Model for Turbulent Backflows

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Introduction

TURBULENT backflow regions exhibit a strong wake-like behavior down to the immediate vicinity of solid surfaces. This behavior precludes the use of the law-of-the-wall as a tool for analyzing such flow regions and dictates development of turbulence models dedicated to treating these flows.

Such a model was developed and used successfully to predict a large class of flows involving detached flow regions.[1] It was an algebraic model applied as a module within a "host" model (such as a $k-\epsilon$ model) to determine the eddy-viscosity field inside backflow regions.

Experiments in turbulent recirculation zones[2,3] indicate that there is a wide class of such flows in which the backflow region is characterized by negligible turbulence production. In such cases, the balance of turbulence energy is between diffusion of energy from the outer (large-scale turbulence) flow into the reversed flow region and its dissipation within that region. This mechanism is used as a basis for a new turbulence model geared for backflow regions. The model, featuring the analytical solution of an ordinary differential equation (ODE) normal to walls, is introduced and tested. Like the previous model,[1] it is used as a module within a host model to determine the eddy viscosity throughout backflow regions; unlike the previous model, it requires a host model that solves a field equation for the turbulence kinetic energy.

Model Formulation

The turbulence kinetic energy equation (with gradient diffusion model) is given by

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho U_i k) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] - \rho\overline{u_i' u_j'}\,\frac{\partial U_i}{\partial x_j} - C_k\frac{(\rho k)^2}{\mu_t} \qquad (1)$$

where $\sigma_k = 1.00$ and $C_k = 0.080$.

This equation will be simplified based on the following experimental observations of turbulent backflows[2,3]: the kinetic energy of turbulence scales as the Reynolds shear stress $-\overline{u'v'}$ and generally behaves in a way representable by a sine function between the wall and the freestream with its local maximum reached approximately at the location where $-\overline{u'v'}$ reaches its local maximum value (see Fig. 1a). The latter usually coincides with the local maximum of the mean streamwise velocity's normal gradient. Thus, the kinetic energy k may be modeled in the form

$$\frac{\rho k}{\rho_s k_s} = \frac{\cos\beta - \cos[\beta(1 + y/y_0)]}{1 + \cos\beta} \qquad (2)$$

