

Numerical Simulations of High Intensity Winds. Downburst Simulations

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1. Introduction

Based on unpublished recent reports by Applied Research Associates more than 66% of all high intensity wind events in North Eastern United States involving damaging effects on buildings and structures are associated with thunderstorms. Also recent analysis of extreme wind speeds in Australia [1] “indicate that thunderstorm downbursts are the extreme wind type at 10 metres height”. In a presentation given 25 years ago to the Norwegian Institute of Technology [2] Alan G. Davenport already inferred the main downburst characteristics. “These storms produce high intensity winds of short duration, (see Fig. 1a). The mean wind profile during these storms is often quite different” from straight boundary layer winds. “The region of strong winds may be confined to much shallower layers and maximum wind speeds are encountered below 500m”. Fig. 1b indicates maximum speeds of 32 m/s at heights of 50 metres or lower.

However, given the above non-uniformity and localization of thunderstorms in both time and space these high intensity winds are difficult to physically simulate in conventional wind tunnels. Most of the current wind engineering tests and codes of practice are based on the effects of straight, boundary layer (synoptic) winds.

Computational Fluid Dynamics (CFD) has recently made significant progress in simulating the effects of wind on structures and has the potential to model the thunderstorm related high intensity winds such as downbursts or tornadoes.

The present study is concerned with numerical simulations of downbursts and tornadoes using state of art CFD. Up to now mean and fluctuating velocity fields for downburst flows have been simulated to be used: (i) for further Finite Element Method (FEM) simulation of loading on structures and (ii) to calibrate simplified analytical models for structural codes implementation.

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2. Numerical set-up

An axial symmetric computational domain has been defined including half of the region of a jet flow perpendicular to a wall, see **Fig. 2**. The domain is $5.5d$ high and $8d$ wide where d is the downburst “jet outlet” diameter situated at approx. $3d$ over the ground.

A numerical structured grid of approx. 250,000 cells is used with an increased grid density in the vicinity of the ground wall where a boundary layer flow develops and which is the region of interest of the present simulations.

Several two-dimensional steady state simulations have been first performed at different scales varying from $1/20,000$ to $1/20$ of a typical downburst full scale. Based on the grid density at the wall the wall length y^+_{\max} is of the unity order, therefore no wall functions have been employed for the simulation of the boundary layer flow. Several turbulence models have been tested (e.g. standard k-epsilon, RNG k-epsilon and Reynolds Stress Model) and the best results have been obtained with the RSM two layer model.

For the smallest scale ($1/20000$ of full-scale) unsteady (time-dependent) simulations have been performed. These simulations are important in determining the vortex flow dynamics for downburst.

The boundary conditions were set as follows: outlet conditions at the top and side boundaries, symmetry in the symmetry plane of the domain and a smooth wall for the ground boundary. A constant velocity of 7.5 m/s has been prescribed at the upper downburst boundary and turbulence intensities of 1% have been prescribed for all outlets.

3. Results

3.1 Steady-state simulations

The radial velocity profiles for the steady state simulations at $1/20000$, $1/2000$ and $1/20$ of the full-scale are plotted in Fig. 2a, 2b and 2c, respectively. Each of these figures shows velocity profiles at various radial distances, between $r=0.8d$ to $r=3d$. The radial velocity gradually increases after the impingement point reaching maximum values at $r=1d$ and gradually decreasing afterwards ($r>1d$).

It is observed that the maximum value at $r=1d$ is close to the initial downburst jet velocity of 7.5 m/s and that these maximum values occur very close to the ground (the ground level is on the right-hand side of all Figures 2). An average distance from the ground is $0.03d$ (d being the diameter of the downburst jet). For an average full-scale downburst of say $d=900$ metres this implies the maximum velocities are encountered under 30 metres height.

