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# Review and assessment of turbulence models for hypersonic flows

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**Abstract**

Accurate aerodynamic prediction is critical for the design and optimization of hypersonic vehicles. Turbulence modeling remains a major source of uncertainty in the computational prediction of aerodynamic forces and heating for these systems. The first goal of this article is to update the previous comprehensive review of hypersonic shock/turbulent boundary-layer interaction experiments published in 1991 by Settles and Dodson (Hypersonic shock/boundary-layer interaction database. NASA CR 177577, 1991). In their review, Settles and Dodson developed a methodology for assessing experiments appropriate for turbulence model validation and critically surveyed the existing hypersonic experiments. We limit the scope of our current effort by considering only two-dimensional (2D)/axisymmetric flows in the hypersonic flow regime where calorically perfect gas models are appropriate. We extend the prior database of recommended hypersonic experiments (on four 2D and two 3D shock–interaction geometries) by adding three new geometries. The first two geometries, the flat plate/cylinder and the sharp cone, are canonical, zero-pressure gradient flows which are amenable to theory-based correlations, and these correlations are discussed in detail. The third geometry added is the 2D shock impinging on a turbulent flat plate boundary layer. The current 2D hypersonic database for shock–interaction flows thus consists of nine experiments on five different geometries. The second goal of this study is to review and assess the validation usage of various turbulence models on the existing experimental database. Here we limit the scope to one- and two-equation turbulence models where integration to the wall is used (i.e., we omit studies involving wall functions). A methodology for validating turbulence models is given, followed by an extensive evaluation of the turbulence models on the current hypersonic experimental database. A total of 18 one- and two-equation turbulence models are reviewed, and results of turbulence model assessments for the six models that have been extensively applied to the hypersonic validation database are compiled and presented in graphical form. While some of the turbulence models do provide reasonable predictions for the surface pressure, the predictions for surface heat flux are generally poor, and often in error by a factor of four or more. In the vast majority of the turbulence model validation studies we review, the authors fail to adequately address the numerical accuracy of the simulations (i.e., discretization and iterative error) and the sensitivities of the model predictions to freestream turbulence quantities or near-wall $y^+$ mesh spacing. We recommend new hypersonic experiments be conducted which (1) measure not only surface quantities but also mean and fluctuating quantities in the interaction region and (2) provide careful estimates of both random experimental uncertainties and correlated bias errors for the measured quantities and freestream conditions. For the turbulence models, we recommend that a wide-range of turbulence models (including newer models) be re-examined on the current hypersonic experimental database, including the more recent experiments. Any future turbulence model validation efforts should carefully assess the numerical accuracy and model sensitivities. In addition, model corrections (e.g., compressibility corrections) should be carefully examined for their

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effects on a standard, low-speed validation database. Finally, as new experiments or direct numerical simulation data become available with information on mean and fluctuating quantities, they should be used to improve the turbulence models and thus increase their predictive capability.
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