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Fire Whirls, Fire Tornadoes and Firestorms: Physical and Numerical Modeling

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ABSTRACT:

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. This paper will examine historical observations of urban and forest fire whirls, fire whirl dynamics, the physical simulation of fire whirls in the laboratory, and consider numerical simulations of laboratory and building scale fire whirls.

1 INTRODUCTION

Fire whirls are usually associated with fires limited by fuel extent, while fire tornadoes, mass fires or firestorms occur when fuels available are massive and concentrated over a large area. In the former situation a combination of local wind, fuel configuration and terrain produce enhancing winds and vorticity, and in the latter situations the size of the fire produces its own wind environment that results in fire vortices so large some are associated with up to F-5 size tornadoes on the Fujita scale. During the Middle Ages when most building materials were highly combustible, medieval cities were repeatedly burnt over during enormous fires. One of the most famous cases is the London fire of 1666 that burnt over an area greater than the entire region damaged during the World War II bombing blitzkrieg. Observers described fire motions that appear to have been augmented by fire vortices.

1.1 *Fire Whirls Formed During Accidents and Natural Disasters*

During the Great Chicago Fire of October 1871, in which 766 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].

In San Francisco, CA, the stick-slip earthquake in the San Andreas Fault on the morning of April 18 1906 overturned coal and wood stoves and kerosene lanterns and broke gas and water mains. Fires started simultaneously in wood buildings all over the city producing a major firestorm. With alarm lines down and firehouses collapsed (and the fire chief killed under one of these collapses) fires burning over the next two days destroyed 28,000 buildings across four square miles and killed some 1188 people. [3]

On September 1, 1923, just before noon, the Kanto earthquake of magnitude 8.3 occurred near the densely populated, modern industrial cities of Tokyo and Yokohama, Japan. The epicenter was placed in Sagami Bay, just southwest of Tokyo Bay. Destruction ranged from far up into the Hakone mountains, home to popular tourist resorts, to the busy shipping lanes of Yokohama Bay, north to the city of Tokyo. Though not the largest earthquake to ever hit Japan, the proximity to Tokyo and Yokohama and the surrounding areas, with combined populations numbering 2 million made it one of the most devastating quakes ever to hit Japan. Tokyo's principle business and industrial districts lay in ruins. Deaths were estimated at nearly 100,000, with an additional 40,000 missing. Hundreds of thousands were left homeless in the resulting fires. Fires in the Honjo and Fukagawa districts of Tokyo surrounded over 30,000 people who took refuge in a large open area. A huge fire tornado formed and crossed the refugee area. The meager possessions they had fled with became additional fuel for the firestorm and they were literally incinerated on this spot. A lithograph prepared from drawings by a survivor depicts the incredible size of the fire tornado. [4]

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 [5].

The Oil Tanker Heimvard spilled 14.7 million gallons off Hokkadio Island, Japan on May 22, 1965. This was 29th largest marine oil spill. The ship loaded with 27,283KL of crude oil entered the port, and collided against a quay by an error in ship maneuvering while it was advancing toward the shore. The crude oil caught fire and exploded immediately after it flowed out from the ship. It went on burning for as many as 28 days. Persistent fire whirls formed downwind of the burning oil spill.

Fires produced by lightning and carelessness in US National Forests frequently produce destructive fire whirls and tornadoes. 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 [6, 7]. In other cases 1 m diameter by 10 m long logs were carried significant distances. Fire seasons in the US in 1999, 2000 and 2001 produced remarkable pictures and videos of fire whirls during the Lang Syne Fire near Winnemuca, NV; the Bitteroot National Forest Fire, MT; the Doyle, CA Fire; and the Missionary Ridge and Hayman Fires, CO. During the Missionary Ridge Fire (June 2002), a huge fire tornado formed which crossed the dry lakebed of Vallectio Reservoir and destroyed cars, trucks, boats and recreational vehicles parked by residents away from the burning hillsides. It also uprooted and broke off 1m diameter trunk trees. [8]

Fire whirls have also been observed during volcanic eruptions. Volcanic activity vortices have been reported previously about Paricutin volcano, Mexico 1945; Mt Hekla, Italy 1947-1948; and Myojin Island, 1954. On 14 November 1963 a submarine eruption broke through the ocean surface 33km off the south coast of Iceland in water that were about 130m deep. Within 24 hours it had formed a new island, which has now been named Surtsey. The volcano continued its activity through 1991 and is now about 2 km long and 170 m high.

