4.2 INVESTIGATING CAUSES OF LARGE SCALE FIRE WHIRLS USING NUMERICAL SIMULATION

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Large scale fire whirls of tornadic size and strength represent a significant safety hazard to fire fighters, yet very little is known about their causes. This paper reports on initial fire whirl simulations done with a large eddy simulation (LES) model called FDS. The simulated L-shaped fire in cross flow compares qualitatively well with published wind tunnel studies. From this and other published works using FDS, it appears to be a promising tool for study of fire whirl behavior in the future.

1. INTRODUCTION

Fire whirls are vertically oriented, rotating columns of air found in or near fires. They have been observed in volcanic eruptions, and wildland, urban, and oil spill fires. Whirls are usually visually observable because of the presence of flame, smoke, ash, and/or debris. The definition of a fire whirl used in this paper includes those whirls with no inner core of flame. Fire whirls range in size from less than 1 meter in diameter and rotational velocities less than 10 m/s up to possibly 3 kilometers in diameter and winds greater than 50 m/s (Goens 1978). They represent a considerable safety hazard to fire fighters (Emori and Saito 1982; Moore 2008).

Although there is still much to learn about fire whirl behavior, observation and past research has revealed some of the main features of fire whirls. It is commonly accepted that the formation of fire whirls requires a source of ambient vorticity, a concentrating mechanism, and a favorable environment for their stability and growth (Meroney 2003; Zhou and Wu 2007). In the wildland fire context, it appears that there are many possible sources of ambient vorticity that could contribute to fire whirls. The shear layer that develops when ambient wind flows over the ground surface produces horizontally oriented vorticity. This vorticity can be reoriented by the fire's buoyant flow into the vertical (Jenkins, Clark *et al.* 2001) and may be a major contributor to many fire whirls. Similarly, it is likely that the in-drafting to a buoyant plume develops a shear layer near the ground that generates horizontally oriented vorticity that can also reorient to the vertical. This source of vorticity could be present even in zero ambient wind situations. Complex terrain can also generate vorticity through channeling and shear of ambient and fire induced winds (Pirsko, Sergius *et al.* 1965). Also, turbulent wake regions behind hills/mountains are thought to produce favorable vorticity for fire whirls (Countryman 1964; Countryman 1971; Goens 1978; Graham 1957). Vorticity can also be generated by non-uniform horizontal densities that can occur between a buoyant plume and surrounding ambient air. Last, a source of ambient vorticity for some whirls may be vorticity present along frontal boundaries (Umscheid, Monteverdi *et al.* 2006).

The concentrating mechanism used by fire whirls is buoyancy from the fire. The buoyancy acts to draw in surrounding ambient vorticity, reorient vorticity to the vertical, and stretch the vortex along its axis. The stretching causes a reduction in diameter and corresponding increases in rotation speed to conserve angular momentum. This stretching is the mechanism that allows whirls to reach such impressive rotational speeds. It results in lower axial pressures, which in turn encourages further entrainment of ground level vortex-rich air (Meroney 2003). 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 momentum outward from the core (Meroney 2003).

Historically, most information on fire whirls has been gained from either bench-scale

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experiments or anecdotal observational evidence from full-scale fires. These methods have proven useful and shed some light on the complex phenomena. For example, Emmons and Ying (1967) used a bench-scale burning pool fire surrounded by a rotating cylindrical mesh to show that increased whirl speed lengthens the plume. Martin et al. (1976) built a bench-scale "whirlwind chamber" that constrains air drawn into a buoyant plume to have a rotational component that causes a fire whirl. They showed that the burning rate of solid fuel cribs increased up to 4.2 times when a fire whirl was present. Other researchers have constructed similar bench-scale equipment to examine fire whirl behavior.

