A comparison of turbulence models for an impinging jet in a crossflow

C. Diaz and J. Tso
Aerospace Engineering Department, California Polytechnic State University, USA.

Abstract

A numerical simulation of a previous wind tunnel experiment on an impinging jet in a crossflow was conducted. This study compared the results of the two-equation $k-\varepsilon$ turbulence model with those obtained with the one-equation Baldwin-Barth and the zero-equation Baldwin-Lomax turbulence model. From the $C_p$ distribution along the ground level of the symmetry plane, it was shown that among the three turbulence models tested, the flow field of the ground vortex and its location were best simulated by the $k-\varepsilon$ turbulence model. Lower $C_u$ and $\sigma_f$ coefficients in the $k-\varepsilon$ model yielded best results for the vortex location, but did not accurately capture the ground vortex strength represented by $C_{p_{\text{min}}}$. The one-equation Baldwin-Barth turbulence model gave a poor prediction of the ground vortex behavior, and the Baldwin-Lomax model just failed for this type of problem.

1 Introduction

The flow field created by an impinging jet in a crossflow has long been used to model the flow under a vertical/short take-off and landing (VSTOL) aircraft near the ground, where the crossflow could be caused either by the aircraft moving relative to the ground or by a crosswind. After the jet flow encounters the ground, it expands over the ground surface radially outwards from the impingement point, forming a wall jet. As the wall jet encounters the crossflow from the upstream direction it tends to roll itself into a ground vortex surrounding the impinging jet.
Table 1: Summary of turbulence models

<table>
<thead>
<tr>
<th>CASE #</th>
<th>TURBULENCE MODEL</th>
<th>DESCRIPTION</th>
<th>COEFFICIENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$k-\varepsilon$</td>
<td>Standard coef.</td>
<td>$C_{\varepsilon_1}, C_{\varepsilon_2}, C_{\mu}, \sigma_k, \sigma_\varepsilon$</td>
</tr>
<tr>
<td>2</td>
<td>$k-\varepsilon$</td>
<td>Modified coef. (I)</td>
<td>$1.44, 1.92, 0.09, 1.0, 1.3$</td>
</tr>
<tr>
<td>3</td>
<td>$k-\varepsilon$</td>
<td>Modified coef. (II)</td>
<td>$1.30, 1.80, 0.06, 1.0, 0.869$</td>
</tr>
<tr>
<td>4</td>
<td>Baldwin-Barth</td>
<td>Standard</td>
<td>****</td>
</tr>
<tr>
<td>5</td>
<td>Baldwin-Lomax</td>
<td>Standard</td>
<td>****</td>
</tr>
</tbody>
</table>

Table 2: Summary of vortex location and strength for numerical and experimental data.

<table>
<thead>
<tr>
<th>CASE #</th>
<th>DESCRIPTION</th>
<th>$X_i/D_j$</th>
<th>$(X_v-X_i)/D_j$</th>
<th>$(X_s-X_i)/D_j$</th>
<th>$(X_p-X_i)/D_j$</th>
<th>$C_p_{max}$</th>
<th>$C_p_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K-e (Standard)</td>
<td>-0.01</td>
<td>5.07</td>
<td>6.74</td>
<td>7.83</td>
<td>102.67</td>
<td>-2.38</td>
</tr>
<tr>
<td>2</td>
<td>K-e (Modified-I)</td>
<td>-0.03</td>
<td>6.59</td>
<td>8.16</td>
<td>9.36</td>
<td>102.77</td>
<td>-2.07</td>
</tr>
<tr>
<td>3</td>
<td>K-e (Modified-II)</td>
<td>-0.005</td>
<td>5.39</td>
<td>7.15</td>
<td>8.20</td>
<td>103.05</td>
<td>-2.27</td>
</tr>
<tr>
<td>4</td>
<td>Baldwin-Barth</td>
<td>-0.004</td>
<td>4.50</td>
<td>7.69</td>
<td>8.47</td>
<td>103.75</td>
<td>-1.51</td>
</tr>
<tr>
<td>5</td>
<td>Baldwin-Lomax</td>
<td>-0.11</td>
<td>NA</td>
<td>8.18</td>
<td>9.89</td>
<td>104.2</td>
<td>-0.28</td>
</tr>
<tr>
<td>Cimbala</td>
<td>Small Jet config.</td>
<td>NA</td>
<td>6.50</td>
<td>8.70</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Cimbala</td>
<td>Large Jet config.</td>
<td>-0.17</td>
<td>4.13</td>
<td>5.87</td>
<td>NA</td>
<td>103</td>
<td>-5.00</td>
</tr>
</tbody>
</table>

