NUMERICAL SIMULATION OF WIND-DRIVEN FIRE PLUMES

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ABSTRACT

In many large urban-fire scenarios one of the critical issues is to attempt to protect the lives of fire fighters in helicopters deployed to flying over the fires and also the lives of people trapped in open areas downwind of the fires such as in parks. The strategies of such protection measures depend significantly on our knowledge of the size and extent of such fires as affected by the prevailing winds. In this study, the shape or profile of the fire plume typical of large urban fires, as affected by a steady unidirectional wind with or without imposing a shear flow on the fire plume, has been simulated numerically by a field model. The results show that the simulations provide realistic flame profiles and at least qualitatively, the same flame dynamics when compared to those from the experiments, and that the fire plumes are sensitive to small variations in the asymmetry of the wind shears, including the appearance of swirling flames within the fire plumes.

INTRODUCTION

It is known that large urban fires in open areas are often accompanied by highly destructive fire whirls, caused by the interaction between the fires and the prevailing winds. In one instance in the infamous 1923 Tokyo Earthquake in Japan, for example, more than 30 thousands of lives were lost to the fire at the same time in a large localized open area in Tokyo.

Counter-measures for such large fires often require the deployment of helicopters that fly over the fire. Only for the reconnaissance flight the helicopter pilots can select a sufficiently safe altitude or area over the fires. However currently demanded fire fighting by helicopters may require an operation involving flying near the heated smoke. And another assessment required is the design of evacuation strategies to disperse people in the immediate vicinity of the fire in order to limit the extent of loss of lives and property damage. Such counter-measures, unfortunately, cannot be successfully implemented without knowledge of the extent or profile of the fire, especially when there is interaction between the fire and the prevailing wind. In addition, information is also needed concerning the conditions under which the destructive fire whirls can occur within the fire plumes, in terms of the interaction with the ambient wind.

In the present study, the shape or the profile of the fire plume as affected by a steady unidirectional wind, especially in those cases where the wind is blown asymmetrically toward the fire and where the resulting shear-flow field may cause fire whirls, is simulated numerically by a field model. Then the numerical results are compared with the fire profiles in the experiments.

NUMERICAL FIELD MODELING OF LARGE URBAN FIRES

The ever-increasing computing power now available enables us to simulate large urban fires and fire spread numerically based on field models. The authors have used the three-dimensional UNDSAFE field model [1], which accounts for full compressibility and strong buoyancy, to gain the needed insight to the phenomena of the swirling fires in a channeled enclosure with gaps, together with the experimental investigation [2 and 3], where it has been found that the gap size of the channel has a significant role to produce the swirling fire.

The National Research Institute of Fire and Disaster of Japan and the Tokyo Fire Department have jointly conducted an experimental assessment for the safe fire fighting by helicopters over the fires [4]. Figure 1 shows the typical smoke profile due to the real-scale fire in the experiments mentioned above. The fires were based on the 4 x 5 real scale one-storied wooden houses located in an area of 40 m x 50 m. The ambient wind velocities during the combustion of the houses were reported to be approximately 2 to 3 m/sec. The heat load of burning houses relevant to the buoyant fire plume was estimated to be about 300 MW in the initially burning area (roughly 30 m x 30 m), excluding radiative heat losses in the total heat generation. Thus in the simulations the radiative heat transfer is neglected.

The objectives of this numerical study are firstly to examine the shape and profile of the large fires in the prevailing wind through the comparison between the simulation and the experiments mentioned above. A second aim is to examine the phenomena of swirling fires caused by the prevailing wind, particularly with asymmetrical horizontal shear flows in the wind.

