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Technical Notes

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Comparison of Four Turbulence Models for Wall-Bounded Flows Affected by Transverse Curvature

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I. Introduction

IN many engineering applications, such as flow along ships, missiles, aircrafts, torpedoes, and underwater towed cables, and during fabrication of glass and polymer fibers, the boundary-layer thickness δ can be of the order of or greater than the body radius and thus the transverse curvature effects become important, i.e., the boundary layers are thick. The objective of the present work is to check the applicability of four eddy-viscosity-based turbulence models for two configurations of flows affected by transverse curvature: 1) the zero pressure-gradient boundary layer developing on the surface of a circular cylinder of radius a aligned with the flow and 2) the axial fully developed flow between concentric cylinders. For turbulent flow, two parameters a^+ and δ/a can be used to represent the effects of transverse curvature in the inner and the outer parts of flow, respectively; $a^+ = au_\tau/\nu$. (For the second flow type, δ denotes the radial location of zero shear stress from the inner cylinder surface of radius a.)

The four models are the low-Reynolds-number (low-Re) and two-layer k-E models recently developed by Michelassi et al.[1] and Rodi et al.[2] [termed the Rodi–Mansour (RM) and two-layer (TL) models, respectively] on the basis of direct numerical simulation (DNS) data for planar wall-bounded flows, the low-Re k-ϵ model of Chien (CH), which is quite accurate for planar wall-bounded flows; and the simple zero equation model of Cebeci and Smith! Earlier Cebeci[4,5] had used the zero equation models to compute thick axisymmetric boundary layers, using, however, the displacement thickness as defined for planar flows to calculate the eddy viscosity in the outer region. The zero equation model in the latter paper: which was supposed to be an improvement on the standard model in Ref. 4 for thick axisymmetric boundary layers, actually turns out to be worse for flows with small a^+ as compared with the now available accurate experimental data.[6,7] In Refs. 8 and 9 the near-wall region of thick axisymmetric boundary layers has been modeled using two different mixing length distributions.

In the experimental studies on thick axisymmetric boundary layers,[6,7,10] mostly mean velocity profiles have been measured and measurements of turbulent quantities, especially for small a^+ and large δ/a, are very limited. The skin-friction coefficient has been deduced from the mean velocity profile.[6,7,10] An added problem in the experiments is the difficulty in maintaining perfect axisymmetry of flow. These problems are avoided in DNS but with a penalty of not being able to achieve high Reynolds numbers."

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II. Results

The two definitions of the displacement thickness, one for axisymmetric flows (δ^*_{ax}) and the other for planar flows (δ^*_{pl}), are used to compute eddy viscosity in the outer region (for definitions see Refs. 6 and 7) using the zero equation model. The corresponding models are denoted by the zero equation (δ^*_{ax}) and zero equation (δ^*_{pl}) models, respectively. With an increase in δ/a, the ratio $\delta^*_{ax}/\delta^*_{pl}$ increases and only in the limit of $\delta/a \to 0$, $\delta^*_{ax}/\delta^*_{pl} \to 1$. For the axial developed flow between cylinders the intermittency is taken equal to 1.0 throughout. The equations were solved using the control volume method. For the boundary-layer flow, 120 radial grids were taken, and for the axial developed flow between concentric cylinders, 90 radial grids were taken. To resolve sharp gradients close to the wall, about 50 grids in both the flows were located within $y^+ = 50$. For details of code validation see Ref. 12.

A. Thick Axisymmetric Boundary-Layer Flow

1. Effect of Transverse Curvature on the Predicted C_f

For this flow configuration 10 cases with different values of δ/a and a^+ were studied. A plot of C_f vs a^+ (Fig. 1) shows that with an increase in a^+ the deviation between the predicted and measured C_f decreases (hereafter when we write deviation, it means the deviation between the measurements and the predictions by the five models and the deviation between the predictions themselves). For $a^+ \simeq 30$, the zero equation (δ^*_{ax}) model underpredicts C_f by about 15%. At this a^+, the other models underpredict C_f by larger amounts, with maximum underprediction of about 45% by Chien's model. At $a^+ \gtrsim 300$, the values of C_f predicted by the five models are within experimental uncertainty.[1] At $a^+ \simeq 300$, however, the transverse curvature effects may still be important in the near-wall region, but for $a^+ \geq 500$ the curvature effects appear to be small. It can be shown that, in contrast, the transverse curvature effects in the outer region (represented by δ/a) have negligible effect on the predicted C_f.[12]

In Fig. 2 the predicted mean velocity profiles for $a^+ = 46.2$ are compared with the measurements.[1] To remove the dependence on C_f, whose predicted and measured values are different, the mean velocity profiles are plotted as u/u_∞ vs y/θ_{ax} (for the definition of θ_{ax} see Refs. 6 and 7), so that a direct comparison of just velocity can

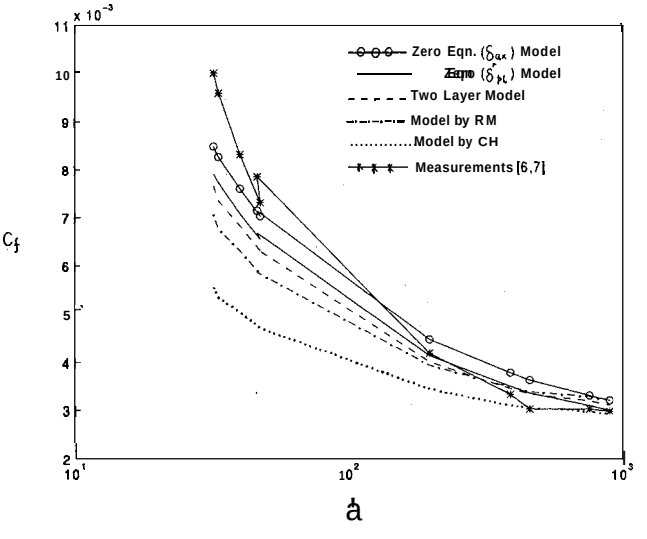


Fig. 1 Thick axisymmetric boundary-layer flow: the predicted skin-friction coefficient compared with the measurements.