Turbulent Flow Over Bump
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This validation test case is based on experimental data from Bachalo and Johnson [1]. A turbulent boundary layer develops over an axially symmetric bump. Under the specified flow conditions a stationary shock wave occurs and the flow separates on the rear portion of the bump and reattaches a bit downstream of the bump. The tests were performed in the AMES 2- by 2-foot transonic pressure tunnel. According to data obtained from Harvey, Stainback, and Owen [2], the turbulence intensity in the wind-tunnel test section should be between 0.5% and 0.6% but closer to the first value.

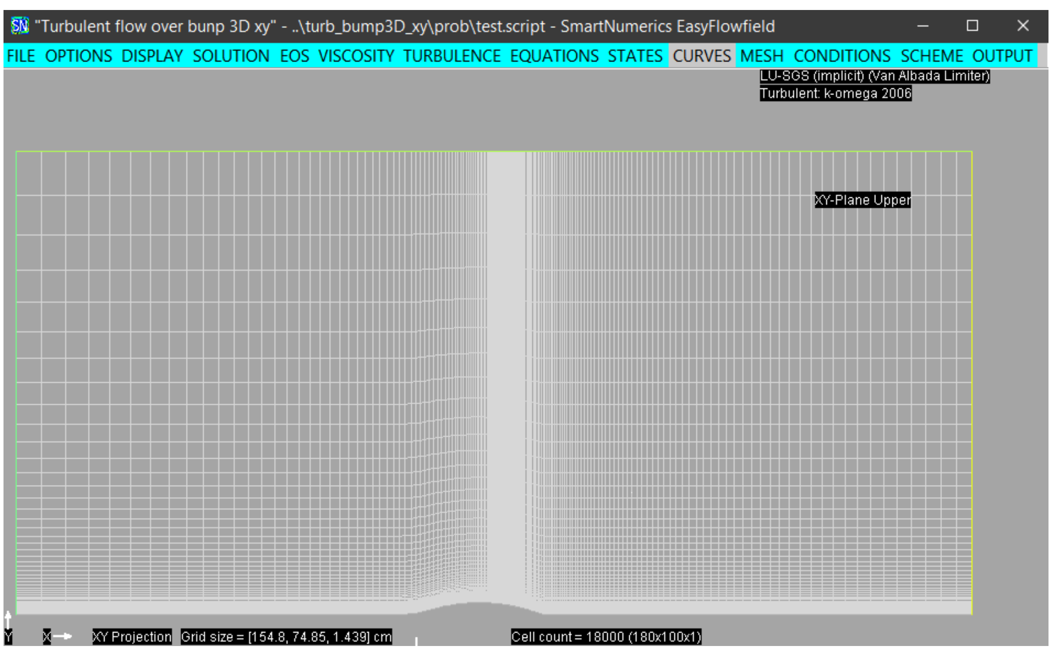

Fig. 1: Three-dimensional grid used to simulate flow over pipe with a bump.

Figure 1 displays the upper face of the 3D grid used to simulate flow over the axisymmetric bump. An inflow condition with fixed mass flow and total temperature is imposed at the west face of the grid and an outflow condition is with fixed static pressure is imposed on the east face. A far-field condition is imposed on the north face and the pipe wall and bump are modelled using a no-slip condition on the south face. The upper and lower faces of the grid (white) are joined by a periodic interface. The angle between the upper and lower faces is 1 degree. The bump has a length of 20.4 cm. The grid was imported from a file using the CGNS format and is a modified version of a grid originally obtained from the CGNS web site http://cgns.sourceforge.net/CGNSFiles.html.

The initial condition and the reference condition used at the boundaries is for Mach 0.875 flow of air at a static pressure of 55,791 Pascals and a static temperature of 255.6 °K. The molecular viscosity is computed from temperature using the Sutherland formula. The resulting Reynolds number based on bump length is 2.66×10^6. The far-field turbulent intensity was set to 0.5% and the far-field eddy viscosity was set to one tenth of the molecular viscosity.

An (implicit) LU-SGS solver was used with an initial CFL number of 30 which was gradually increased to 60 after a delay of 500 cycles. The HLLC fluxes were used in conjunction with the van Albada limiter.