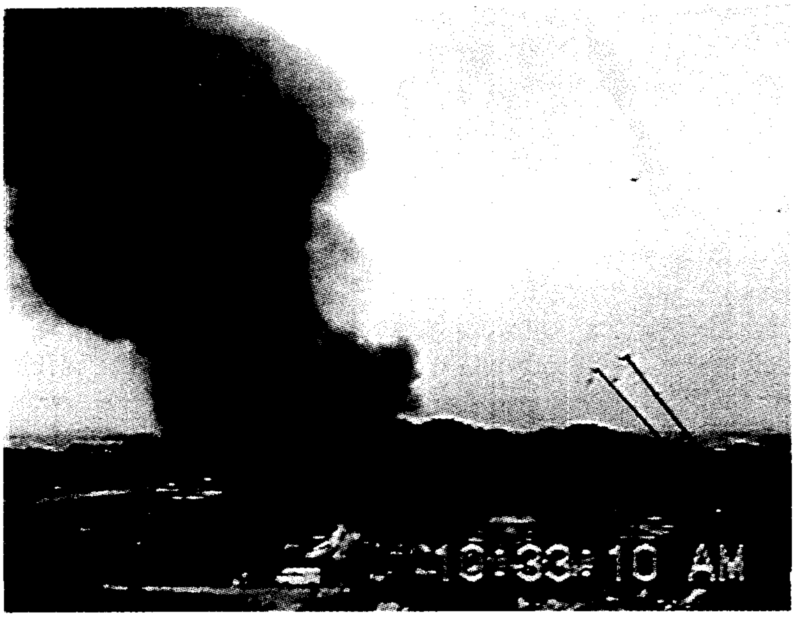


Figure 1 The profile of the smoke due to the large scale fires in the experiments conducted by the National Research Institute of Fire and Disaster of Japan and the Tokyo Fire Department[4].

Simulations in this study based on the same three-dimensional UNDSAFE fiel model [1] were made in the numerical domain consisting of 81 x 81 x 61 uniform cubical cells. Each cube corresponds to 1 cubic meter of spatial physical volume. Therefore the computational domain is 81 m x 81 m x 60 m (height). Similarly to the experimental fires shown in Figure 1, a steady and mild unidirectional wind is imposed at one boundary, where the initial wind speed is taken to be 0.21 to 0.3 m/s. And the standard no-stress conditions are imposed on the other free boundaries. For the bottom boundary no slip conditions are employed. The temperature conditions at the free boundaries are simply that if the normal velocity represents flow leaving the domain, the temperature flux is taken to be zero, and when the normal flow is entering the domain, the temperature is at the ambient temperature (To=27 deg C). In addition, since we are also interested to see how a shear-flow field would affect the generation of fire whirls, the imposed wind velocity is allowed to have a horizontal linear variation from end to end, thus giving rise to an imposed horizontal shear. However, there is no local vertical variation. The difference of the velocities between the horizontal ends divided by the maximum imposed horizontal velocity is a measure of the shear asymmetry which varies from 1 % to 5 %. In this mildly imposed shear-flow field, a uniformly- distributed volumetric fire load is placed at the center of the base of the computational domain in a volume of 23 m x 23 m and 6 m in height to represent the fire source. And the total heat load of the fire is taken as either 264.5 MW or 317.4 MW. The time increments in the computations were successively reduced in order to maintain the proper numerical stability and accuracy [1]. The three-dimensional algebraic turbulence model and the constant (100 times the laminar viscosity) viscosity model were used for the simulations. However, most of the simulation cases employed the latter model for simplicity.

Based on the above conditions, five cases shown in Table 1 are numerically examined in terms of the parameters of heat load and wind with shear:

Table 1 Simulated fires in a shear flow

	Total heat load	Initial wind	Entrained wind	asymmetry of shear
CASE 1	264.5 (MW)	0.21 (m/s)	2.06 (m/s)	1 %
CASE 2	264.5	0.21	2.06	2 %
CASE 3	264.5	0.21	2.06	5 %
CASE 4	317.4	0.21	2.06	1 %
CASE 5	264.5	0.30	2.93	1 %

NUMERICAL RESULTS

Calculations were carried out only up to 600 seconds (10 minutes), corresponding to the time of the maximum burning stage of the wooden houses initially ignited in the experiments. A linearly increasing heat load in time was used as input up to 420 sec and it was then fixed constant. At this stage the upward heat flow rate in an arbitrary horizontal cross section of the fire plume is almost equal to the total heat load input in the volumetric heat source, in all Cases 1 to 5. This is used as one of the measures to check the calculation accuracy.