where

$$\beta = \frac{\pi}{1 + y_{u_s}/y_0}$$

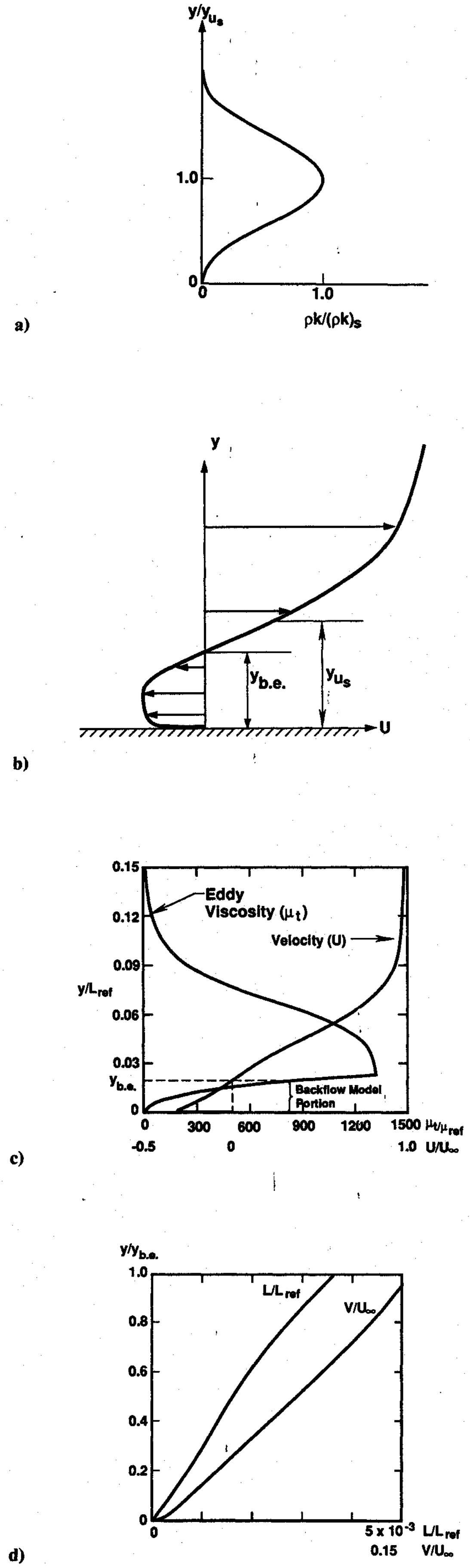

Fig. 1 **Nomenclature and basic properties of backflow model.**

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y_{u_s} is the distance from the wall to the location of $u_s = \sqrt{-\overline{(u'v')}_{\max}}$ (see Fig. 1b), and $k_s = k_{\max}$ is the turbulence kinetic energy at that location. k_s must be provided by the host model since y_{u_s} is outside the backflow region.

To estimate the value of y_0, $\mathrm{d}k/\mathrm{d}y$ is evaluated at the wall ($y = 0$) using Eq. (2):

$$\left[\frac{\mathrm{d}(k/k_{\max})}{\mathrm{d}(y/y_{u_s})}\right]_{y=0} = \frac{\beta \sin\beta}{1+\cos\beta}\,\frac{y_{u_s}}{y_0} \tag{3}$$

Based on experimental evidence,[3] the left-hand-side of this equation is ≈ 0.15. Solving for y_0 yields

$$y_0/y_{u_s} \approx 0.03 \tag{4}$$

However, y_0 is not a sensitive parameter as long as $0 < y_0/y_{u_s} \ll 1$.

For the purpose of modeling the turbulence within backflow regions, k will be treated as a function of y given by Eq. (2), with streamwise variations in k effected implicitly through the corresponding variations in $(\rho k)_s$ and y_{u_s}. Using this concept in Eq. (1) and retaining only the diffusion and dissipation terms[2] results in the equation

$$\frac{\mathrm{d}}{\mathrm{d}y}\left[(\mu+\mu_t)\frac{\mathrm{d}k}{\mathrm{d}y}\right] - C_k\frac{(\rho k)^2}{\mu_t} = 0 \tag{5}$$

Further experimental evidence[2] indicates that the near-wall zone within backflow regions, in many cases, contributes little to the turbulence energy balance. Therefore, molecular diffusion will be neglected, and Eq. (5) is further reduced to read

$$\frac{\mathrm{d}}{\mathrm{d}y}\left(\mu_t\frac{\mathrm{d}k}{\mathrm{d}y}\right) - C_k\frac{(\rho k)^2}{\mu_t} = 0 \tag{6}$$

or, equivalently,

$$\frac{\mathrm{d}\phi}{\mathrm{d}y} = \left[C_k(\rho k)^2\frac{\mathrm{d}k}{\mathrm{d}y}\right]\frac{1}{\phi} \tag{7}$$

where

$$\phi \equiv \mu_t\frac{\mathrm{d}k}{\mathrm{d}y}$$

Using the model Eq. (2) for k and $\mathrm{d}k/\mathrm{d}y$, the solution to Eq. (7) is given by

$$\mu_t = \left\{\frac{1}{\pi\sin\varphi(y)}\sqrt{\frac{2}{3}C_k\frac{\rho_s}{\rho}\frac{[\cos\beta-\cos\varphi(y)]^3}{1+\cos\beta}}\right\}\rho\sqrt{k_{\max}}(y_0+y_{u_s}) \tag{8}$$

where

$$\varphi(y) = \frac{y_0+y}{y_0+y_{u_s}}\pi$$

with the boundary condition $\mu_t = 0$ at $y = 0$ applied.

It is noted that, while

$$\frac{\mathrm{d}k}{\mathrm{d}y} = \frac{\beta\sin\varphi(y)}{1+\cos\beta}\,\frac{(\rho k)_{\max}}{\rho y_0} - \frac{\partial \ell n\rho}{\partial y}k$$

the term involving the density gradient has been neglected in the solution of Eq. (7). This simplification is not expected to significantly change the quality of the predicted eddy-viscosity field in near-wall reversed flow regions for a wide range of practical flow situations.

