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Onsetting Internal Fire Whirls in a Room with Ceiling Vents

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Abstract

Onset of internal fire whirls in a room with ceiling vents was studied numerically with Computational Fluid Dynamics. Two different ventilation arrangements were set up by varying the door height. Two fires of 0.12 MW and 0.24 MW were considered. Swirling air flow, changes in eddy size and whirling speed near to the fire source were simulated. CFD predictions indicate that air swirled up from the lower to the upper part of the room. Onset of an internal fire whirl depends on the interaction between the indoor hot air and the outdoor cool air flows. Swirling motion results when there is ventilation provision at the sidewall.

Keywords: buildings, structures & design, fire engineering, thermal effects, numerical model

1. Introduction

Fire whirls in mass fires were observed several times including the 2007 forest fire in California, USA. As proposed by Emmons and Ying [1], flame whirling burns the fuels faster and more vigorously. There are also concerns [2] on inducing internal fire whirls in atrium buildings storing large amounts of combustibles with natural smoke venting design. For a room with natural ventilation provided at the sidewalls, flame swirling would be different from fire whirls induced in bigger buildings or in open atmosphere. Both experimental and numerical studies on flame whirling due to natural ventilation were carried out by Satoh and Yang [3,4]. A kerosene pool fire of 0.12 m diameter was burnt in a 0.7 m square shaft model of height 1.8 m. The flame height was observed to stretch up to 1.7 m upon onsetting an internal fire whirl. The flame height was several times longer than the normal value while burning the pool fire in free space. Ventilation arrangement was identified to be a key factor. The air inlet and pool fire were placed symmetrically in that particular scenario. Stability of the fire whirl and the resulting swirling frequency depend on the symmetry of ventilation outlets and changes in heat release rate. For rooms with natural ventilation provisions such as a door opening, a ceiling vent or sidewall vents, an internal fire whirl can onset under some conditions [5]. A tall flame of much higher heat release rates could be induced. It is necessary to study the hazard of such fire scenarios.

Experimental studies on internal fire whirls produced within two semi-circular glass shields were reported by Hassan *et al*. [6]. A shallow 5 cm propanol pool fire was burnt at the centreline. Two gaps appeared on both sides with the two centres of glass shields overlapped. Outside air was entrained to burn more vigorously. A maximum air speed of 0.7 to 0.9 ms^{-1} was measured by particle image velocimetry. Lower air density of 0.4 to 0.7 kgm^{-3} was found at the upper part of the pool fire. The value was much lower than 1.21 kgm^{-3} at the air inlet. Outside cold air was drawn in at 1.0 ms^{-1} due to the pressure difference caused by the density difference.

Experiments were carried out by Snegirev *et al*. [7] to investigate the conditions for onsetting buoyant whirling flame. A test room of size 2.77 m by 2.4 m with height 2.29 m was constructed of corrugated steel with a hardwood floor. A door of width 0.8 m and height 1.95 m was placed in the front wall at a distance 0.135 m away from the sidewall. A ceiling vent of size 0.8 by 0.9 m was located at the centre. A pool fire with commercial fuel gas of diameter 0.6 m and lip height 0.3 m was placed at the room centre. Room-scale whirling flames were observed. The period between onset and destruction of the whirling core was recorded. The reduction in burning time for a fixed amount of liquid fuel with fire whirls was also reported. Numerical simulations on inducing buoyant whirling flames in the experiments were carried out. Predicted results illustrated that the rotational flow was induced by buoyant turbulent diffusion flame. Effects of the opening ventilation condition were discussed. Rotating flames were predicted when the doorway was fully open. Flame swirling was not predicted when the incoming airflow was deflected towards the axis. Burning rate for flame swirling would increase from 0.029 to 0.039 $kgm^{-2}s^{-1}$, compared with that from 0.017 to 0.027 $kgm^{-2}s^{-1}$ for non-whirling flames. Swirling of fire in the compartment was described in detail. Swirling patterns at different times and correlation with heat release rates were derived. Numerical results indicated that the Swirl number is proportional to the external circulation.

An internal fire whirl [5,8] can be set up readily by burning a small fire in vertical shafts with sidewall ventilation. In a compartment with a vent, motion of the fire plume is not stable with swirling observed at the side of the compartment in many experiments. An internal fire swirl might be induced when vents along the symmetric room axis are provided. Internal fire whirls induced by a pool fire in a vertical shaft of height 15 m with different ventilation conditions were studied experimentally [9]. Ventilation was provided from the sidewall with a gap of different widths. Gasoline pool fires with diameters up to 0.46 m were put inside the shaft. Average flame height was found to be 1 to 4.5 m when whirling onset. Experimental studies indicated that air supply to the upper part of the shaft is a key factor for initiating internal fire whirls. Oxygen is required to sustain combustion to generate heat for inducing whirling motions. Therefore, flames will not whirl without adequate oxygen supply.

