Numerical Prediction of Fire Propagation in Idealized Wildland and Urban Canopies

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Paper prepared for

12th International Conference on Wind Engineering
1-6 July 2007

at
Cairns International Hotel
Cairns, North Queensland
Australia

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ABSTRACT: Numerical methods are used to examine the development of fires within porous urban canopies. Idealized generic porous models of 2-D and 3-D city structures are used together with inserted heat sources to predict combined flow circulations. The presence of structures of different densities, height and distribution produce unique flowfields associated with the porous canopy structure of cities, but the buoyancy produced by combustion products modifies, and for large fires, dominates the urban canopy flow.

KEYWORDS: fire, fluid modeling, forest canopies, urban canopies

1 INTRODUCTION

Fires caused by lightening or volcanic activity moved across the earliest vegetative landscape whether grassland or forest scourging away all life before its path. Uncontrolled fires and their associated smoke have been part of mankind's hazard environment since prehistoric times. 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. The wild-land urban interface (WUI) in the conterminous United States covers 719 156 km^2 (9% of land area) and contains 44.8 million housing units (39% of all houses).[1] In the eastern United states WUI areas cover up to 79% of such states as Connecticut. 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.

Recent publication of world fire statistics reveals that costs of fires including prevention, protection and repression 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 $13 bn/year.[2] 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 exceeded the sum of all losses from volcanic eruptions, hailstones, flash floods, Tsunamis, landslides, avalanches, water drainage, frost, and local and winter storms combined![3, 4] (Of course extreme events like the Baran earthquake, the European heat wave, floods, and severe and tropical storms like Katrina can individually exceed forest fire losses.)

2 SIMULATING FIRES BY CFD

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 (A review of these alternatives is found in Meroney, 2007).[5, 6] In this paper we will focus on the potential of numerical simulations (Figure 1).

2.1 *Merits of Computational Fluid Dynamics for Fire Modelling*

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.[7] Several idealized calculations of fire behavior are considered in this study for both two and three-dimensional fires ignited in idealized urban canopies immersed in a deep atmospheric shear layer.

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 urban communities 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.

2.2 *Limitations of Computational Fluid Dynamics for Fire Modelling*

Realistically, however, many of our computational sub-modules 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. Models are also constrained by the simulation model chosen, since 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 including the programs NISTs FDS, the European Union's Fire Star, Los Alamos National Laboratory's FIRETEK, and NCAR's Clark-Hall/BEHAVE/BURNUP coupled models.[8, 9, 10, 11]

3 URBAN CLIMATE METEOROLOGY

The dynamics of fire growth is strongly influenced by the kinematics of flow through porous 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.[12, 13] 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 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.[14, 15] Both zone and field calculations have improved to the point operational models for fire prediction and management in complex urban situations are close to reality.[16, 17]

4 URBAN FLOW STRUCTURE

A good summary of urban behavior is contained in the recent book edited by Moussiopoulos (2003) titled Air Quality in Cities.[18] 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, wind tunnel 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."

5 NUMERICAL EXPERIMENTS

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.[19] 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 (κ-ε 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 (α = 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.

5.1 *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 (See Figure 2).

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 4). The thermal plume calculated by a steady state κ-ε 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 (Figure 6a).[20] It is also similar to studies by Meroney (1979) of point, area, and line source plumes of Helium released in deep turbulent wind-tunnel boundary layers (Figure 6b).[21] 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 (Figure 5). When the plume reached the canopy ceiling it had substantial vertical velocity and lofted above the canopy in a conventional bent-over turbulent plume. The plume calculated by a steady state κ-ε 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.

5.2 *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 (Figure 3).

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 Figures 7 & 9). Note the characteristic parabola shaped wind-driven burn pattern, also observed during Australian grassland fire experiments (Figure 11) and WFDS simulation of such experiments (Figure 12).[22]

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. (Figures 8 & 10)

5.3 *Conclusions*

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.

