A HORIZONTAL FIRE-WHIRL DESIGN SCENARIO FOR ENGINEERING PERFORMANCE-BASED FIRE-CODE APPLICATIONS

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ABSTRACT

Among all the design fire scenarios studied for the purpose of satisfying the current-generation engineering performance-based fire codes, one important scenario for fire hazards in building compartments that has not received much attention deals with multiple fires occurring in a single compartment. Under certain commonly-encountered conditions, such multiple fires merge into an almost continuously rotating fire whirl close to the confining walls near the floor, which is highly destructive. In the present study, experiments and numerical simulations have been carried out for a rectangular walled open-ceiling enclosure with a single corner gap and four equi-distant fires in a 2 x 2 array on the enclosure floor, simulating a room-fire scenario with horizontal fire whirls. Results of the study are discussed in conjunction with the relevant engineering performance-based fire design scenarios.

1. INTRODUCTION

The relatively recent movement in the adoption of performance-based fire codes in the developed and developing countries of the world are irreversible and unmistakable. The basic concept of such fire codes has been widely articulated [1,2]. Briefly, instead of the mandatory adherence to detailed rigid instructions regarding fire safety in building designs as in the past traditional practice, the performance-based fire code emphasizes meeting certain fire-protection performance requirements based on design scenarios involving significant fire hazards, with any justifiable engineering methodology of analysis of such hazards. To satisfy the fire-protection performance requirements may then simply involve the mitigation of such design hazard scenarios in the designed building based on the analysis. The implementation of performance-based fire code thus depends heavily on the risk assessment of a relatively large number of significant design fire scenarios [3].

Many design fire scenarios, mostly based on past fire incident statistics, have been identified and studied [4]. Despite the general complexity of such scenarios because of combustion and inherent complex geometries involved in building interiors, many of them can either be analyzed reasonably well by using simplistic models with the results justified on straight-forward physical grounds, or by available experimental data. However, other fire scenarios, particularly those related to the propagation of fire and smoke, are difficult to analyze and only very fragmented experimental data base is available. As argued recently by Yang [5], such scenarios can be dealt with effectively by the proper use of CFD (computational fluid dynamics) techniques, and therefore it is not unreasonable to presume that as time goes by, many more design fire scenarios can be studied by such CFD techniques, thus adding more to the knowledge base of significant fire scenarios for performance-based fire-code applications.

One class of severe fire hazards in compartments that can be studied by CFD techniques is related to swirling fires or fire whirls which are known to be quite destructive, especially in confined spaces. Early studies largely dealt with the free-standing vertical swirling fires based on laboratory experiments [6]. They were generated by imposing a forced rotating flow into a free-standing fire plume. More recently, it was demonstrated experimentally that a stable vertical swirling fire could be obtained by placing a fire on the floor of a four-walled open-top enclosure with four symmetrically-placed corner gaps, which provided tangential air entrainment flows into the enclosure [7], and this vertical fire whirl was subsequently simulated satisfactorily by CFD modeling [8]. This numerical study demonstrated that the vertical fire whirl was very largely a hydrodynamic phenomenon, in which combustion and radiation only played indirect and minor roles. While the vertical fire whirl is of fundamental interest in its own right, its relevance to building fires is somewhat questionable, as it is difficult to imagine that there is a realizable room-fire scenario involving something like four symmetrically-placed corner gaps. However, a different whirling fire in a similar enclosure with a single gap provides a significant design fire scenario which is far more realistic for performance-based fire-code applications. This whirling fire can be designated as a horizontal fire whirl resulted from multiple flames on the enclosure floor and the fact that the air entrainment through the single gap is choked so that most of the air entrainment comes downward from the enclosure top, thus maintaining the stability of the rotating whirling flames in the lower wall region of the enclosure. The relevance of the horizontal whirling fires to the realistic room-fire scenario rests with multiple fires occurring in a room with a fire load greatly exceeding that corresponding to the air-entraining capability of a single doorway. The main purpose of the present study is to carry out an experimental study of this horizontal whirling-fire phenomenon in a laboratory enclosure, which provides data to complement the results of a companion numerical CFD study, so the overall results can form a basis to address the horizontal-whirl design fire scenario for performance-based fire-code applications.

In the following sections, the experiments will first be described, and then followed by some details of the numerical simulations. The numerical results on the horizontal fire whirls will then be compared with that from the experiments. Finally, the implications of these results in terms of the performance-based fire-code applications will also be discussed.

