Chapter 8

Discussion and Conclusions

8.1 Preliminary Remarks

The aim of this thesis was to develop a computationally efficient wall function which can predict complex turbulent flows with an accuracy similar to full low-Reynolds-number model treatments, which involve the costly integration of transport equations all the way across the viscous sublayer to the wall. To assess the performance of the new wall function, three challenging test-cases were selected: an impinging jet, a spinning disc and a three-dimensional "Ahmed" car body flow. Each of these test cases provides challenges for the wall treatment. Near the stagnation point in the impinging jet flow, the turbulence energy is generated primarily by normal stresses and convection both normal and parallel to the wall are significant. The spinning-disc flow involves "natural" transition and the velocity vector undergoes significant skewing across the near-wall sublayer (a feature which cannot be captured accurately by standard log-law-based wall functions). The 25° Ahmed car body flow was chosen as an industrially-relevant three-dimensional flow which involves elements of the other two cases: flow impingement on the nose and strong near-wall skewing of the flow over the rear slant, whilst introducing additional complexities such as the use of a non-orthogonal multiblock grid.

The new wall function, UMIST-N, was presented in detail in Chapter 4. In summary, the wall function solves boundary-layer-type transport equations for wall-parallel velocity, turbulence parameters (such as k and $\tilde{\varepsilon}$), and temperature across an embedded grid situated within the near-wall cell. The wall function transport equations include terms for convection both parallel and normal to the wall, diffusion normal to the wall, pressure gradient and sources. The wall-normal velocity is obtained from continuity, with some additional scaling to allow for consistent boundary conditions. Since the wall function decouples the solution of the near-wall flow from that in the main-grid domain and a pressure-correction equation is not solved across the subgrid, the new wall function does not suffer from the slow convergence problems of a full low-Reynolds-number model treatment. Subgrid values of velocity, turbulence parameters and temperature are saved at each iteration so the overall storage requirements of the new wall function are roughly equal to those of a full low-*Re* model (although there are some savings since subgrid pressure is not stored and due to the grid arrangement).

The three test-cases were each examined using full low-*Re* models[1], the UMIST-*N* wall function and at least one standard log-law-based wall function. Linear and non-linear $k-\varepsilon$ models were used in the impinging jet and spinning-disc flows whilst only linear $k-\varepsilon$ results were presented for the Ahmed body flow. Discussions have already been presented on a case-by-case basis at the end of each of the flow calculation chapter. It is not intended to go through the same discussions again, but to highlight the salient points and draw some overall conclusions.

8.2 Conclusions

Impinging Jet Flow

Overall, the UMIST-*N* wall function predictions of the impinging jet flow were in excellent agreement with the low-*Re* model predictions using both linear and non-linear $k-\varepsilon$ models. Different wall-function grid arrangements were tested to assess the sensitivity of the models to the size of the near-wall cell. The UMIST-*N* wall function showed practically no sensitivity to the near-wall cell size, in contrast to the log-law-based wall functions. There was a small discrepancy between the heat transfer predictions of the low-*Re* linear $k-\varepsilon$ model and the UMIST-*N* wall function near the stagnation point in the impinging jet flow, but it was shown that this was due to the coarse wall-function grid providing an insufficient resolution of the near-wall variation of turbulence parameters. Computing times for the UMIST-*N* wall function were approximately 60% higher than those of the log-law-based Chieng & Launder wall function but an order-of-magnitude less than the low-*Re* NLEVM calculations.

Spinning "Free" Disc Flow

The near-wall tangential velocity exhibits a logarithmic profile in the fully-turbulent region of the spinning disc flow whilst the radial velocity increases from zero at the wall to a peak and then decays with distance from the disc. Standard wall functions which assume a logarithmic velocity profile in both directions therefore adequately approximate the tangential velocity profile but do not capture the radial velocity distribution. Traditionally, in order to predict accurately the flow and heat transfer over the disc, one has been forced to use full low-*Re* model treatments. The UMIST-*N* wall function showed excellent agreement with low-*Re* model predictions of both the radial and tangential velocity profiles.

The location of transition from laminar to turbulent flow was not specified in the calculations. Instead, an initial level of turbulence was left to decay in regions where there was insufficient straining of the flow field, near the disc axis. It was found that the predicted location of transition was slightly sensitive to the size of the near-wall cell with the UMIST-*N* wall function, although the results were close to those obtained with low-*Re* models. This sensitivity was shown to be significantly worse with

[1] with the exception that a low-*Re* model calculation of the Ahmed body flow was not undertaken due to the large computing time required.

standard wall functions, which use a criterion based on the local y^+-value to switch from assumed laminar to turbulent profiles.

Computing times with the UMIST-*N* wall function were approximately double those of the Chieng & Launder wall function but still an order-of-magnitude less than low-*Re* computations.

"Ahmed" Body Flow

The flow around the Ahmed body with a rear slant angle of 25° was examined. Experimental measurements have shown that the flow separates at the top edge of the rear slant, reattaches roughly half-way down the slant and thereafter remains attached due to the presence of strong side-edge vortices. Capturing this behaviour over the rear slant is crucial in obtaining the correct drag predictions.