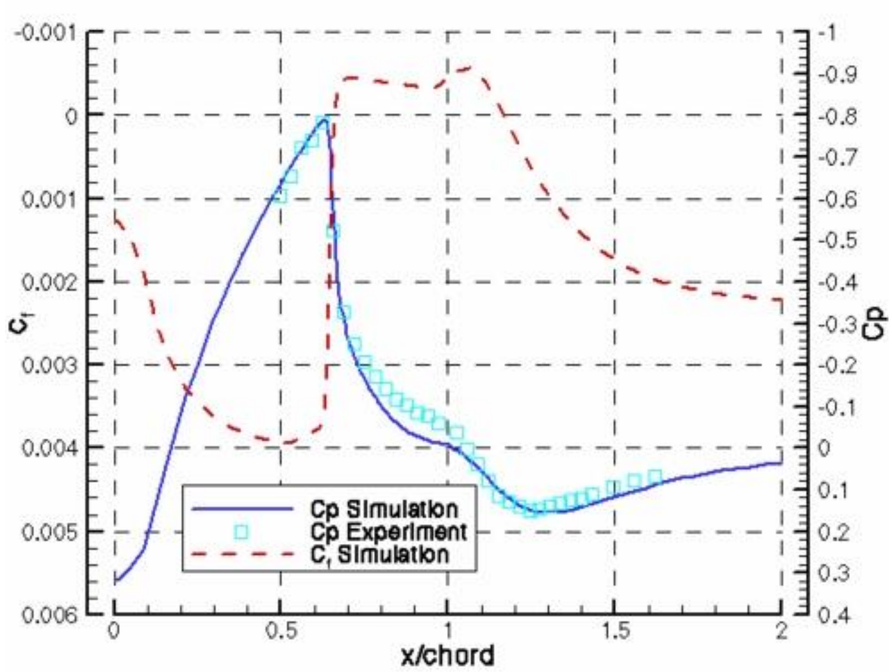

Fig. 2: Pressure and friction for flow about axisymmetric bump (k-ω 2006).

Figure 2 compares the pressure coefficients

$$c_p = 2\frac{p_w - p_\infty}{\rho_\infty U_\infty^2}$$

obtained using the k-ω 2006 model of Wilcox [3] to the experimental values. Here p_w is the local pressure at the wall, p_∞ is the far-field pressure, ρ_∞ is the far-field density, and U_∞ is the far-field velocity. The leading edge of the bump is at x equal to zero and chord is the bump length.

Also displayed are the skin friction coefficients computed using

$$c_f = 2\frac{\rho_w (u^*)^2}{\rho_\infty U_\infty^2} sign(u*)$$

using the local friction velocity, u^*, output by the solver. Here, ρ_w is the local density at the wall. No experimental values are available. The friction velocity is output with a negative sign if the flow along the wall is reversed. Thus, the plotted friction is negative where the flow reverses. Flow separates near 0.66 of chord and reattaches near 1.16 of chord. The corresponding experimental values are 0.7 of chord and 1.1 of chord, respectively. Figure 3 displays Mach contours obtained using the k-ω 2006 turbulence model.

