Calculation of Two-Dimensional Turbulent Boundary Layers Using the Baldwin-Lomax Model

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Abstract

THE algebraic turbulent eddy-viscosity model of Baldwin and Lomax is critically evaluated for a class of two-dimensional, nonseparated, turbulent boundary-layer flows exhibiting adverse and favorable pressure gradients, and boundary-layer bleed. The flows are computed using the two-dimensional, mass-averaged, boundary-layer equations. Overall, the results obtained using the Baldwin-Lomax model compare favorably with the experimental data. Two quantities in the outer eddy-viscosity formulation are examined by comparison with the eddy-viscosity model of Cebeci and Smith.

Contents

The present capabilities for numerical simulation of high-speed turbulent flows are based on a variety of turbulence models. Algebraic eddy-viscosity models are still among the most popular. Certain algebraic models require the determination of the boundary-layer edge velocity and thickness, which can result in large variations in the computed outer eddy viscosity due to the uncertainty in determining the boundary-layer edge.[1] Baldwin and Lomax[1] have developed a two-layer, algebraic eddy-viscosity model in an attempt to eliminate this difficulty. This model has been patterned after the model of Cebeci and Smith[2]; however, it does not require the determination of the boundary-layer edge.

The Baldwin-Lomax turbulence model was evaluated by its originators for several cases, including a shock-wave, turbulent boundary-layer interaction on a flat plate, a supersonic turbulent compression corner, and a transonic airfoil.[1] Visbal and Knight[3] noted that the constants C_{cp} and C_{Kleb} in the Baldwin-Lomax outer formulation were dependent on flow Mach number. They also identified difficulties with the determination of the length scale in the outer eddy viscosity. Similar difficulties have been encountered by other computors.[4] Despite the difficulties identified with the Baldwin-Lomax model, and its increasing popularity and extensive application to two- and three-dimensional flows with strong viscous-inviscid interaction, a critical evaluation of this model for nonseparated, two-dimensional, turbulent boundary-layer flows has not been performed. The present investigation seeks to contribute to the evaluation of the model by critically examining its performance for a class of turbulent boundary-layer flows.

Baldwin and Lomax determined the constants C_{cp} and C_{Kleb} appearing in the outer formulation[1] by comparison with the Cebeci-Smith model for transonic, constant-pressure, boundary-layer flows, and obtained the values $C_{cp}=1.6$ and $C_{\text{Kleb}}=0.3$. In the present study, the quantities C_{cp} and C_{Kleb} were examined by comparison with the Cebeci-Smith model for Mach numbers up to 5. The comparison was performed by assuming the velocity profile satisfies the combined Laws of the Wall and Wake,[5] and equating the outer formulations for the two models. The inner formulations are essentially identical for nonseparated boundary layers. Complete details and results are provided in Refs. 4 and 6. The results of the comparison indicate that the values of C_{cp} and C_{Kleb} depend significantly upon the Mach number M, local skin-friction coefficient c_f, and wake parameter[5] Π in the Law of the Wall and Wake. As an example, for $c_f=1\times10^{-3}$, the values of C_{cp} and C_{Kleb} are approximately 1.3 ± 0.15 and 0.59 ± 0.06 for Mach numbers from 0 to 5.[4]

In the authors' opinion, the purpose of this examination is to estimate the uncertainty in the quantities C_{cp} and C_{Kleb}. The inherent simplicity of the algebraic turbulent eddy-viscosity approach does not warrant the inclusion of elaborate interpolatory functions for various quantities such as C_{cp} and C_{Kleb}. Instead, the results[4,6] are deemed to be useful in determining approximate values of C_{cp} and C_{Kleb} for a given flow condition, based upon estimated "average" values of M and c_f. Furthermore, the comparison performed is not unique. The choice of a different velocity profile or calibration to a different reference (e.g., different turbulence model other than Cebeci-Smith or set of experiments), would lead to different results.

A series of nonseparated, turbulent boundary-layer flows from the 1968 and 1980-1981 Stanford Conferences[7,8] were chosen for evaluation of the Baldwin-Lomax model. A total of five flows was considered,[4,6] three of which are presented here. The first case is an incompressible, flat-plate, turbulent boundary layer subject to uniform bleed (Favre et al.[8]). The Reynolds number Re_θ based on the momentum thickness at the start of bleed is 1598. Five bleed flow rates $F=\rho_w v_w/\rho_e u_e$ were examined, where $\rho_w v_w$ is the bleed mass flow rate at the surface, and $\rho_e u_e$ is the freestream mass flow. The quantities $C_{cp}=1.2$ and $C_{\text{Kleb}}=0.646$ were used. In Fig. 1, the computed and measured Reynolds stress for the maximum bleed rate $F=-0.0144$ are shown at $x=0.4$ m downstream of the start of bleed. The results of several computors from the 1980-1981 Stanford Conference[8] are also shown. The Baldwin-Lomax model provides a good prediction of the velocity and Reynolds stress profiles for this case, and the results are comparable to those of the other computors. For the other four bleed rates ($F=0$, -0.002, -0.0053, -0.0099), the computed and measured velocity profiles were generally good. However, the comparison with the Reynolds stress improved uniformly as the bleed increased.