As the combustion involves many complicated intermediate chemicals, those reactions were not considered in this paper. The effect of the door opening and ceiling vent on the creation of internal fire whirls was studied.

Swirling of flame under natural ventilation in small compartments with ceiling vents and two different ventilation arrangements were described in this paper. Ventilation provision at the sidewall is a key factor for the onset of internal fire whirls with a ceiling vent. This point is demonstrated in this paper by numerical simulations in a normal room with ceiling vent using Computational Fluid Dynamics (CFD) [10].

2. An Extended Discussion

As observed experimentally by Snegirev *et al.* [7] in studying a room fire, hot smoke moved out through the ceiling vent and the upper part of the door opening. The flaming and the plume regions were not clear with swirling motion. The fuel burnt very vigorously after onset of whirling motion. The burning rates were from 0.029 to 0.039 $kgm^{-2}s^{-1}$ for whirling fires. Note that the burning rate was only lying from 0.017 to 0.027 $kgm^{-2}s^{-1}$ for non-whirling fires, increased by 70% for swirling fires. This process lasted for a period of 10 to 15 s until all the fuel was consumed. The swirling flame motion was observed to be determined by external air motion.

Numerical simulations were carried out by Snegirev *et al*. [7] in a room similar to their experimental studies. The CFD software Fire3D was used. Predicted CFD results were similar to their experimental observation. Transient whirling fires were predicted. The period with and without fire whirl would be reduced if the fuel supply rate increased. Increasing the burning mass rate would reduce the oscillation period further.

Note that the effect of whirling motion is not included in the turbulence models in Fire3D. The Richardson number R_i was defined to include centrifugal acceleration of the mean flow explicitly in terms of the ratio square of the centrifugal acceleration, V_θ^2 / r_c with V_θ being the angular velocity and r_c the local radius of curvature of the streamlines of the mean flow, and the corresponding turbulent quantities *k* and ε as:

$$R_i = \frac{(V_\theta^2 / r_c)^2}{\varepsilon^2 / k} \tag{1}$$

The coefficient C_μ appeared [11] in the turbulent viscosity μ_t:

$$\mu_t = C_\mu \rho k^2 / \varepsilon \tag{2}$$

Value of C_μ was modified by two adjustable constants C_μ^{min} and C_w:

$$C_\mu^* = (C_\mu - C_\mu^{min}) \exp(-C_w R_i^2) + C_\mu^{min} \tag{3}$$

The values used under whirling conditions were suggested by Snegirev *et al*. [7].

A single-step global reaction in complex fuel oxidation to give carbon dioxide, water vapor, carbon monoxide and soot was used. The generation efficiencies for soot and carbon monoxide were taken as constants in their studies. The chemical reaction rate is determined by the eddy break-up model. For vaporized kerosene, $C_{14}H_{30}$, the enthalpy of formation is -387.5 kJ mol^{-1}, the boiling temperature is 523 K, and the soot and carbon monoxide efficiencies are 0.04 and 0.007 respectively. The Monte Carlo statistical method was used to model thermal radiation transfer in a gas-soot mixture.

Numerical experiments on varying the swirl number S under whirling conditions were carried out by Snegirev *et al*. [7] in a room under free boundary conditions. Two fire conditions with different fuel loss rate $\dot{m}_{fuel}$ and heat release rate $\dot{Q}$ were used:

$$\begin{cases} \dot{m}_{fuel} = 0.02 \text{ kgm}^{-2}\text{s}^{-1} \\ \dot{Q} = 258 \text{ kW} \end{cases} \tag{4}$$

and

$$\begin{cases} \dot{m}_{fuel} = 0.04 \text{ kgm}^{-2}\text{s}^{-1} \\ \dot{Q} = 516 \text{ kW} \end{cases} \tag{5}$$

Results for non-whirling conditions were compared with those for whirling condition. Maximum values of V_θ were 0, 0.2 and 0.6 ms^{-1} respectively under three major conditions. However, the simulated flame height did not increase with the whirling speed. The results would be improved by selecting appropriate turbulence models with swirling. It was concluded that when the swirl number S exceeded 0.6, the flame height was shortened. This phenomenon was also observed in jet swirling.

In simulating the whirling condition inside the room with air flowing in and out freely, a hot air layer was predicted. Hot air was flowing out through the ceiling vent and the doorway. Fire whirls were induced and passed through the ceiling vent. Unsteady whirling motion with high temperature core was predicted and agreed with experimental observations. The maximum value of vorticity component along the vertical axis ω_z depends on the supply rate of different burning fuel. Faster burning rate and larger burning mass would give higher temperature and larger value of ω_z.