Observation of fire whirls on full scale fires have also been a valuable learning technique. For example, Umscheid et al. (2006) observed a large fire whirl in a wheat stubble burn on flat terrain. They suggest that vorticity from a pre-existing frontal boundary passing over the fire area contributed to the whirl occurrence. Pirsko et al. (1965) observed a large whirl that formed in a wildland fire on the lee side of a ridge. The particular topography was blamed for causing the whirl because it formed adjacent to the outlet of a V-shaped canyon that would naturally form an eddy from ambient winds flowing out the canyon. Several other observers have indicated that lee wind slopes are common locations for whirls to form (Countryman 1971; Emori and Saito 1982; Graham 1952). Graham (1957) states that 20 of 28 fire whirls examined in his study occurred on lee slopes. Finally, observation of an extraordinarily large whirl is reported by Ebert (1963). The whirl occurred during the World War II bombing of Hamburg, Germany and was an estimated 3 kilometers in diameter. It occurred in flat terrain, and may have been due to multiple interacting thermal plumes or mesoscale ambient vorticity already present in the atmosphere.

A technique for investigating fire whirl behavior that has been less commonly used is numerical simulation using computational fluid dynamics models (CFD). One advantage CFD has over observation and physical modeling is that various combinations of parameters can be changed easily and the effect examined. Meroney (2003) used the general purpose CFD model FLUENT and the NIST model FDS (McGrattan, Baum *et al.* 1998) to replicate bench scale experiments (Byram and Martin 1962; Satoh and Yang 1996) and investigate fire whirl formation in large, ventilated building atria. Battaglia et al. (2000) also used FDS to simulate bench scale experiments. In an interesting study, Zhou and Wu (2007) used FDS and bench scale experiments to show that fire whirls can form from multiple interacting plumes with no cross flow wind. All studies were able to generate good qualitative agreements with the experiments.

The objective of this study is to make an initial step toward investigating causes and behavior of fire whirls using CFD. To this end, simulations have been done to qualitatively recreate a published wind tunnel experiment.

2. SIMULATIONS

In 1921, a magnitude 7.9 earthquake hit the Tokyo, Japan area causing a mass urban fire. This fire spawned an extremely large fire whirl that killed an estimated 38,000 people in less than 15 minutes. Later, Soma and Saito (1988; 1991) investigated the cause of the whirl using a scaled model in a wind tunnel. They believed that the whirl was caused by the particular shape of the fire area as it burned around the unburnable area the victims had gathered in. In wildland fire terminology, this area might be termed a "safety zone". It was approximately 0.16 km^2 (40 acres) in size. At one point, as the fire burned around the safety zone, it formed an L-shape when viewed from above. At this time a large whirl formed on the inside corner of the L, which is where the safety zone was located and the victims died. Soma and Saito believe that the combination of this L-shape and the ambient wind speed and direction caused the whirl (see Figure 1). Ambient surface wind at the time was reported to be a moderate 4-5 ms^{-1} (9-11 mph). Using the scaled wind tunnel model and trays of burning liquid fuel, Soma and Saito were able to successfully generate a whirl on the inside corner of the L.

