# Fire Whirls and Building Aerodynamics

Robert N. Meroney

*Civil Engineering, Colorado State University, Fort Collins, CO, USA*

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ABSTRACT: Numerical modeling of the behavior of fire and smoke within proposed building atria have revealed the possible presence of violent fire whirls or fire tornadoes induced by an inadvertent combination of ventilation and exhaust openings. Such fire vortexes can accelerate combustion up to ten times that seen during conventional fires, rapidly move fire and debris across available evacuation routes, and produce fire and smoke risks beyond those traditionally considered by existing fire codes. Past laboratory studies of fire whirls are used to validate the ability of a numerical code to reproduce fire whirl dynamics. Subsequently, the cfd code is used to evaluate the strength and character of fire whirls produced by a combination of fire, mechanical ventilation or natural ventilation in a generic atrium.

*KEYWORDS: Fire and smoke, HVAC, building atriums, cfd, physical modeling*

## 1 INTRODUCTION

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

During the Great Chicago Fire of October 1871, in which 300 died, burning planks were lifted by fire whirlwinds and dropped as far as 600 m (3/8 mile) ahead of the main fire. Musham (1941) attributes a large part of the destruction of the city to burning material carried by the fire whirlwinds [1]. On the same day in 1871 an even greater fire destroyed Peshtigo, Wisconsin killing up to 2,500 people and scorching more than 1.5 million acres (2,400 square miles). Eyewitnesses reported firestorms in which the wind drove fireballs into town and lifted a house off its foundations. Some estimates suggest the resulting fire tornado was equivalent to an F5 Fujita scale tornado, the strongest possible (Gess and Lutz, 2002) [2].

Hissong (1926) described a fire whirl which formed near burning petroleum tanks at San Luis Obispo, CA, that lifted a cottage and carried it 45 m (150 ft), then dropped it, and killed the owner and his son occupying the building [3]. Graham (1952, 1957) describes some 28-fire whirlwinds seen in the Pacific Northwest during forest fires between 1950 and 1953. He reports fire tornadoes, which twisted the trunk on a Douglas-fir tree, which was a breast height 102 cm (40 in) diameter, and broke it off about 20 feet above the ground [4, 5]. In other cases 1 m diameter by 10 m long logs were carried significant distances.

More recently, CFD calculations performed by the author of atria fires inside a proposed building produced very energetic fire whirls 5 to 20 m diameter and 40 m tall which roared from one end of the 45 m open space to the other and back in less than a minute (Meroney *et al.*, 2002) [6]. This paper will examine past observations of urban and forest fire whirls, fire whirl dynamics, the simulation of fire whirls in the laboratory, and consider CFD simulations of laboratory and building scale fire whirls.

## 2 FIRE WHIRL DYNAMICS

The formation of fire whirls requires a source of ambient vorticity, a concentrating mechanism, and a favorable environment for fire whirl stability and growth (augmentation physics). Emmons and Ying (1966) wrote the defining paper about fire whirl behavior [7]. They identified the primary mechanisms, performed laboratory scale experiments in a laboratory apparatus 3 m high which used a 2.25 m diameter rotating screen mesh to introduce angular momentum and a pan of burning fuel (acetone) to provide a source of buoyancy. They also proposed a fire plume model based on a one-dimensional entrainment theory, but it failed to reproduce the growth of the fire plume with height.

Later Mayle (1970) continued their research by performing measurements of velocity and pressure within the fire whirl [8]. He found that the behavior of the plume was governed by dimensionless plume Froude, Rossby, second Damkohler Mixing Coefficient and Reaction Rate numbers. For plumes with a Rossby number less than one the plume is found to have a rapid rate of plume expansion with height. This phenomenon is sometimes called “vortex breakdown”, and it is a “hydraulic jump” like phenomena caused by the movement of surface waves up the surface of the fire plume that are greater than the speed of the fluid velocity. Unfortunately, even improved entrainment rate type models do not predict these phenomena very well.

