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Modification of the Two-Equation Turbulence Model in NPARC to a Chien Low Reynolds Number k-ε Formulation

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SUMMARY

This report documents the changes that were made to the two-equation k-ε turbulence model in the NPARC (National-PARC) code. The previous model, based on the low Reynolds number model of Speziale, was replaced with the low Reynolds number k-ε model of Chien. The most significant difference was in the turbulent Prandtl numbers appearing in the diffusion terms of the k and ε transport equations. A new inflow boundary condition and stability enhancements were also implemented into the turbulence model within NPARC. The report provides the rationale for making the change to the Chien model, code modifications required, and comparisons of the performances of the new model with the previous k-ε model and algebraic models used most often in PARC/NPARC. The comparisons show that the Chien k-ε model installed here improves the capability of NPARC to calculate turbulent flows.

SYMBOLS

C_D	constant for turbulent kinetic energy dissipation expression (equal to 0.164)
C_f	skin friction along flat plate
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	k-ε turbulence model terms
C_μ	k-ε turbulence model constant (equal to 0.09)
f_μ, f_1, f_2	k-ε turbulence model terms
H	distance from centerline to top or bottom wall of ejector nozzle
I	turbulence intensity
k	turbulent kinetic energy
ℓ	turbulent mixing length
Re_t	Reynolds number based on turbulent quantities
Re_θ	Reynolds number based on momentum thickness
t	time

u, v, w	velocities
u', v', w'	turbulent velocity components
$u_{ref(k\text{-}\varepsilon)}$	reference velocity for turbulent kinetic energy limiter
u_{tot}	local inflow velocity magnitude
x, y	Cartesian coordinates
y+	distance from wall normalized by shear length scale
ε	rate of turbulent kinetic energy dissipation
μ	dynamic viscosity
μ_t	turbulent viscosity
$\mu_{t\text{-}max}$	maximum turbulent viscosity limiter
Π	production term in k-ε model
ρ	density
σ_k, σ_ε, σ_τ	turbulent Prandtl numbers
τ	turbulent time scale

Subscripts:

i, j	computational coordinates

INTRODUCTION

The PARC Navier-Stokes code (refs. 1 and 2) has been used extensively by government and industry to analyze propulsion flows. Despite advances in flow-solving capabilities, the ability of codes such as PARC to calculate complex flows is strongly dependent on the turbulence model employed. Until recently, only algebraic models have been available in PARC for turbulent flow simulations. The standard algebraic turbulence model in PARC is based on the work of P.D. Thomas (ref. 3). This model calculates turbulent viscosity near surfaces (wall-bounded part of the model), and in regions where two or more flows are mixing (free shear layer part of the model) but was optimized for the latter. The Baldwin-Lomax algebraic turbulence model (ref. 4), which only calculates turbulent viscosity in wall-bounded regions, is available also. Algebraic turbulence models such as these often model complex flow cases inadequately because the single mixing length distributions used to calculate turbulent viscosity are normally tuned to a particular case and often are not applicable to all flows.

Two-equation models avoid this single mixing length limitation by solving two additional transport equations to calculate turbulent viscosity. These models have been installed previously in PARC to improve the code's capability to calculate turbulent flows. The Chien low Reynolds number k-ε model (ref. 5) with modifications for compressibility added by Nichols (ref. 6) has been available in the 2D/axisymmetric code (PARC2D) but was not successfully installed in PARC3D. Another k-ε model based on the work of Speziale (ref. 7) was installed in PARC2D and PARC3D but has not provided desirable accuracy or stability.

To provide the U.S. aerospace community with a reliable Navier-Stokes propulsion flow simulator, the NPARC (National-PARC) Alliance was recently instituted and the PARC code has been renamed to NPARC. As part of this effort, modifications to the two-equation turbulence model in NPARC were made to improve the model's accuracy and to enhance its stability. This report documents these modifications. The following sections provide the rationale for making the required code modifications, recommendations for using the model, and comparisons of the new model with the turbulence models most often used in PARC/NPARC for two benchmark cases.

BACKGROUND OF SPEZIALE AND CHIEN k-ε TURBULENCE MODELS

The two-equation turbulence model in the NPARC code (Version 1.0) was installed by Nichols (ref. 8) in 1991. It is a k-ε model (two equations are solved: one for turbulent kinetic energy k and the other for the rate of turbulent kinetic energy dissipation ε) based on the work of Speziale (ref. 7). In reference 7, Speziale develops a k-τ two-equation turbulence model (the quantity solved in the second equation, τ, is a turbulent time scale and is equal to k/ε) to avoid solving for ε, which he states does not have a natural boundary condition near solid surfaces. Speziale, however, shows that his τ-transport equation is equivalent to the ε-transport equation if an assumption holds (to be discussed shortly). This provides the following k-ε model, which has been available for use in NPARC:

$$\mu_t = C_\mu f_\mu \rho k^2 / \varepsilon \tag{1}$$

$$\frac{D(\rho k)}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + \Pi - \rho\varepsilon \tag{2}$$

and

$$\frac{D(\rho\varepsilon)}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{\varepsilon 1} f_1 \Pi \frac{\varepsilon}{k} - C_{\varepsilon 2} f_2 \rho \frac{\varepsilon^2}{k} \tag{3}$$

with

$$\Pi = \mu_t \frac{\partial u_j}{\partial x_i}\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right] \tag{4}$$

and

$$f_\mu = (1 + 3.45/\sqrt{Re_t})\tanh(y+/70) \tag{5}$$

$$f_1 = 1.0 \tag{6}$$

$$f_2 = (1 - e^{(-y+/4.9)})^2 \tag{7}$$

$$Re_t = \frac{\rho k^2}{\mu\varepsilon} \tag{8}$$

with $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.83\,(1 - .22\,e^{(-Re_t/6)2})$, $\sigma_k = 1.36$, and $\sigma_\varepsilon = 1.36$.