2. EXPERIMENTS

The fire apparatus for the present study utilized a square enclosure 90 cm x 90 cm at its base and 180 cm in height, open at the top. This enclosure is very similar to the one used in our earlier studies [7,8], except that one wall of the enclosure was provided in its corner with a single vertical rectangular gap, 11 cm wide over the entire channel height, as schematically shown in Fig. 1. Four identical fuel pans, 7.5 cm in diameter and originally containing 70 g of n-heptane fuel, were placed symmetrically in a square array with sides parallel to the enclosure walls. The inter-pan distance D was allowed to vary between 10 cm and 70 cm from test to test. A video camera pointed downward was mounted above the enclosure opening to continuously monitor the flames during the tests. In addition, the burnout time for each fire in the array was also recorded. Such burnout time is an indication of the average burn rate of the fire. Also, on occasions the entrainment velocities of air flowing into the enclosure at different heights were also measured.

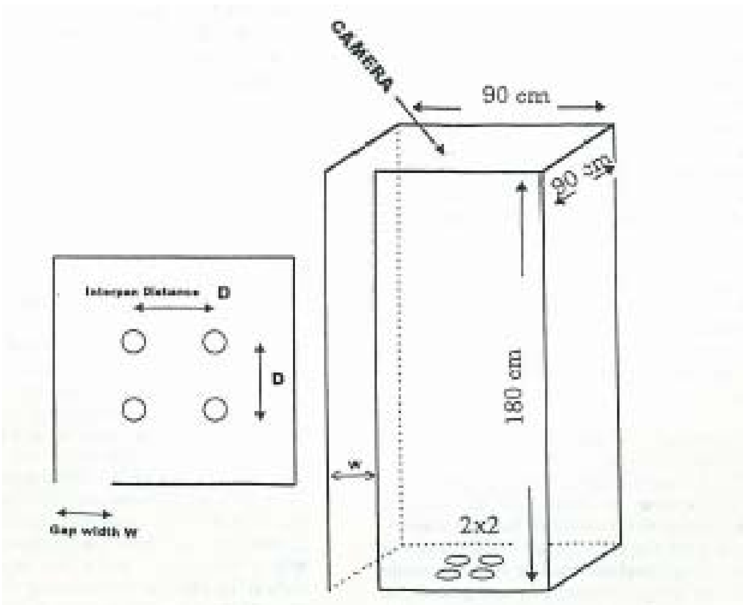


Fig. 1: Schematic of test enclosure

In all tests, the four fires in the array behaved essentially as individual free-standing fires right after the ignition, before significant air-flow entrainment through the gap was established. However soon after, the free-standing fires became affected by the entrainment flow, causing them individually to lean toward the wall and rotate around in the clockwise direction relative to the gap located in the upper left corner of the channel, when viewed from the channel top opening. This is when the inter-pan distance starts to exert its strong effect on the fire dynamics. For small D up to 30 cm, the fires quickly merged into a single fire, which leaned toward the wall and rotated in a horizontal region just over the fuel pans. Here the flame dynamics is essentially dominated by vigorous rotating forces. This is referred to in the present study as a horizontal whirl, in contrast to a vertical whirl where a single fire plume would rise straight up and swirl. The vertical whirl has been known for some time, but the horizontal whirl phenomenon is new and it does not seem to have been studied so far.

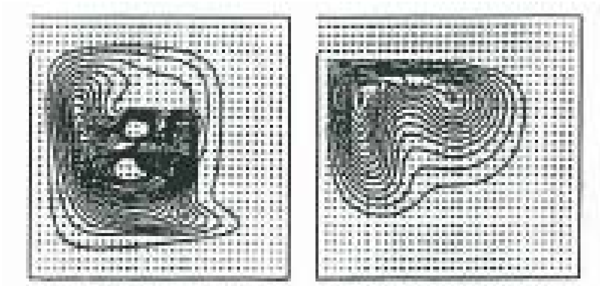
Shortly thereafter, the horizontal whirl started to stand up and evolved into a more commonly-observed vertical swirling whirl. When D increased to 40 cm to 60 cm, the same sequence occurred, but the time duration of the horizontal whirl was lengthened greatly, accompanied by a swift continuous ring flame and a horrendous noise level, signifying the high whirling velocities. Before the fires burnt out, the horizontal whirl again reverted to the vertical swirling whirl. At D = 70 cm, there was a tendency for the whirls again to be more dominated by the vertical swirling type. The left photos in Figs. 2 and 3 are those taken during the experiments, while the right-hand plots are those from the numerical simulations, which will be discussed in some detail later. Fig. 2 shows the fires for D = 20 cm. The top-left view (Fig. 2a) depicts a merged fire, whirling horizontally close to the fuel pans (the gap is at the lower right corner), while in the lower view (Fig. 2b), which was only 4 seconds later, the flame was already standing up in the form of a single vertical swirling flame. An example of a very vigorous horizontal whirl is shown in Fig. 3a for D = 60 cm, where the individual whirling flames can still be discerned.