Figure 1: Typical ground level $C_p$ distribution in the symmetry plane.
Many experimental investigations have been conducted to examine the flow characteristics of an impinging jet in a crossflow [1-6]. Typically the pressure distribution at the ground level of the symmetry plane was measured to describe the ground vortex position and strength. The ground vortex location has been described by the following four parameters: the impingement point, \( x_i \); the vortex center, \( x_v \); the separation point, \( x_s \); and the maximum penetration point, \( x_p \) [1-11].

Figure 1 shows a typical pressure coefficient (Cp) distribution at the ground level of the symmetry plane for a jet impinging vertically over a flat plate in the presence of a crossflow. As seen in the figure, the location where the pressure reaches a maximum value is defined as the jet impingement point. The vortex center, which is defined as the location with the lowest Cp value, is located to the right of the impingement point. The minimum Cp value is also used as an indicator of the ground vortex strength. The separation point is located to the right of the vortex center and is defined as the point where Cp reaches a value of zero. Finally, the maximum penetration point is defined as the point where Cp reaches a maximum value in the upwind section of the vortex. The maximum penetration point is also used as an indication of the vortex length.

In a previous experimental study, Cimbala et al. [5,6] conducted a series of wind tunnel tests on the impinging jet in a crossflow. Their work included the use of high-speed cinema, hot wire anemometry, and laser velocimetry surveys in order to study the steady and unsteady characteristics of the ground vortex. Several numerical studies have also been conducted on the impinging jet in a crossflow problem. Knowles et al. [7-8] performed both numerical and experimental studies on this subject. In general, their numerical results compared reasonably well with their experimental work in terms of the ground vortex position, with less than three diameters difference in most cases. However, their numerical results showed an over-prediction of the maximum penetration point. Later, Roberts and Imlay [9] conducted a numerical study regarding the appropriateness of the standard k-\( \varepsilon \) turbulence model on the impinging jet in a crossflow. Their investigations showed that simple curvature corrections to the k-\( \varepsilon \) model can not provide accurate and cost effective calculations of all the flow phenomena associated with powered-lift vehicles. These models failed to accurately predict the peak pressure at the jet stagnation point and the minimum pressure at the ground vortex center. Barata [10] in his numerical study indicated that the k-\( \varepsilon \) model is adequate for the mean flow, but it failed to predict the structure of the impinging zone.

The numerical studies aforementioned all used the standard k-\( \varepsilon \) turbulence model or modifications of it in their computations. It is known that the k-\( \varepsilon \) model allows some coefficients to be modified depending on the type of flow being studied. One of the purposes of the present study was to explore some of the coefficient modifications in the k-\( \varepsilon \) model in order to examine their effect on predictions for this type of flow. The one-equation Baldwin-Barth turbulence model, developed in the late 1980's, has performed reasonably well in simulating...
the jet in a crossflow [11,12]. Therefore, it was interesting for this study to examine the appropriateness of the Baldwin-Barth model for the impinging jet in a crossflow problem. Despite the fact that the zero-equation Baldwin-Lomax turbulence model was not expected to perform well in this type of flow it was included for comparison.

2 Numerical simulation

The numerical modeling in this study was carried out using a finite volume code called INCA [13]. This code solves the Reynolds-averaged Navier-Stokes equations using a time marching finite volume method. INCA supports three popular turbulence models, the Baldwin-Lomax [14], Baldwin-Barth [15], and $k$-$\varepsilon$ turbulence mode [16]. In order to improve the calculation of low Reynolds number and near-wall turbulent flows, the INCA code incorporates a modification to the standard $k$-$\varepsilon$ model by Nagano and Hishida [17].

This finite volume code was used to simulate a previous wind tunnel experiment done by Cimbala et al. [6]. Therefore, the grid dimensions used in this experiment closely matched those of the experimental setup. The grid had a circular jet of 7.6 cm diameter located three diameters above the ground plane. The top plane was located 0.526 m above the ground plane and the computational domain extended 1.7 m from the jet center line.