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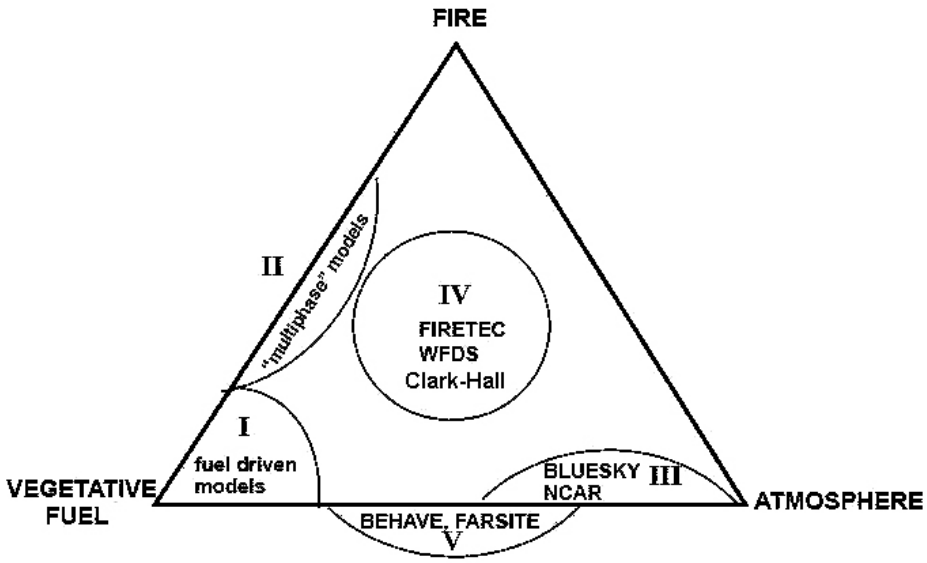

Figure 1: A schematic showing the relationship of different wildland fire models. Each approach is located according to its emphasis on the atmosphere, vegetative fuel, and/or fire component(s) of the working model. Region I emphasizes fuel bed characteristics; Region II includes fire dynamics but atmospheric contribution is small (eg. FIRE STAR); Region III models use semi-empirical expressions for fire spread, fuel consumption, and heat/moisture release, but include atmospheric dynamics; Region V models are very fast operational models, but have no mechanism for fire/atmosphere interaction; and, finally, Region IV models are called "physics based" models because they attempt to limit empiricism and include governing equations for all mechanisms.[22]

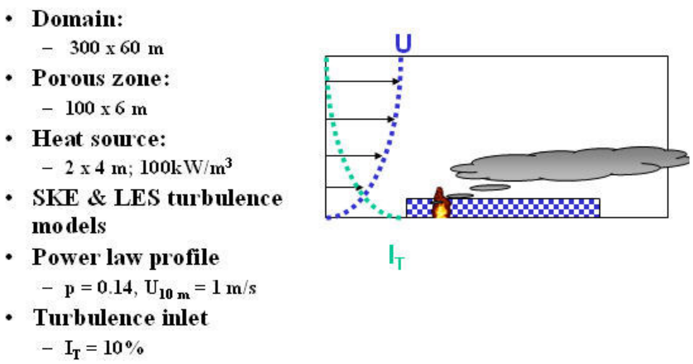

Figure 2: Schematic of 2-d Porous Canopy Simulation

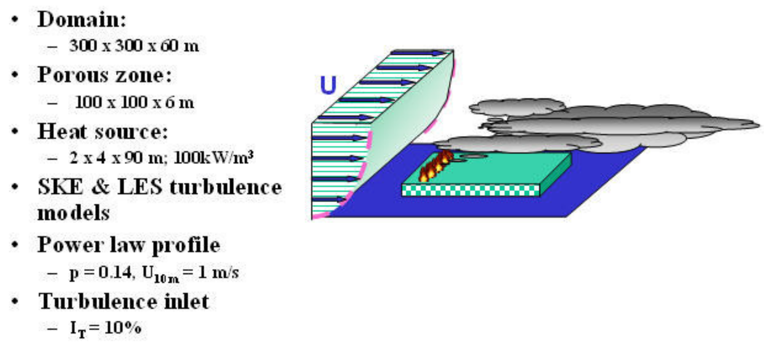

Figure 3: Schematic of 3-d Porous Canopy Simulation

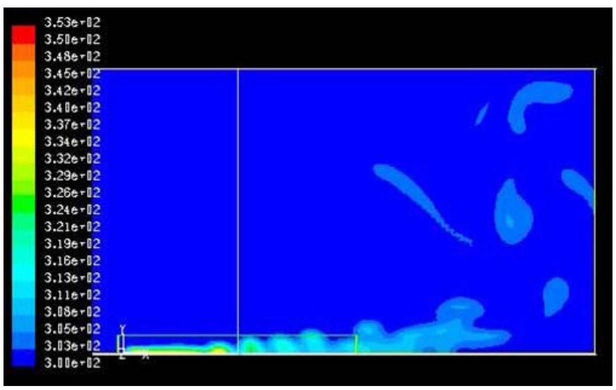

Figure 4: LES Calculation of 2-d thermal plume behavior over clear ground at 160 sec after ignition, T (^{o}K).