The predicted average periods between the formations of straight whirling flame were 17 s for $\dot{m}_{fuel}$ of 0.02 $kgm^{-2}s^{-1}$ and 12 s for $\dot{m}_{fuel}$ of 0.04 $kgm^{-2}s^{-1}$. Results are similar to the average period observed in their experiments with values from 10 to 15 s. Flame length and time-average mass burning rate in whirling fires were found to be greater than those in non-whirling ones.

3. Numerical Experiments

To avoid having repeated cycles of onset and dissipation of fire whirls by Snegirev *et al*. [7], a modified room was used. This design would supply sufficient air to the fire room. A room of length 3.6 m, width 2.4 m and height 2.4 m as in Fig. 1 was considered. The ceiling vent dimensions were changed from 0.8 m by 0.9 m to 1.4 m by 1.0 m. A doorway of width 0.8 m was made on the rear wall. Two different heights of 1.0 m and 2.0 m were used to supply adequate air. Effects of ventilation on the whirling speed and whirling paths were observed. The heat release rate was kept constant in the numerical simulations.

Modifying the room as in above way would give circular air motion. Since there was an additional opening at the sidewall, cool air drawn would give circular motion. As reported by Snegirev *et al.* [7], for rooms without a ceiling vent with the fire located at a corner, only small-scale whirls would be created by a small fire with low heat release rate. This point can easily be studied by investigating the scenarios leading to onset of fire whirl by CFD. The study is not intended to compare the CFD results with those experiments by Snegirev *et al.* [7], but to extend their experiments. The heat release rates in the two scenarios in this paper were much larger than those used by Snegirev *et al.* [7].

Two ventilation conditions V1 and V2 were provided by another door at the rear wall as in Fig. 1:

- V1: Door of height 2 m
- V2: Door of height 1 m

Two pool fires F1 and F2 of the same area of 0.5 m by 0.5 m but different heat release rates were used:

- F1: 0.24 MW and normal flame height 1.6 m in outside air
- F2: 0.12 MW and normal flame height 0.8 m in outside air

Fire whirls can be formed under different ventilation areas, different heat release rates and different room sizes. Numerical experiments were carried out under these two ventilation conditions. The numerical input data used in this study was based on the experimental studies reported by Snegirev *et al.* [7]. The CFD software PHOENICS v3.5 [12] was used with a Pentium personal computer. The software had been demonstrated years ago to be suitable for simulating building fires [10]. A reasonably fine grid size with a total number of computing cells 216,000 was used. There are 60 cells along the x, y and z directions as shown in Fig. 1. The coarse grid size is 3.6 m / 60 or 0.06 m, satisfying the convergence criterion worked out on thermal plume [13]. The time interval was 10 s. The total computing time for 300 s (30 time steps, 10 s each) was 20 hours to give converged results.

Three boundary conditions were used in this study.

- Boundary conditions of wall surface:

The wall was considered to be adiabatic with no slip. The logarithm law was used near the wall surface. Velocity on the wall is zero for the momentum equation. Wall function was used for the enthalpy equation but not for solving the ε equation. The diffusion coefficient of *k* was taken to be that of the momentum equation.

- Inlet boundary conditions:

  Flow variables set to be input conditions with turbulence intensity varying from 0.02 to 0.05%.

- Free boundary conditions:

  At the free boundary, the pressure is taken as the atmospheric value. The normal component of velocity is zero and fluid can flow in or out, depending on the estimated pressure differences.

  For inflow and outflow zones, a zero variable gradient was set along the vertical boundary plane. Pressure was taken to be the atmospheric value at those positions. The variables *k*, ε and T were taken as inflow values.

The above boundary conditions and grid numbers were selected based on CFD simulations for similar problems. These examples had been justified in the past by different experimental studies [10]. Only the effects of the door opening, the ceiling vent and the heat release rate are focused on in this paper. Intermediate chemical reactions in burning the fire were not taken into account. Heat release rate was taken to be the most important input factor affecting the onset of fire whirls.

Selected temperature contours are plotted in Fig. 2. Results for the smaller fire F2 and ventilation condition V1 with the taller door are shown in Fig. 2a at the vertical plane for x at 1.8 m and 120 s. The temperature distribution was observed to be stable at 120 s. The temperature distributions for the bigger fire F1 and the same vent V1 at the same plane at 120 s and 240 s are shown in Figs. 2b and 2c.

Velocity vectors at different heights y at 0.2 m, 0.6 m, 1.0 m, 1.6 m, 2.2 m and 2.8 m for the bigger fire F1 with larger vent V1 at 5 s, 60 s, 120 s, 180 s and 240 s are plotted in Figs. 3a to 3e.