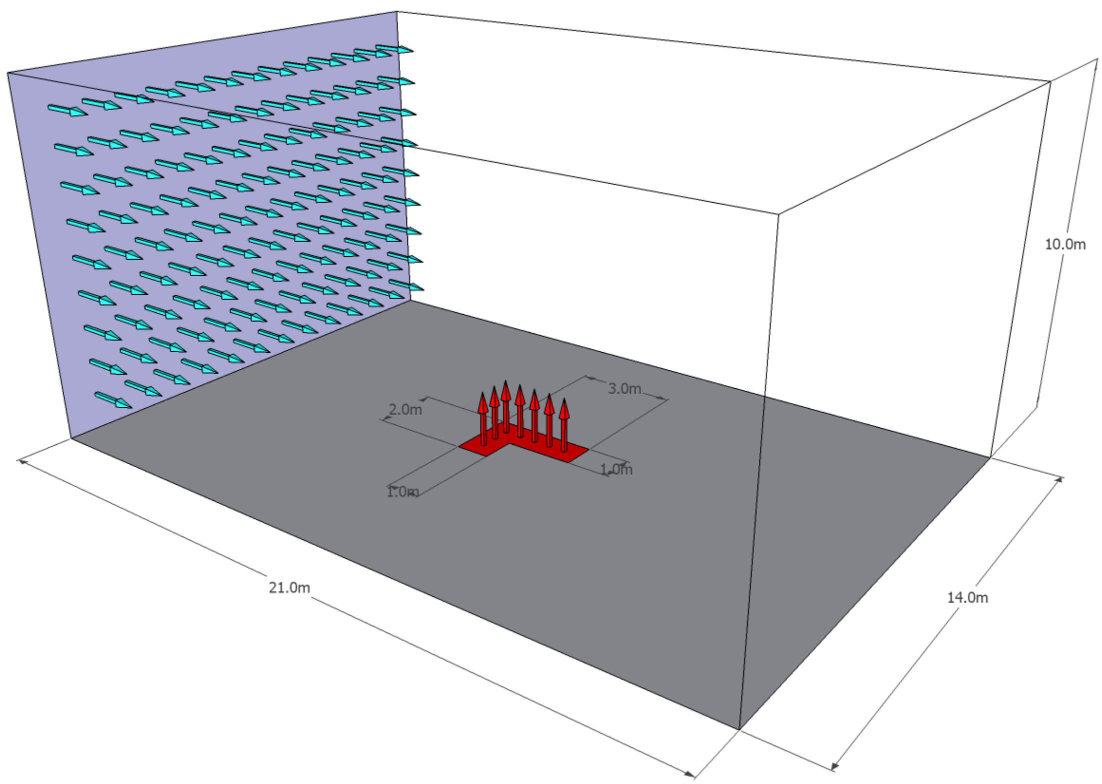

Figure 1. Schematic of L-shaped heat source and ambient cross flow direction. The red area represents the fire and the light blue arrows show the cross flow wind. The gray surface is the ground.

The current study uses the LES model FDS (McGrattan, Baum *et al.* 1998) to qualitatively reproduce Soma and Saito's scaled model. The effects of changing the wind speed and fire shape on fire whirl activity are examined. Soma and Saito found that a critical cross flow wind speed exists for a given fire heat release rate. For this critical speed, the whirl was most likely to occur.

A typical domain used in the LES simulations is shown in Figure 1. The cellsize was nominally 0.1 meters. Ambient wind was specified as a constant value along the inlet surface. The ground boundary condition is the default used in FDS, and all other boundaries were outlets. Combustion was specified in FDS using the heat-release-rate-per-unit-area (HRRPUA) technique (McGrattan, Hostikka *et al.* 2009). Using this technique, the user specifies the desired heat-release-rate-per-unit-area and fuel and FDS computes and releases the required gaseous fuel to match the heat-release-rate-per-unit-area. Combustion is computed using a mixture fraction method. The fuel used in this study is the default choice of propane. Simulations were initialized to the same cross flow speed specified at the inlet an run for 30 seconds.

An initial simulation, shown in Figure 2, was done with the same L-shape as in Soma and Saito's experiments. The figure shows an overhead view of velocity vectors colored by vorticity at 0.5 meters above the ground. With a cross flow wind speed of 0.7 ms^{-1}, a stationary whirl formed in the inner corner of the L.