Figures 2 shows the plume profiles in the simulated vertical central planes of Cases 3 and 5. The profile of the fire plume is qualitatively the same as in the experiments in Figure 1.The lean angle of the plume in Figure 1 is between those for Case 3 and Case 5. It was also seen in this figure that the maximum temperatures near the upper boundary (height=60 m) are about 100 deg C and 80 deg C for Cases 3 and 5, respectively, thus 73 K up and 53 K up from the ambient air. A

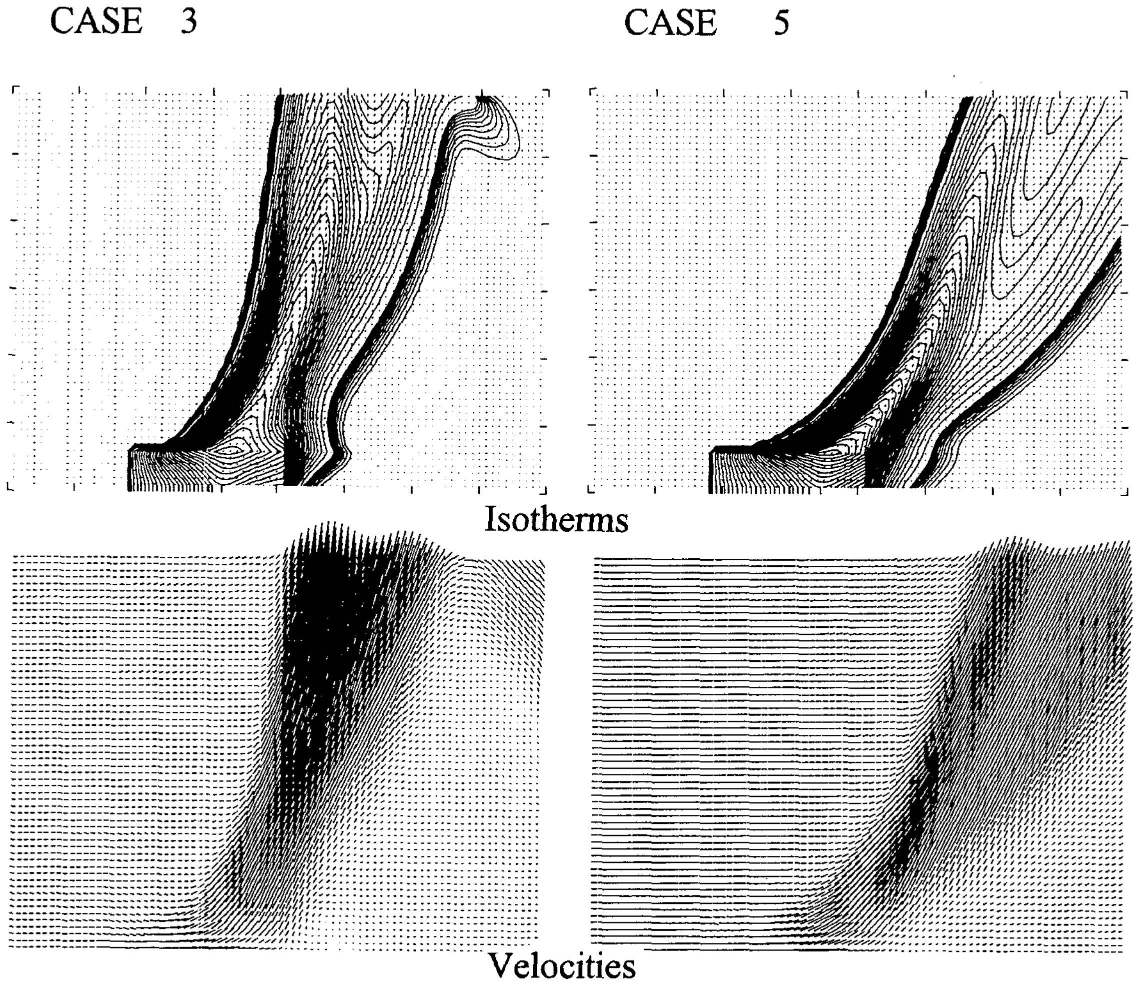


Figure 2 Simulated plume profiles of Cases 3 and 5 in the vertical central cross section.

And the average temperatures of the heated air in the horizontal cells near the upper boundary are about 50 K and 30 K above the ambient temperature. Therefore the temperatures of the fire plumes at high altitude, which are relevant to the safe helicopter flight, are affected by the ambient air velocity from the boundary and the turbulence in the domain.

Figures 3 to 7 show the plume profiles in the horizontal cross section at 4 m and 14 m above the ground for Cases 1 to 5, respectively. The shear wind enters into the domain from the left boundary, with the asymmetry introduced by assigning 100 % at the left bottom boundary and 99 %, 98 % or 95 % at the left top boundary as shown in the Table 1. An anti-clockwise directional swirling motion can be seen near one corner of the volumetric heat source in Cases 2, 3 and 4, according to the direction of the asymmetry of the shear wind. On the contrary the swirl motion is almost not visible in both Cases 1 and 5. Therefore it can be seen from these figures that the shear wind with more than 2 % asymmetry produces clear swirling flow. Furthermore this simulation showed that the swirling motion begins earlier in proportion to the extent of asymmetry as can be noted in the comparison between Cases 2 and 3. When the asymmetry of the shear wind is less than 1 %, the swirling flow is not obvious, as seen in Cases 1 and 5, where the heat load is fixed at constant. However, even in the case of shear wind with 1 %, a swirling motion can be seen in Case 4 where the heat load is 1.2 times larger than in the Cases 1 and 5. Therefore it is clear that the greater heat load does initiate earlier swirl flow in the interaction with the shear wind. On the other hand, the wind speed itself has a relatively minor effect on the swirl motion as mentioned