4. Ventilation V1 with Big Fire

The following are observed from the CFD predictions:

- No whirling motion was formed before 5 s as in Fig. 3a. Only upward air flow due to buoyancy was observed.

- Upward flow with whirling was formed at 5 s with the direction of air flow dependent on the location of the side vent. Air swirled up from near the flame bottom through the ceiling vent. Air speed for swirling along the tangential direction in the compartment is less than 0.5 ms^{-1}. At 5 s, the airflow at the bottom side rotated half a circle in the compartment with a maximum tangential speed less than 0.3 ms^{-1}.

- Stronger whirling flow near the flame bottom was formed at 60 s as in Fig. 3b. The maximum tangential velocity in the rotational direction is up to 1.0 ms^{-1}. The upward velocity at the compartment ceiling due to buoyancy is about 6.0 ms^{-1}. This is the maximum predicted speed up to 300 s when the flow was steady. The maximum predicted speed was found at the ceiling vent.

- Whirling motion was not induced about the flame axis at 120 s as shown in Fig. 3c. Near the top of the compartment, the swirling motion centre moved more towards one side of the compartment with the whirling size decreased. The overall vertical upward speed increased as shown in Fig. 3c due to the increase in buoyancy. Predicted results are different from those at 60 s shown in Fig. 3b. The tangential whirling speed is smaller at the top than at the bottom of the compartment as shown in Fig. 3c.

- As shown from the velocity vectors at 180 s in Fig. 3d, temperature in the compartment distributed more uniformly. The tangential speed for rotation increased, especially at the bottom of the compartment. This is because of the higher flame temperature near the central bottom area and lowest incoming air temperature. Therefore, the maximum speed for whirling was observed there.

- Both the velocity and temperature became stable at 240 s as seen from Fig. 3e. Swirling flow at the bottom of the compartment was observed.

Selected patterns on predicted streamlines at 5 s, 60 s, 120 s, 180 s and 240 s are shown in Fig. 4. Swirling motion depends on the air temperature at the lower part of the compartment. For example, the bigger fire F1 would give high air temperature. The air in the upper part of the compartment would move up due to the temperature difference between the hot air moving at the centre and the cool air at the ceiling vent. The pattern remained the same up to 240 s, demonstrating strong flow.

5. Comparison with Small Fire

Streamlines with the smaller fire F2 with ventilation V1 at 120 s and 240 s are shown in Fig. 5. Air circulated two times before flowing out of the compartment at 120 s. Air temperature was not stable. This is because air temperature near the ceiling vent was lower than that for the bigger fire F1. Therefore, swirling motion was not induced. Note that air swirled many times before moving up to the ceiling for the bigger fire F1 as in Fig. 4.

The three-dimensional streamline pattern at 240 s is shown in Fig. 5b. Air at the upper compartment did not move out at the vent centre after the second swirl. The swirling radius decreased.

The whirling tangential speeds for both big and small fires F1 and F2 under ventilation condition V1 are plotted in Fig. 6a. It is observed that the tangential speeds increased with time. Comparing the scenarios F1 and F2, the difference in the tangential speed also increased with time. The rotating tangential speed of the smaller fire is about 0.5 ms^{-1} at 180 s, lower than 1.2 ms^{-1} for the bigger fire.

Variation of the tangential speed with height y in the compartment at distance from the fire centre of 0.2 m at 300 s is shown in Fig. 6. When the height in the compartment is higher than 1.8 m, the tangential speed changes slightly. In fact, the tangential speed changed slightly with height under the smaller fire. For the smaller fire F2, tangential speed only decreased slightly from 0.6 ms^{-1} at y of 0.25 m to 0.4 ms^{-1} at y of 2.0 m. The tangential speed for the bigger fire F1 changed significantly from 1.9 ms^{-1} at y of 0.2 ms^{-1} to 1.0 ms^{-1} at y of 2.0 m.

6. Ventilation Condition

Variation of tangential speed with time at y of 0.2 m for the two ventilation conditions V1 and V2 is shown in Fig. 7a. There is a slight difference in the tangential speed of the whirling at the bottom for the two ventilation conditions.

It is observed from Fig. 7b that when the height of the vent increased by two times, the compartment temperature at 300 s was stable. The maximum tangential speed of the whirling changed slightly. Despite the increase in the vent height, the tangential velocity decreased by 20 % or 30 % with the height. In other words, the height change of the rear vent has no effect on the extent of decrease of the tangential velocity with height. The slope of the tangential velocity with height remained the same when the height of the rear vent increased two times. Variation of the tangential velocity with height for these two ventilation conditions remain parallel as shown in Fig. 7b.

7. Effect of Flame Height

For the selected room with the same size as that used by Snegirev *et al*. [7], another door was constructed at the rear wall. Two different ventilation conditions V1 and V2 were set up with different heights of door of 1 m and 2 m. The door width and also the size of the ceiling opening were the same as those reported [7].

