Virtual Versus Physical: Examining the Capabilities of CWE/CFD Simulations Through Comparisons to Wind Tunnel Observations

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ABSTRACT: Comparisons between a physical wind tunnel and the tools of CWE/CFD must be done with care. Others have described the wind tunnel as, essentially, an analog computer with near-infinite resolution and memory. The digital, discrete CWE/CFD tools, however, can provide information only at specified grid points. While the sampling points in a wind tunnel are limited by practicality, the full-physics flow field is completely defined. In CWE, however, many discrete data points are available but data between them is not. The amount of information legitimately extractable from a CWE model is not represented by the colorized pictures of CWE, which imply information is available everywhere in the flow field. By comparing CWE simulations with wind tunnel flow visualizations, parameters are defined to begin determining what can be known from a CWE simulations, what can be inferred, and what should not be claimed. The basic, essential issue is the number of cells required to capture phenomena and the resulting implications on the grid size. The disconcerting answer is that for problems practically solvable on today’s commercial workstations (for example, with 4 GB of RAM) the flow field details are low resolution and provide a guide to the mean flow without providing significant local information.

One of the main uses of atmospheric boundary layer wind tunnels is to predict atmospheric dispersion. In order to evaluate a very simple atmospheric dispersion problem, a comparison was made between wind tunnel and CFD concentrations downwind from an isolated single stack. The CFD models for the single stacks were created at model scale, corresponding to the physical size tested in the wind tunnel. The stacks were ~152 mm (6 inches) high and had inner diameters of 5 to 10 mm. Some sample test parameters are provided in Table 1. Wind tunnel sampling occurred at distances of 61 mm, 305 mm, and 915 mm downstream of the stack. The wind tunnel is 3.6 m (12 feet) wide and 2.5 m (8 ft) tall. An open country boundary layer was used, with turbulence intensity at the stack height of 8%.

The baseline grid for the single stack studies is shown in Figure 1a where the stack is at x=0 m. The grid was designed to have sufficient grid upstream (-x direction) to enable the any recirculation in front of the stack to be isolated from the inlet boundary condition and to allow for sampling at all the locations sampled in the wind tunnel. It was also desired to have sufficient grid to capture cross-flow plume behavior. The resulting cell count was 466,610.

Additionally, some highly directional grids were also created in an attempt to model plume rise when the direction and approximate rise was known before the simulation is started. While useful for research purposes, in modeling a complex domain the plume path would not be known a priori, so that a directional grid should not be used, as grid dependence could alter the solution in an unrealistic manner. A highly directional reduced domain 3-layer hexcore grid, Figure 1b, was created to try to capture the initial plume rise very close to the stack. The grid had 524,013 cells and was truncated in all three directions to focus on near-stack plume rise. Increasing grid density along the plume path is complicated since a) the path is not known when the grid is created b) enhanced grid density can affect the plume path.

Algorithm choices fall in two broad categories LES and RANS models. RANS models are less computationally intensive for stable problems, which can be run to steady state without a time dependent solution. For steady inflow conditions, using time steps in a RANS solution is
done to increase solution stability. LES, on the other hand, is unsteady and requires a fully time
dependent solution. LES and unsteady RANS require a similar amount of computational time, so
that when weighing solution time, the choice is really between steady and unsteady solver
methodologies, rather than between turbulence algorithms.

Of the two unsteady solutions, however, only LES will show the time varying eddy structure
associated with the plume, provided the grid is sufficient to resolve the structures. In order to
assess plume rise, the LES solution must be run for several cycles, where a cycle is defined as
the time it takes for a packet of gas to leave the stack and exit the domain.

A picture showing plume spread on the general grid is provided as Figure 2a. What is
immediately obvious is the smeared nature of the LES solution on this 466,610 cell grid. Fickian
diffusion dictates that concentrations move from cells of relative high values to cells of relative
low values. When the cells are large, Fickian diffusion leads to the smearing observed.
Additionally, the cell size is too large for LES to resolve flow features. The grid behind the
contour plot is also shown in Figure 2a. There is clustering near the stack, but in the far field the
cells are obviously larger than the stack diameter.

The LES picture on the highly directional grid, Figure 2b, is more believable in that it looks
more like a snapshot of the plume in the wind tunnel, provided in Figure 3. LES solutions
require more computational resources than steady-state RANS solutions, but since the goal of the
study was to advance the state of the art LES was used for most of this study with the realization
that it is beyond the capabilities of many currently involved in atmospheric dispersion CFD
simulations.