The constants σ_k and σ_ε are turbulent Prandtl numbers appearing in the diffusion terms of the k and ε transport equations (2) and (3). Speziale's assumption allowing his second transport equation for τ to be transformed to an ε transport equation is that $\sigma_k = \sigma_\varepsilon = \sigma_\tau$. Launder and Spalding (ref. 9) and Launder et al. (ref. 10) indicate that the values for the turbulent Prandtl numbers $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ are appropriate for flows involving mixing layers. Reference 9 mentions that values other than these may have been used where strictly wall-bounded flows were to be calculated (as was Speziale's intent) but that $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ are more applicable to a wide class of flows involving wall-bounded and/or mixing regions. From equation (1) and the diffusion terms of equations (2) and (3), note that for a given flow field, increasing σ_k substantially (from 1.0 to 1.36) while holding σ_ε to a smaller change (from 1.3 to 1.36) results in lower turbulent viscosity μ_t, and possibly significantly less calculated mixing for a case involving mixing of flows. Because the low Reynolds number k-ε model of Chien (ref. 5) employs $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ and has been used successfully in many Navier-Stokes codes, the current work incorporates the Chien k-ε model in place of the existing k-ε model in NPARC. For reference, the k-ε model described in equations (1) through (8) will be referred to as the NPARC 1.0 k-ε model in the rest of this report.

The Chien low Reynolds number k-ε model was installed successfully in the PARC2D code in 1990 (refs. 6 and 11). It is presented next to demonstrate the changes required to convert the NPARC 1.0 k-ε model to the Chien model in NPARC:

$$\mu_t = C_\mu f_\mu \rho k^2 / \varepsilon \tag{9}$$

$$\frac{D(\rho k)}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + \Pi - \rho\varepsilon - 2\mu k / y^2 \tag{10}$$

and

$$\frac{D(\rho\varepsilon)}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{\varepsilon 1} f_1 \Pi \frac{\varepsilon}{k} - C_{\varepsilon 2} f_2 \rho \frac{\varepsilon^2}{k} - 2\mu \frac{\varepsilon}{y^2} e^{(-0.5y^+)} \tag{11}$$

with

$$\Pi = \mu_t \frac{\partial u_j}{\partial x_i}\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right] \tag{12}$$

and

$$f_\mu = 1 - e^{(-.0115y+)} \tag{13}$$

$$f_1 = 1.0 \tag{14}$$

$$f_2 = 1.0 - 0.22\, e^{-(Re_t/6)^2} \tag{15}$$

$$Re_t = \frac{\rho k^2}{\mu\varepsilon} \tag{16}$$

with $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.35$, $C_{\varepsilon 2} = 1.8$, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$.

By comparing equations (1) through (8) to equations (9) through (16), note that the Chien and NPARC 1.0 k-ε models differ in $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k, σ_ε, f_μ, and f_2. The Chien model also has an extra near-wall term for each of the two turbulent transport equations (10) and (11) that does not appear in the NPARC 1.0 k-ε model. These terms allow for all of the turbulent quantities to be set to zero at a solid surface by using the Chien model. These changes were made to convert the k-ε model in NPARC from one based on the Speziale model to one based on the Chien model.

INFLOW BOUNDARY CONDITIONS

Free Inflows

The standard boundary condition in NPARC for subsonic inflows is the free boundary (type 0). The previous implementations of the Chien and NPARC 1.0 k-ε turbulence models extrapolated the quantities k and ε from the interior when this free boundary was specified at an inflow. This has been shown to result in artificially low levels of turbulent kinetic energy and calculated turbulent viscosity near inflows (ref. 12).

To allow for more accurate simulation of turbulence at an inflow when using the free boundary, a new inflow boundary condition for the k and ε equations was added in the current work. Turbulent kinetic energy is defined as

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \tag{17}$$

If isotropic turbulence is assumed,

$$I^2 = \frac{\overline{u'^2}}{u_{tot}^2} = \frac{\overline{v'^2}}{u_{tot}^2} = \frac{\overline{w'^2}}{u_{tot}^2} \tag{18}$$

so that the turbulent kinetic energy may be defined as a function of the turbulence intensity:

$$k = \frac{3}{2} I^2 \cdot u_{tot}^2 \tag{19}$$

The implementation of this boundary condition in NPARC requires the intensity I to be specified which allows k to vary as the local velocity magnitude at the free boundary inflow. With k obtained from equation (19), one possibility for specifying ε is to set the turbulent viscosity equal to the laminar viscosity or a multiple of the laminar viscosity, as suggested in reference 13. Equation (9) is then used to determine the corresponding value of ε at the boundary. A second method for obtaining ε is to use the following expression from reference 14, which requires a turbulent mixing length ℓ to be specified:

$$\varepsilon = C_D \, k^{3/2} / \ell \tag{20}$$

The input of the turbulent intensity and either the turbulent viscosity or turbulent length scale required when using this free boundary condition is described in the code usage section.

Fixed Inflows

If a fixed boundary (type -10), which is recommended for supersonic inflows, is specified at an inflow, all main flow and turbulent quantities remain unchanged from the values on the restart file.

STABILITY ENHANCEMENTS

Experience with the NPARC code has shown that the previous k-ε model had stability difficulties, especially in the NPARC3D code. To enhance the stability of the current k-ε model, the following modifications were made to the NPARC code:

1. With the k-ε model previously installed in NPARC, only the turbulent viscosity was relaxed, and for 50 iterations following initialization of the k-ε model from an algebraic turbulence model. In the current Chien model, the updated turbulent quantities k and ε were relaxed in addition to the turbulent viscosity, and for 500 iterations after initialization of the k-ε model. This was the method used successfully in PARC2D (ref. 11).

