FLOW AND HEAT TRANSFER PREDICTIONS FOR FILM COOLING

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ABSTRACT

The continued push for higher turbine-inlet-temperatures by gas turbine designers requires the development of more effective blade cooling strategies. Film cooling, where the coolant jet is injected at an angle to the crossflow over the blade surface, is commonly employed to protect the blades. Reynolds-Averaged Navier Stokes (RANS) solvers are often used by the gas turbine industry for film-coolant flow injection design. Unfortunately, this approach has been plagued by the lack of an universal physics-based turbulence model capable of reliably predicting blade heat transfer for a variety of film cooling configurations. Designers currently compensate for the inherent inaccuracies in the turbulence models by building significant safety margins. However, this leads to inefficient designs and loss of aerodynamic performance.

In recent years, with advances in computing technology, high-accuracy, temporally and spatially resolved calculations (called Direct Numerical Simulations or Large Eddy Simulations) are becoming possible, and these can be applied to film cooling configurations to understand the essential flow physics without the inaccuracies introduced by ad hoc turbulence models. In Direct Numerical Simulations (DNS), all essential flow scales are resolved correctly by the numerical scheme, and no *ad hoc* turbulence models are required. In Large Eddy Simulations (LES), the dynamics of all eddies beyond a cut-off width are resolved, and only the unresolved motions are modeled. DNS/LES do not use *ad hoc* models for the energy carrying scales, and therefore correctly reproduce the flow physics. These numerical explorations can therefore be used to guide the development and/or optimization of improved turbulence models for film cooling configurations.

In this paper, we will review the literature reported on film cooling predictions. RANS predictions using models ranging from two-equation models to Reynolds-Stress Transport models (RSTM) will be reviewed. We will compare representative model predicitions with LES and DNS predictions in order to highlight the potential of DNS/LES in accurately capturing the flow physics.

Representative numerical investigations typically use the k-ε and k-ω models (see for example, Garg and Gaugler[1], Kim and Benson[2], Walters and Leylek[3], and Hoda and Acharya[4]; a more complete literature survey is provided in the full paper). Varying degrees of success have been reported with the two-equation models. A systematic study of film cooling by Demuren et al.[5] revealed that the very complex flow field established behind the jet was not properly resolved and the turbulent mixing process was crudely simulated with the eddy viscosity model. Ajersch et al.[6] conducted an extensive experimental investigation and a companion numerical simulation using a low-Re k-ε

model along with a non-isotropic extension to the effective viscosity for near wall turbulence. Noticeable overprediction of shear stresses was observed and the simulation could not capture the local minimum in kinetic energy which was measured in the wake region of the jet. Demuren[7] and Hoda and Acharya[8] have carried out computations using RSTM to solve for the Reynolds stresses. The RSTM predictions do not incorporate the isotropic assumptions of the eddy viscosity models, but also fail to accurately reproduce the measured behavior in the near-field of the film cooling jet.

The above studies based on RANS underscore the inability of the turbulence models to correctly predict the near field behavior, and is because these models can not correctly capture the dynamics of the large scales in the near field. Muldoon and Acharya[9] and Tyagi and Acharya[10-13] have attempted to address these deficiencies using DNS/LES which are capable of correctly capturing these dynamics.

The film cooling configuration chosen for DNS/LES studies by Acharya and coworkers corresponds to the experimental study of Ajersch et al.[6] where measurements are presented for normal injection through square holes. The physical domain consists of a single row of six square jets on a flat plate which represents the turbine blade surface. The Reynolds number of the jet is 4,700 and the blowing ratio is R=0.5. The general flow characteristics for this case as predicted by DNS, LES and RANS with several different turbulence models are evaluated by comparison with the measurements.

Figure 1 compares the mean velocity predictions with a Lam-Bremhorst k-ε model and LES predictions with measurements of Ajersch et al[6]. It is apparent that significant improvements in the velocity predictions are obtained with LES. As noted earlier, these are attributed to the inability of the turbulence models to correctly capture the flow physics of the near-field coherent structures. In the full paper, detailed LES and RANS predictions of the six Reynolds stress components and their comparisons with the measurements are reported. Anisotropy maps, as computed from LES, are also presented and reveal the inadequacies of eddy viscosity models in representing the near-field anisotropies.

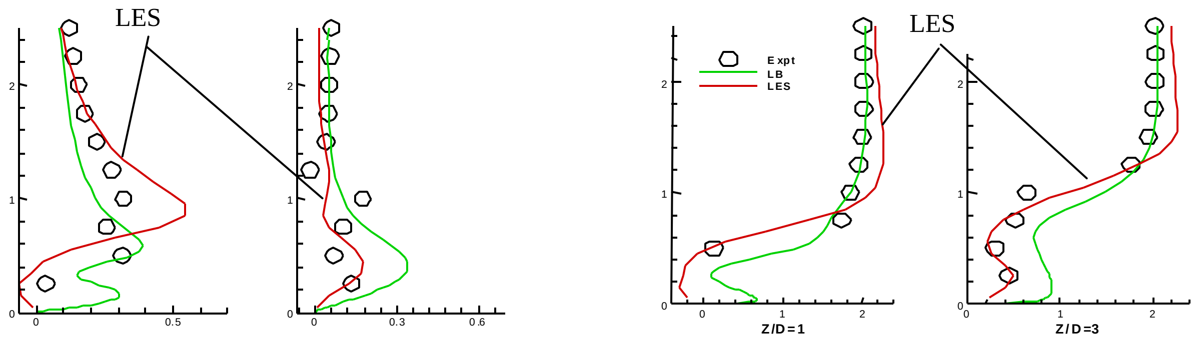

Figure 1: Comparison of LES, RANS (with Lam-Bremhorst model) and measurements (Ajersch et al., 1995). Left picture is for the vertical velocity, while right picture is for streamwise velocity. Streamwise locations, Z/D=1 and 3 are shown

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