Experiment

(a)

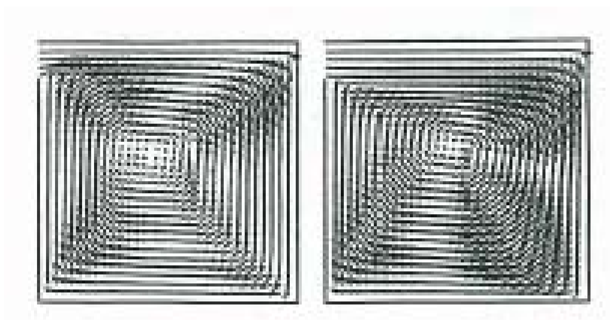
(b)

Simulation (time 76.29 sec)



(c) (e)

Isotherms



(d) (f)

Velocities

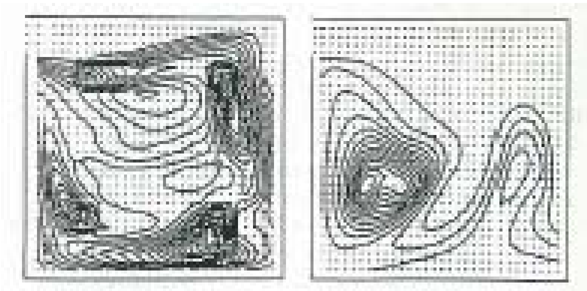
Height 15 cm Height 45 cm

Fig. 2: Comparison of experimental observation and simulated results at small D (D = 20 cm experimental, D = 15 cm simulation)

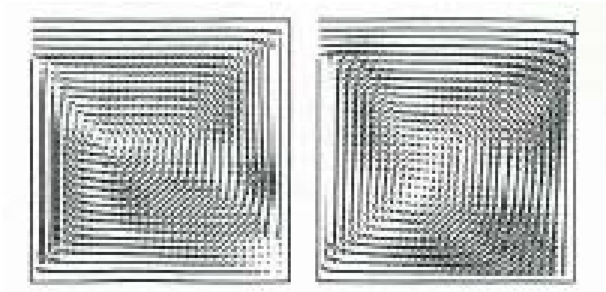
Simulation (time 48.64 sec)

Experiment

(a)



(b) (d)



(c) (e)

Velocities

Height 15 cm Height 45 cm

Fig. 3: Comparison of experimental observation and simulated results at large D (D = 60 cm experimental, D = 51 cm simulation)

While the scenarios of the flame dynamics, as described above can be observed and seem to be somewhat confusing, it is indeed difficult to interpret such observations in terms of what is really happening, since the only thing that is observable is the luminous flame. This is the very reason why it is important to carry out numerical simulations so that a more complete picture can emerge. While details of the simulated results will be described in a later section, it suffices here to indicate that the actual flow pattern in the enclosure is very much more complicated. The four fires in the array represent a very substantial heat load relative to the size of the enclosure. A very strong buoyant plume rises from the lower part of the enclosure. However, to maintain such a strong plume flow requires entrainment of air flow into the plume. Since there is only a single gap, the air flow through the gap is also strong, but still not sufficient to supply what is needed by the rising plume flow. As a result, additional air flow is drawn into the enclosure from the enclosure top opening, resulting in counter flows of hot gas (up) and cool air (down), and thus creating an unstable shear zone which is extremely unstable. This downward flow of cool air near the wall region cannot be seen in the fire test, nor can the hot-gas core inside the hot plume. Also, it is this downward flow of cool air prevents the dissipation of the horizontal whirl in the near-floor region. For small D values (10 to 30 cm), the hot plume was concentrated in the central region, and the downward flow only interacted weakly with the plume. The result is a dominant vertical swirling flow which essentially contains the flame. As D became larger (40 to 60 cm), the flames were more spread out and the downward flow directly impinged on the flames to maintain them in the lower part of the enclosure.

