MODELING AND SIMULATION OF GAS-TURBINE FLOW AND HEAT TRANSFER

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Computational fluid dynamics (CFD) has undergone tremendous advances during the past quarter century. The gas-turbine industry is now using CFD with increasing regularity to address design and analysis issues associated with components that involve fluid-flow. For gas-turbine stages, these problems include aerodynamic and thermal loads on blades and vanes and coolant flow management through internal, film, and impingement cooling.[1] Despite the greater acceptance of CFD as a design and analysis tool, there are still serious concerns about its reliability, especially when applied to problems without an experimental database. Basically, designers are uncertain about how much of the CFD results can be believed because of the inherent errors in CFD through turbulence modeling, poor-quality grids, and diffusive differencing schemes. This concern is compounded for complicated problems because for them, time and resource constraints often prohibit the use of the best turbulence models and the generation of grid-independent solutions so that additional errors are introduced.

TURBULENCE MODELING

On turbulence modeling, two-equation eddy-diffusivity models (EDMs) such as k-ε, k-ω, and SST are the most widely used. The main reasons for this popularity are simplicity and robustness. But, are these reasons good enough? For many, the answer is yes. This is because though these methods do not account for some physics, they still provide useful insights. For others, the answer is an emphatic no. Their reason is that for some designs, there is little room for mistakes. For example, in turbine cooling designs, every 50^oF increase in material temperature from insufficient cooling at any location within the turbine reduces the turbine's service life by a factor of two. For these problems, the turbulence model used must be able to account for all of the key physics correctly.

So, what is so unacceptable about the two-equation EDMs? The most critical is the molecular analogy invoked in which Reynolds stresses are taken to be linear functions of the mean rates of strain, and the eddy diffusivity is an isotropic scalar. As a result of these two assumptions, EDMs cannot account for streamline curvature, rotation, buoyancy, and stress-induced secondary flows. Also, the anisotropic nature of eddy diffusivities has been confirmed by many experiments.[2]

If two-equation EDMs are inadequate, then what are the alternatives? Within the Reynolds- or ensemble-averaged Navier-Stokes (RANS) framework, there are at least three alternatives. The first is to modify the two-equation EDMs to account for effects of anisotropy. Many such modifications have been suggested and tuned to specific experimental data sets. Examples include adding additional terms to the length-scale equation (ε or ω). Unfortunately, the success of these modifications has been limited to two-dimensional flows and to the classes of problems for which they are calibrated.

The second alternative is to employ Reynolds-stress models (RSMs), which involve seven transport equations, one for each of the six Reynolds stresses and one for the length scale. Depending on how velocity-temperature fluctuations are modeled, three additional transport equations may be needed. In these transport equations, many terms such as dissipation of Reynolds stresses by the smaller scales and pressure-strain redistribution of Reynolds stresses need to be modeled. The modeling of these terms has been guided by a set of mathematical and physical arguments such as realizability, isotropy of the small scales, symmetry, consistency in tensorial representation, and kinematic constraints. The major advantage of RSMs is that they are founded on a more rigorous foundation and can account for more physics of turbulent flows such as streamline curvature, rotation, and stress anisotropy in a natural way. Also, RSMs can account for effects of unsteadiness, where the turbulence field lags the mean-flow variation in time. Unfortunately, RSMs are not without problems. First, most RSMs are still based on single-point correlations with only one time and one length scale. Second, RSMs cannot fully account for near-wall effects due to pressure reflection and eddy flattening and squeezing.[3] In fact, modeling of the low-Reynolds number regions is still an unresolved problem. So, most users of RSMs revert to two-equation EDMs in the near-wall region, which only dampens the eddy diffusivity as one approaches the wall without regard for the transfer of wall normal momentum to components parallel to the wall.

The third alternative in the RANS framework is to compromise between EDMs and RSMs by either simplifying RSMs or embarking on nonlinear constitutive relations. On simplifying RSMs, two approaches have been taken. One is to seek conditions under which the RSMs simplify. Algebraic RSMs are an example in which all convection and diffusion terms in the Reynolds-stress transport equations are neglected. These models unfortunately are better than EDMs only in being able to predict stress-induced secondary flows. The other approach is to selectively model key flow physics deemed essential. Durbin's k-ε-$\overline{v^2}$ model is an example in this category in which damping functions are not used in the near-wall region. Instead, the eddy diffusivity near a wall is explained largely through kinematic blocking of the fluctuating velocity normal to the wall. On models from nonlinear constitutive relations, the explicit versions, which are robust, have performances similar to those of algebraic RSMs.

If not RANS because of deficiencies, then what else? Direct numerical simulation (DNS) of turbulence is clearly impractical for realistic engineering problems. To some, large-eddy simulation (LES) may be feasible. Though LES has the potential to be the most realistic, like RANS models, it is not without problems. First, though dynamics subgrid-scale (SGS) models are adequate for regions away from walls, an adequate near-wall SGS model does not exist.[4] Thus, near-wall physics are invariably simulated by DNS. Second, initial and boundary conditions are unclear. If small variations in turbulence statistics on boundaries can have significant effects on the instantaneous turbulent flow field, then how many simulations are needed to obtain a mean needed for engineering design. Third, resolving all scales up to the inertial subrange for realistic engineering problems may still be impractical. Perhaps, VLES with PDE models for the SGS models are needed.

If we have infinite resources, DNS and LES are clearly the best. But, we do not have infinite resources. Despite the tremendous advances in computing power, we can always find more complicated problems to challenge even the most powerful computers once they are developed. With the computing power in the foreseeable future, RSMs and VLES appear to be our best bets. This paper gives the details of these two methods and summarizes some key modeling and simulation issues.

GRID-QUALITY MEASURES AND ERROR ESIMATES

Since the accuracy of CFD solutions are strongly affected by the quality of the mesh – structured or unstructured, it is important to develop measures that link grid quality to solution accuracy. Most grid-quality measures only consider the geometry of cells in a mesh. Others from solution-adaptive meshing, consider only the scalar nature of the solution. In CFD, the solution is a vector field, and the different components of the vector field should be considered collectively instead of individually. For example, a highly anisotropic mesh is optimal only if all cells are aligned with the flow direction, which requires a link between the cell geometry and a vector quantity. In this paper, grid-quality measures that account for the vector nature of CFD solutions are presented.[5] Also, a method is described that show how these grid-quality measures can be used to estimate solution accuracy.

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