In the case of Surtsey, there were often multiple vortices present. Some were visible to the surface, others were not, but water surface disruption clearly showed presence of tornadoes. These vortices ceased when winds were not present. Their frequency and intensity varied directly with the intensity of the eruption. Vortices formed downwind of the eruption in region 100m to 1000m away. They formed both as cyclonic and anti-cyclonic vortices. Thorainsson and Vonnegut (1964) suggested that necessary angular momentum may come from a) meso-scale vorticity already present, b) vorticity produced when cloud/island interact with wind, and from c) vorticity directly introduced by the volcano. Sources for vortex energy could be a) hot gases and lava, b) high velocity gas jets in the eruption, c) falling of particulate matter ejected which induce hot columns of steam when they fall in ocean, and d) the electrified volcanic cloud which produces lightning. [9]

1.2 *Fire Whirls Produced Deliberately During Field Experiments*

During the post-World War II period there was great concern about the destructive nature of conventional and nuclear bomb-produced urban firestorms. Incredibly destructive fire whirls were observed during the firestorms over Dresden and Hamburg during World War II. [10, 11] During the 1960s civil defense, defense department and forest service agencies from the United States, Australia and Canada cooperated on the *Project Flambeau* studies of large mass fires. Huge piles of fallen timber and slash were arranged in rectangular arrays to represent suburban and urban homes. Measurements were made of combustion rates, radiation, temperatures, and winds. Fire whirls were recorded on photograph and films [12, 13]. Unfortunately, most of these visual records seem to have been lost or destroyed.

The Centre de Rechereches Atmospherique, France, carried out a large-scale program on the effect of massive heat release in the atmosphere over a twenty year period beginning in 1961. [14, 15] Experiments were performed on the Lannemezan Plateau 20 km north of the central Pyrenees Mountains, France, to try and create a cumulus cloud. Later experiments were deliberately designed to study rotating vortex plumes. The main apparatus called the *Meteortron* consisted of 100 burners regularly spaced over an area 125 x 125 m burning up to one ton of fuel/min with a heat release of 7×10^5 kW. In June 1961 observers saw after about 6 minutes of heat release a tornado like structure in the lee of the fire translating downwind with a wind speed of 100 m/min. Later trials often observed intermittent tornadoes, and on August 31 a 40 m diameter whirl formed centered over the burners that was so strong it inclined the burner flames to 45 degrees and blew out a number of the burners.

1.3 *Virtual Fire Whirls*

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) [16]. Subsequently, the author used CFD to replicate laboratory simulations of fire whirls and examine atria whirls in greater detail (Meroney, 2003) [17]. 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 [18]. 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 [19]. 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 was 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 [20]. 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 [18]. 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 [21]. 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) [22, 23].

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 [24]. 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 [25]. 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) [26].

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 [27, 28]. 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) [29].

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 [30, 18]. Satoh and Yang (1997) used the UNDSAFE code with associated 3d, compressible, buoyant, and constant turbulent viscosity specifications [28]. 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 [31]. 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) [32]. Unfortunately, this code did not replicate the time dependent character of the developing vortex, probably because the simulation did not include adequate grid resolution over the combustion region [33].

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 US fire codes depend upon the National Fire Protection Association (NFPA) guidebooks [34, 35]. 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 [40]. CFD, sometimes called "field-modeling" in the fire community to distinguish it from 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 [36]. Nonetheless, as discussed by Yang [37] , 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. [16] compared the behavior of a developing fire in a proposed building atria using a conventional NIST ASMET zone model, the FDS model [32] and the commercial finite volume cfd code FLUENT [38]. 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 [20] and Satoh and Yang [27] 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" [20] 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 [28]. 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. Mean and RMS Y (lateral) velocity profiles at heights ranging from z = 20 to 200 cm are shown in Figures 4a and 4b, respectively. Velocity vectors at sections 20 and 60 cm from the chamber base are shown in Figures 5a and 5b, respectively. The sequence of events and flow characteristics observed during the numerical simulation are in the same order, occur at similar times and have similar magnitudes to those observed by Satoh et al. [27, 28].

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 [39] 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 6.