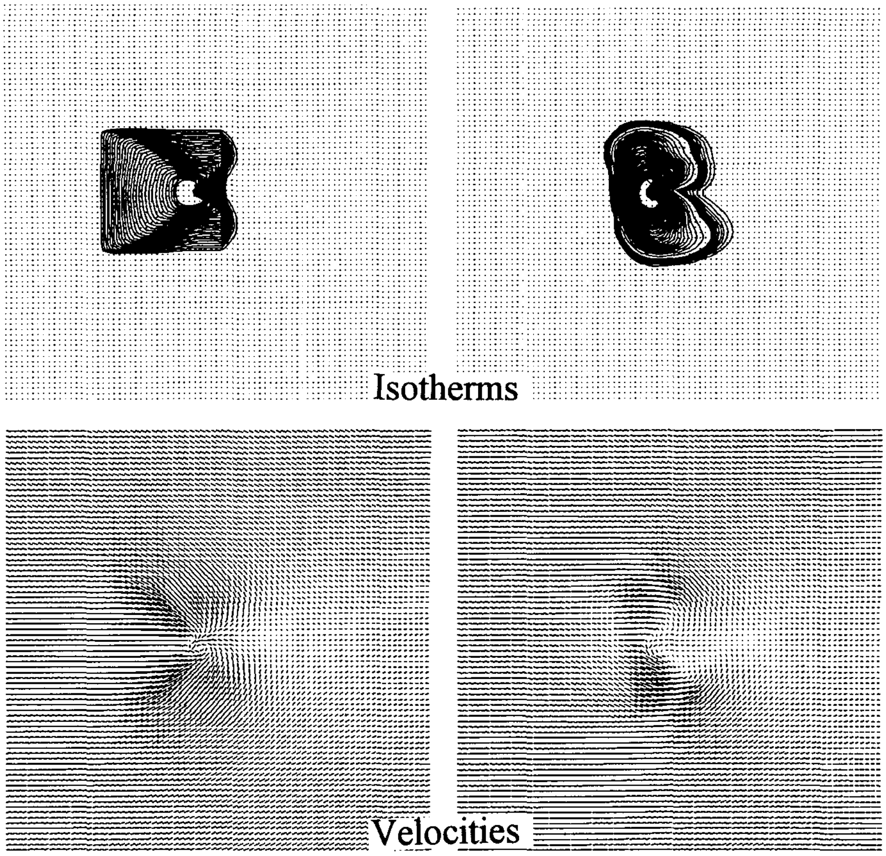


Figure 3
Plume profiles of Case 1 in the horizontal cross section
(left top and bottom : H=4 m
right top and bottom : H=14 m)

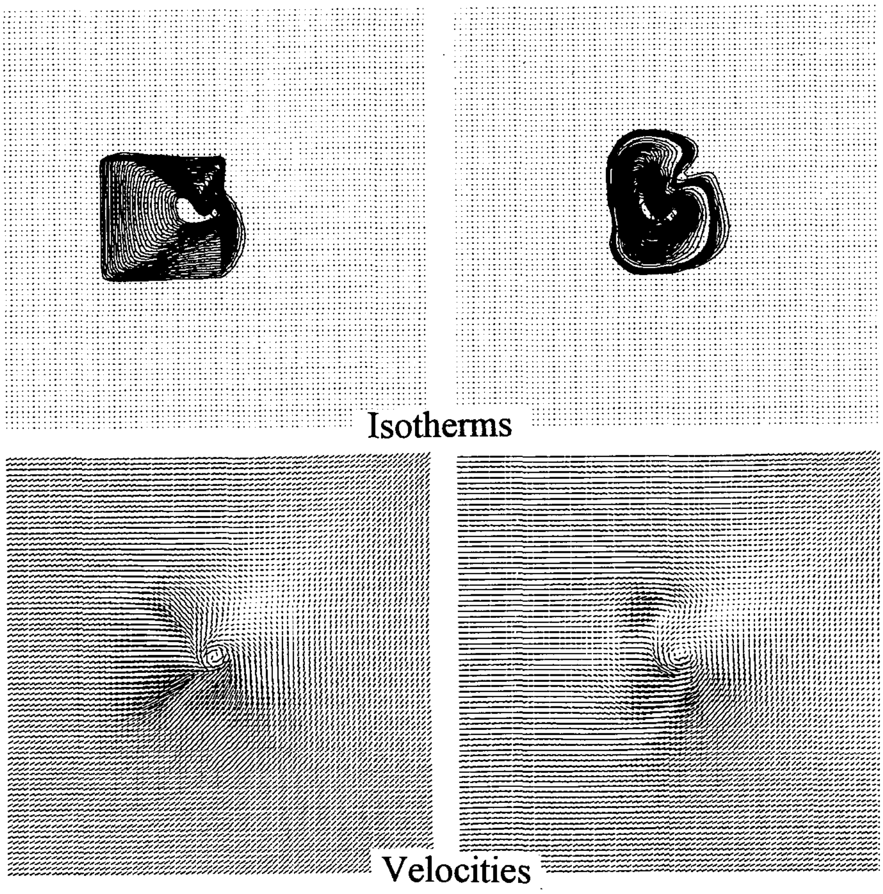


Figure 4
Plume profiles of Case 2 in the horizontal cross section
(left top and bottom : H=4 m
right top and bottom : H=14 m)

Figure 5

Plume profiles of Case 3 in the horizontal cross section
(left top and bottom : H=4 m
right top and bottom : H=14 m)