With the heat source at the centre of the room, swirling was formed with cool air drawing in under natural ventilation. The flow velocity depends on the heat release rate, flame bottom temperature and the outside air temperature. As the heat inside the room accumulated, the rotational speed also increased. Finally, when a steady state thermal balance between the heat inside the room and the cool air entering from outside was reached, a steady swirling motion due to the heat source was formed. Numerical simulations indicated that there were no particular patterns for the flow.

With the increase in heat release rate and fire height, the rotational speed along the tangential direction of the whirling at the bottom would increase. The extent of increase changes with time. When temperature becomes stable in the compartment (after $t = 240$ s in this paper), the maximum tangential velocity of the whirling is observed. The speed would no longer change with time.

When temperature and velocity become stable, with the increase in heat release rate and fire height, the tangential velocity of the whirling would increase significantly. In the simulation for the smaller fire F2 (0.12 MW and 0.8 m height), the maximum tangential velocity decreased from 0.6 ms^{-1} at 0.2 m to 0.3 ms^{-1} at 2.4 m. For the bigger fire F1 (0.24 MW and 1.6 m height), the maximum tangential velocity decreased from 1.9 ms^{-1} at 0.2 m to 0.93 ms^{-1} at 2.4 m. The tangential velocity decreased by 50% with height. When the heat release rate and height doubled, the maximum tangential velocity changed from 0.6 ms^{-1} to 1.9 ms^{-1} at the height of 0.2 m; and changed from 0.3 ms^{-1} to 0.93 ms^{-1} at 2.4 m. The maximum tangential velocity of the rotation in the compartment increased three times.

When the fire height is lower than 0.8 m at the bottom of the compartment, the air whirling would move out of the ceiling vent after circulating twice. When the fire height is 1.6 m, the air at the same location would move out of the ceiling vent after circulating less than 1.5 times.

8. Conclusions

Numerical experiments on the onset of internal fire whirls were carried out based on some earlier studies by Snegirev *et al.* [7]. The following conclusions can be drawn from the above CFD simulations:

- The height of the rear vent has no effect on the swirling flow.
- Upon the onset of fire whirl, air temperature became stable in the compartment.
- Increasing the rear door vent height has no effect on the variation of rotational speed of the whirling with height. Swirling air flow is induced at the bottom of the compartment. Air flow at the upper part of the compartment is mainly upward moving through the ceiling vent.

These observations are useful to assess fire hazard for a room fire with different ventilation provisions. The possibility of fire whirls and the associated hazards should be further studied in compartments or spaces with a ceiling vent or side openings, particularly for bigger fires with higher heat release rates.

9. Additional Comments

The paper was published as a journal paper [14]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [15-43] in the past 10 years. Projects by the authors funded by Research Grants Council of Hong Kong are:

- Onsetting of internal fire whirls in buildings and associated safety provisions.
- A study of internal fire whirl in vertical shafts with open roofs.
- A study on electric and magnetic effects associated with an internal fire whirl in a vertical shaft.
- A study of the hazardous consequences of fire whirls generated in a room.

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JAFS_GaoIFW2010B-R2
A442UL22-1e

Record:
A442UL22-1a (opened 23 June 2023, open from JAFS_GaoIFW2010B-R2.doc)
A442UL22-1b (opened 5 July 2023)
A442UL22-1c (opened 5 July 2023)
A442UL22-1d (opened 5 July 2023)
A442UL22-1e (opened 6 July 2023)