2. Examination of unstable flow cases indicated that the instability was caused by unrealistically large values of k which often were calculated during the initial iterations after switching from an algebraic model. Examining equation (9), very large values of k cause μ_t to become very large. To prevent such large values of k and resulting μ_t, code was added to limit any value of k from

exceeding 10 percent of a reference kinetic energy obtained from a velocity characteristic of the flow ($u_{ref(k\text{-}\varepsilon)}$):

$$k = \text{minimum}\left(k - \text{calculated};\ 0.10 \cdot \frac{1}{2} u^2_{ref(k-\varepsilon)}\right) \tag{21}$$

In addition, the turbulent viscosity is prevented from exceeding a maximum turbulent viscosity $\mu_{t\text{-}max}$. Input of this characteristic velocity and maximum turbulent viscosity is discussed in the next section.

CODE USAGE

The NPARC code with the Chien k-ε model implementation is run essentially as described in reference 8. The k-ε model is initialized from an algebraic turbulence model solution at the iteration level set by the input NTURB. As previously mentioned, all turbulent quantities are relaxed for the first 500 iterations after NTURB to assist stability. The limiters in the code are set with the inputs UREFKE and TMUMAX. UREFKE is the characteristic velocity nondimensionalized by AREF (the reference speed of sound for NPARC), and TMUMAX is the maximum turbulent viscosity nondimensionalized by the reference viscosity. Default values for these inputs are UREFKE = 1.0 and TMUMAX = 3000.0. These should be reasonable upper bounds for many flows of interest; however, if the flow to be calculated is at very high or very low Mach number, the UREFKE variable can be set to a velocity considered characteristic of the flow to be calculated. In addition, if the flow contains a high-speed free shear layer, TMUMAX can be increased appropriately.

The new inflow boundary condition (used with the main flow solver's free boundary) allows up to 3 different inflows to be set in namelist TURBIN. Values for intensity are specified through the inputs TUIN1, TUIN2, TUIN3, and the corresponding turbulent viscosities can be set through the inputs TMUIN1, TMUIN2, and TMUIN3. For example, a flow has two inflow boundaries. The first has a measured turbulence intensity of 2 percent and the turbulent viscosity is to be set equal to the laminar viscosity; the second has a turbulence intensity of 5 percent and the turbulent viscosity is to be set to 10 times the laminar viscosity. The inputs would be set as follows:

```
&TURBIN
TUIN1 = .02,
TUIN2 = .05,
TMUIN1 = 1.,
TMUIN2 = 10.,
&END
```

Also, the EDGE (JEDGE, KEDGE, or LEDGE) parameters must be set to -1 for the first boundary and -2 for the second boundary. A value of -3 would have been specified if there were a third inflow boundary. Negative integers are used to avoid confusion with the EDGE used for no-slip surfaces. If anything other than -1, -2, or -3 is specified for an EDGE input, the default extrapolation boundary condition is used for k and ε at that inflow boundary. A turbulent length scale can be specified instead of a turbulent viscosity by specifying the length (nondimensionalized by the NPARC reference length) as a negative value with the TMUIN1, TMUIN2, or TMUIN3 input. For example, at an inflow boundary, the turbulence intensity is 2 percent and the desired turbulent mixing length is 0.05 ft (with the reference length equal to 1 ft). The inputs would be

```
&TURBIN
TUIN1  =  0.02
TMUIN1 = -0.05
&END
```

If a fixed boundary (type -10) is specified, the turbulent quantities will remain the same as those values on the restart file at the boundary, just as for the main flow quantities. Outflow boundary conditions can be specified with the free boundary (type 0) and nothing set for the EDGE parameters. The free boundary condition will extrapolate the turbulent quantities, which is appropriate at outflows. Slip surfaces or planes of symmetry can be modeled with the slip wall boundary (type 50) and axes of symmetry are modeled with the type 51 boundary in the NPARC2D code. These boundary conditions also extrapolate the turbulent quantities from the flow interior. The no-slip boundary conditions (types 60 and 61) set all of the turbulent quantities to zero at the boundary. The pole boundaries (types 81 to 83) and block interface boundaries (types 70 to 75) operate the same for the turbulent flow quantities as for the main flow quantities.

RECOMMENDATIONS

Four recommendations for using the Chien k-ε model are (1) All INVISC values, which control the directions for which viscous terms are calculated, should be set to 1. (2) When the k-ε model is initialized, DTCAP should not be increased from the value that was locked on while using the algebraic model. The time step should be examined after turning on the Chien model, especially during the iterations immediately after the iteration level corresponding to (NTURB + 500) as it may change from what was acceptable when using the algebraic model. DTCAP will most likely need to be reduced slightly. (3) The grid should be packed to solid walls such that the first grid point off of the wall is within y+ = 5 and preferably positioned closer to y+ = 1. Avva, Smith, and Singhal (ref. 15) have shown the sensitivity of low Reynolds number k-ε models to the grid packing near solid surfaces and the importance of locating the first point away from the wall well within the laminar sublayer. (4) As a calculation approaches convergence, the flow field should be examined to be sure that UREFKE and TMUMAX are not limiting the turbulent kinetic energy and turbulent viscosity. These inputs are intended only to assist stability of the Chien k-ε model in the iterations after initialization from an algebraic turbulence model.

It is necessary to run all of the blocks in turbulent mode when using the k-ε model because it is not possible to interpolate the turbulent quantities from an inviscid or laminar block.

INVESTIGATION OF NPARC TURBULENCE MODELS

Two benchmark test cases are investigated in this section to compare the performance of this Chien k-ε turbulence model, the previous NPARC 1.0 k-ε model, and the algebraic turbulence models used most frequently in PARC and NPARC. The first case is flow over a flat plate to investigate the models' performance for a wall-bounded flow, and the second is flow through an ejector nozzle to investigate a more complex propulsion flow case with the mixing of two flows as the dominant flow feature. Both flows are two-dimensional so that they could be properly modeled with NPARC2D or NPARC3D. The Baldwin-Lomax model was not applied to the ejector nozzle case because it is a wall-bounded turbulence model and this flow is dominated by turbulent mixing. Calculations were obtained with both versions of the code for each test case and turbulence model. However, because the results obtained by using NPARC2D or NPARC3D for each case were very similar, only the NPARC3D results are presented in the following discussion.