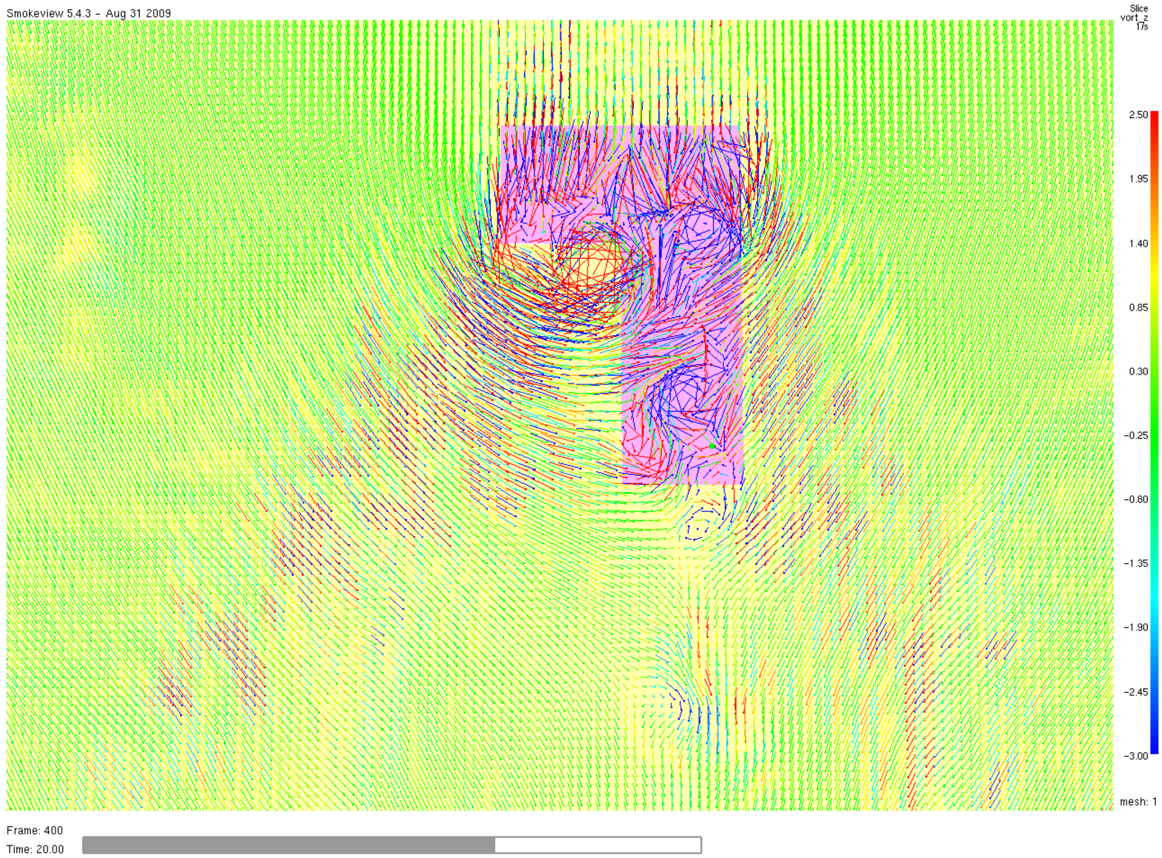

Figure 2. FDS simulation with a 1200 kWm^{-2} heat source and a 0.7 ms^{-1} cross flow speed. L-shape is the standard shape used in Soma and Saito's experiments. View is overhead, showing velocity vectors colored by vorticity at 0.5 meters above the ground.

Next, a set of simulations was done using an L with equal length legs in an attempt to produce a stronger whirl. Four simulations were done with the same 1200 kWm^{-2} HRRPUA, but with different cross flow wind speeds. Figure 3 shows results using cross flow speeds of 0.35 and 0.7 ms^{-1}, and Figure 4 shows cross flow speeds of 1.4 and 2.8 ms^{-1}. For the lowest cross flow speed of 0.35 ms^{-1}, a low vorticity whirl forms mostly over the heat source. As the cross flow speed is increased, higher vorticity whirls form at distances increasingly downstream. It is hypothesized that the stronger vorticity is due to increased ambient vorticity from the cross flow shearing. At the highest cross flow speed of 2.8 ms^{-1}, the whirl formed intermittently and often detached and advected downstream. This behavior of cross flow "strength" versus buoyancy "strength" is in qualitative agreement with Soma and Saito's work and that of Kuwana, Sekimoto *et al.* (2007) and Kuwana, Sekimoto *et al.* (2008). Interestingly, it is reminiscent of Byram's ratio of "power of the fire" and "power of the wind" (Byram 1959; Nelson 2003). Byram believed this ratio could be used to identify situations likely to produce *"phenomena associated with blowup behavior such as firewhirls, spotting, and strong indrafts."* Another interesting result of these simulations and the tragedy in 1921 is the potential impact on fire fighter safety zones. Additional work should be focused on examining convective heat transfer in fire fighter safety zones if fire whirls are likely.

3. CONCLUSIONS

An initial set of simulations was done for an L-shaped heat source in cross flow that gives similar qualitative results to published wind tunnel studies. The simulations correctly depict the formation and behavior of the fire whirl in increasingly stronger cross flow winds. This initial study, along with other published studies, show that the FDS model is a promising tool for investigating other fire whirl behavior. Future work should quantitatively compare against bench scale studies as well as other configurations.