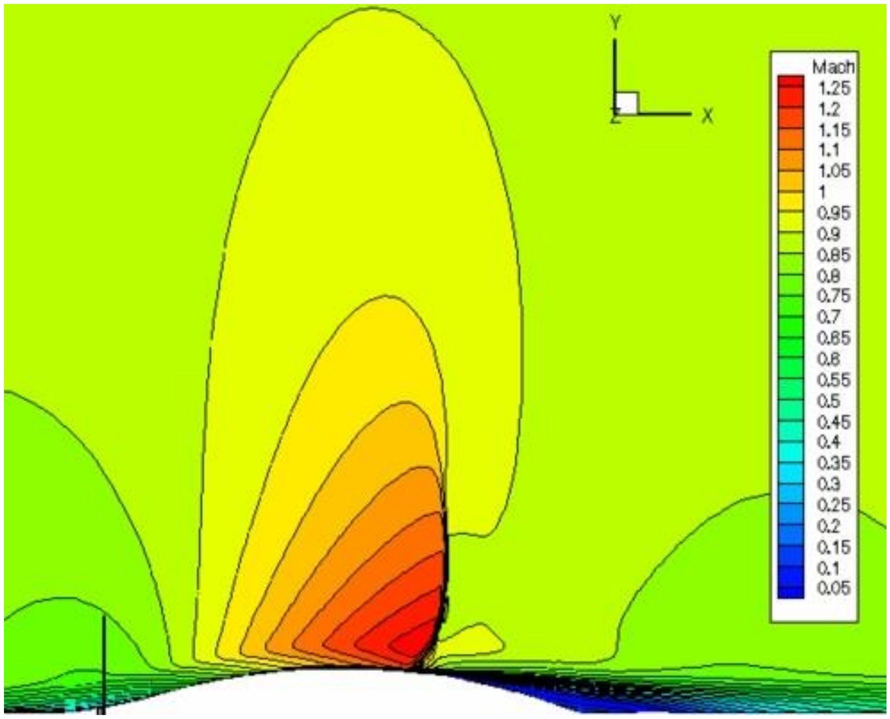

Fig. 3: Contours of Mach number for flow about axisymmetric bump (k-ω 2006).

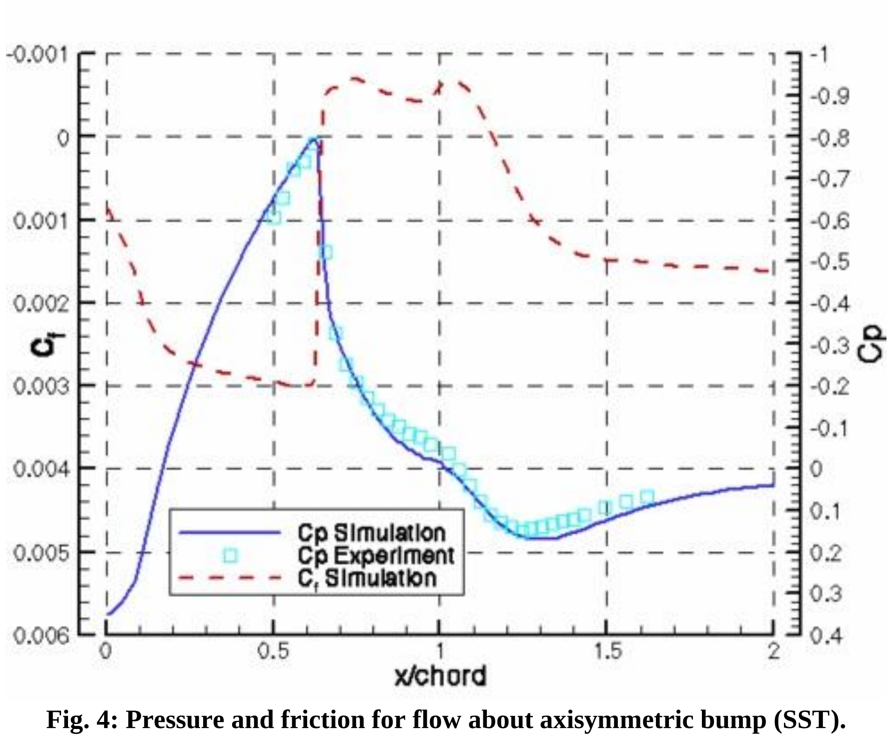

Fig. 4: Pressure and friction for flow about axisymmetric bump (SST).

Figure 4 displays the results using the SST turbulence model of Menter [4]. In this case, flow separates near 0.65 of chord and reattaches near 1.16 of chord.

Increasing the turbulence intensity from 0.5% to 0.6 percent produces minor changes in the pressure and friction curves but the points of separation and reattachment remain essentially unchanged for both turbulence models. The k-ω turbulence model is more sensitive than the SST turbulence model to large changes in the far-field values of turbulence intensity or eddy viscosity.

References

[1] Bachalo, W., Johnson, D., "An Investigation of Transonic Turbulent Boundary Layer Separation Generated on an Axisymmetric Flow Model," AIAA 79-1479, 1979.
[2] Harvey, W. D., Stainback, P. C., Owen, F. K., An Evaluation and Assessment of Flow Quality in Selected NASA Wind Tunnels, MASA TM-85659, 1983.
[3] Wilcox, D. C., Turbulence Modeling for CFD, 3rd ed., DCW Industries Inc., 2006.
[4] Menter, F. R., Improved two-equation k-ω Turbulence Models for Aerodynamic Flows, NASA TM-103975, 1992.