Flat Plate

A schematic of the flat plate case investigated with NPARC is shown in figure 1. The inflow total pressure and outflow static pressure, both free boundaries, provided a Mach 0.2 flow over the plate. The grid had 111 points in the horizontal direction and 81 points in the vertical direction and was packed tightly to the wall to resolve the boundary layer. Five points were used in the z-direction to accommodate the NPARC3D code. A fixed inflow profile was not used. Instead, the flow reached the leading edge of the plate at grid point 15 in the horizontal direction where the boundary layer began and then continued downstream over the no-slip surface. Two inflow boundary conditions were specified for use with the new Chien model: (1) the default extrapolation, and (2) turbulence intensity set to 5 percent and the turbulent viscosity set to 100 times the laminar viscosity. This second inflow was specified to determine if setting a relatively high turbulence intensity (5 percent) would have an effect on the flow calculation, and not because these specific turbulence quantities were measured in an experiment. The calculations showed that the flow over the flat plate was independent of the upstream condition.

NPARC3D calculations are compared with experimental data of Wieghardt (ref. 16) in figure 2. The skin friction calculated by using the Thomas model is very low because of the very small turbulent viscosity values that the Thomas model calculates for purely wall-bounded flows (such as this flat plate test case). The Baldwin-Lomax model produces very good agreement with experimental data as expected because it was tuned to attached wall boundary layer flows. The NPARC 1.0 k-ε model provides reasonable agreement with the data and the Chien k-ε model (installed in this work) provides somewhat closer agreement. The Chien solution shown in figure 2 was obtained by using the extrapolation inflow boundary condition for the turbulent quantities, but both Chien calculations provided the same flow solution as mentioned earlier.

Ejector Nozzle

A schematic of the ejector nozzle test case is shown in figure 3. This flow is dominated by mixing of the primary flow with entrained secondary flow and is similar in fundamental operation to nozzles that have been considered for vertical and short takeoff or landing (VSTOL) and high-speed transport application. The grid had 131 points in the horizontal direction by 121 points in the vertical direction. Five points were used in the z-direction with NPARC3D, as for the flat plate case. Free boundaries were specified at the inflow to both the primary nozzle and ejector inlets and at the outflow. Initial calculations with the NPARC 1.0 k-ε and new Chien k-ε models used the default extrapolation boundary because no turbulence measurements were available from the experiment. Atmospheric pressure was specified at the ejector inflow while the total pressure specified for the primary nozzle was set to provide a nozzle pressure ratio (nozzle total pressure divided by atmospheric static pressure) of 2.44. The outflow pressure was the static pressure measured in the experiment (ref. 17) at approximately 26.9 cm downstream of the primary nozzle exit. Because the geometry of the nozzle is symmetric about a plane passing through the center of the ejector nozzle assembly, only one half of the ejector nozzle was modeled with NPARC.

Velocity profiles obtained from the NPARC calculations are compared to experimental data in figure 4. The axial positions were measured relative to the primary nozzle exit plane and the vertical positions were nondimensionalized by the local half-duct height H. The velocity profiles at 7.6, 12.7, 17.8, and 26.7 cm downstream of the primary nozzle exit plane show that the Chien k-ε model added in this work provided much better agreement with the experimental data than that provided by the Thomas algebraic model (which was optimized for free shear layers such as in this ejector nozzle case) and the NPARC 1.0 k-ε model, despite the inflow boundary condition. Total temperature profiles in figure 5 indicate the same mixing behavior. The Thomas and NPARC 1.0 k-ε models produce significantly less turbulent viscosity than the Chien model (fig. 6) which is directly responsible for the large differences in predicted mixing. The large differences in the two k-ε solutions for this mixing-dominated problem is due to the specification of constants σ_k and σ_ε. As mentioned earlier, the values for the turbulent Prandtl numbers used by the Chien model, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$, have been shown to provide more realistic flow predictions than the values $\sigma_k = 1.36$ and $\sigma_\varepsilon = 1.36$ used by the NPARC 1.0 k-ε model. The enhancements added in this work gave the Chien k-ε model more stability than the NPARC 1.0 k-ε model in the iterations immediately following initialization from the algebraic model.

Additional calculations were obtained with the Chien k-ε model while varying the inflow boundary condition to determine the effects of specifying the turbulent quantities on the mixing downstream. In addition to the extrapolation case (the default inflow) previously discussed, two other inflows were examined: (1) turbulence intensity = 5 percent and turbulent viscosity = 500 times the laminar viscosity for the primary flow, turbulence intensity = 2 percent and turbulent viscosity = 100 times the laminar viscosity for the secondary flow; and (2) turbulence intensity = 5 percent and a turbulent length scale set to 5 percent of the nozzle exit height for the primary flow, turbulence intensity = 2 percent and turbulent length scale = 5 percent of the secondary inlet passage height at the primary nozzle exit plane. These two additional inflows were specified arbitrarily, since no turbulence measurements were available from reference 17.

Figures 7 and 8 compare the solutions obtained with the Chien k-ε model and the three different inflow boundary conditions. The calculation that specified the turbulence intensity and turbulent viscosity for the primary and secondary flows more closely matches the data than the calculation using extrapolation at the inflows or the calculation specifying the turbulence intensity and turbulent mixing length. The specified turbulence intensities and viscosities cannot be justified based on these results because these quantities were not taken from the experiment. However, these results do show that the new inflow boundary condition may enable more accurate calculations for such flow cases when turbulence measurements are available to set as inflow boundary conditions.

CONCLUSIONS

The two-equation turbulence model in the NPARC code was modified so that the model is based on the low Reynolds number k-ε model of Chien and no longer is based on the Speziale model. The most significant change was made to the turbulent Prandtl numbers appearing in the transport equations for k and ε. Stability enhancements and a new inflow boundary condition for the turbulent quantities were also added to the k-ε model. Comparisons of the NPARC solutions obtained using the previous and new k-ε models with experimental data indicate that the Chien k-ε model installed in this work improves the capability of NPARC to calculate propulsion flows. In addition, the limiters added for code stability seem to improve the convergence characteristics of NPARC relative to that observed with the NPARC 1.0 k-ε model. The specification of different inflow boundary conditions resulted in different mixing solutions for the ejector nozzle case. The new inflow boundary condition will be examined further to establish guidelines for appropriate specification of the turbulent quantities at inflows.