4. REFERENCES

Battaglia F, McGrattan KB, Rehm RG, Baum HR (2000) Simulating fire whirls. *Combustion Theory Modeling* **4**, 123-138.

Byram GM (1959) Forest fire behavior. In 'Forest fire: control and use'. (Ed. KP Davis) pp. 90-123. (McGraw-Hill: New York)

Byram GM, Martin RE (1962) Fire whirlwinds in the laboratory. *Fire Control Notes* **33**, 13-17.

Countryman CM (1964) 'Mass fires and fire behavior.' Pacific Southwest Research Station, Berkeley, CA.

Countryman CM (1971) 'Fire whirls... why, when, and where.' USFS Pacific Southwest Research Station, Berkeley, CA.

Ebert CHV (1963) Hamburg's firestorm weather. In ' NFPA Quarterly'. pp. 253-260.

Emmons HW, Ying SJ (1967) The Fire Whirl. In 'Proceedings of the 11th International Symposium on Combustion'. Pittsburgh, PA pp. 475-488. (Combustion Institute)

Emori RI, Saito K (1982) Model experiment of hazardous forest fire whirl. *Fire Technology* **18**, 319-327.

Goens DW (1978) 'Fire Whirls.' NOAA Technical Memorandum NWS WR-129, Missoula, MT.

Graham HE (1952) A firewhirl of tornadic violence. In 'Fire Control Notes'. pp. 22-24.

Graham HE (1957) Fire-whirlwind formation as favored by topography and upper winds. In 'Fire Control Notes'. pp. 20-24.

Jenkins MA, Clark T, Coen J (2001) Coupling atmospheric and fire models. In 'Forest Fires: Behavior and Ecological Effects'. (Eds EA Johnson and K Miyanishi))

Kuwana K, Sekimoto K, Saito K (2007) Can we predict the occurrence of extreme fire whirls? *AIAA Journal* **45**, 16-19.

Kuwana K, Sekimoto K, Saito K, Williams FA (2008) Scaling fire whirls. *Fire Safety Journal* **43**, 252-257.

Martin RE, Pendleton DW, Burgess W (1976) Effect of Fire Whirlwind Formation on Solid Fuel Burning Rates. *Fire Technology*, 33-40.

McGrattan KB, Baum HR, Rehm RG (1998) Large eddy simulations of smoke movement. *Fire Safety Journal* **30**, 161-178.

McGrattan KB, Hostikka S, Floyd J (2009) 'Fire Dynamics Simulator (Version 5) User's Guide.' US Department of Commerce, National Institute of Standards and Technology.

Meroney RN (2003) Fire whirls and building aerodynamics. In 'Proceedings of PHYSMOD2003: International Workshop on Physical Modelling of Flow and Dispersion Phenomena'. Prato, Italy

Moore T (2008) 'Indians Fire accident prevention analysis.' USFS Pacific Southwest Region.

Nelson RM (2003) Power of the fire - a thermodynamic analysis. *International Journal of Wildland Fire* **12**, 51-65.

Pirsko AR, Sergius LM, Hickerson CW (1965) 'Causes and behavior of a tornadic fire-whirlwind.' Pacific Southwest Forest & Range Experiment Station, Berkeley, CA.

Satoh K, Yang KT (1996) Experimental observations of swirling fires. In 'Proceedings of ASME Heat Transfer Division, HTD-Vol. 335' pp. 393-400

Soma S, Saito K (1988) A study of fire whirl on mass fires using scale modeling. In 'International Symposium on Scale Modeling'. Tokyo, Japan. (The Japan Society of Mechanical Engineers)

Soma S, Saito K (1991) Reconstruction of fire whirls using scale modeling. *Combustion and Flame*, 269-284.

Umscheid ME, Monteverdi JP, Davies JM (2006) Photographs and analysis of an unusually large and long-lived firewhirl. *Electronic Journal of Severe Storms Meteorology*, 1-6.