An extensive grid study involving more than 16 grids with different densities and distributions was conducted. The results of this grid study showed that the best compromise between time and accuracy was obtained with a grid resolution of $83\times74\times27$. This final grid is shown in Figure 2. As seen in the figure, fine grid clustering was used in the jet shear layer, wall jet, boundary layer, and ground vortex region where velocity gradients are expected to be high. Also, the ratio between the distances of adjacent grid points was all kept at around 1.2 to ensure a smooth grid.

This final grid was later used to simulate the wind tunnel experiment and to compare turbulence models. In all the computations, the jet exit was kept at a height of 3 jet diameters above the ground plane ($h/D_j = 3$). The jet was injected perpendicularly to the crossflow with a velocity ratio ($V_j/V\infty$) of 10. The computed flows had a free stream Mach number of 0.0132 and a Reynolds number of 23,413, based on the free stream velocity and jet diameter. The flow was assumed to be viscous in all the calculations. A subsonic inflow boundary condition was chosen for the jet exit. This type of boundary condition allows the user to specify the total pressure at each cell of the boundary. In order to better match the experimental conditions, the power law for turbulent flows through pipes, described by Schlichting [18], was used to shape the jet exit profile.
Figure 2: Grid used in the turbulence model study (83x74x27).

Figure 3: Comparison of \( C_p \) in the ground vortex region for all turbulence models.
3 Results and discussion

The following section compares the results obtained by the three turbulence models used in this study and the experimental results of Cimbala et al. [5,6]. Table 1 lists the turbulence models used in each case plus a description of the coefficients used in the three cases where the $k-\varepsilon$ turbulence model was used. This table shows that the $k-\varepsilon$ turbulence model was used in Cases 1 through 3. The $k-\varepsilon$ model requires the input of five coefficients which may be slightly modified depending on the type of flow being computed. Case 1 was calculated using the standard coefficients recommended by Jones and Launder [19]. For Cases 2 and 3 the coefficients were changed following the guidelines given by Bradshaw, Cebeci and Whitelaw [20]. The standard Baldwin-Barth turbulence model was used in the numerical computation corresponding to Case 4. The last model tested was the zero-equation Baldwin-Lomax turbulence model which was used in Case 5.

3.1 Ground level $C_p$ in the symmetry plane

Typically experimental data were taken in the symmetry plane due to the fact that there are no lateral velocity components and major flow physics involved in this flow can be observed in this plane. Figure 3 shows the $C_p$ distribution in the vortex region along the ground level of the symmetry plane for all the turbulence models used in this study. As seen in Figure 3, the curve corresponding to Case 1, the standard $k-\varepsilon$ case, shows that the vortex center, defined as the lowest pressure point, is located at $x_D = 5.08$. The separation point, defined as the point in the curve where $C_p = 0$, is located at $x_D = 6.75$. And the maximum penetration point, defined as the point with a maximum pressure value, is located at $x_D = 7.84$. The curve for Case 2 where coefficients $C_\mu$ and $\sigma_\varepsilon$ were given lower values shows that the vortex center has moved 1.5 diameters farther upstream when compared to Case 1. However, the vortex strength, represented by $C_{\text{p,min}}$, seems to be lower than in the standard $k-\varepsilon$ model case. The last case where the $k-\varepsilon$ turbulence model was used is Case 3 ($k-\varepsilon$, modified-II). Figure 3 shows that for Case 3, the vortex strength increased when compared to Case 2. However, its vortex location moved downstream to a location of 5.4 diameters from the impingement point. The curve corresponding to the Baldwin-Barth turbulence model (Case 4) shows a dramatic deviation from the $k-\varepsilon$ model cases. It has an almost constant low pressure section extending from $x_D = 2.5$ to 5. A closer look at the $C_p$ distribution reveals that the vortex center is located at $x_D = 4.5$, but with a dramatic reduction in vortex strength as compared to Cases 1-3. However, the separation point at $x_D = 7.69$ and the maximum penetration point at $x_D = 8.47$ of Case 4 are comparable to the previous three cases. The curve corresponding to the Baldwin-Lomax turbulence model clearly shows that this turbulence model failed to capture the ground vortex. In this curve $C_p$ values close to zero (free stream values) are found in the region where low $C_p$ values are
expected due to the presence of the ground vortex. The results are so poor that it is impossible to determine where the vortex core is in the symmetry plane.