Also by comparing Figures 2a, 2b and 2c it can be observed that the maximum radial velocity increases with the scale of the simulation and also that the height above ground

of this maximum is slightly decreasing with scale. This is a very important observation as it relates to scale dependency, or Reynolds number dependency. In other words simulations performed at 1/20000 or 1/2000 of the full-scale of a downburst (typical laboratory scales) are NOT entirely relevant for the full-scale phenomena. This is an aspect that has not yet been emphasized in the wind engineering community. This scale dependency means that: (i) care should be taken when extrapolating laboratory results to full-scale interpretations and that (ii) further investigation is needed into determining if there is a Reynolds number limit over which the phenomena becomes quasi-independent of scale.

A comparison between full-scale based [3] models and the present CFD simulations at various scales is presented in Fig. 3 showing the maximum radial velocity profiles (at $r=1d$). Also Fig. 3 shows a typical boundary layer profile (1/7 power law) that is currently used in wind engineering related wind tunnel testing and codes of practice. Firstly it is obvious that the downburst velocity profile differs substantially from the typical boundary layer (synoptic) wind profiles, as previously inferred by Davenport [2]. Not taking yet into consideration temporal non-uniformity we observe that the maximum average velocity in downbursts is located very close to the ground compared to the classical wind profile. Therefore damages due to thunderstorm winds potentially affect more the low-rise buildings and structures as opposed to synoptic winds affecting mostly high-rise buildings and structures. This is a fundamental difference and it is interesting to correlate the high occurrence of thunderstorms to perceived damages on low-rise buildings.

Secondly, the previously noted scale dependency (Fig. 2) is observed in Fig. 3 as well. The larger the simulation scale the closer to the ground the maximum velocity becomes. It is important to clarify why Reynolds number or scale effects are present in this type of flow. In order to answer this question time-dependent (unsteady) simulations have been performed.

3.2 Unsteady simulations

Unsteady simulations have been performed for the case of 1/20000 of full-scale. Fig. 4 shows the velocity vectors as well as the maximum and minimum vorticity contours for one snapshot (one moment in time) of the unsteady simulation. It is important to note the vortex flow dynamics: due to the initial shear layer generated instability, at the downburst jet level, large and quasi-periodic vortex-rings are formed. These vortices impinge on the ground and afterwards are advected (translated radially), see the main vortex in Fig. 4. Once the downburst flow impinges on the ground a boundary layer (on the ground) starts forming. Under the action of the negative pressure (suction) provided by the passing main vortex ring the newly formed boundary layer detaches from the ground and reattaches later, see the ground “bubble” formed to the right (downstream) of the main ring vortex. Inside this separation-reattachment bubble a secondary, counter-rotating vortex is formed. The two counter-rotating vortices are stretching and accelerating the flow in the

radial direction. As a result maximum radial velocity is induced right at the separatrix between these two vortices, very close to the ground and at a radial position around $r=1d$.

It is well-accepted that once a separation-reattachment mechanism occurs (such as the one shown herein) flows are susceptible to be Reynolds number (scale) dependent. This explains and confirms the dependency of the mean radial velocity profiles on Reynolds number (scale) observed in Figures 2 and 3.

4. Conclusions

Numerical simulations of downbursts generally confirm the main characteristics of downbursts previously inferred based on scarce full-scale results or empirical models previously developed: they are highly localized winds (in both time and space) with maximum velocities occurring very close to the ground. **Therefore thunderstorms are strongly related to low-rise building damages as opposed to the well-studied boundary layer (synoptic) winds that affect mostly the high-rise buildings and structures.**

The present CFD results show that the maximum radial velocities in downbursts are expected to happen within $1d$ radial distance from the downburst location and that the maximum wind speeds are likely to happen in the immediate vicinity of the ground. **This means that the loading patterns of structures subjected to downbursts will be effectively different from the loading of structures due to synoptic winds that are used in present structural design.**

Also, even if the results are not fully converged for all simulations (the $1/20$ scale) there is a strong indication of flow dependence of scale, or Reynolds number. Therefore **there is a clear need to: (i) identify what is the scale limitation for physical modeling of downbursts.(ii) determine how to extend the results of physical experiments to full-scale.**

