fire locations, and combustible canopy structure. It will also be intriguing to examine those fire configurations which lead to the presence of intense fire whirls and the associated lofting of fire brands.

8. FIRE WHIRLS AND FIRE TORNADOES

Fire whirls are a typically rare but a potentially catastrophic form of fire. They are observed during urban and forest fires, where fire “tornadoes” are characterized by large-scale whirling flames which rise in 2 to 360 m diameter vortices from 10 to 1200 m high. These fire whirls accelerate combustion, produce significant suction pressures and lifting forces, and can carry burning debris, logs and even buildings thousands of meters from the main fire.

The formation of fire whirls requires a source of ambient vorticity, a concentrating mechanism, and a favorable environment for fire whirl stability and growth (augmentation physics). Emmons and Ying (1966) wrote the defining paper about fire whirl behavior. They identified the primary mechanisms, performed laboratory scale experiments in a laboratory apparatus 3 m high which used a 2.25 m diameter rotating screen mesh to introduce angular momentum and a pan of burning fuel (acetone) to provide a source of buoyancy. They also proposed a fire plume model based on a one-dimensional entrainment theory, but it failed to reproduce the growth of the fire plume with height.

Later Mayle (1970) continued their research by performing measurements of velocity and pressure within the fire whirl. He found that the behavior of the plume was governed by dimensionless plume Froude, Rossby, second Damkohler Mixing Coefficient and Reaction Rate numbers. For plumes with a Rossby number less than one the plume is found to have a rapid rate of plume expansion with height. This phenomenon is sometimes called "vortex breakdown", and it is a "hydraulic jump" like phenomena caused by the movement of surface waves up the surface of the fire plume that are greater than the speed of the fluid velocity. Unfortunately, even improved entrainment rate type models do not predict these phenomena very well.

Ambient vorticity can be produced by ground level boundary layers generated by the wind, wind shear from non-uniform horizontal densities, the earth's rotation, or wind shear produced as air passes over a ridge or hill. Concentrating mechanisms include rising air in a buoyant column from unstable layers forming over sun-heated ground, the presence of a storm front, or hot gases from a fire. The concentrating mechanisms rotate the horizontal vorticity into the vertical and stretch the vortex tubes. Through conservation of angular momentum the stretched tubes induce more rapid rotation resulting in lower axial pressures, which in turn encourages further entrainment of ground level vortex-rich air. Finally, the rotational structure of the vortex induces centrifugal forces which dampen turbulence near the vortex core; thus, reducing any tendency for the fire whirl plume to diffuse outward from the core

8.2 Physical Modeling of Fire Whirls

Byram and Martin (1962) used external vertical cylinders with tangential slots oriented to produce rotating flow about a fire source. They examined two sets of equipment of diameters and heights, 33 and 183 cm, or 66 and 335 cm, respectively. Burning alcohol pools within their apparatus, they reported visible fire whirls up to 300 cm tall with inner fire tube columns 2 cm in diameter. They observed horizontal velocities at the surface of the inner column of about 9 m/sec (~6000 rpm) and vertical velocities to 18 m/sec.

Emmons and Ying (1966) used the rotating-screen apparatus described above to systematically evaluate the effects of angular rotation (Rossby number) and plume buoyancy (Froude number) on fire whirl dynamics. They reported that turbulent mixing coefficient decreases with increasing angular momentum, and increases with elevation above the ground. Later Chigier et al. (1970) reproduced their apparatus but used a turbulent jet diffusion flame . Since these early experiments several investigators have re-created similar laboratory apparatus while evaluating the character of fire whirls (Martin *et al*., 1976; Muraszew *et al*., 1979).

Other investigators have reproduced fire tornadoes as they develop in simulated outdoor environments. Lee and Otto (1974) examined how city fires might develop by simulating in a wind tunnel a simple urban street arrangement. Their results revealed that strong street level vortices could develop due to building fire interaction. Emori and Saito (1982) simulated a fire whirl formed during a forest fire burning over a mountain ridge top that injured several Japanese fire fighters. Soma and Saito (1991) recreated fire tornadoes that occurred during the Kanto earthquake in Tokyo (1923), the Hamburg firestorms during WW II (1943), and oil-tanker fires in Hokkaido bay, Japan (1965).

More recently Satoh and Yang (1996, 1997) produced laboratory scale fire whirls by adjusting symmetrical vertical gaps separating the square vertical bounding walls surrounding a central fire pan. They examined the effect of gap size, wall height, fuel size, and heat load on the fire whirl. They determined that there is a critical gap size, which is not so large or small that it inhibits the entrainment of air needed to sustain the fire. Stable whirls were generally associated with flame heights smaller than the wall height of the square enclosure. Flame temperatures were primarily affected by the magnitude of the volumetric heat source.

8.3 Numerical Modeling Fire Whirls

Murgai and Emmons (1960) and Emmons and Ying (1966) describe integral plume models, which are calibrated with experimental data. Satoh and Yang (1997) used the UNDSAFE code with associated 3d, compressible, buoyant, and constant turbulent viscosity specifications. Ten cases were considered which included validation exercises and parameter sensitivity studies.

Battaglia et al. (2000) simulated the laboratory experiments of Emmons and Ying (1966), Chigier et al. (1970), and Satoh and Yang (1997), which included cases for fixed circulation and variable fire strength, fixed fire strength and variable circulation, and jointly varied fire strength and circulation. The numerical code used was the NIST shareware FDS (Fire Dynamics Simulator) which includes 3d, compressible, buoyant and LES turbulent models (Baum et al., 1996).

Meroney (2001, 2003, 2004) considered the growth of fire whirls in large building atria and their effects on distribution of smoke and building evacuation. Using the commercial cfd code, FLUENT 6.1, he reproduced the transient growth and stabilization of laboratory fire whirl configurations used by Byram and Martin (1962), Emmons and Ying (1966) and Satoh and Yang (1997). Figure 17 present the transient appearance of fire whirls generated within fire whirl simulation chambers.

9. CONCLUSIONS AND RECOMMENDATIONS

The development of large fires in vegetation and building environments continues to be a major concern as population increases results in larger urban areas and the intersection of wildland and urban regions. Although the total number of fires observed seem to be constant, the proximity of wildland and urban populations has resulted in steadily increasing economic infrastructure losses. Continued research into the mechanisms of fire spread and their possible mitigation are appropriate. This review suggests that:

a. Fire and smoke movement through forests and building arrays are imbedded in flows defined by the porous nature of the burning media. Initially it is the flow through the permeable media that determines the nature of the growth and spread of the fire.
b. Fires growing within porous media inherently are different from fires burning over flat surfaces.
c. Flow through forest canopies and building arrays are very similar with respect to their mean behavior in terms of distributions of velocity, turbulence and shear profiles, but
d. Building arrays are NOT locally porous only in the average.
e. Improved fire spread models should be developed to determine the effects of street

arrangement, street canyon aspect ratio, building heights, etc. on fire propagation. CFD appears to be a valuable tool in investigating these phenomena systematically.

f. Simple parametric models are needed to use in numerical models to permit simulation of fire pyrolysis and spread.

g. Porous canopy models maybe improved by using various degrees of porosity to model individual buildings, vegetation, and other structures.

h. Future calculations need to include realistic thermal radiation models to predict drying, pyrolysis and ignition. These same calculations need simple but realistic models for fire spread.

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