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 FLUENT using a Large Eddy Simulation turbulence model and the Smagorinsky-Lilly subgrid scale model coefficients simulated the flow. 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 7 and 8, 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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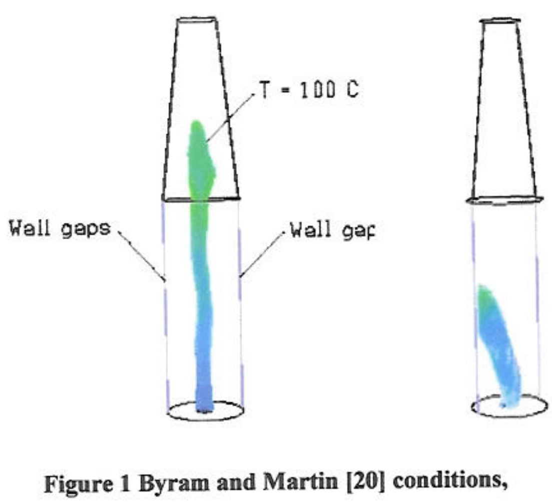

Figure 1 Byram and Martin [20] conditions, Fluent Calculations at t = 5 and t = 9 seconds

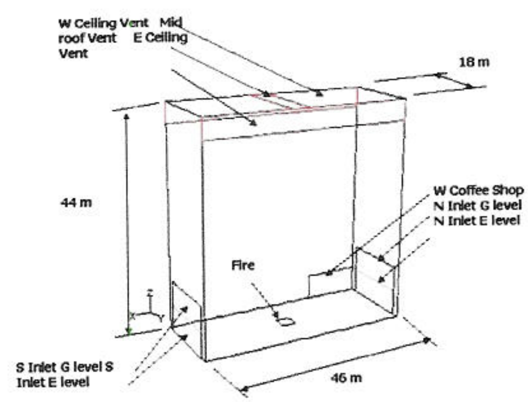

Figure 6 Generic atrium schematic

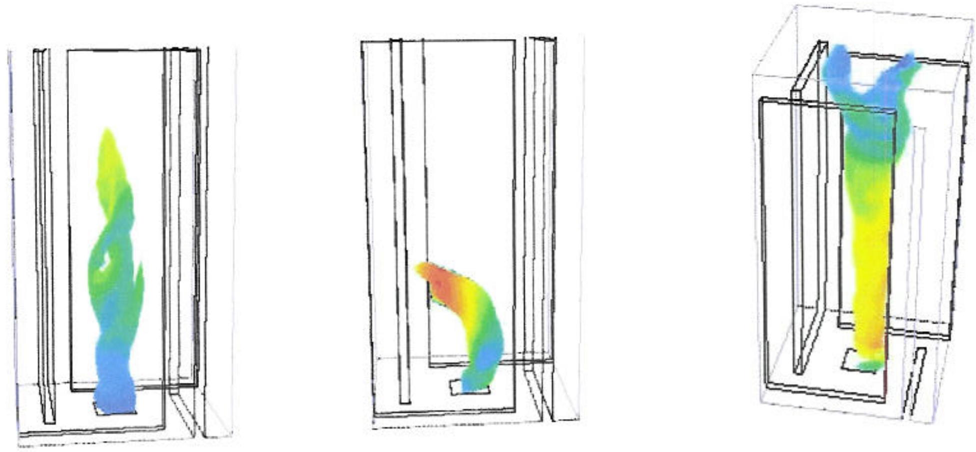

Figure 2 Satoh and Yang [27] conditions, Fluent Calculations at t = 0 to 10, 10 to 30 and 35 to 50 seconds