In order to link full-scale, laboratory and numerical experiments **the implementation of physical boundary conditions in numerical (CFD) wind models is the next necessary step to be undertaken.**

References

- [1] J.D. Holmes, "A Re-analysis of Record Extreme Wind Speeds in Region A", Australian Journal of Structural Eng., Vol. 4, No. 1, 2002
- [2] A.G. Davenport "Wind Structure and Wind Climate", Safety of Structures under Dynamic Loading, Vol. 1, Norwegian Institute of Technology, Trondheim, 1977
- [3] G.S. Wood, K. C.S. Kwok, N.A. Motteram, D. F. Fletcher, "Physical and numerical modeling of thunderstorm downbursts", J. Wind Eng. And Ind. Aerodynamics, 89, pp 535-552, 2001

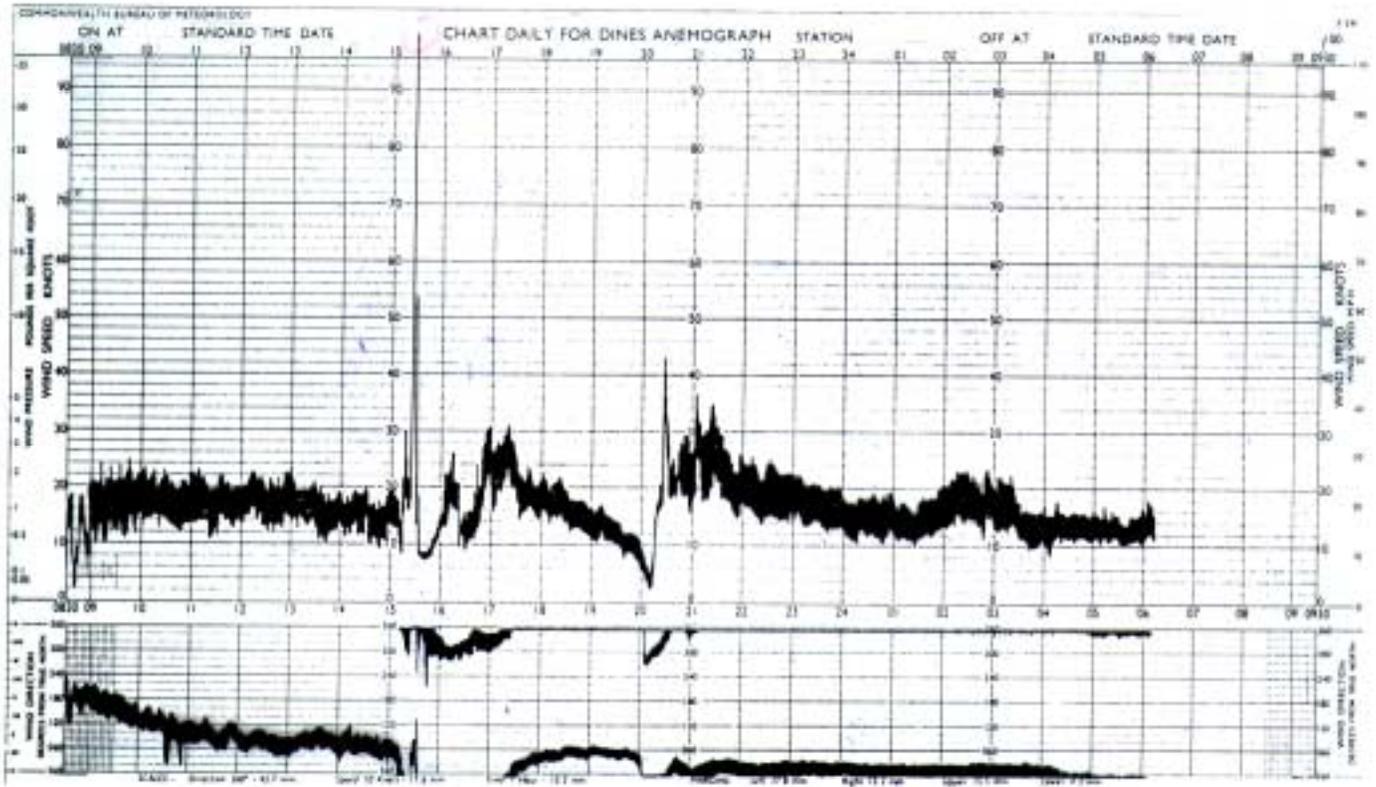


Fig. 1a: Full-scale thunderstorm downburst data record; Maximum wind speed : 52 m/s (100 knots); Daily Dines, Forrest, W.A., 20/11/59, Australia;

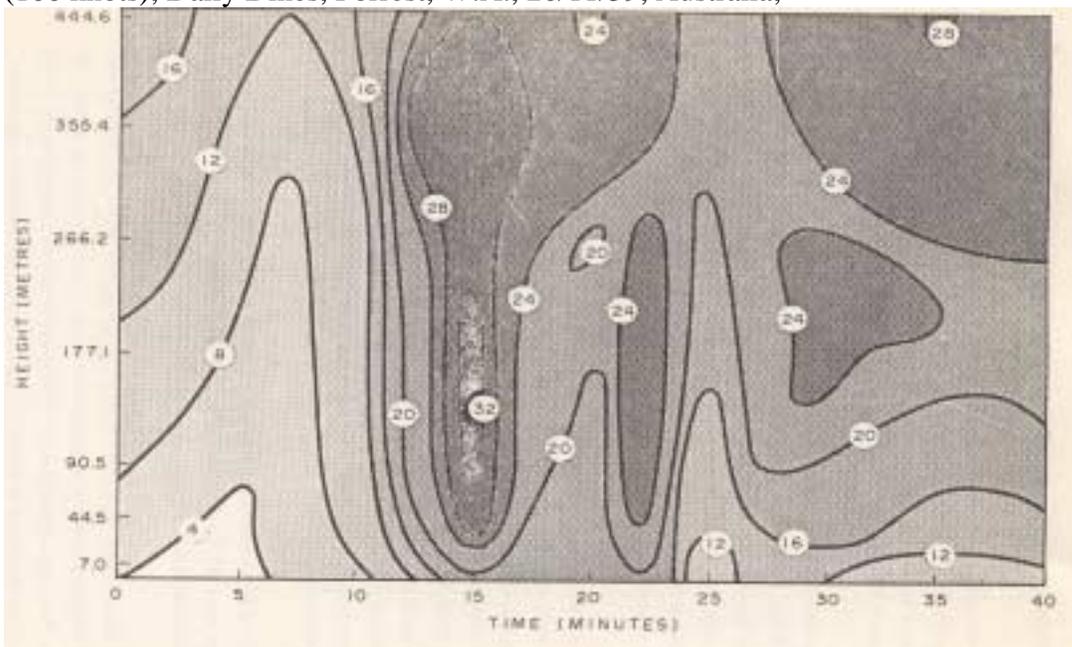
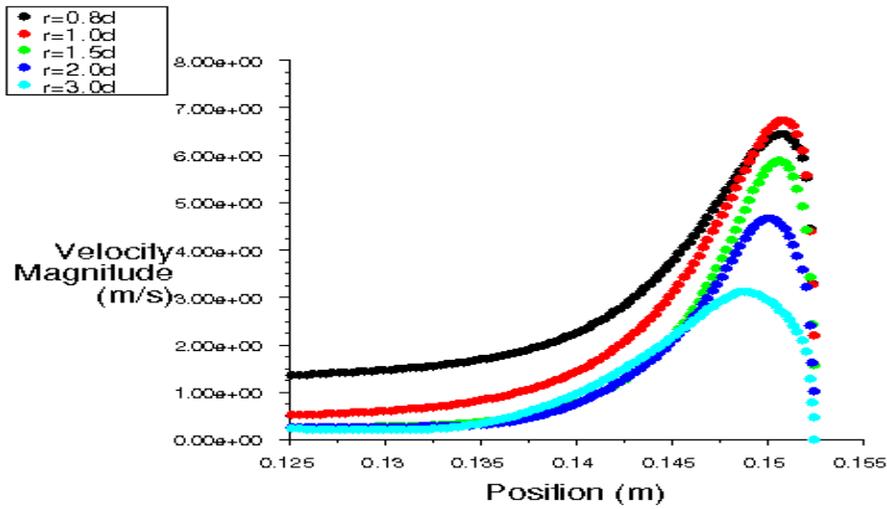
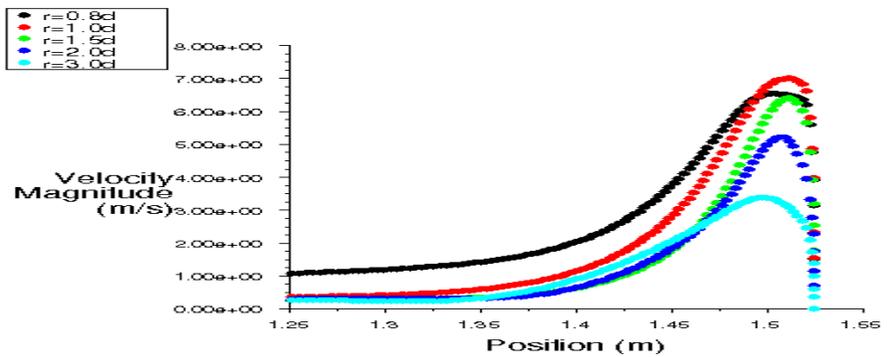