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REFERENCES

1. Cooper, G.K. and Sirbaugh, J.R., "The PARC Distinction: A Practical Flow Simulator," AIAA Paper 90-2002, July 1990.
2. Cooper, G.K. and Sirbaugh, J.R., "PARC Code: Theory and Usage," Arnold Engineering Development Center Report AEDC-TR-89-15, December 1989.
3. Thomas, P.D., "Numerical Method for Predicting Flow Characteristics and Performance of Nonaxisymmetric Nozzles, Theory," NASA CR-3147, September 1979.
4. Baldwin, B.S. and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows," AIAA Paper 78-257, January 1978.
5. Chien, K.-Y., "Predictions of Channel and Boundary-Layer Flows With a Low-Reynolds-Number Turbulence Model," *AIAA Journal*, January 1982, Vol. 20, No. 1, pp. 33-38.
6. Nichols, R.H., "A Two-Equation Model for Compressible Flows," AIAA Paper 90-0494, January 1990.

7. Speziale, C.G., Ridha, A., and Anderson, E.C., "A Critical Evaluation of Two-Equation Turbulence Models for Near Wall Turbulence," NASA CR-182068, June 1990.
8. Nichols, R.H., "Addition of a Two-Equation Turbulence Model to the Blocked PARC3D Code," Calspan Corporation-AEDC Operations Memorandum, October 28, 1991.
9. Launder, B.E. and Spalding, D.B., "The Numerical Computation of Turbulent Flows," *Computer Methods in Applied Mechanics and Engineering,* 1974, Vol. 3, pp. 269-289.
10. Launder, B.E., Morse, A., Rodi, W., and Spalding, D.B., "Prediction of Free Shear Layer Flows - A Comparison of the Performance of Six Turbulence Models," NASA SP-321, July 1972, pp. 361-426.
11. Cooper, G.K., Huddleston, D.H., and Varner, M.O., "Addition of a k-ε Turbulence Model to the Blocked PARC Codes," Sverdrup Technology-AEDC Operations Memorandum, September 4, 1990.
12. Georgiadis, N.J. and Yoder, D.A., "Use of Navier-Stokes Methods for the Calculation of High-Speed Nozzle Flow Fields," AIAA Paper 94-3212, June 1994.
13. Choi, D., Sabnis, J.S., and Barber, T.J., "Application of an RNG k-ε Model to Compressible Turbulent Shear Layers," AIAA Paper 94-0188, January 1994.
14. Anderson, D.A., Tannehill, J.C., and Pletcher, R.H., *Computational Fluid Mechanics and Heat Transfer*, McGraw-Hill, New York, 1984.
15. Avva, R.K., Smith, C.E., and Singhal, A.K., "Comparative Study of High and Low Reynolds Number Versions of k-ε Models," AIAA Paper 90-0246, January 1990.
16. Wieghardt, K. and Tillman, W., "On the Turbulent Friction Layer for Rising Pressure," NACA TM-1314, 1951.
17. Gilbert, G.B. and Hill, P.G., "Analysis and Testing of Two-Dimensional Slot Nozzle Ejectors With Variable Area Mixing Sections," NASA CR-2251, May 1973.

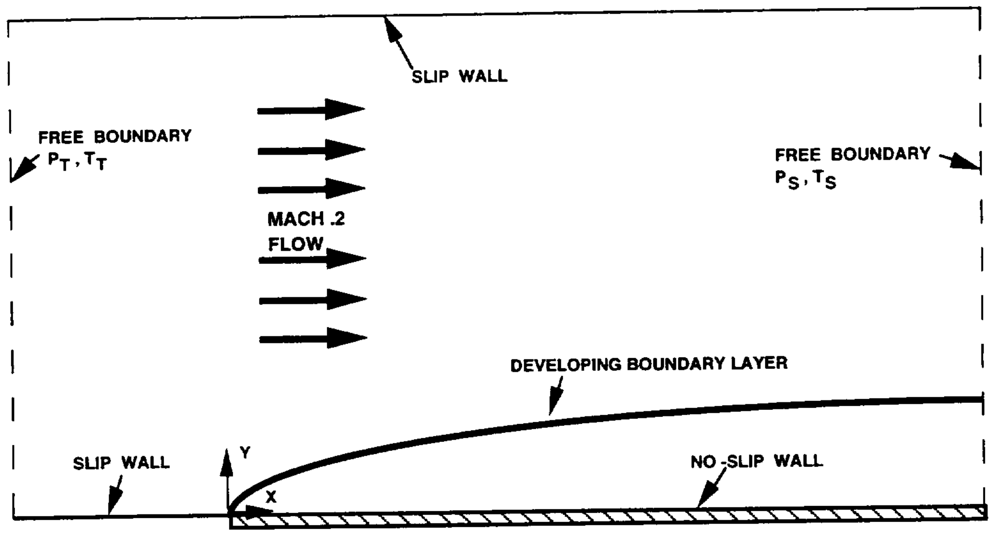


Figure 1. Schematic of the flat plate test case.

