CFD and Experimental Modelling of an Impinging Jet for Thunderstorm Downburst Simulation

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1. INTRODUCTION

A thunderstorm downburst in its simplest form can be modelled as a steady flow impinging air jet. Although this simplification neglects some important atmospheric and physical parameters it has proven to be a useful tool for understanding the kinematics of these events. Assuming this simple impinging jet model also allows numerical models to be developed which can be directly compared with experimental results to validate the use of CFD. Confidence gained from these simulations will allow the use of more complex atmospheric impinging jet models that cannot be directly validated. Thunderstorm downbursts are important for wind engineers because in many parts of the world they produce the design wind speeds used in design standards, but are not structurally represented in these documents.

For this paper a steady flow impinging jet was used to model velocity profiles along an impingement surface as the simple conceptual model of an isolated downburst. This model does not consider the vortex or any transient characteristics associated with a downburst generated front. As well as the typical perpendicular jet/surface impingement, several angles of tilted jet were studied to determine the effect of jet tilt on mean velocity profiles. Many examples in [1] show downdraft columns approaching the ground at angles up to approximately 45°. Hjelmfelt [2] suggests that a tilted downdraft core may occur when momentum from surrounding flow is transferred to the downdraft column. The presence of velocity shear over the height of the downdraft generating cloud will also tilt the downdraft. These tilted jet tests, at least in principle, also represent an approximation of the mean velocity profiles that may be observed due to a steady flow downburst from a slowly translating storm cell. Specific topographical features, namely, an escarpment, and a triangular hill have also been modelled on the impingement surface to determine their effect on the mean velocity profile above the crest of both features. These velocity profiles have been compared with the flat (no-topography) case.

Both experimental and numerical simulations have been carried out for all test cases as shown in Table 1. All test types are outlined in the following section. Numerical results were compared with experimental results to ascertain the applicability of the numerical modelling of impinging jets and therefore the applicability of numerical methods for modelling a downburst like wind field.

<table>
<thead>
<tr>
<th>Test type</th>
<th>Perpendicular Jet</th>
<th>Sloping Jet</th>
<th>Perpendicular jet with topography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Axi-symmetric 2-D CFD</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>3-D CFD</td>
<td>X</td>
<td>X</td>
<td>-</td>
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2. TEST SETUP

Experimental simulations were carried out at the University of Sydney Impinging Jet Facility, and numerical simulations were carried out using ANSYS CFX 10.0 software.

The impinging jet facility has a 0.104 m diameter circular pipe which runs uninterrupted for 6 m (58 jet diameters, 58D) and expels air onto a smooth impingement surface 0.208 m (2D) from the outlet (Fig. 1). The 58D length of pipe is long enough to obtain fully developed velocity and turbulence profiles. The air jet was run so that the average velocity ($V_{bulk}$) through the pipe was 10 m/s ($R_e=70 000$) with a centre line mean velocity of approximately 12 m/s. For both perpendicular jet and tilted jet tests the distance from the pipe outlet to the impingement surface was measured along the centre line axis of the pipe. It should be noted that for the tilted jet tests this axis is not normal to the surface. Velocity profiling was performed
with a 4-hole cobra probe sampled at 1250 Hz for 30 seconds. Comparisons with hot-wire results proved the cobra probe to be suitable to within 2 mm (measured to centre of probe) of the surface. Two topographical features were chosen for modelling with the perpendicular jet/surface configuration: a two dimensional escarpment and triangular hill. Velocity profiles were measured above the crest of each feature, which was located at a radial position of x/D = 1.0. A single upwind slope of Φ = 0.5 was modelled, where Φ = H/2Lu as described in [4]. Both features had a height of 5 mm (~0.05D).

Fig. 1: Experimental apparatus

An example CFD domain is shown in Fig.2. For all 2D simulations a 2° sector of the geometry was used. Fig. 2 shows a domain with an escarpment included, for cases of no topography the geometry was altered as required. The CFD inlet conditions were generated in a separate simulation which modelled developed flow in a 60D long pipe – analogous to the experimental setup described earlier. The 3D CFD simulations use a 180° rotation, with symmetry plane, of the geometry shown in Fig.2. To keep the computational mesh size practical, the 3D simulations extend radially to 4D instead of 5D used for 2-D simulations. Validation tests showed that this reduction in geometry size did not influence velocity or turbulence results in the region x/D<2. Mesh independence studies for the hexahedral meshes used here were carried out for all cases, with all simulations being mesh independent in both velocity and turbulence (TKE). Of the available turbulence models in ANSYS CFX 10.0 the Shear Stress Transport (SST) model has been shown to be the most suitable for modelling the mean characteristics of a steady impinging jet [3]. This turbulence model was subsequently used for all simulations.

3. RESULTS

3.1 Perpendicular impinging jet

The first tests run were for the perpendicular impinging jet case. Fig. 3 presents a velocity profile measured at x/D=1.0 with normalised velocity plotted against a normalised elevation (from impingement surface). Results for both the 2D and 3D CFD simulations are shown along with experimental results from the current tests and also those obtained by [5]. The experimental setup for [5] is similar to that described earlier, but with velocities measured by a single-film anemometer and a jet pipe length of 80D. Fig. 3 shows a velocity profile that increases to a maximum close to the surface (z/D~0.02) then decreases with increased elevation. As expected this profile is similar to previously reported impinging jet profiles, and from a wind engineering perspective is distinctively different to the atmospheric boundary layer profile used in codes and standards.