The eddy-viscosity formula, Eq. (8), is used inside backflow regions, i.e., between the wall and the local backflow edge, designated as $y_{\mathrm{b.e.}}$ in Fig. 1b. Figure 1c shows a typical eddy-viscosity profile calculated with this model. The corresponding velocity profile is also shown on the same plot. Thus, in this model the velocity scale is

$$V = \sqrt{k} = \sqrt{\frac{\cos\beta-\cos\varphi}{1+\cos\beta}\,\frac{\rho_s}{\rho}\,k_{\max}} \tag{9}$$

and the length scale results implicitly from the μ_t distribution:

$$L = \frac{\mu_t}{\rho\sqrt{k}} = \frac{1}{\pi}\sqrt{\frac{2}{3}C_k}\,\frac{\cos\beta-\cos\varphi}{\sin\varphi}(y_0+y_{u_s}) \tag{10}$$

Figure 1d shows typical length and velocity-scale profiles within the backflow.

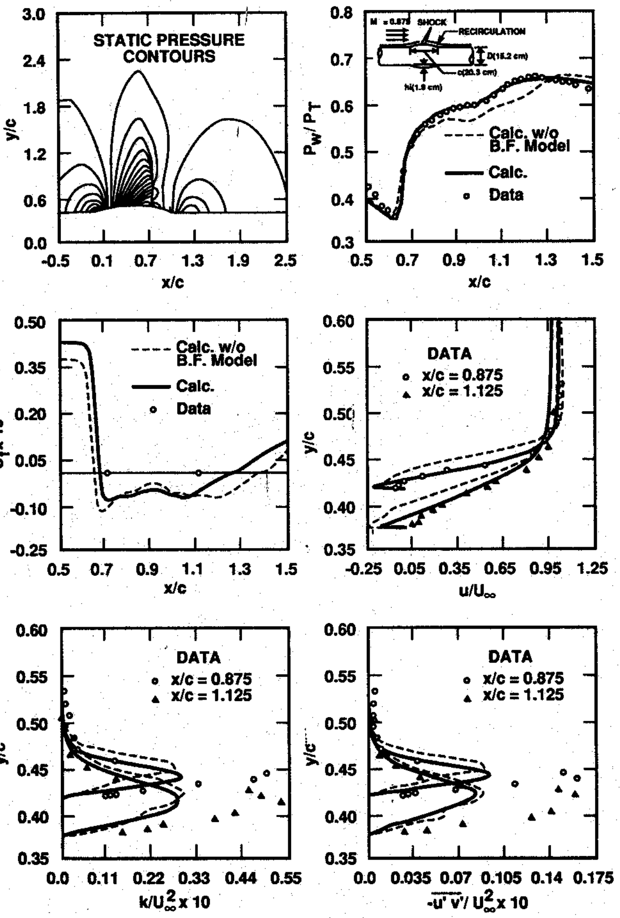

Fig. 2 Predictions and data comparisons for case 1 (Ref. 5).

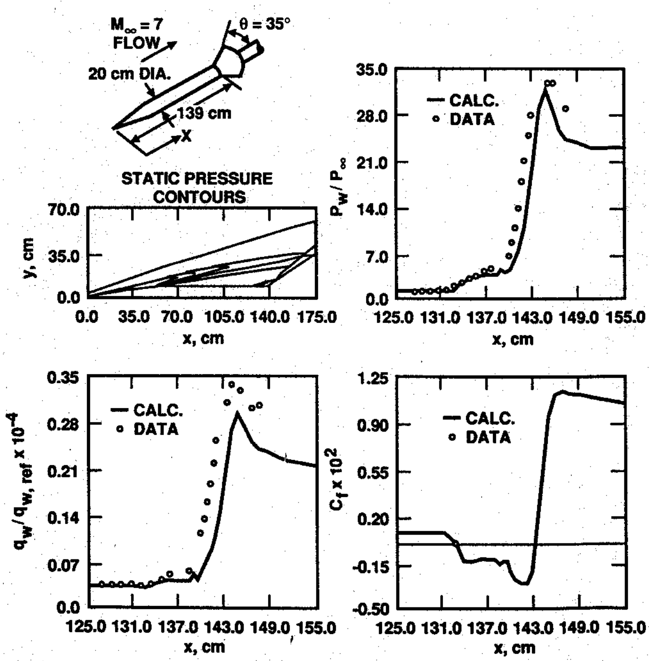

Fig. 3 Predictions and data comparisons for case 2 (Ref. 6).