Zhou R, Wu Z-N (2007) Fire whirls due to surrounding flame sources and the influence of the rotation speed on flame height. *Journal of Fluid Mechanics*, 313-345.

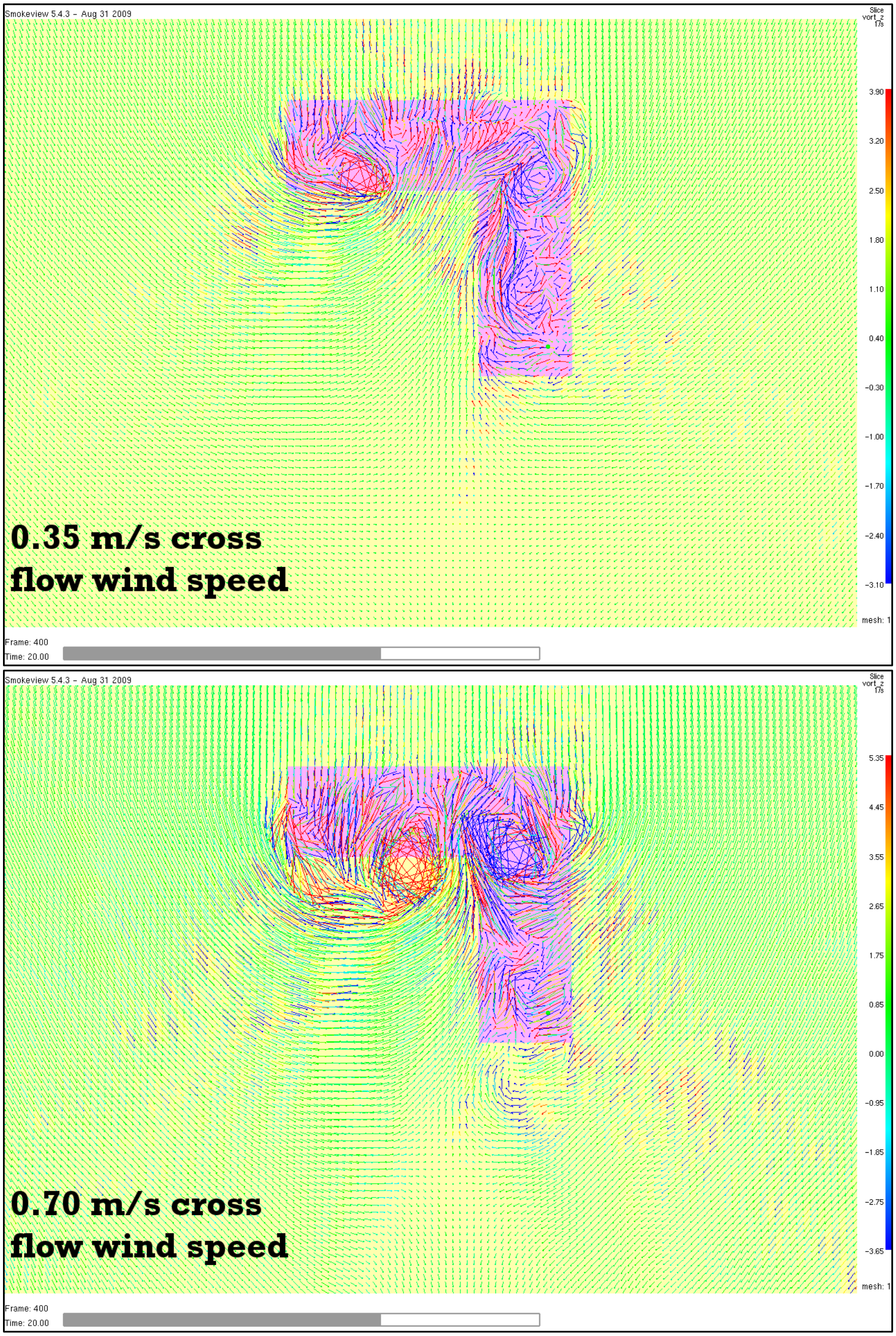

Figure 3. FDS whirl simulation at low cross flow wind speeds. View is overhead, showing velocity vectors colored by vorticity at 0.5 meters above the ground.