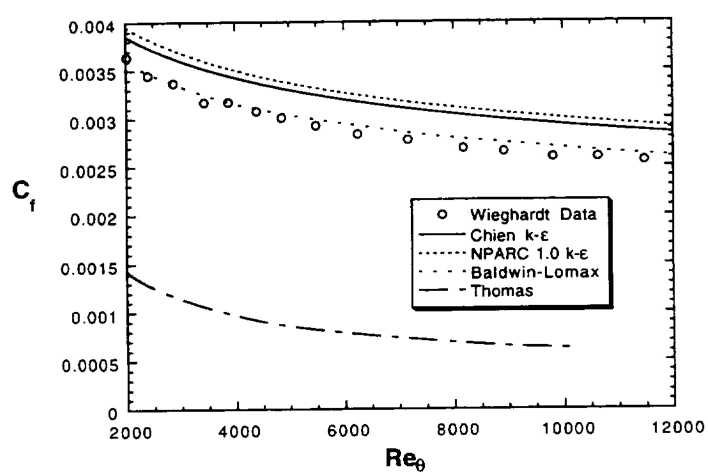


Figure 2. Skin friction for the flat plate flow.

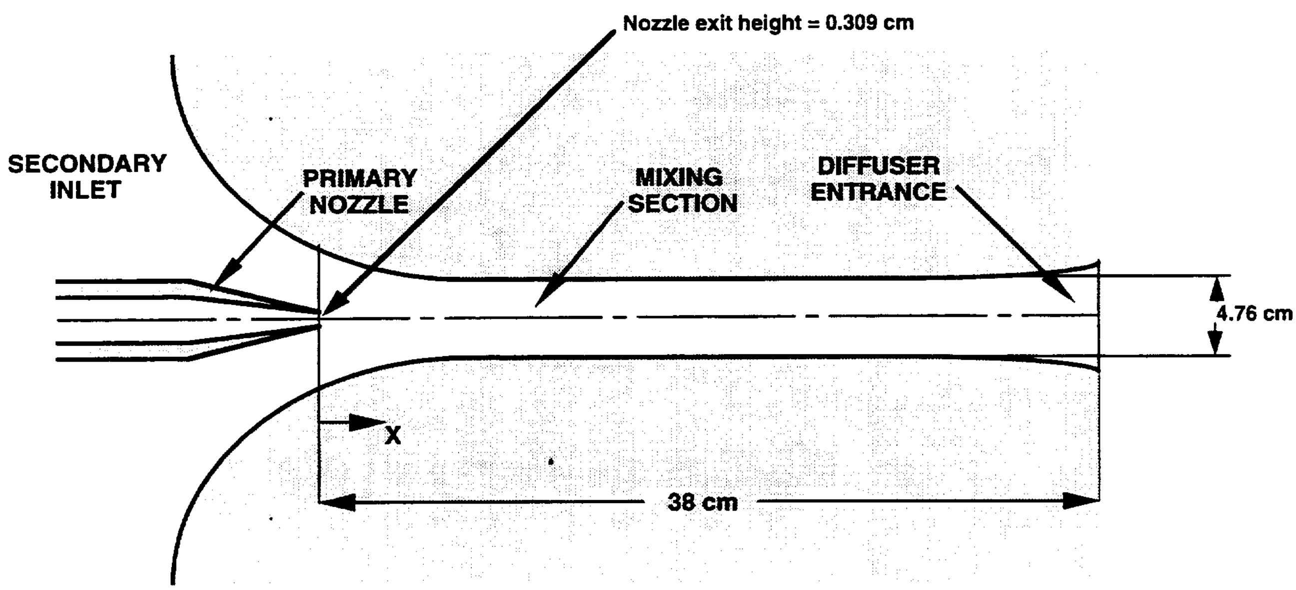
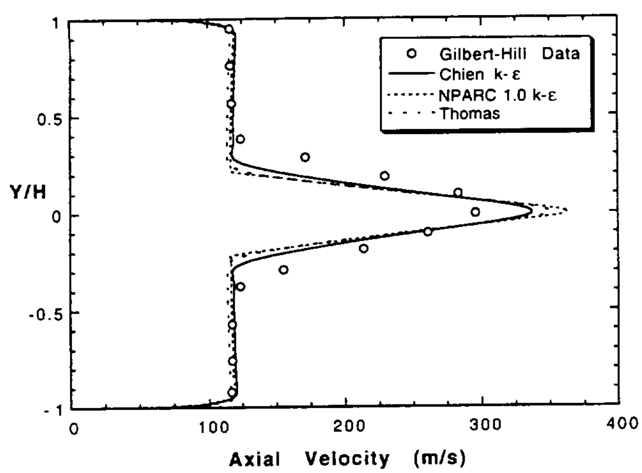
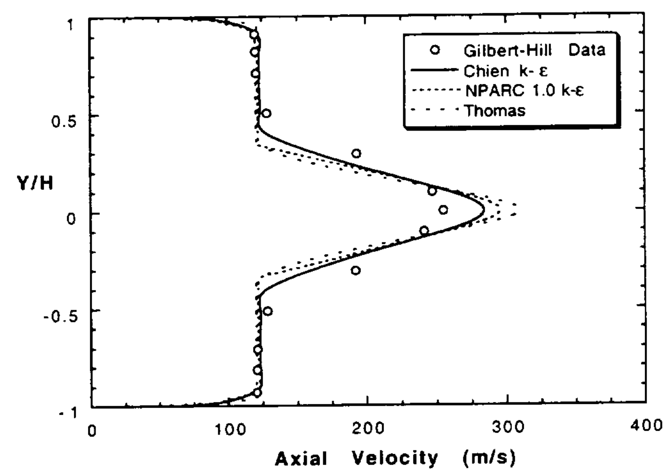


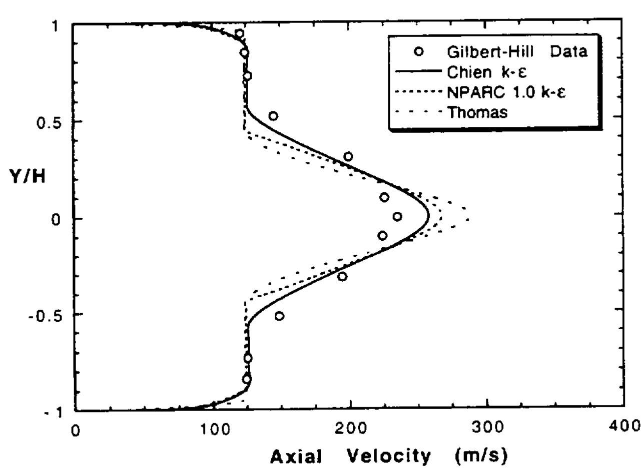
Figure 3. Schematic of the 2D ejector nozzle test case.