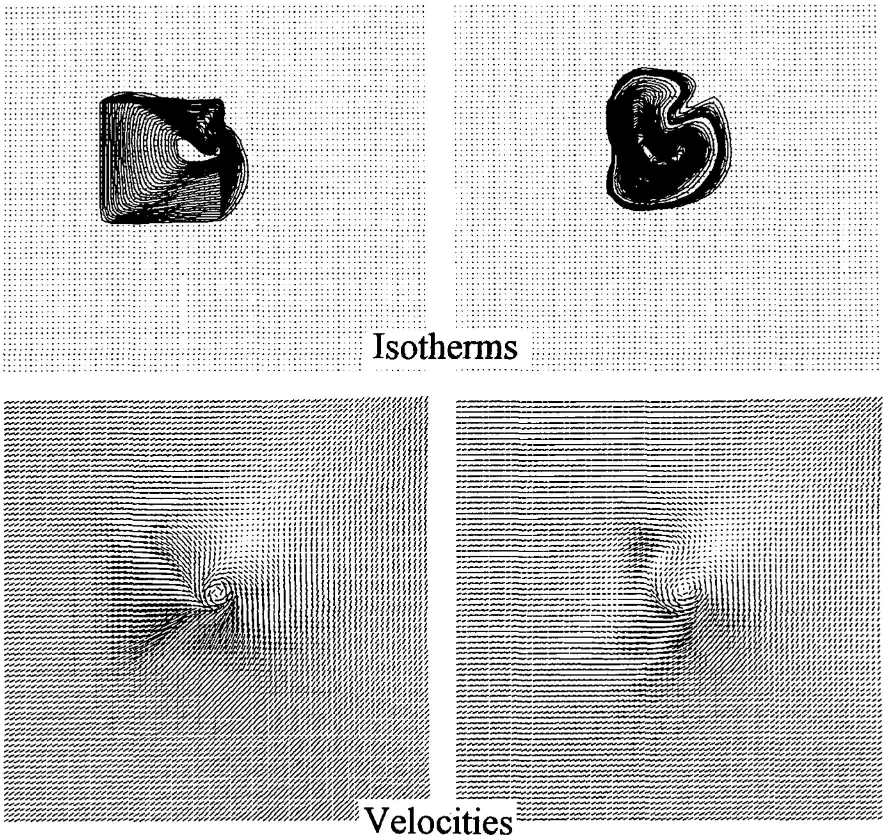


Figure 6

Plume profiles of Case 4 in the horizontal cross section
(left top and bottom : H=4 m
right top and bottom : H=14 m)