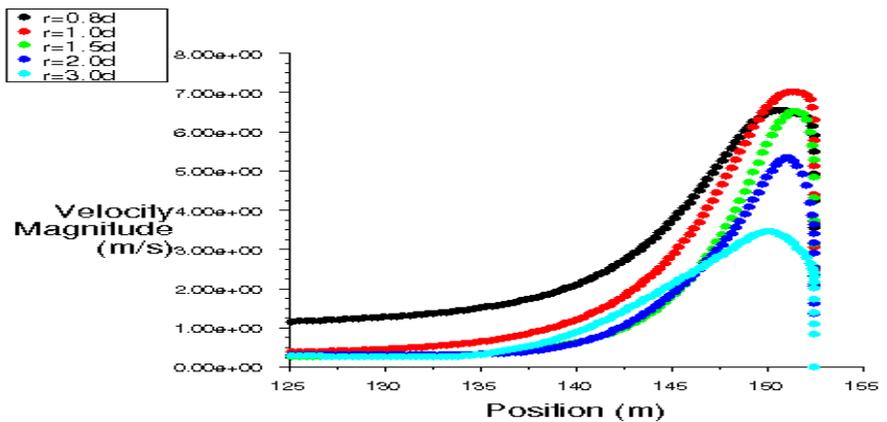
Fig. 1b: Isotachs of Windspeed in a thunderstorm, Oklahoma 31 May 1969 (units m/s)



Velocity Magnitude
 Jun 07, 2002
 FLUENT 6.0 (axi, dp, segregated, RSM)



Velocity Magnitude
 Jun 07, 2002
 FLUENT 6.0 (axi, dp, segregated, RSM)



Velocity Magnitude
 May 23, 2002
 FLUENT 6.0 (axi, dp, segregated, RSM)

Fig. 2: 2D Steady-state simulations; Radial velocity profiles for: a) 1/20,000 b) 1/2000 and c) 1/20 of full-scale