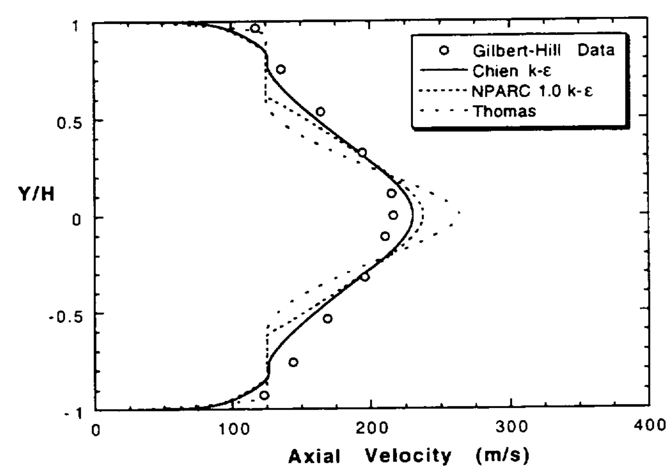
(a) x = 7.6 cm.



(b) x = 12.7 cm.

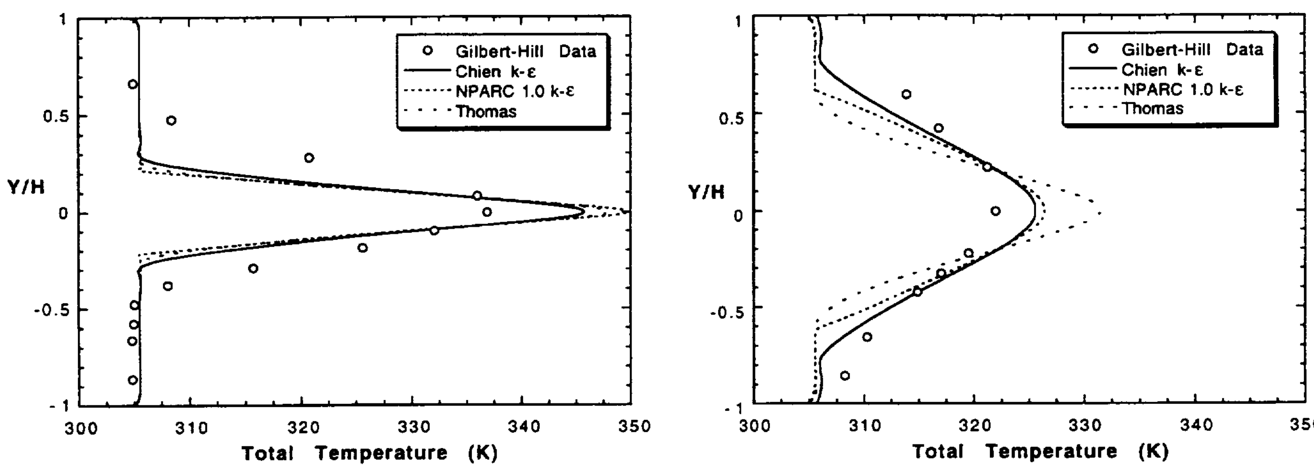


(c) x =17.8 cm.



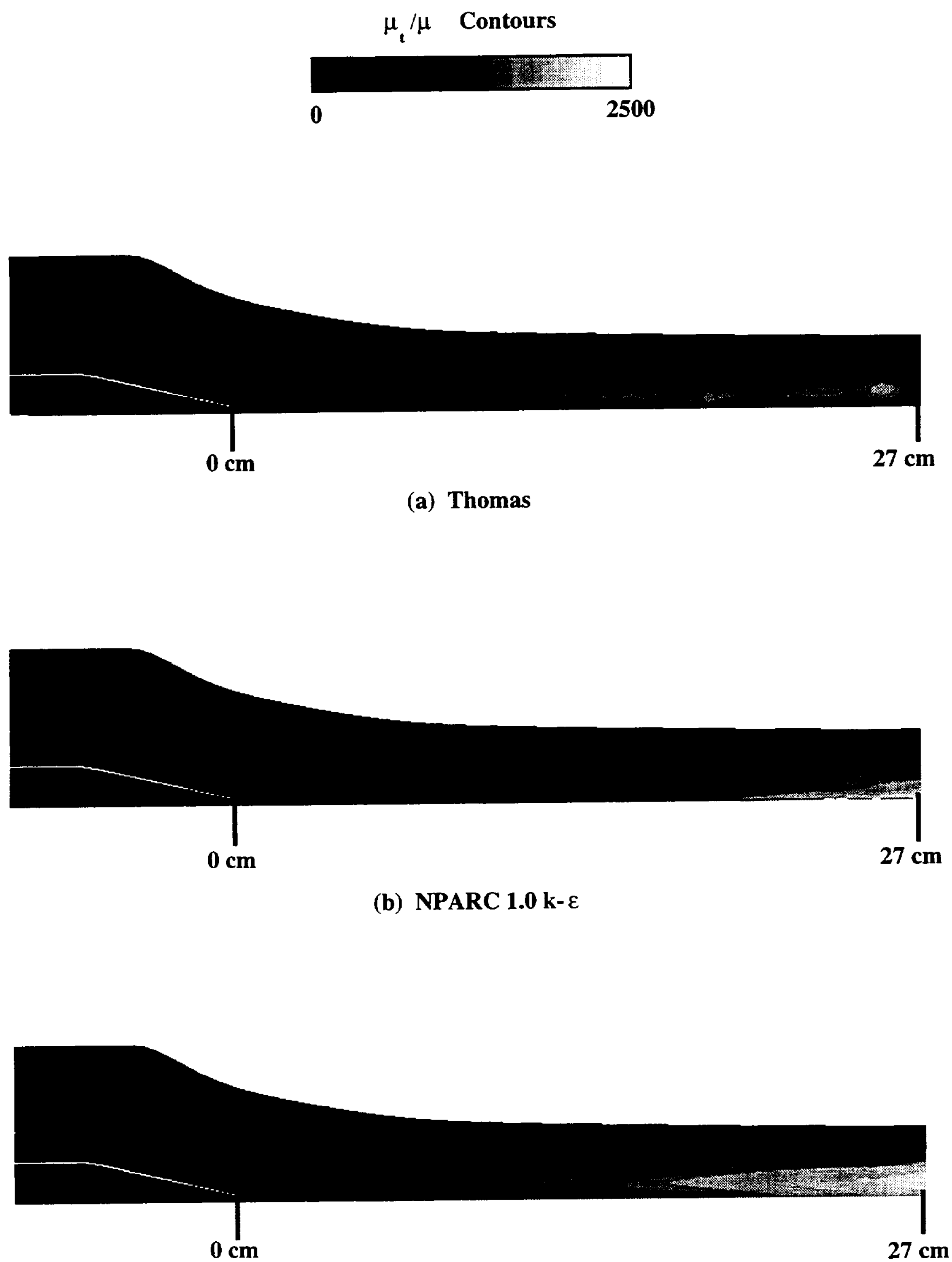
(d) x = 26.7 cm.