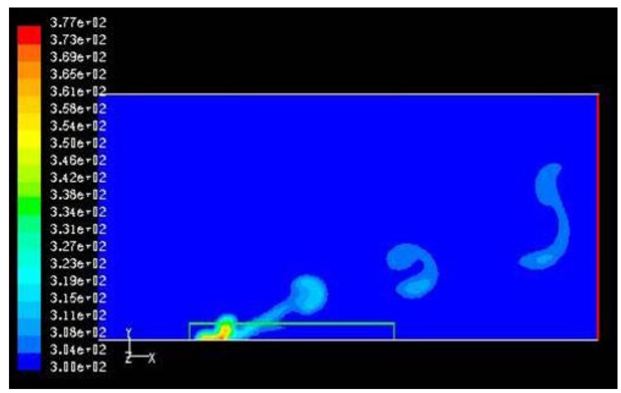

Figure 5: LES Calculation of 2-d thermal plume behavior within porous canopy at 160 sec after igntion, T (^{o}K).

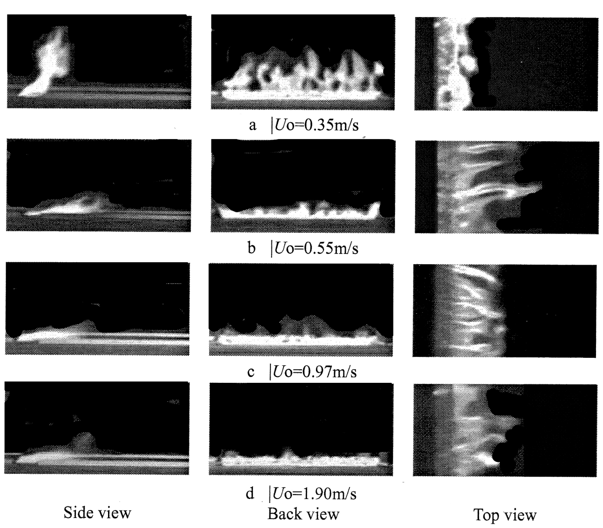

Figure 6a: Thermal image behind 2-d flame front in turbulent boundary layer (Maruyama & Tanaka, 2002).[20]

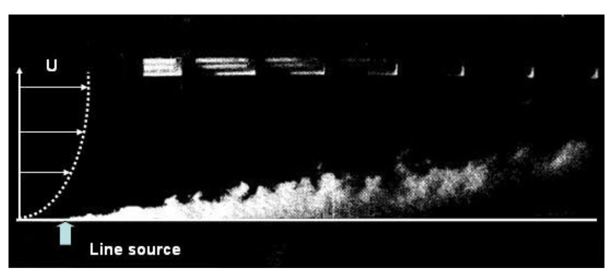

Figure 6b: Image of helium plume released from ground source, Q = 708 cc/sec, U = 0.76 m/sec, p = 0.12 (Meroney, 1979)[21]

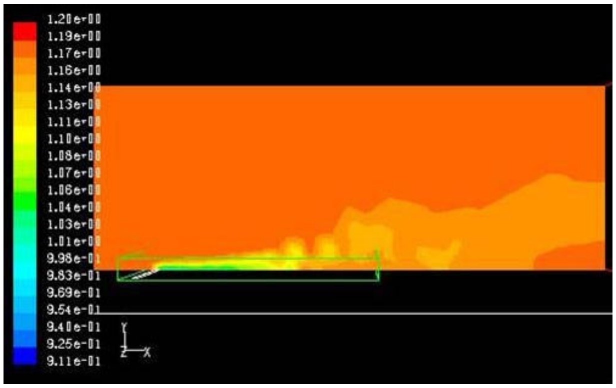

Figure 7: LES Calculation of 3-d thermal plume behavior over clear ground at 160 sec after ignition. Centerline section, T (°K).