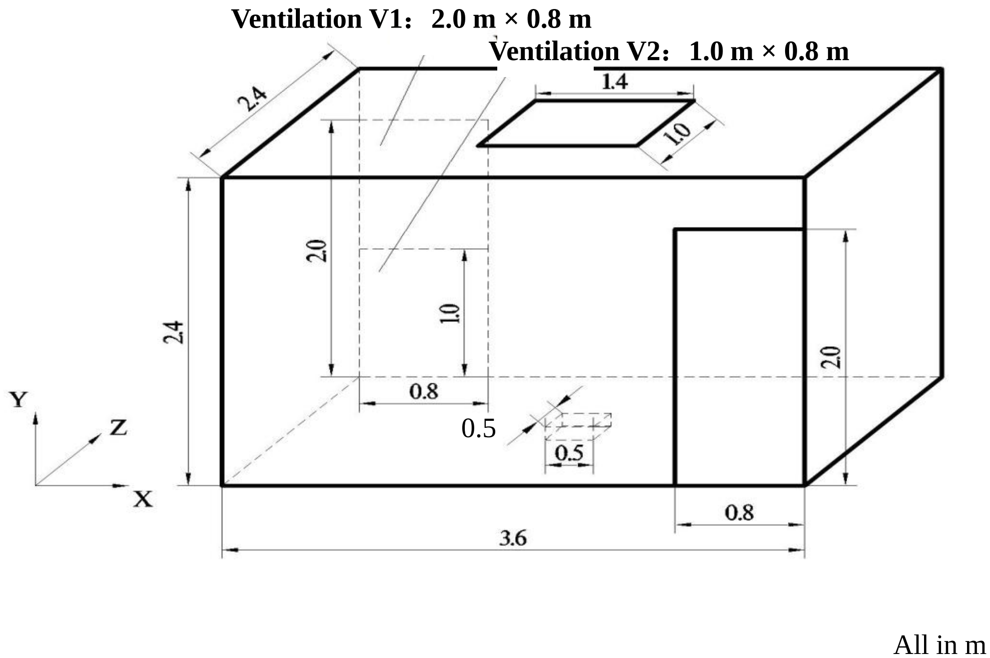
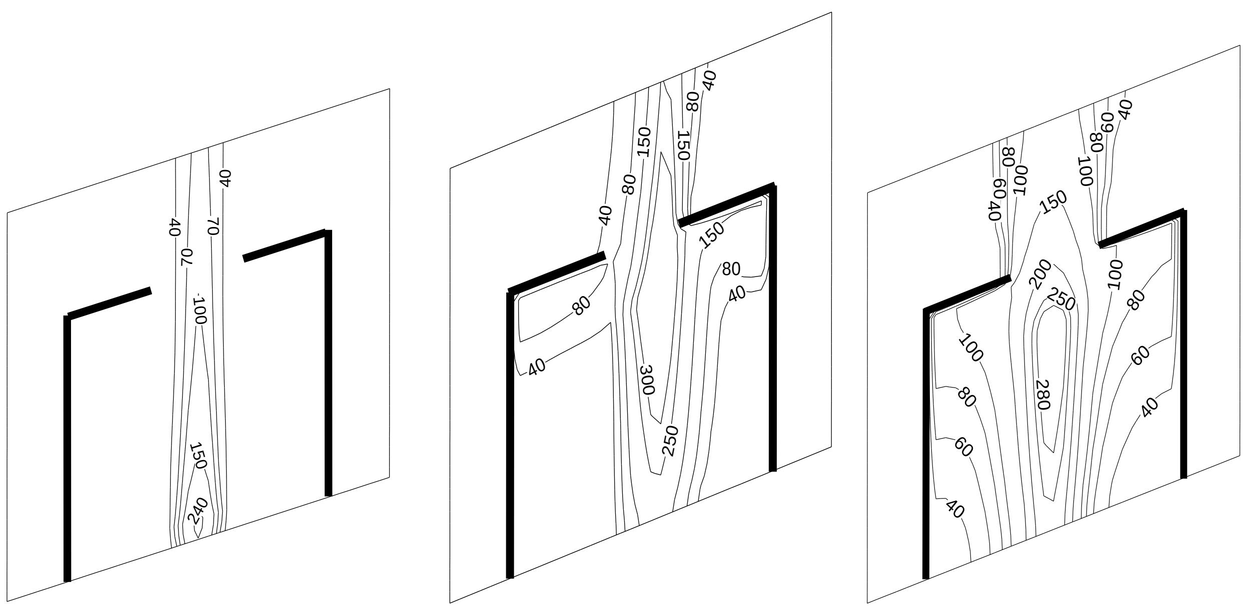


Fig. 1: The compartment



(a)120 s for F2

(b) 120 s for F1

(c) 240 s for F1

Fig. 2: Temperature contours at a vertical plane (x = 1.8 m) across the fire for ventilation V1