A summary of the data obtained from Figure 3 is given in Table 2. Table 2 covers the values of the jet impingement point, vortex core location, separation point, maximum penetration point, $C_{p_{\text{max}}}$, and $C_{p_{\text{min}}}$. Table 2 also includes Cimbala's experimental data for both the large and small jet configurations. As the information for the small jet is rather incomplete, the large jet results are included for comparison. Table 2 indicates that Case 1, where the standard $k$-$\epsilon$ model was used, shows about 23 percent difference between numerical and experimental results for both the vortex core and separation point locations. These differences between numerical and experimental data are greatly reduced in Case 2 ($k$-$\epsilon$, modified-I). For this case, the percent difference is reduced to 6 percent for the separation point and is even lower for the vortex core location. The results for Case 3 show a small improvement in the vortex location over Case 1 where the standard coefficients were used. Comparison between numerical and experimental results for the Baldwin-Barth turbulence model shows a large difference, over 30 percent, in vortex core location. The Baldwin-Barth turbulence model shows much better prediction of the vortex separation point.

### 3.2 Flow velocity in the symmetry plane

The velocity vector plot over the symmetry plane for Case 2 is shown in Figure 4. Comparison of vector plots for Cases 1, 2, and 3 showed no significant differences on the general shape of the vortex. However, the Baldwin-Barth turbulence model results showed that the shape of the vortex had flattened. The velocity vector plot for the Baldwin-Lomax model failed in capturing the ground vortex.

### 3.3 $C_p$ flood maps

The flooded contours of the pressure coefficient in the symmetry plane for Case 2 are shown in Figure 5. This figure shows that the high pressure region on the upstream section of this figure is caused by the freestream slowing down due to the presence of the ground vortex. The ground vortex is represented by the low pressure region in the middle of the figure. Its extent and shape are marked by the constant pressure contours and its center by the lowest pressure inside the vortex. The jet section is characterized by a low pressure region near the jet exit. As the jet flow moves downward the pressure increases due to the presence of the ground (stagnation point). A high pressure region is also noted on the upwind side of the jet exit and jet nozzle due to the slow down of the free stream.

The ground level $C_p$ flood map for Case 2 is shown in Figure 6. As seen in this figure, the surface pressure on the right-hand (upstream) side of the plot
slowly increases as the free stream senses the presence of the wall jet. The increase accelerates and reaches a maximum close to a large low-pressure region surrounding the jet impingement point near the center of the symmetry plane. This low-pressure region denotes the occurrence of the ground vortex. It depicts the vortex's horseshoe shape. This figure shows that that the vortex extended laterally up to a location of $z/D_j = 15.65$. Furthermore, it shows that the vortex is strongest in the symmetry plane upstream of the jet. The ground level $C_p$ flood map for the Baldwin-Barth model (Case 4) showed that the horseshoe vortex was wider than in the cases where the $k-\varepsilon$ model was used. The ground level $C_p$ flood map for the Baldwin-Lomax turbulence model showed almost no trace of the ground vortex.

4 Conclusions

A numerical simulation of a wind tunnel experiment on an impinging jet in a crossflow was conducted. This study compared the results of the two-equation $k-\varepsilon$ turbulence model with those obtained with the one-equation Baldwin-Barth and the zero-equation Baldwin-Lomax turbulence model. From the comparison, the following conclusions could be reached:

(1) Among the three turbulence models tested, the general features of the flow field were best modeled by the $k-\varepsilon$ turbulence model. The one-equation Baldwin-Barth turbulence model gave a poor prediction of the ground vortex behavior. The Baldwin-Lomax model just failed for this type of problem.

(2) The $k-\varepsilon$ model with lower $C_v$ and $\sigma_\varepsilon$ coefficients yielded fairly accurate results for the vortex location. But it does not capture accurately the ground vortex strength represented by $C_{p_{\text{min}}}$.

(3) Fine clustering in the jet shear layer and vortex region are crucial in order to capture the ground vortex features.

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References


Computational Methods and Experimental Measures