As mentioned previously, burnout time data for all the fires in the tests were also recorded. The use of such burnout data to delineate at least qualitatively the dynamics of multiple fires in arrays has been recently exploited by Satoh et al. [9,10]. When the burnout time of a given fire in an array is compared to that of a free-standing fire, the difference is an indication of the interaction effects of the fire with neighboring fires in the array. The burnout time data from the experiments in this study are shown in Fig. 4 as a function of the inter-pan distance D. The vertical bar indicates the maximum and minimum burnout times for the four fires in a given test, and the circle refers to the average of the burnout times of the four individual fires in the array. From Fig. 4, it is seen that for the case of D

= 10 cm, the burnout times are short (i.e. high burning rates). For this case, the fires merged very quickly after ignition and essentially behaved as a single fire. The burnout time signifies high interactions among the fires in the array. In addition, the spread between the maximum and the minimum is rather small, indicating that it is difficult to differentiate between the individual fires. As D increases, an opposite effect will become increasingly more important, and the fires in the array will be farther apart from one another, but will also get closer to the wall region to be in better contact with the entrainment flows from either the gap or the top enclosure opening. As a result, the burnout time increases with D until a maximum is reached at about D = 60 cm. Beyond that, the more favorable contacts with the cool air by the flames overcome the loss of interactions between the fires, thus resulting in a reduced burnout time or increased average burn rate. As D becomes larger, the spread between the maximum and minimum burnout times among the four fires in the array also becomes larger, since the net difference in the two opposite effects among the individual fires would be expected to increase.

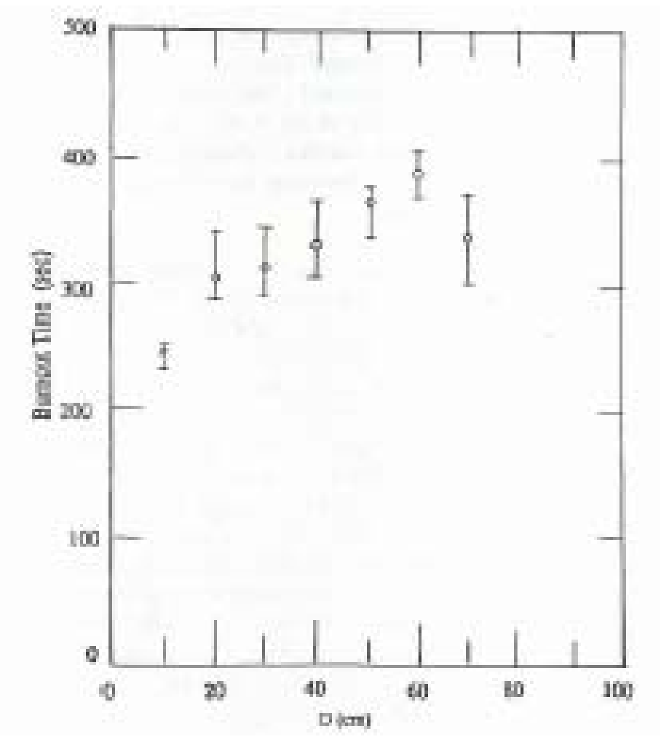


Fig. 4: Effect of inter-pan distance on burnout time

3. NUMERICAL SIMULATIONS

At the outset of the present study, it was realized that experimental observations alone would be highly deficient in determining the whirling characteristics as such observations could only discern the luminous flames. Consequently, a parallel effort was carried out to numerically simulate the velocity and temperature fields in a computational domain representing the confines of the experimental vertical enclosure. The principal purpose of this effort is to provide computed results to supplement the experimental observations. It is very important to realize that this simulation effort is not to attempt to predict the entire dynamics of the flames and flows in the channel, but only to provide additional insight to the flow features in the channel for the purpose to understand the physical mechanisms for the whirling fires. It is in this sense that the simulation model can be simplified appropriately, as long as the important physics is retained, but simple enough to obtain the needed additional information readily [5]. A similar effort was successful in our earlier study dealing with the single-fire phenomena inside a similar enclosure with four symmetrical corner gaps [8].

The simulation model utilized was the three-dimensional UNDSAFE (University of Notre Dame Smoke and Fire in Enclosures) fire field model, which was successfully verified and applied to a relatively large number of fire scenarios for room and compartment fires [11-15], several of which have also been validated with experiments. The field model accounts for full compressibility, buoyancy, turbulence, and radiation from participating gases, but does not incorporate a combustion sub-model. Combustion effects are accommodated by a prescribed non-uniform and time-dependent volumetric heat source and the heat release rates from an appropriate zone model has also been utilized [15]. On the other hand, it is known in the field of fire modeling that the most important single parameter is the strength of the fire load [16], which needs to be prescribed a priori, since at the present stage of development of the field fire modeling, such data still cannot be accurately determined, particularly for burnable materials encountered in building fire hazards. For the present study, further simplifications included the use of a constant turbulent viscosity which was taken to be 100 times the laminar viscosity and no radiation heat exchange. The prescribed turbulent viscosity is expected to be a reasonable one, as in the type of enclosures treated here, turbulence was not fully developed. While radiation effects are certainly important, it is also known that the origin of fire whirls is essentially hydrodynamic in nature, as already demonstrated in our earlier study [8].