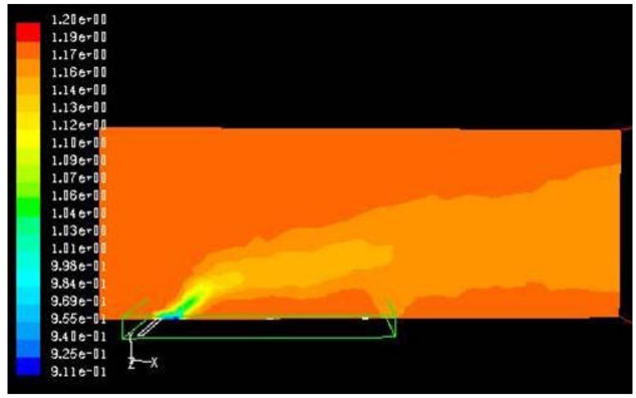

Figure 8: LES Calculation of 3-d thermal plume behavior within porous canopy at 160 sec after igntion. Centerline section, T (°K).

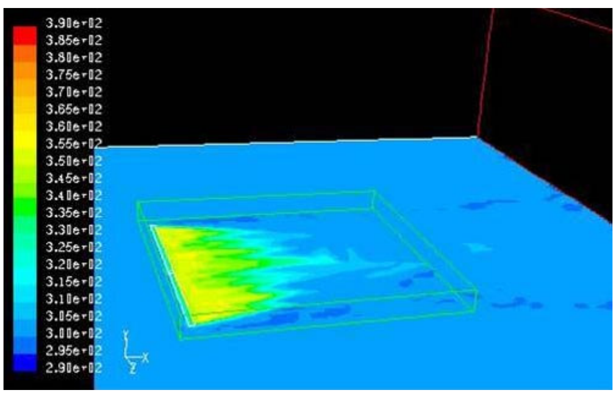

Figure 9: LES Calculation of 3-d thermal plume behavior over clear ground at 160 sec after ignition. Ground level, T (°K).

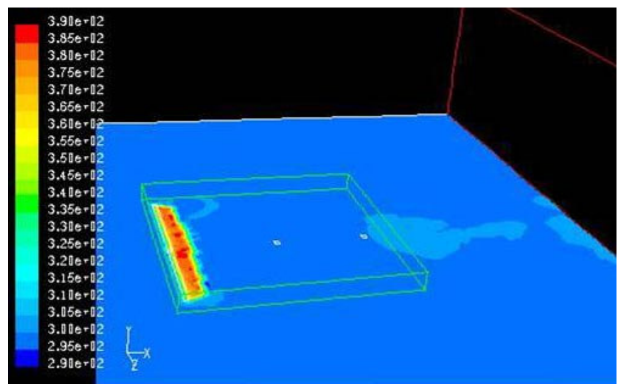

Figure 10: LES Calculation of 3-d thermal plume behavior within porous canopy at 160 sec after igntion. Ground level, T (°K).

Figure 11: Fire pattern observed during 1993-95 Australian Grassland experiments, 200 m x, 200 m plot 5 m/s wind from left, line source ignition, at T = 56 seconds.[22]

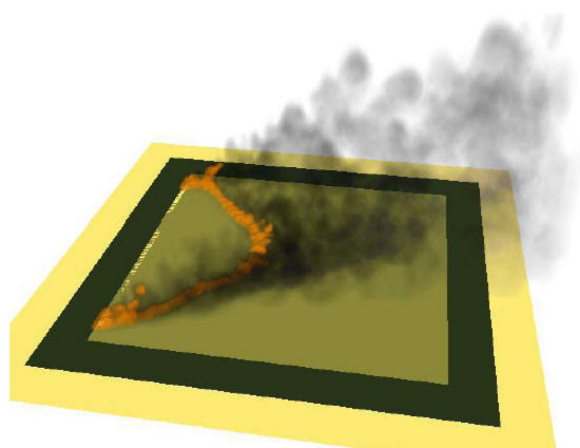

Figure 12: Fire pattern calculated using WUI-FDS software for same conditions as Fig. 11. (Mell et al., 2006)[22]