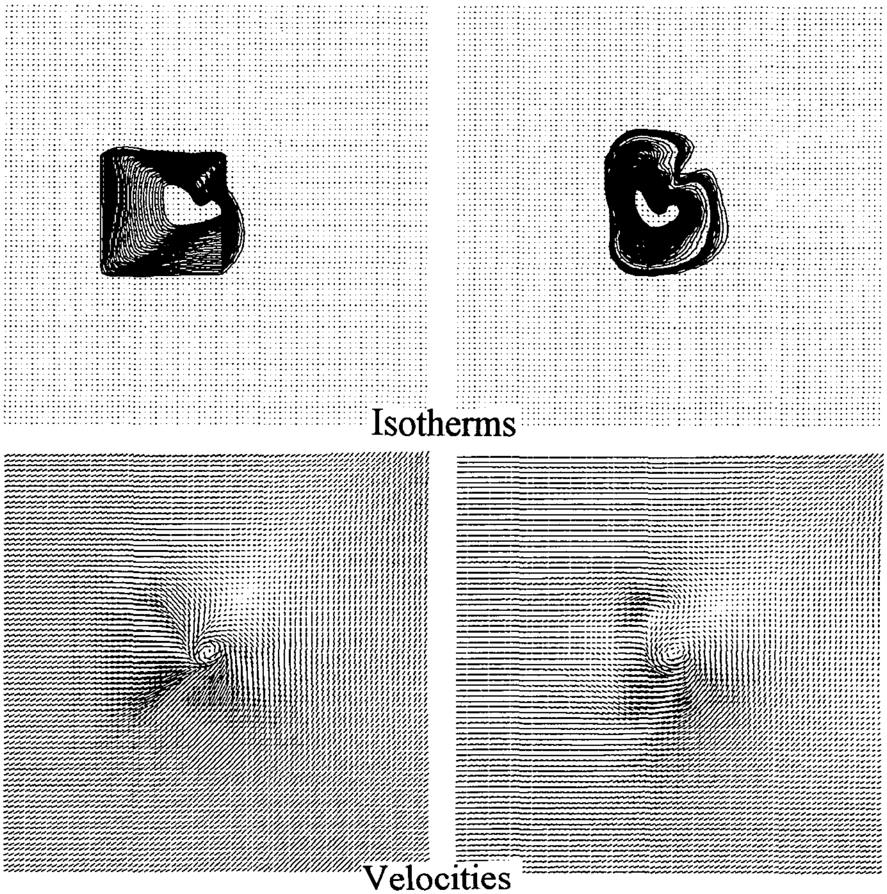
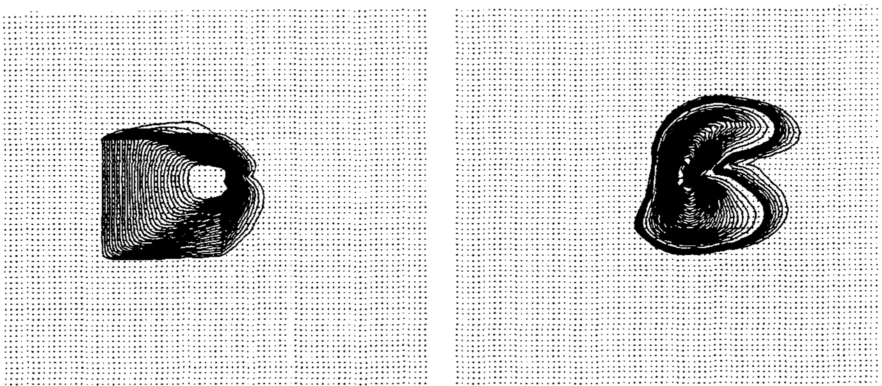
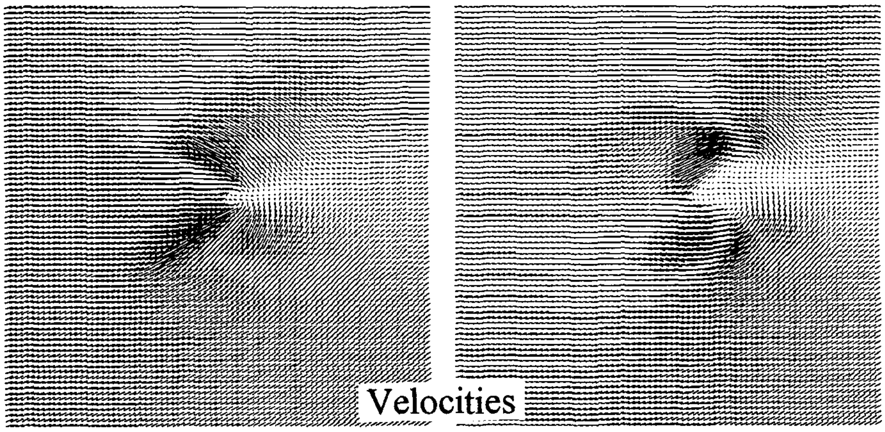


Figure 7
Plume profiles of Case 5in the horizontal cross section
(left top and bottom : H=4 m
right top and bottom : H=14 m)



Isotherms



Velocities

above, compared with the wind asymmetry. In addition it has been found that the swirling direction (anti-clockwise direction in the cases mentioned above) varied into clockwise direction when the asymmetry of the shear was reversed, opposite from the cases mentioned above.