The governing equations used in the model, which will not be shown here because of space limitations, were the usual conservative and fully-compressible forms of the continuity, momentum, and energy equations, and at any opening of the enclosure, the no-flux conditions were used for all the velocity components and the same condition was used for the temperatures, except that when the flow is coming into the channel, in which case the temperature was taken to be that in the ambient. The computational model was based on the finite-volume formulation, including upwind differencing for all the advective and convective terms. A uniform grid of 32 x 32 x 61 with 60 cells in the vertical direction representing a physical dimension of 180 cm was adopted. All four square fires, each 9 cm on a side, were of the same strength with a prescribed heat release rate in kW, which was distributed uniformly in a volume of 1215 cm^3 above each fire. A total of 11 cases were simulated, as described in Table 1, with the intent not only to provide results for comparison with the experimental observations, but also to give sufficient data so that effects of changing inter-pan distance D, gap width W, and fire strength Q could all be evaluated.

Table 1: Numerically simulated cases

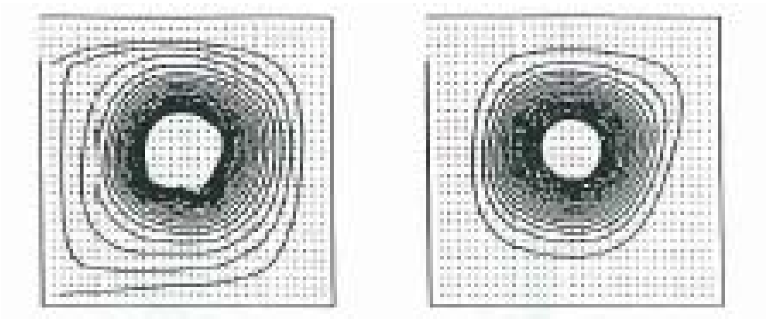
Case	**D** (cm)	**W** (cm)	**Q** (kW)
1	21	12	4 x 12
2	33	12	4 x 12
3	21	39	4 x 12
4	9	12	4 x 12
5	51	12	4 x 6
6	51	12	4 x 12
7	57	12	4 x 12
8	15	12	4 x 6
9	57	12	4 x 6
10	57	12	4 x 9
11	57	12	4 x 3

The results of Cases 8 and 9 are used to compare with that from the experiments, as also shown in Figs. 2 and 3 for two values of D. The slight differences in the D values for the comparisons are not expected to materially change the conclusions. Additional simulated flow patterns at different time instants in the same cases as in Figs. 2 and 3 are shown in Fig. 5. It is clearly seen that the numerical simulations do catch the horizontal whirling phenomena at the lower levels shown. Also of interest are the velocity and temperature fields at the two levels. For D = 15 cm, an essentially merged flame can be seen at the lower level, but degenerates into two close, but separate flames at the higher level, even though the velocity field at both levels indicate a single plume in the central region. For the case of D = 57 cm, the isotherms surrounding the fuel pans look very much like the flames in the experiments at the lower level. At the higher level, the single plume still persists, even though the flames now become weaker and coalesced into one stronger and one much weaker flames. This behavior is very similar to what was observed in the experiments in that the stronger horizontal whirl occurs essentially in the lower portion of the enclosure.

Another somewhat unexpected, but highly interesting behavior of the simulated field data is that there is a relatively large region outside the lowest isotherm in the enclosure cross sections shown in both Figs. 2 and 3, and yet there are still active velocity fields in this region. The computed data show that this low or almost ambient-temperature region is not caused entirely by the inflow through the gap, but also by the inflow at the open top of the enclosure in the near-wall region. When D is small, this down draft can reach all the way down into the lowest portion of the channel. However for high D values, the fires are placed much closer to the wall and thus, the local buoyancy prevents this deep penetration. The simulated data in Figs. 2 and 3 clearly show this behavior. Consequently, we expect to see a very complex flow structure inside the enclosure with essentially a very strong buoyant plume rising in the central region, accompanied by a somewhat smaller downward flow from the top opening of the channel, with the balance coming in from the vertical gap. To better show this behavior, the upward incremental flow in grams per second per unit height of 3 cm (one calculation cell), denoted by $\dot{m}_1$ and the corresponding downward incremental flow, $\dot{m}_2$, are plotted in Fig. 6 for the computed Case 6 in the full-burn region. It is seen that the upward incremental flow is consistently higher than the downward incremental flow, indicating that the driving force in the enclosure is still the buoyant plume, and the surprising behavior is that the differences between the two counter flows are relatively small.