Downburst Mean Velocity Profiles

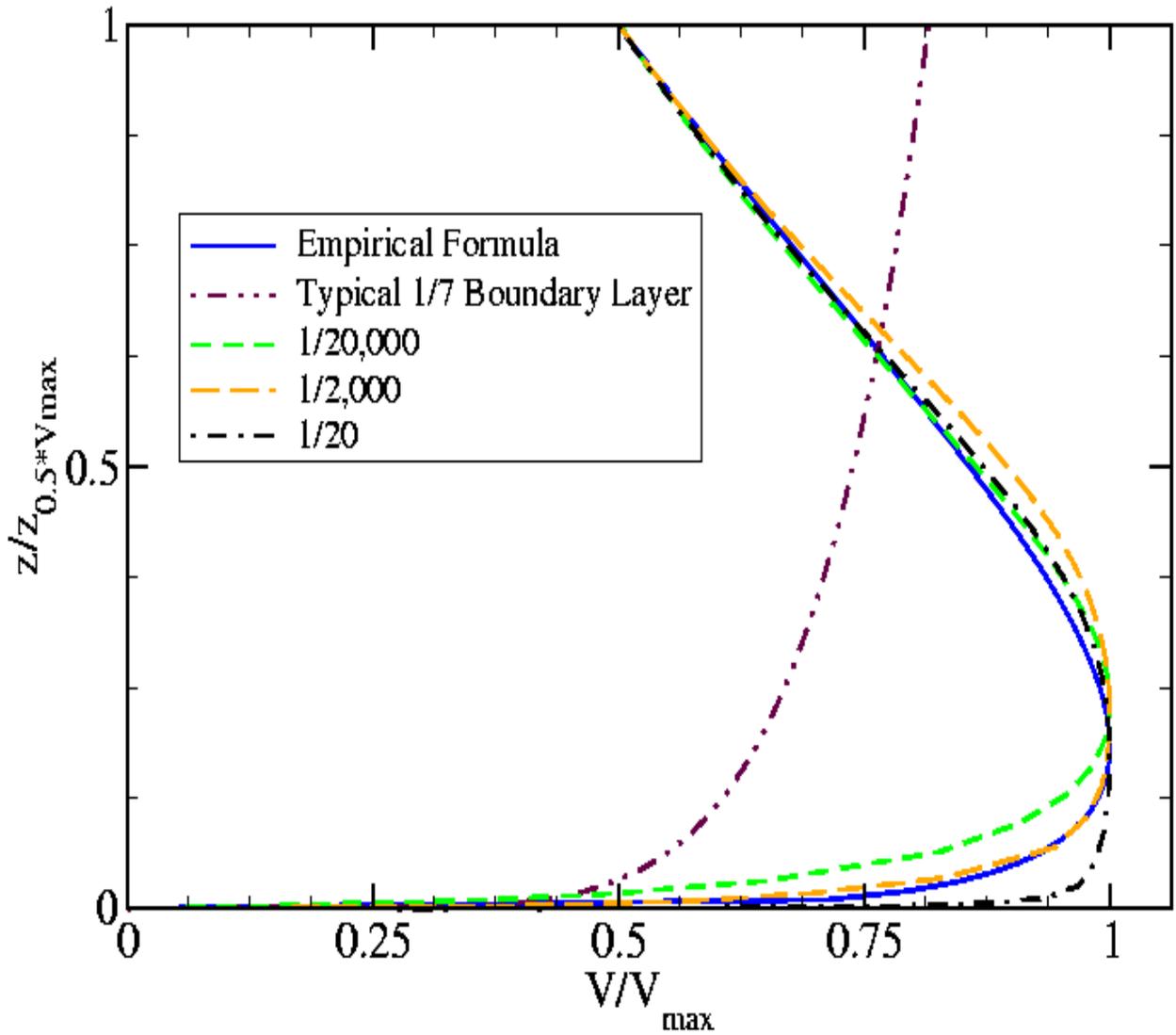


Fig. 3: Comparison of downburst maximum radial velocity profiles; Full-scale based model and 1/100 and 1/10 present CFD simulations; Typical 1/7 power law boundary layer (synoptic) profile