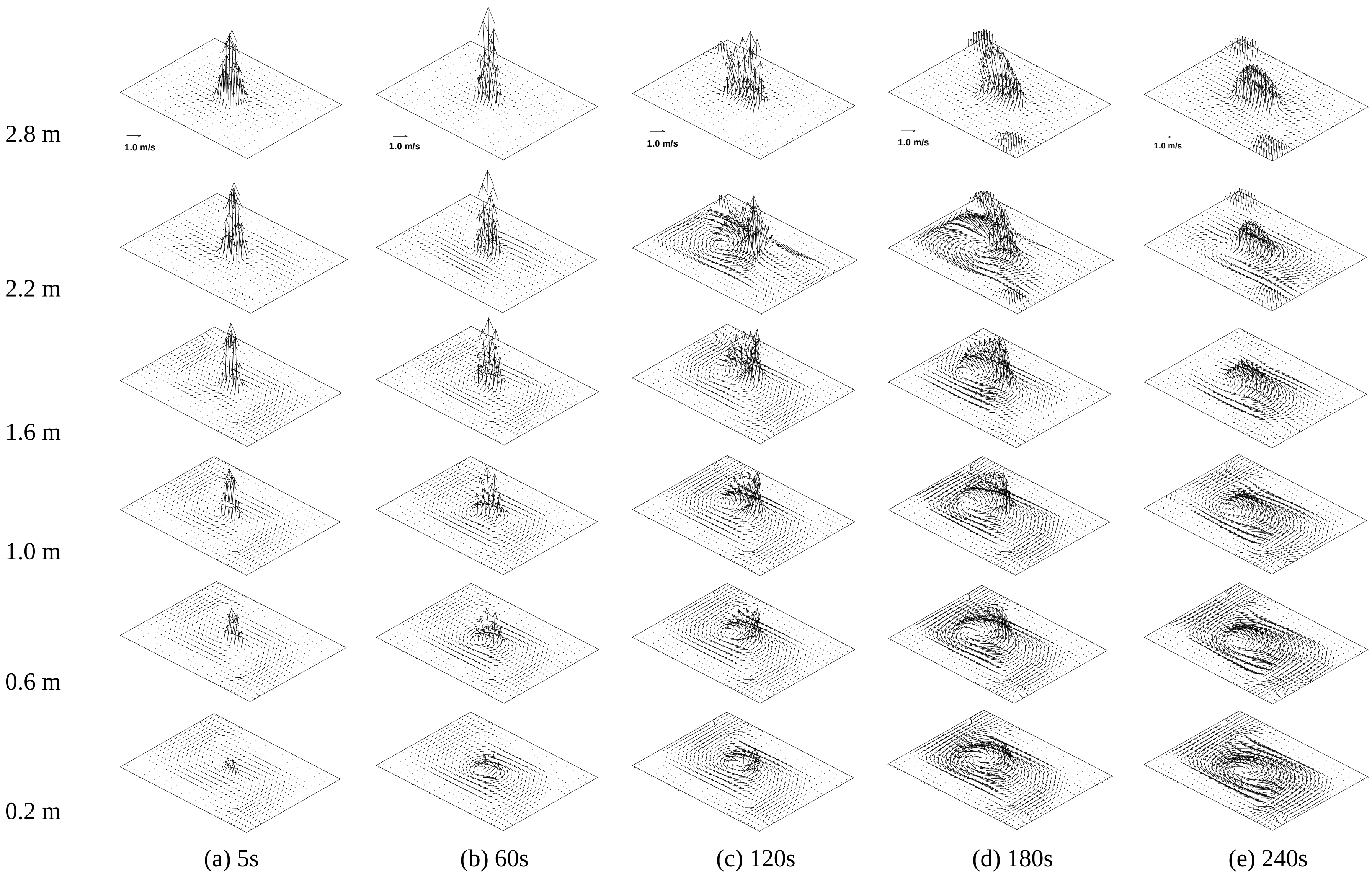
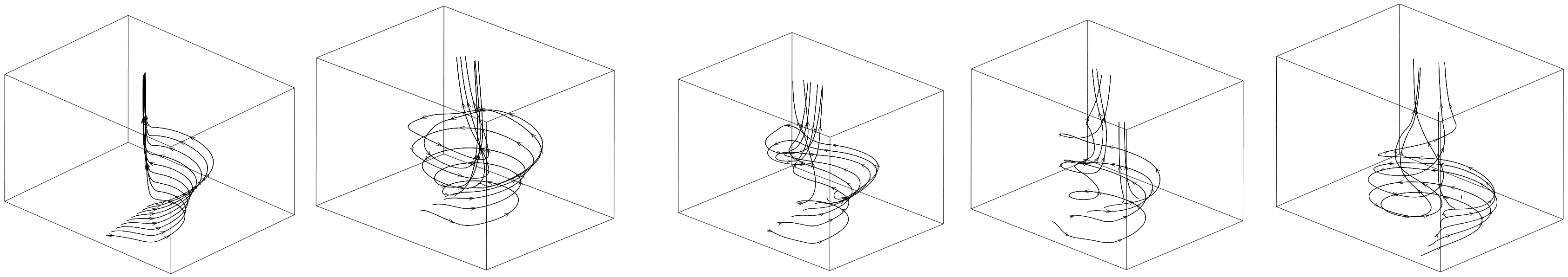
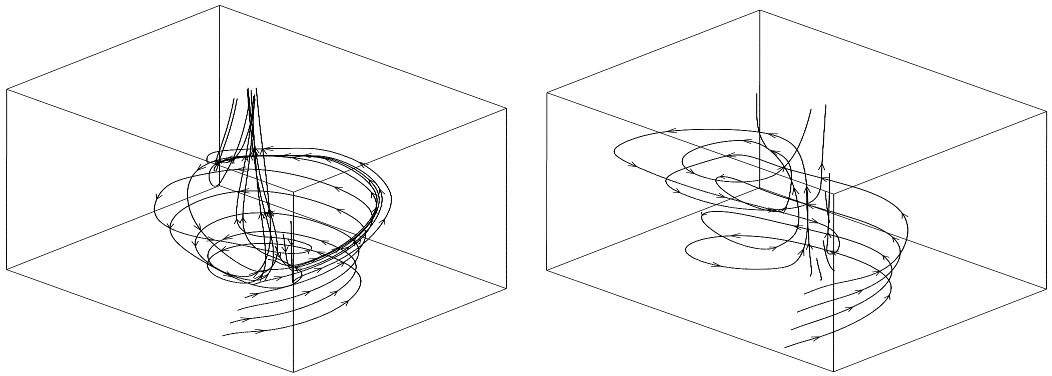