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

## 3 LABORATORY FIRE WHIRLS

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

Emmons and Ying (1966) used the rotating-screen apparatus described above to systematically evaluate the effects of angular rotation (Rossby number) and plume buoyancy (Froude number) on fire whirl dynamics [7]. They reported that turbulent mixing coefficient decreases with increasing angular momentum, and increases with elevation above the ground. Later Chigier et al. (1970) reproduced their apparatus but used a turbulent jet diffusion flame [10]. Since these early experiments several investigators have re-created similar laboratory apparatus while evaluating the character of fire whirls (Martin *et al*., 1976; Muraszew *et al*., 1979) [11, 12]

Other investigators have reproduced fire tornadoes as they develop in simulated outdoor environments. Lee and Otto (1974) examined how city fires might develop by simulating in a wind tunnel a simple urban street arrangement [13]. Their results revealed that strong street level vortices could develop due to building fire interaction. Emori and Saito (1982) simulated a fire whirl formed during a forest fire burning over a mountain ridge top that injured several Japanese fire fighters. [14] Soma and Saito (1991) recreated fire tornadoes that occurred during the Kanto earthquake in Tokyo (1923), the Hamburg firestorms during WW II (1943), and oil-tanker fires in Hokkaido bay, Japan (1965) [15].

More recently Satoh and Yang (1996, 1997) produced laboratory scale fire whirls by adjusting symmetrical vertical gaps separating the square vertical bounding walls surrounding a central fire pan [16, 17]. They examined the effect of gap size, wall height, fuel size, and heat load on the fire whirl. They determined that there is a critical gap size, which is not so large or small that it inhibits the entrainment of air needed to sustain the fire. Stable whirls were generally associated with flame heights smaller than the wall height of the square enclosure. Flame temperatures were primarily affected by the magnitude of the volumetric heat source.

Large scale simulations have been produced for video and movie effects by combining shrouded helicopter blades and ancillary fans to produce vortices 12 m (40 ft) high and core diameters of 30 cm (1 ft) by Reel Efx (1995) for car commercials and adventure movies (Volvo-850 commercial (1995) and Twister) [18].

## 4 SIMULATING FIRE WHIRLS BY CFD

Murgai and Emmons (1960) and Emmons and Ying (1966) describe integral plume models, which are calibrated with experimental data [19, 7]. Satoh and Yang (1997) used the UNDSAFE code with associated 3d, compressible, buoyant, and constant turbulent viscosity specifications [17]. Ten cases were considered which included validation exercises and parameter sensitivity studies.

Battaglia et al. (2000) simulated the laboratory experiments of Emmons and Ying (1966), Chigier et al. (1970), and Satoh and Yang(1997), which included cases for fixed circulation and variable fire strength, fixed fire strength and variable circulation, and jointly varied fire strength and circulation [20]. The numerical code used was the NIST shareware FDS (Fire Dynamics Simulator) which includes 3d, compressible, buoyant and LES turbulent models (Baum et al., 1996) [21].

### 4.1 *Fire Behavior in Building Atria*

Conventional fire and smoke control systems use pressure differences across small openings and cracks in physical barriers as a means to restrict smoke propagation from one space to another and water-spray curtains to diminish or eliminate fire and smoke. Most fire codes depend upon the National Fire Protection Association (NFPA) guidebooks [22, 23]. In turn these propose the use of simple zone models that solve conservation of mass and energy in a control-volume sense for each zone. One weakness of zone modeling is that momentum conservation is only captured through use of loss coefficient at openings. The strength of zone models is that they are very fast compared with computational fluid mechanics (CFD) based models.

Atria, covered shopping malls, convention centers, airport terminals, sport arenas, and warehouses are examples of large spaces for which these conventional zone-model approaches are not always effective and in which large fires may produce strong fire whirls [4]. CFD, sometimes called "field-modeling" in the fire community to distinguish it form zone-modeling, has an unparalleled potential as an engineering estimator of fire consequence in atria since it permits specification of momentum conservation as well as much finer spatial and temporal resolution of the fire physics [24] . Nonetheless, as discussed by Yang [25] , none of these modeling efforts are trivial, even though many of the effects individually can be modeled at the present time, modeling of turbulent fire combustion is still problematic. Despite the claims of some CFD package vendors, there does not exist a general-purpose field model for all types of fires.