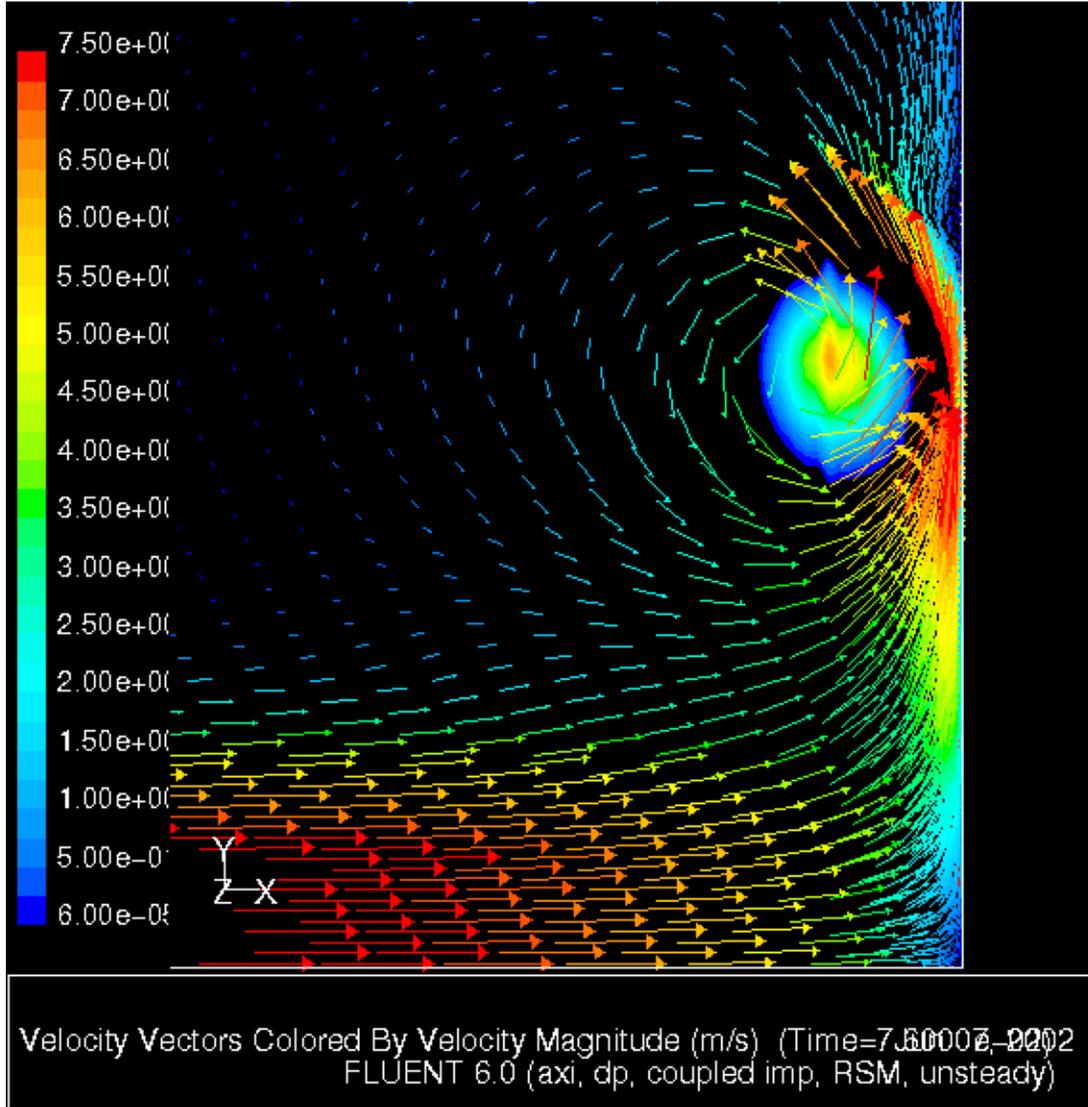


Fig. 4: Unsteady Simulation for 1/20,000 full-scale; Velocity vectors and Vorticity contours