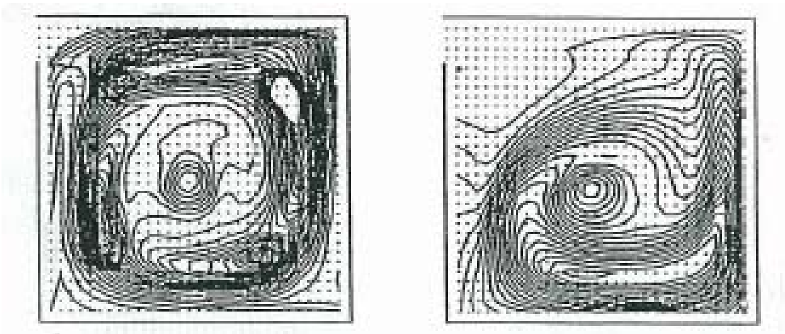
Such complex flow patterns have indeed been found in almost all the computed cases. These are shown, for examples, in Fig. 7 for Case 1 (D = 21 cm), Fig. 8 for Case 2 (D = 33 cm), and Fig. 9 for Case 7 (D = 57 cm), respectively, all at time instants where the fires are in the full-burn region. In each of these three figures, the temperature and velocity fields are shown at two mutually-perpendicular vertical sections through the center axis of the enclosure, with the left showing the section perpendicular to the wall containing the gap, and the right, the section parallel to the same wall. Fig. 7 shows the case with the small D value of 21 cm. While there is still a strong central plume, the instability wave form can be clearly seen close to the walls, suggesting the presence of recirculating cells there. As D increases to 33 cm, the fires now move outward, resulting in more complex flows in the lower part of the channel and the somewhat regular wave form seen in the 21 cm case now becomes more irregular. As the fires are moved even closer to the wall at D = 57 cm, the strong horizontal whirl is now all concentrated in the lowest part of the enclosure, and the plume is now well contained inside the enclosure. For this case, only the left vertical section is shown, since the right-section view depicts very similar irregular flow patterns.

Simulation for Case 8 Time = 57.48 sec
Isotherms



(a) Height = 15 cm (b) Height = 45 cm

Simulation for Case 9 Time = 94.37 sec
Isotherms



(c) Height = 15 cm (d) Height = 45 cm

Fig. 5: Simulated flow patterns for small and large D

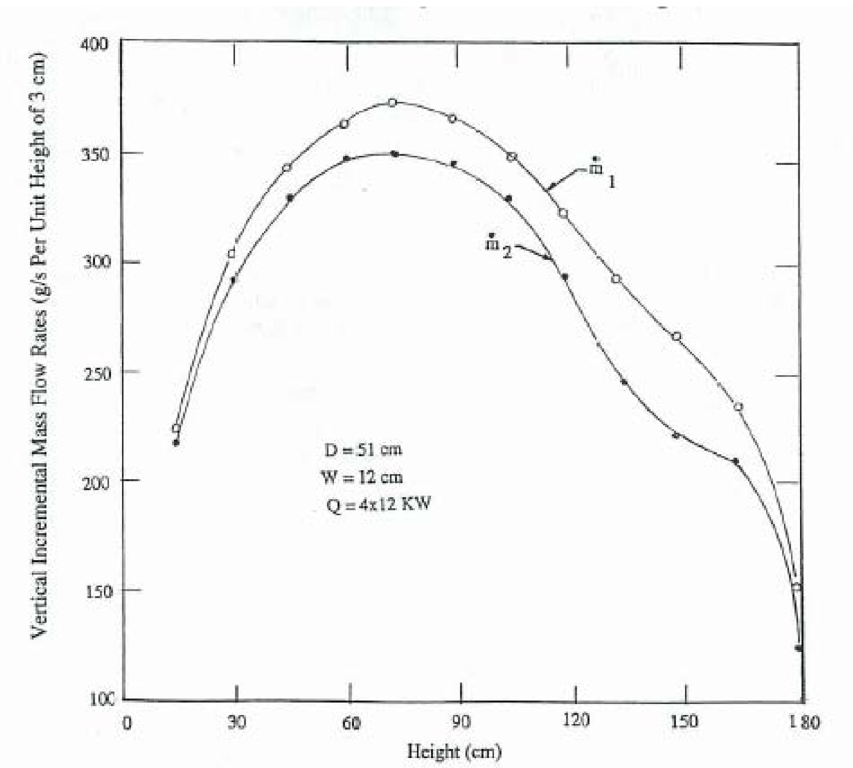
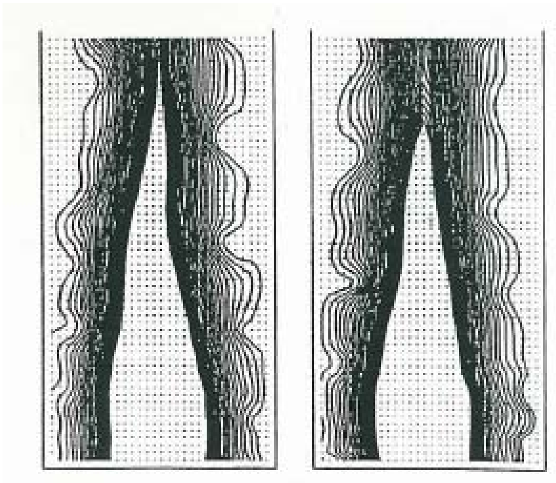