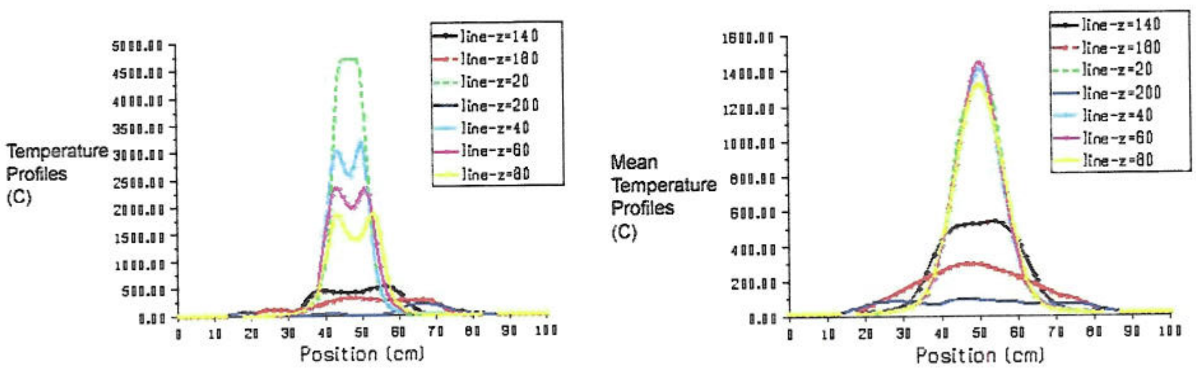

Figure 3 Temperature profiles, t = 50 seconds (left) , and statistical ensemble, t = 40-50 seconds (right), z = 20-180 cm

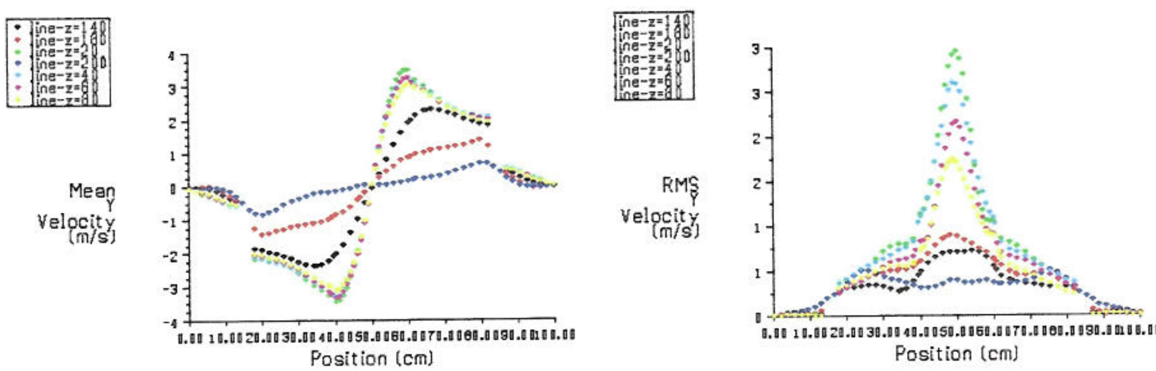

Figure 4 Mean (left) and RMS (right) Y Velocity profiles, t = 40-50 seconds, z = 20-200 cm

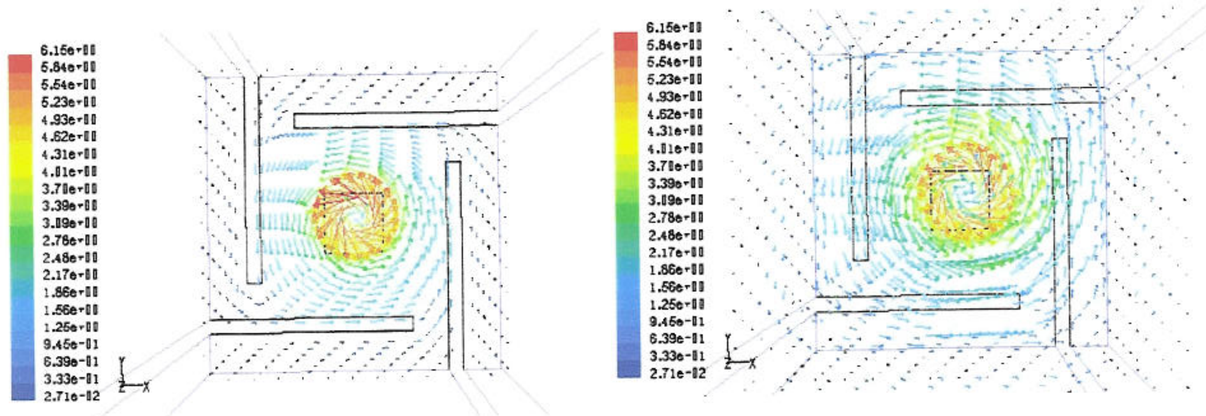

Figure 5 Velocity vectors, t = 40-50 seconds, z = 20 cm (left) and 60 cm (right)