Meroney et al. [6] compared the behavior of a developing fire in a proposed building atria using a conventional NIST ASMET zone model, the FDS model [21] and the commercial finite volume cfd code FLUENT [26]. The zone model was unable to identify critical features of the fire and smoke progression, but the cfd codes were able to identify and subsequently suggest mitigation strategies to promote safe building evacuation. Subsequent cfd calculations for another building atrium case by the author identified the presence of violent fire whirls within the atrium.

### 4.2 *Numerical Modeling of Laboratory Fire Whirls*

Laboratory tests from Byram and Martin [9] and Satoh and Yang [17] were reproduced with FLUENT 6.0 to study the dominant features of fire whirl kinematics and to verify the codes suitability for fire whirl research. The Byram and Martin laboratory configuration consists of a cylindrical shell 66 cm diameter and 183 cm high over which is mounted a truncated conical shell 152 cm high that tapers from a base of 66 cm diameter to a top of 33 cm diameter. Air enters the chamber through two 0.6 cm tangential slits located on opposite sides of the cylindrical section, producing rotation of the air inside. The heat source is a 11.4 cm diameter pool of burning alcohol located at the cylinder base at the central axis which releases about 11,600 watts of energy.

The numerical domain was configured with similar dimensions, included 75,604 hexagonal cells, and imposed a 11.6 kW heat source at the chamber base. Figure 1a displays the rising flame produced within the cylindrical enclosure five seconds after ignition as predicted by FLUENT. "As the heated air rises and cool air flows tangentially into the chamber, the flame tilts in the form of a curved arm which slowly rotates around the pan" [9] as shown after 9 seconds in Figure 1b. Eventually the flame curls back on itself and begins to spiral upward, but, as noted by Byram and Martin, "This wander appeared to be caused by some inherent instability of the fire whirl, since 6 months of effort failed to find any external cause." Subsequently, the fire whirl lengthens, stretches and rises along the chamber axis in a tube-like column.

To replicate the Satoh and Yang experiments a rectangular chamber was formed from finite height vertical walls 180 cm tall rising around a 63 cm square courtyard with four 12 cm wide gaps extending along each corner. The chamber resided within a 1m x 1m x 2m computational domain that included 22,300 tetrahedral cells. In this case the heat source was presumed to be a vertical volume centered over a 21 cm square fire pan extending 90 cm tall. 20 kW of heat were released throughout the flame volume at rates varying from 0.3 to 1.9 MW/cubic meter to replicate the behavior of burning heptanes as suggested by Satoh and Yang [17]. Figure 2a displays the rising flame produced within the rectangular enclosure during the initial flame development period from 0 to 10 seconds. Next, down flow from the top causes the flame to tilt over and revolve around the burner in the form of a nearly horizontal arm of flame, which precesses about the chamber every 3 seconds (Figure 2b). After about 30 seconds the flame stabilized itself and began to stand upright and elongate. By 40 seconds the vortices coalesce into a single spiral fire whirl column as shown in Figure 2c. Instantaneous and time averaged temperature profiles at different chamber heights are shown in Figures 3a and 3b, respectively. The sequence of events and flow characteristics observed during the numerical simulation are in the same order, occur at similar times and have the same magnitudes as observed by Satoh et al. (16, 17).

Given that the cfd model reproduces fire whirl kinematics observed during different laboratory experiments, it was felt reasonable to perform sensitivity studies to determine what ventilation and exhaust geometries might produce fire whirls at building atria scales.

### 4.3 *Simulation of Fire Whirls in a Hypothetical Building Atria*

Hypothetical building atria configurations are now examined to evaluate the nature of fire whirl behavior. Meroney [27] first described the occurrence of fire whirls within actual building atria during the CERCA Virtual HVAC workshop in Montreal in 2002. Simplified atria of similar dimensions were constructed to evaluate the effects of the placement of ventilation inlets and use of mechanical versus natural buoyancy exhausts. A schematic of the test atria is shown in Figure 4.