These cases are important because the grid size (approx. 500,000 cells) is consistent with
what can be run on the desktop workstations available to most in the engineers tasked with
modeling plume dispersion and because the grid, while clustered to the stack, is not otherwise
prejudiced to the plume path. This would be the grid one would create if the plume path was not
known at the start of the solution (or if multiple wind direction were to be simulated). Plume
height and width are a function of wind speed and exhaust rate, both of which need to be varied
in a typical simulation, so that a directional grid would have to be tailored to each case. For a
non-isolated stack, the nearby structures will also influence initial direction and spread, and the
plume interaction with the structures downwind makes creating a grid focused on the plume path
extremely difficult.

Comparison of the plume centerline profiles as measured in the wind tunnel and as calculated
from the CFD directional grid solutions is shown at two downwind locations (305 mm and 905
mm) in Figure 4. The profiles are seen to be Gaussian. From Figure 4b, we learn to be wary of
centerline height matching as a measure of simulation validation, as the centerline matches well
but the concentrations do not.

Theoretical calculations of the plume centerline position were made using the US
Environmental Protection Agency plume rise model and compared to centerlines estimates for
both the CFD and wind tunnel data. Two approaches were used to calculate the plume centerline
position from the CFD data. The first approach used a Gaussian curve fit. This procedure was
also used for the analysis of wind tunnel data. While this approach yields full statistics, it is
based on a single vertical line of data from the CFD. This fails to take into account flow
structures, like a horseshoe vortex, which would have an overall height lower than the centerline.
The second approach used to obtain plume height was based on the following weighted average
equation applied over a plane. In the equation $h$ is height, $C$ is concentration, and $A$ is area. This
method provides a planar average at a specific downstream location.

$$h_c = \frac{\sum h_n C_n A_n}{\sum C_n A_n}$$
Table 2 provides a percentage comparison of CFD and wind tunnel data to the EPA theoretical solution for plume rise. A negative number indicates data is too low compared to the theory. For the initial studies the trends had the CFD under predicting the theory, but as the study was expanded the trends ceased to be uniformly low.

In summary, the CFD results showed that grid density issues are crucial to atmospheric dispersion modeling, and can be as important as the choice of turbulence algorithm. The grid density issue is simply a result of the small source area relative to the computational domain. As the grid is further refined, the LES algorithm is able to resolve turbulent structures and the flow field begins to resemble the flow as observed in the wind tunnel.

DISCUSSION

Some people wonder how it is that CFD has been used to obtain good results for many complex Aerospace applications, while solutions to seemingly simple problems like diffusion from a single stack remain a challenge. With airplanes, the objective is to obtain surface forces over a relatively small area where cells are highly clustered, and a Y+ of 1 can be achieved. This is a very different problem than the plume rise model where the objective is to resolve turbulent flow structures along an unknown path in open space where clustering is not practical. Adaptive gridding can help, but getting a ten-fold increase in local grid by adaptation is challenging. The atmospheric dispersion problems are very different from the aerospace problems. Many CFD turbulence models have undergone extensive validation and verification in aerospace contexts. The underlying physics are correct, but atmospheric dispersion applications require high resolution in the farfield. Presently this is beyond the capabilities of most in the atmospheric dispersion modeling industry.

Figure 1. a) General grid for the stack study (left) and b) highly directional grid for the stack study (right).

Figure 2. LES simulation on the general grid (left) and b) on the directional grid (right).
Figure 3. Wind Tunnel flow visualization

Figure 4 Vertical Gaussian plume profiles 305 mm and 905 mm downwind of the stack as obtained from the wind tunnel and the CFD.

Table 1. Summary of the single stack study cases.

<table>
<thead>
<tr>
<th>Stack Diameter</th>
<th>Stack Height</th>
<th>Stack Exit Velocity (m/sec)</th>
<th>Velocity Ratio</th>
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<tbody>
<tr>
<td>10 mm</td>
<td>2.5</td>
<td>6.089</td>
<td>2.4356 case 1</td>
</tr>
<tr>
<td>10 mm</td>
<td>4</td>
<td>4.871</td>
<td>1.21775 case 2</td>
</tr>
<tr>
<td>5 mm</td>
<td>4</td>
<td>16.245</td>
<td>4.06125 case 3</td>
</tr>
</tbody>
</table>

Table 2. Percentage comparison of CFD and wind tunnel data to the theoretical solution for plume rise. “CFD zbar” denotes the Gaussian fit, and “CFD hc” the planar weighted average. A negative number indicates data is too low compare to the theory.