An important consequence of the Baldwin-Lomax outer eddy-viscosity formulation was identified for flows with bleed. The outer function[1] $y\omega D$ (where y is the distance, ω the vorticity, and D the Van Driest damping factor) is used to determine the length and velocity scales of the outer eddy viscosity. In an incompressible flat-plate boundary layer, this function displays a well-defined maximum at $y/\delta=0.65$ using $C_{cp}=1.2$ and $C_{\text{Kleb}}=0.646$, where δ is the local boundary-layer thickness. In the presence of bleed, however, this func-

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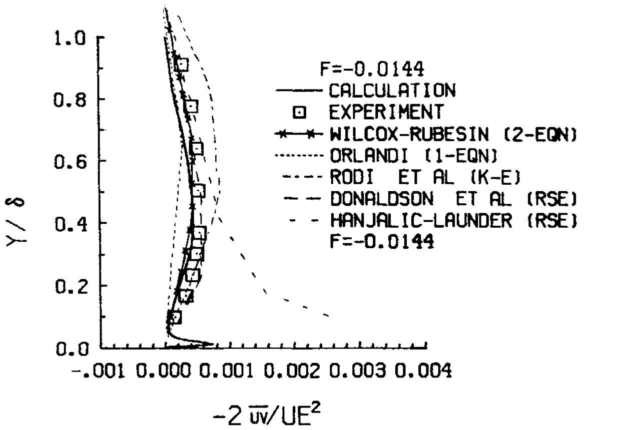

Fig. 1 Comparison of computed and measured Reynolds shear stress at $x=0.4$ m for $F=-0.0144$.

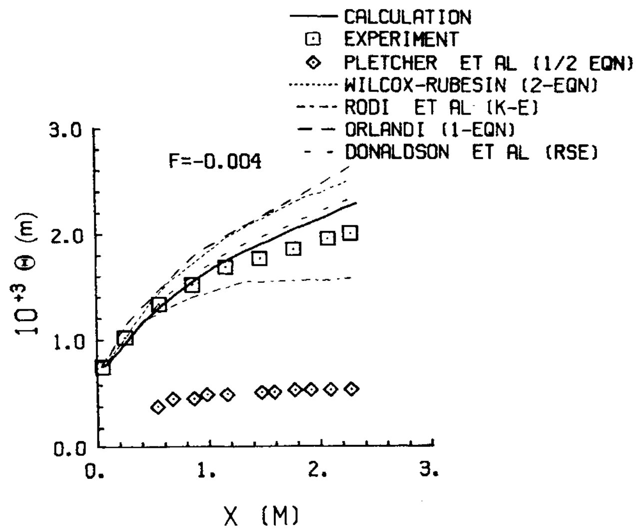

Fig. 2 Comparison of computed and measured momentum thicknesses.

tion may develop a smaller secondary inner peak close to the wall. For $F=-0.0144$, a secondary peak developed at $y/\delta=0.013$ in the bleed region. Since the length scale of the outer eddy viscosity is determined from the location of the maximum of this function, problems will arise if the inner peak exceeds the outer peak, resulting in a sudden large unphysical drop in the eddy viscosity. Additional computations at $F=-0.02$ demonstrated this behavior. A similar sudden decrease in eddy viscosity has been encountered by other computors[4] in different circumstances.

The second case is an incompressible turbulent boundary layer in an adverse pressure gradient and bleed with $F=-0.004$ (Anderson et al.[8]). The start of bleed and adverse pressure gradient coincide at the location where $Re_\theta=438$. The quantities $C_{cp}=1.2$ and $C_{\text{Kleb}}=0.646$ were used. The computed and measured momentum thicknesses are displayed in Fig. 2, together with the results of several of the Stanford 1980-1981 computors. The Baldwin-Lomax model accurately predicts the evolution of the momentum thickness. Similar

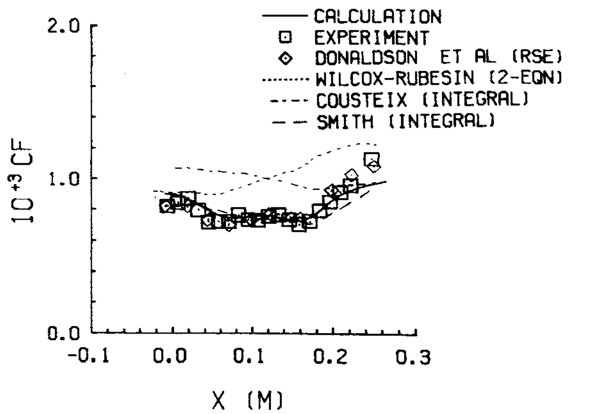

Fig. 3 Comparison of computed and measured skin-friction coefficients.

good comparison is obtained for c_f, the displacement thickness, and the velocity profiles.[4,6]

The final case is a compressible turbulent boundary layer in an adverse pressure gradient (Zwarts et al.[8]). The surface is isothermal and $Re_\theta=3.8\times10^4$ at the start of the adverse pressure gradient. The Mach number of the external flow decreases from 4 to 3 over a distance of 0.16 m. The quantities $C_{cp}=1.5$ and $C_{\text{Kleb}}=0.56$ were employed based upon the analysis cited above. The computed and measured c_f are shown in Fig. 3, together with the results of several computors from the Stanford 1980-1981 Conference. The Baldwin-Lomax model provides an accurate prediction of c_f. Similar close agreement was obtained for the shape factor and several velocity profiles.

Acknowledgments

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