The test atria had dimensions 46 m long, 10 m wide and 44 m high. Optional inlet regions were placed at and near ground level on three sides of the room. Outlets to be driven by either mechanical fans or natural ventilation were placed on and at roof level as shown. Fires were located at ground level at various locations around the room. Fire combustion was not actually simulated, but an equivalent heat source was placed at floor level over a 9 square meter area or generated within a prescribed 18 cubic meter volume above the virtual fire to produce a prescribed fire of 5,250 kW. The numerical room volume was filled with 2,445,090 tetrahedral cells, and the flow was simulated by FLUENT using a Large Eddy Simulation turbulence model and the Smagorinsky-Lilly subgrid scale model coefficients. During mechanical ventilation simulations air was withdrawn at the roof at 404 cubic meters/seconds, but during the natural ventilation simulation the buoyancy of the plume determined the exhaust rate.

In the absence of inlet or outlet openings the fire developed in a standard manner, the fire plume grew upwards, impacted the ceiling, and the smoke and fume layer descended more or less uniformly over the atria cross section reaching within a few meters of the floor within 4 minutes. When ground level openings were present the fire plume initially grew upwards, but very quickly became unstable, the plume bent over and begin to rapidly travel throughout the room often producing strong vortices and bathing all walls with heat and fumes. The erratic nature of the plume occurred for both mechanical and natural ventilation as shown in the pathline sequences shown in Figures 5 and 6, respectively. The large atria simulation reproduced many of the same unsteady characteristics of the laboratory simulations of fire whirls within ventilated chambers.

CONCLUSIONS The validation runs were considered satisfactory; hence, case study results should be representative and trustworthy. Implied hazards exceed those mitigated by traditional design methods.

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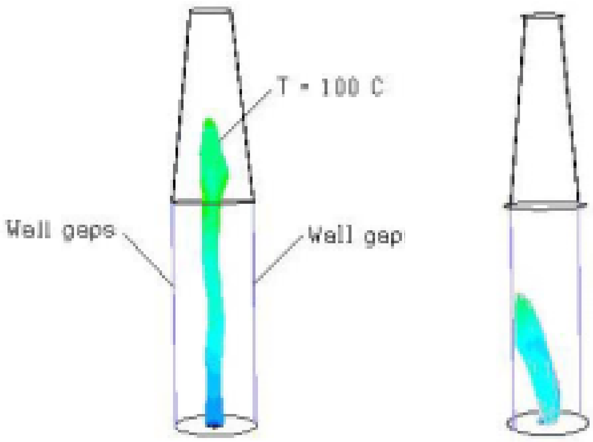