Using a linear $k-\varepsilon$ model, the UMIST-*N* wall function was shown to give similar flow predictions to those obtained using a standard log-law-based wall function. This was surprising since the earlier spinning-disc calculations showed that the new wall function was better able to predict highly-skewed boundary layers and it had been anticipated that this would influence the formation of the side-edge vortices. Although the results are therefore slightly disappointing, this behaviour is broadly in agreement with low-*Re* linear $k-\varepsilon$ model predictions presented by other researchers at a recent ERCOFTAC workshop on the Ahmed body flow. Computing times with the UMIST-*N* wall function were around 24% higher per iteration than those of the standard wall function.

General Comments

In terms of the aims of this thesis, it has been demonstrated that the new wall function provides flow predictions in good agreement with full low-Reynolds-number model simulations. There is a modest computational overhead in switching from a standard log-law-based wall functions to the UMIST-*N* but in both the impinging jet and spinning disc cases it was shown that computing times were still an order-of-magnitude less than a full low-*Re* calculation. In the Introduction a number of features of the "ideal" wall function were discussed under the headings of flexibility, validation and robustness. The UMIST-*N* wall function has been applied with two turbulence models, a linear and a non-linear $k-\varepsilon$ model. In principle, it can be used with any turbulence closure and a step-by-step derivation has been included for both Cartesian and non-orthogonal grid arrangements to aid further developments. The wall function can be modified relatively easily to work as a stand-alone parabolic solver and various other means of testing and validating the code were discussed in Section 4.4. In the impinging jet and spinning disc flows, the UMIST-*N* wall function was found to converge in slightly fewer iterations than the Chieng & Launder wall function and was not found to cause problems with robustness of the overall flow calculation. However, there were some unresolved issues with the use of the NLEVM and UMIST-*N* wall function in the Ahmed body flow which are discussed below.

8.3 Further Work

Ahmed Body Simulations

Simulations of the Ahmed body flow using the UMIST-*N* wall function with the non-linear $k-\varepsilon$ model were numerical unstable. Various possible causes were investigated. Using the NLEVM across the wall-function region and a linear $k-\varepsilon$ model throughout the main-grid flow domain gave a stable solution; similarly, using a linear model across the subgrid and in a few cells near the wall whilst using the NLEVM elsewhere gave a stable solution. It was only when the NLEVM was used in the subgrid and the main-grid region close to the wall that stability problems arose.

In previous simulations of the Ahmed body flow using the NLEVM, Robinson [35] found that there was some transient motion in the wake of the Ahmed body which prevented the steady-state solution converging. Some preliminary time-dependent calculations were carried out with the UMIST-*N* wall function which seemed to indicate that this was not the cause of the stability problems.

There are known stability issues with the NLEVM in flows involving strong strain-rates. A feedback loop exists due to the strain-dependent c_μ term: an overpredicted strain-rate leads to a reduced c_μ, which in turn reduces the eddy-viscosity and leads to an increased strain-rate, which then reduces c_μ etc. A number of recent modifications by Craft *et al*. [67] have improved the stability of the model. These were tested but did not provide any improvement for the present test case. It seems unlikely that this is the root cause of the stability problems, however, since Robinson was able to obtain stable solutions for the Ahmed body flow using the same model with a log-law-based wall function.

It was remarked earlier that an incorrect prediction of the pressure distribution across the subgrid with the linear $k-\varepsilon$ model could cause numerical instability, due to large strain-rates arising at the outer boundary of the subgrid. The calculation for the subgrid pressure gradient $(\partial P/\partial\zeta)$ is based on local gradients of the Reynolds stress. It is therefore possible that there was some feedback between the subgrid Reynolds stress distribution generated by the NLEVM and the calculation for $\partial P/\partial\zeta$ which introduced numerical instability. However, a stable solution could be obtained using the NLEVM across the subgrid and linear model in the main-grid, which would indicate that this too was not the cause of the stability problem.

Clearly, it is necessary to investigate the possible causes of the numerical instability and find a solution. The Ahmed body flow is large and complex and it would be easier to investigate the causes of the problem in simpler geometries which contain similar flow features. Backward facing step and diffuser flows could be examined using grids with cells skewed at 45° to emulate the flow over the rear of the Ahmed body.

Internal Corners

The Parabolic Sub-Layer (PSL) treatment of Iacovides & Launder [59] shares some common features with the UMIST-*N* wall function. Neither of the approaches solves a pressure-correction equation within the near-wall region and instead the wall-normal velocity is determined from continuity. The

PSL treatment was found to be numerically unstable in flows involving internal corners where the wall-normal velocity in the corner cell was calculated from the wall-parallel velocity, which was itself calculated from continuity. These problems are not expected to occur with the UMIST-*N* wall function, since it does not directly calculate the main-grid velocities from continuity. However, this should be confirmed by tests with the UMIST-*N* wall function in flows involving internal corners.