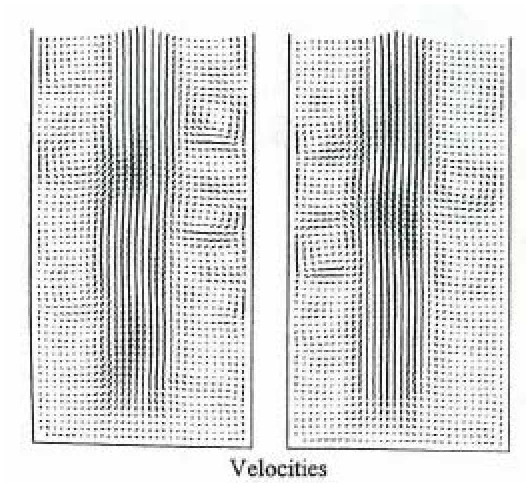
Fig. 6: Incremental mass flow rates $\dot{m}_1$ (upward flow) and $\dot{m}_2$ (downward flow) at different heights

Case 1 (D = 21 cm)



Isotherms

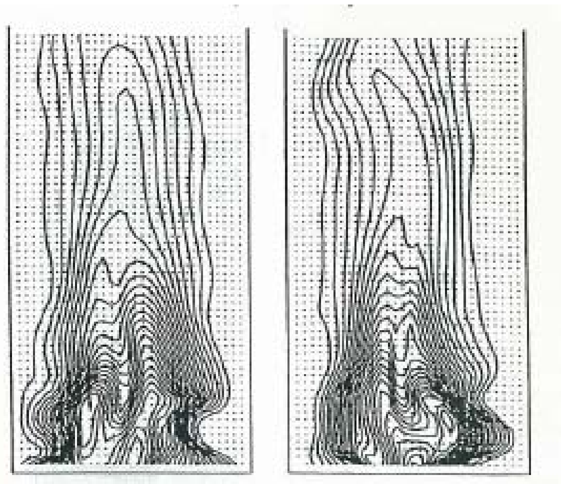
(a) (b)



(a') (b')

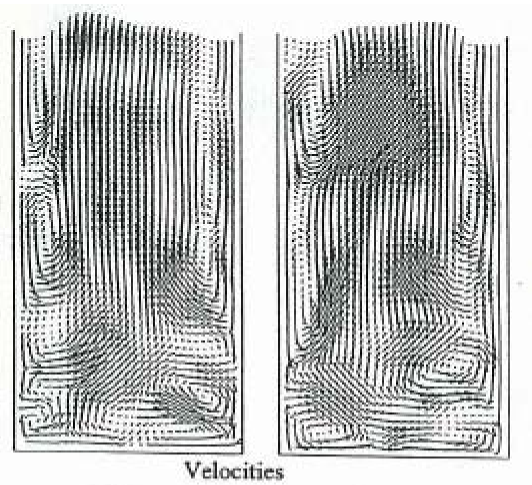
Fig. 7: Vertical section temperature and velocity fields for Case 1 (W = 12 cm, D = 33 cm and Q = 4 x 12 kW)

Case 2 (D = 33 cm)



Isotherms

(a) (b)



(a') (b')

Fig. 8: Vertical section temperature and velocity fields for Case 2 (W = 12 cm, D = 21 cm and Q = 4 x 12 kW)