Fig. 3: Velocity vectors for F1 and V1



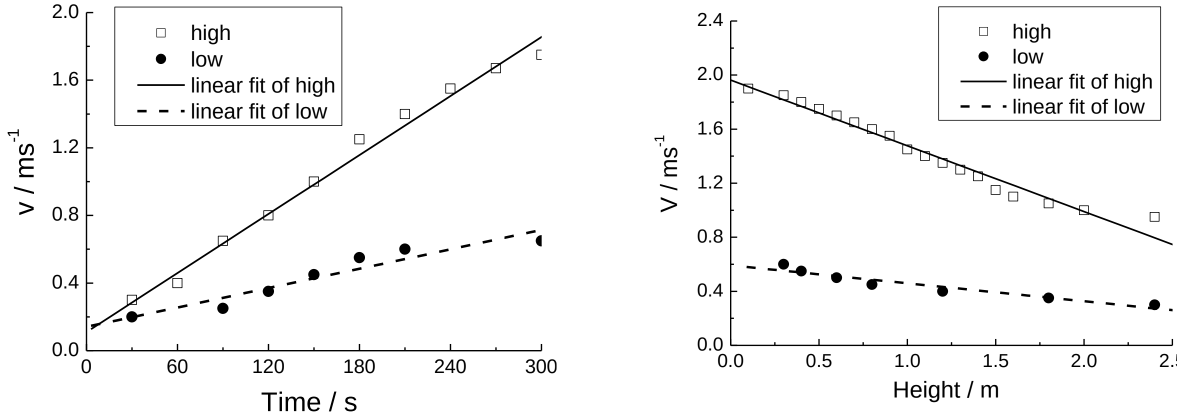
(a) 5s (b) 60 s (c) 120 s (d) 180 s (e) 240 s

Fig. 4: Streamlines for F1 and V1



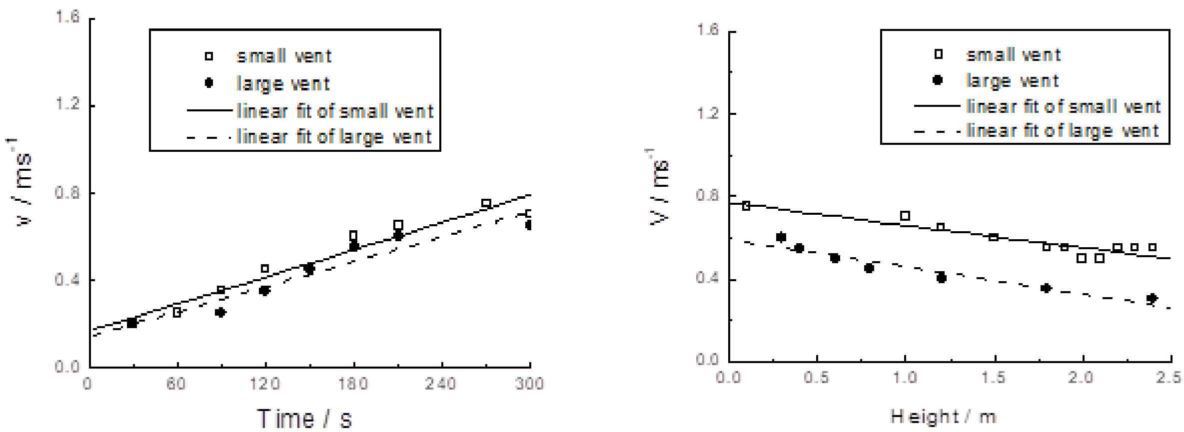
(a) 120 s (b) 240 s

Fig. 5: Streamlines for F2 and V1



(a) Variation with time (b) Variation with height

Fig. 6: Tangential speed for V1



(a) Variation with time (b) Variation with height

Fig. 7: Tangential air speed for F2