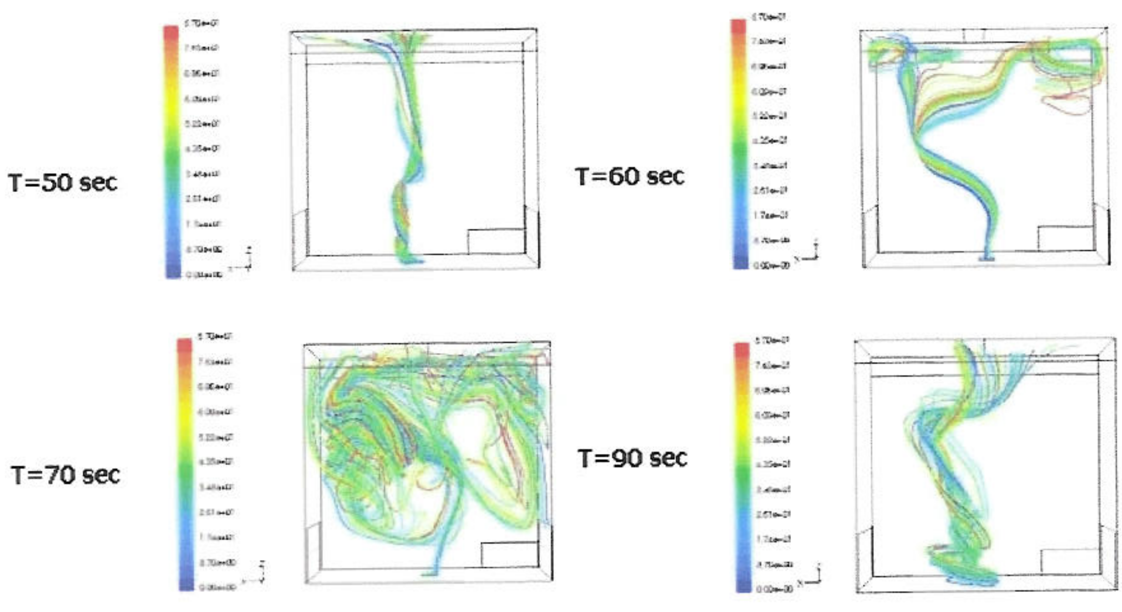

Figure 7 Generic atrium, mechanical exhaust Q=404 cubic meters/second

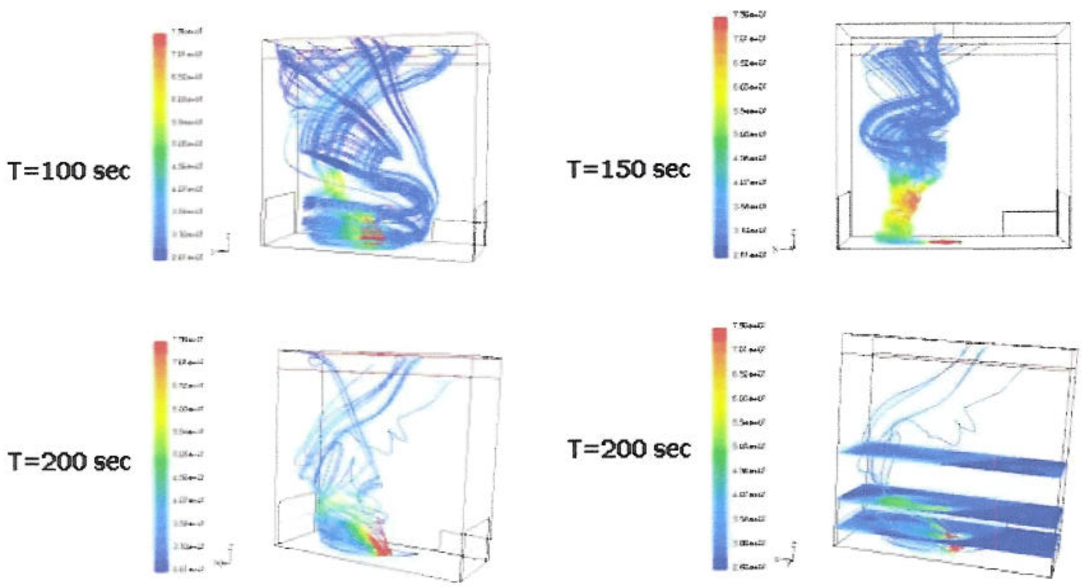

Figure 8 Generic atrium, natural buoyancy exhaust