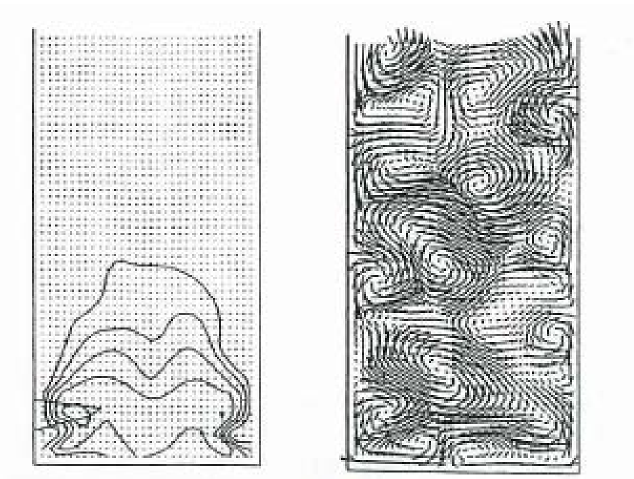


Fig. 9: Vertical section temperature and velocity fields for Case 7 (W = 12 cm, D = 57 cm and Q = 4 x 12 kW)

Comparison of the simulated results for Cases 1 and 3 provides an indication of the effect of changing gap-width W. When the gap becomes wider, the inflow through the gap also increases and that coming in from the enclosure top is correspondingly reduced. This results in simpler flow patterns in the enclosure due to less instabilities in the shear zones. The comparison also shows that at D = 39 cm, the horizontal whirl occurs only briefly soon after the ignition, which reverts to a more commonly-observed vertical swirling whirl.

Case 6 has a fire strength double that of Case 5, and their comparison from the computed results would provide an inkling on the effect of fire strength on the whirling characteristics. The results show that for the same D and W, reducing the fire strength simply reduces the driving force for the whirling phenomena. Therefore, both velocities and temperatures are also reduced, thus reducing the likelihood of sustained horizontal whirl. At least qualitatively, this effect is similar to that for increased gap width, but keeping the fire strength the same.

4. HORIZONTAL FIRE WHIRLS AS A BUILDING DESIGN FIRE SCENARIO

Most material contents in rooms like furniture are inflammable and represent potential fire loads in any building fire scenario, and are expected to be placed on the room floors. It is also not uncommon that such rooms have single doorways located at one of the walls. In addition, ducted vents close to the ceilings are common design features for ventilation and air-conditioning purposes. All these elements are very similar to those in the four-walled enclosure fire scenario described in this paper. The results of our study indicate that under similar geometrical conditions when the combined fire load due to discrete fire sources on the floor exceeds certain threshold, very destructive horizontal fire whirls stably located at the lower parts of the rooms near the walls can and may occur, thus resulting in severe fire hazards which have not been heretofore realized. One way to mitigate such hazards is to insure that the anticipated combined fire loads of the room contents do not exceed this threshold. The exact thresholds as a function of the fire loads, room-doorway geometry, and inter fire-source distances are not yet known, and more studies based on systematic field-model simulations and experimental measurements are needed to develop such relationships. The present study is simply a demonstration of a dangerous fire-hazard scenario which has not been particularly recognized in the past and which should receive more attention in the future in dealings with the application of performance-based building fire codes.

5. CONCLUDING REMARKS

The purpose of this experimental and numerical simulation study is to address a possible building design fire scenario for performance-based fire-code applications. The fire scenario studied deals with a vertical four-walled enclosure with an open top and a vertical single corner gap in one of the corners, along with four discrete symmetrically-placed fires at the floor of the enclosure. The enclosure simulates a building room and the corner gap represents a vertical opening in the room such as a doorway. The open top is related to ceiling vents, and the four floor fires would correspond to burning furniture in a room fire-hazard situation. The results of the study clearly show that the severe fire hazards in the form of horizontal fire whirls located near the lower parts of the room walls with a high destructive power. In addition, the results also show the detailed complex flow regimes and the mechanisms which are responsible for the maintenance of the horizontal fire whirls. More studies are needed to determine the quantitative relations between the fire-load threshold, beyond which the horizontal fire whirls are expected to occur, and other pertinent geometrical parameters in the room.

NOMENCLATURE

D	interfuel-pan distance, cm
$\dot{m}_1$	mass incremental flow rate of upward buoyant flow, gs^{-1}
$\dot{m}_2$	mass incremental flow rate of downward air flow, gs^{-1}
Q	prescribed fire strength in simulations, kW
W	vertical gap width, m

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