Model Evaluation

The new backflow model was included as a module in the $k-L$ and $k-\epsilon$ turbulence models available in the USA Reynolds-averaged Navier-Stokes solver.[4] Several flow cases were computed and the results agreed well with experimental data. Two of these cases are presented here:

Case 1

This case is the transonic flow over an axisymmetric bump of Bachalo and Johnson.[5] Figure 2 presents comparisons between predictions and data for surface pressure, skin friction, axial velocity profiles at two streamwise locations within the reversed flow region, and the corresponding Reynolds shear stress and turbulence kinetic energy profiles. Pressure contours are also included to show the shock location. The host turbulence model was the one-equation $k-L$ model.[1] For comparison, the figure includes computation results without incorporation of the backflow module.

It is seen that $k_{\max}$ is underpredicted by about 50%; however, since Eq. (8) involves $k_{\max}^{1/2}$, this translates into a 29% underprediction of the eddy-viscosity magnitude, not severe enough to harm the overall predictive quality, especially that of the wall pressure distribution. It is also noted that the skin-friction prediction is inferior to that shown in Ref. 1, using the algebraic backflow model. However, the current model is based on a more rigorous derivation that avoids the need for a near-wall term as in the old model. Therefore, the new model deserves further evaluation before a fair comparison of the two models is possible.

Case 2

This case is the hypersonic axisymmetric flow over an ogive-cone-cylinder 35-deg flare configuration of Kussoy and Horstman.[6] Figure 3 shows predictions and data comparisons for surface pressure, skin friction, and surface heat transfer. The pressure contour plot is included to show shock structure and extent of upstream influence. Here, too, the $k-L$ turbulence model served as the host model.

Summary

A model for turbulent backflows was introduced and tested. The model is based on experimental observations, in particular, the wake-like behavior of the turbulence and the type of energy balance observed in detached flow regions. This leads to an ODE for the eddy viscosity, resulting from a reduced form of the kinetic energy equation. This ODE is solvable analytically. The model is applied as a module within a "host" eddy-viscosity model (such as a $k-\epsilon$ model) to predict the eddy-viscosity field inside backflow regions. Predictions of several reversed flow cases are encouraging. Further testing of this model, covering a wide range of Mach numbers and geometries, will be reported in future work.

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Effect of Leading-Edge Geometry on a Turbulent Separation Bubble

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Introduction

SEPARATION bubbles are found in a variety of fluid dynamics devices and processes, and they often have a critical impact on performance. Understanding of the mechanisms which affect and control the size and characteristics of separation bubbles is therefore important. Several studies on sharp-edged bluff bodies[1-3] have shown that increased freestream turbulence can reduce the separation bubble size by up to 45%. The shortening of the bubble is attributed to an increased spreading rate of the separated shear layer, but there is yet no comprehensive explanation for the interaction mechanism between the stream turbulence and the separated shear layer. Dziomba[4] used trip wires on the front face of a blunt rectangular plate to control the separation bubble length. The trip wire was found to have the same qualitative effect as an increase in freestream turbulence; however, it was argued that the shortening of the bubble was mostly due to an alteration of the front face geometry resulting in an effective change in the angle of separation.

This Note presents the results of an experimental study showing the effect of the separation angle on both pressure distribution and size of a separation bubble forming on a blunt thick plate (Fig. 1). Flow-visualization results for laminar and transitional flow on a similar geometry were reported by Ota et al.[5] The present measurements were made at a fully turbulent, Reynolds-number-independent flow regime ($Re = 5 \times 10^4$), and the reattachment lengths were deduced directly from surface measurements using a pulsed-wire wall probe.

Model and Experimental Facility

The experiments were conducted in the $2.4 \times 1.6 \times 25$ m University of British Columbia (UBC) low-speed wind tunnel. A model that was previously used for detailed measurements of the turbulent flowfield around a blunt rectangular plate[6] was modified for the present experiments. The model had a chord of 800 mm, a thickness D of 89.9 mm (3.5 in.)—corresponding to a solid blockage ratio BR of 5.6%—and a span between end plates of 1000 mm, giving an aspect ratio AR of 11.1. The angle α at which the shear layer separates from the plate could be altered (from 45–90 deg) by attaching various triangular front pieces to the modified front face of the model.

Two-dimensionality and symmetry (spanwise and top-to-bottom) were verified by surface flow visualization and mean pressure measurements. The use of side plates and side extensions ensured a nominally two-dimensional separation region extending over the central two-thirds portion of the plate. The surface pressure distribution was measured using a Barocel differential pressure transducer and a 48-port Scanivalve system connected to a series of pressure taps along the centerline of the model. The mean reattachment length x_r, defined as the

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