There is no discernable difference between the 2D and 3D numerical results shown in Fig. 3. This relationship suggests comparisons between different angles of tilt simulated in 3D give similar accuracy to the 2D simulations where these can be made. When comparing the numerical results with the experimental data an excellent replication is observed. Only a slight overestimation by the numerical results is seen below z/D = 0.1. The comparison between the numerical and the experimental results, although not exact, gives a good level of confidence to progress forward.

3.2 Tilted impinging jet

To determine the influence a tilted jet would have on the surface based velocity profiles three additional impingement angles were tested. Along with the perpendicular impingement described in the previous section, tilt slopes of 8:1, 4:1 and 2:1 have been tested. Fig. 4 compares normalised velocity profiles
measured at x/D=1.0 on the forward flank of the jet outflow for all four tilts. It is evident that by increasing the angle of tilt the maximum velocity is relatively unchanged, but high velocities are maintained to higher elevations. Additional tests have indicated that a reduction in profile size occurs at the rear flank for the same set of experiments. These findings indicate that even though a tilted jet may not produce a significantly larger maximum wind speed, if these profiles were to be integrated over a reasonably tall building the difference in loading would be significant.

Fig. 4 shows strong similarity between numerical and physical results, the only discrepancy being the numerical simulations marginally overestimate (<5%) the wind speeds below z/D = 0.15, particularly for the larger tilt slopes.

3.3 Topographic effects

In boundary layer flow the presence of topographic features increases the maximum wind speed over the feature when compared with the velocity at an identical elevation above a flat surface. To determine if similar phenomena occurred for simulated downburst flow a linear triangular hill and an escarpment (Φ=0.5) were positioned with crest at x/D=1.0 and velocity profiles measured above these points. Measurements were only taken for the perpendicular impingement case. Fig. 5 shows normalised velocity plots for each topographic feature compared with the velocity at x/D=1.0 for a flat surface. As with the ABL case, it is evident from Fig. 5 that topographic features increase the maximum wind speed above the crest. The triangular hill was shown to increase the maximum wind speed by approximately 10%, while the escarpment increased the maximum wind speed by almost 25%. This substantial difference indicates the importance of the topographic feature lee shape. The primary reason the hill shape does not produce as large a speed-up as the escarpment is because the large vortex formed behind the triangular hill allows the wall jet to effectively “ski-jump” off the hill which lifts the entire wall jet layer. The relationship between speed-up due to the hill and escarpment is however reversed when a shallow hill (Φ=0.2) is studied (results not shown) as the large vortex is no longer present behind the hill shape.

Fig. 6 compares the results obtained over the crest of an escarpment in impinging jet and boundary layer flows. Wind speed results are presented as topographic multipliers (wind speed at an elevation above the topographic feature / wind speed at the same elevation above a flat surface at the same radial location) plotted against normalised elevation based on the topographic height (H) (z/H = 2 roughly equates to z/D = 0.1). Using wind tunnel data from [6], boundary layer results are shown to produce higher topographic multipliers than those measured for impinging jet flow. This finding agrees with conclusions drawn by [7] and is due to the non-confinement of the wall jet layer. This suggests that topographic multipliers based on ABL flow, as used in Codes and Standards, may overestimate the speed-up that would occur during a stationary downburst. Fig. 6 also compares current results with similar tests by [7,8] with similar results observed for z/H<1, but differing results for z/H>1, the latter likely due to differing initial profile shapes.
Both Figs. 5 and 6 show excellent agreement between experimental results and CFD simulations. Unfortunately, due to the small scale of the experiments, measurements were unable to be made in the highest velocity region of flow over the topography. Despite this, the simulation accuracy in other regions suggests that the CFD is modelling the mean velocity field satisfactorily.

![Graph showing velocity profiles](image1.png)

**Fig. 5:** Velocity profiles at x/D=1.0 above topographic feature crests.

![Graph showing topographic multipliers](image2.png)

**Fig. 6:** Topographic multipliers over an escarpment, ABL compared with impinging jet x/D = 1.0.

### 4. CONCLUSIONS

An impinging jet has been modelled both numerically and experimentally to simulate a stationary downburst. Different angles of jet tilt have been studied and it was shown that an increasing angle of jet tilt produced wind speed profiles which maintained large speeds to increasingly higher elevations but did not significantly increase the maximum wind speed recorded. This observation has a significant effect on wind induced structural loading. The speed-up effect of topographic features within a simulated downburst flow field was studied and compared with speed-up due to boundary layer flow. It was found that for a single topographic slope angle the feature lee shape is important for determining the speed-up observed at the crest. It has been shown that the speed-up due to simulated downburst flow is lower than the speed-up due to boundary layer flow, which agrees with previous researchers.

### 5. REFERENCES