**Figure 1 Byram and Martin [9], t = 5 and t = 9 seconds**

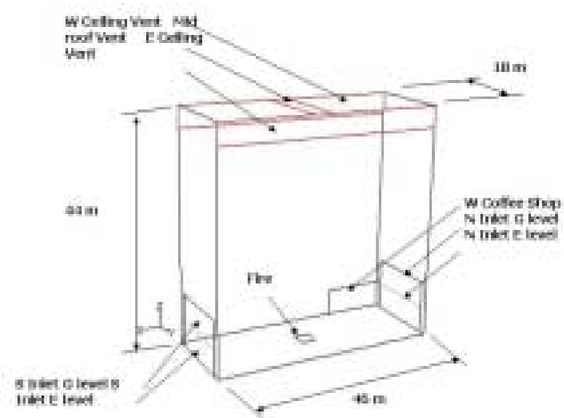


**Figure 4 Generic atrium schematic**

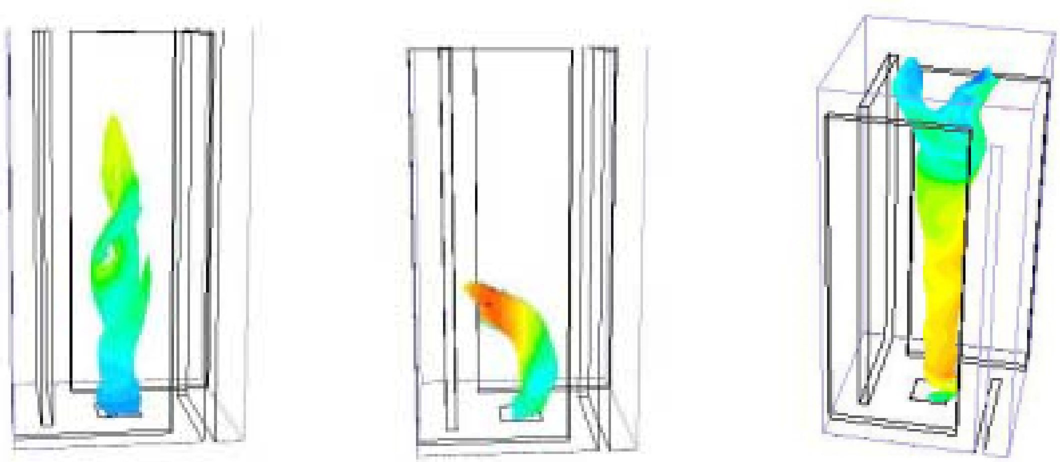

**Figure 2 Satoh and Yang [16], t = 0 to 10, 10 to 30 and 35 to 50 seconds**

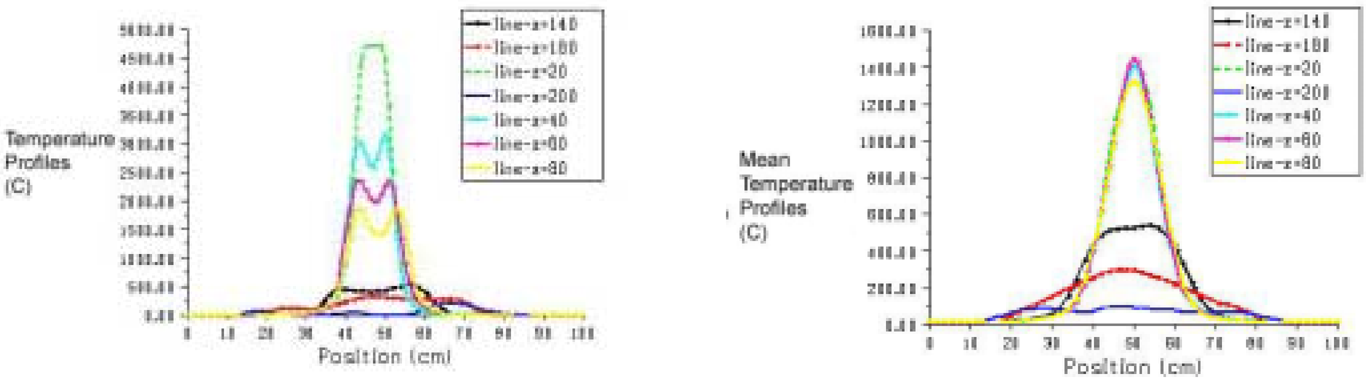