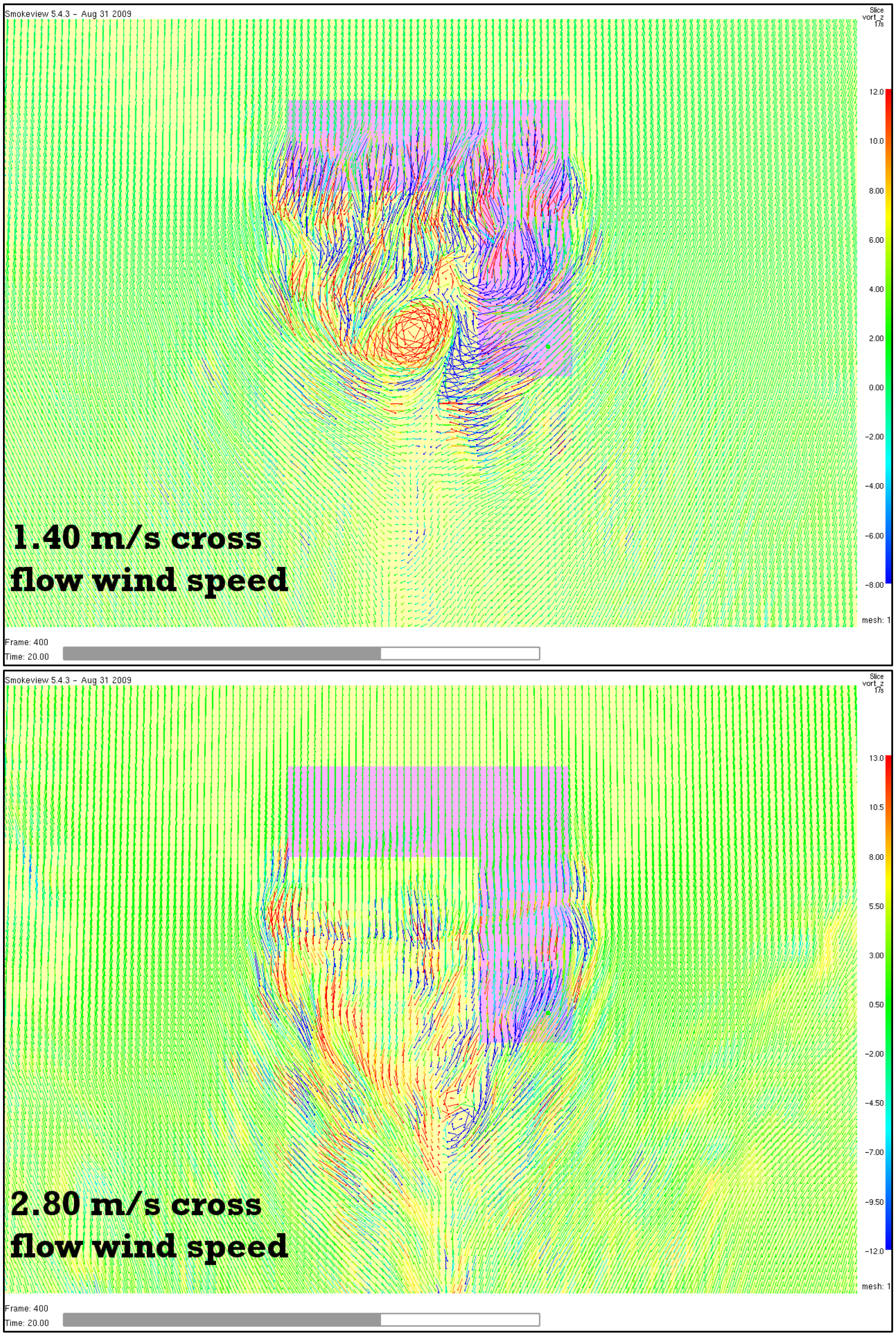

Figure 4. FDS whirl simulation at high cross flow wind speeds. View is overhead, showing velocity vectors colored by vorticity at 0.5 meters above the ground.