In addition, it is also interesting to note in comparing Cases 1 and 5 that when the initially imposed velocity is changed from 0.21 m/s to 0.3 m/s, the calculated wind speed at this boundary from their values to 2.06 m/s and 2.93 m/s, respectively.

It is difficult to examine the large scale swirling fires experimentally. Therefore, a small scale experiment on swirling fire was conducted, in a laboratory, with a 20 cm x 20 cm x 2 cm (depth) steel pan An n-heptane flame was placed from an imposed wind source at 40 cm away laterally and 15 cm down wind, a swirling

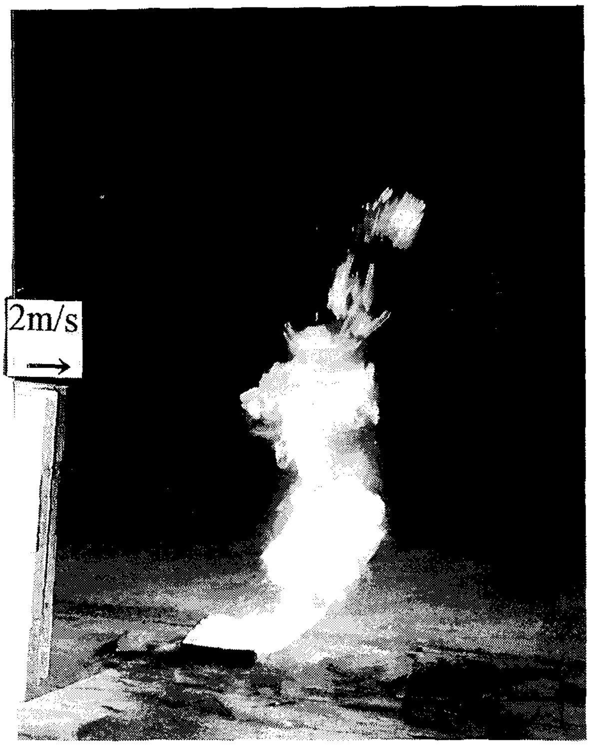


Figure 8 Typical swirling flame in a shear wind blowing through a vertical slit.

flame was repeatedly observed for a short time, about 3 to 10 second, when the wind speed is between 1 m/s to 3 m./s. This swirling flame shown in Figure 8 is quite similar to the shape shown in the simulations.

CONCLUDING REMARKS

In this study, numerical simulations were conducted corresponding to the real large scale fires in the experiments jointly conducted by the National Research Institute of Fire and Disaster of Japan and the Tokyo Fire Department, aiming to assess the safety of helicopters flying over the fires. And since swirling fires can cause major disasters in large scale urban fires, swirling flows of plumes in an asymmetric shear-wind were examined, together with the qualitative comparison with a small scale swirling flame. Results in this numerical study shown that:

(1) The simulations provide realistic flame profiles and at least qualitatively, the same flame dynamics when compared to those from the experiments.
(2) The fire plumes are sensitive to small variations in the asymmetry of the wind shears. More than 2 % asymmetry of the shear wind at the boundary causes swirling flow of fire at the heat loads considered.
(3) The increase of initial ambient wind from 0.21 m/s to 0.30 m/s for the cases with small asymmetry causes the increase of the entrainment at the boundary from 2.06 m/s to 2.93 m/s. But the effect to enhance the swirl is minor.
(4) The increase of the extent of the asymmetry of the shear wind at the boundary causes the earlier initiation of the swirl in proportional to the asymmetry of the wind.
(5) The increase of the total heat load leads to earlier and stronger swirls.
(6) The behavior of the swirling motion by simulations is similar to the small scale swirling flame in laboratory experiments.

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