**Figure 3 Temperature profiles, t = 50 seconds, and statistical ensemble, t = 40-50 seconds, z = 20-180 cm**

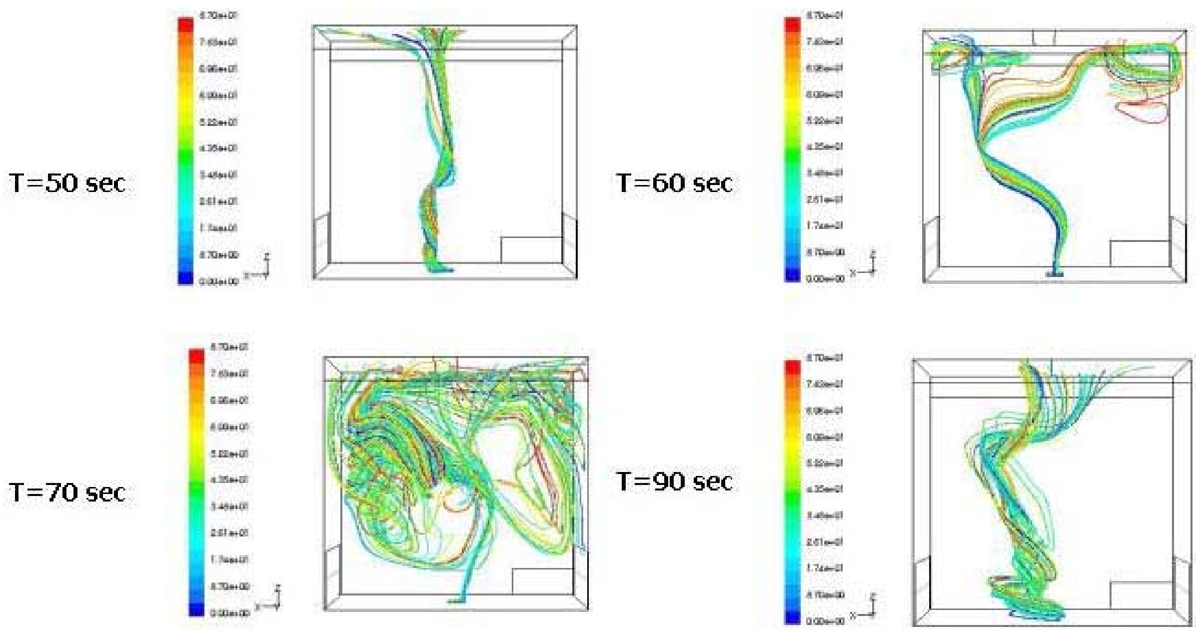


**Figure 5 Generic atrium, mechanical exhaust Q=404 cubic meters/second**

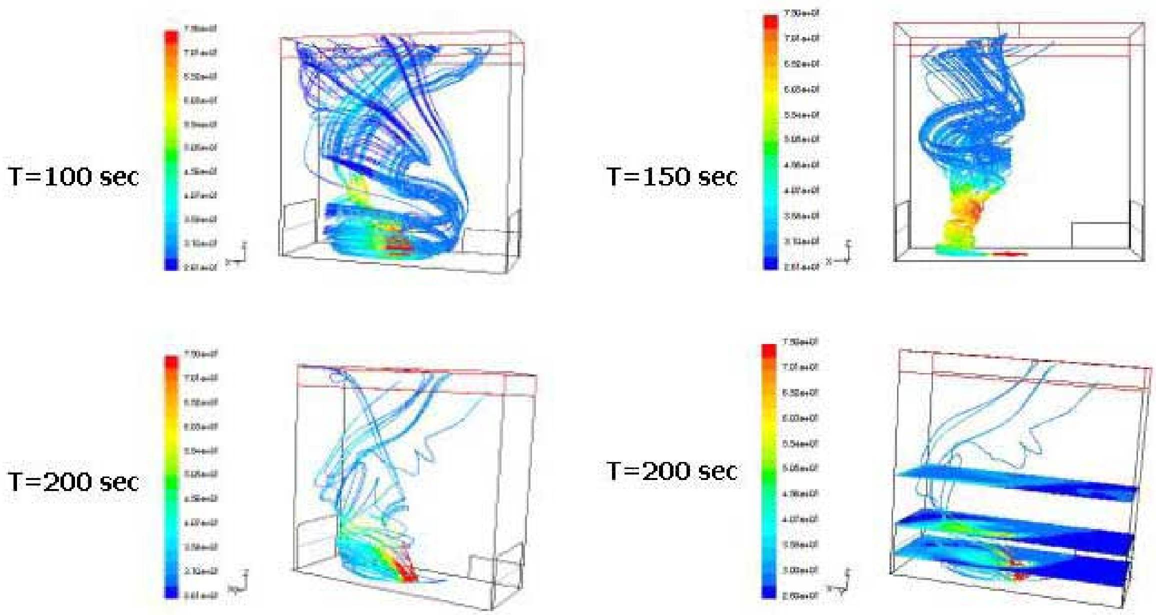


**Figure 6 Generic atrium, natural buoyancy exhaust**