Figure 4. Velocity profiles for the 2D ejector nozzle flow.



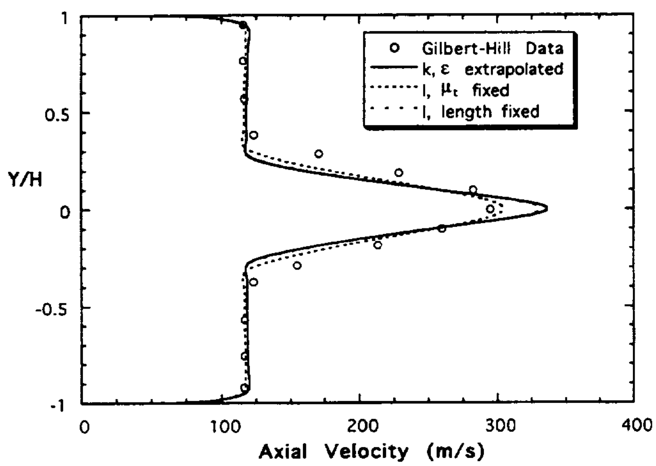
(a) x = 7.6 cm. **(b) x = 26.7 cm.**

Figure 5. Total temperature profiles for the 2D ejector nozzle flow.

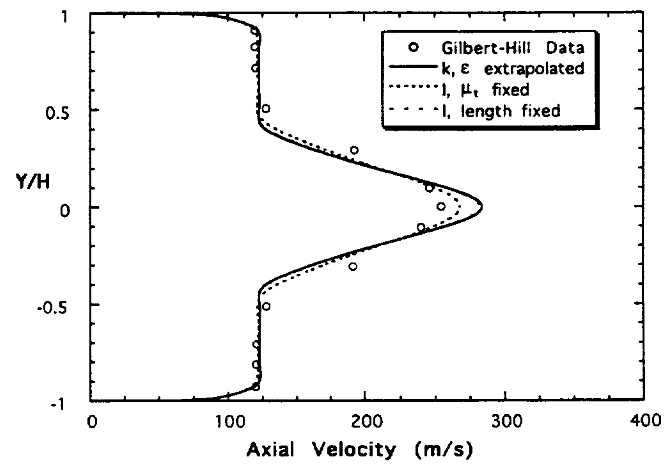


(c) Chien k-ε

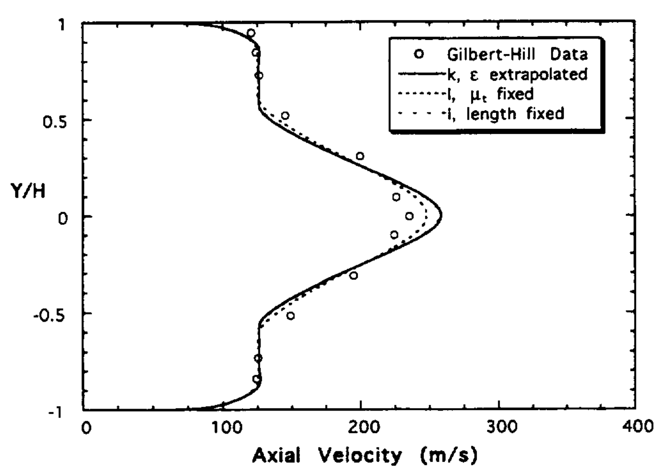
Figure 6. Turbulent viscosity contours for the 2D ejector nozzle.



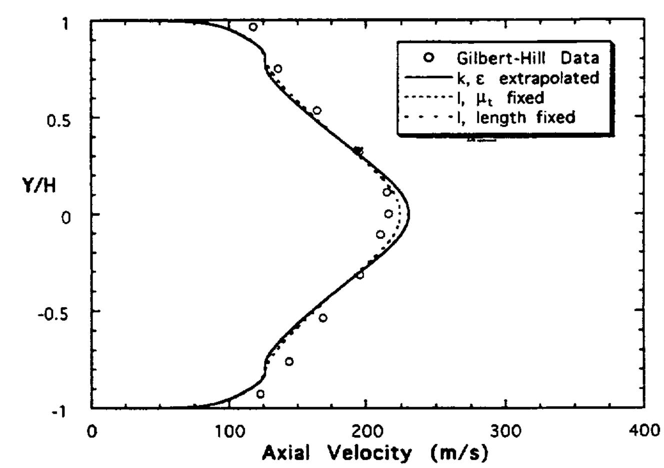
(a) x = 7.6 cm.



(b) x = 12.7 cm.

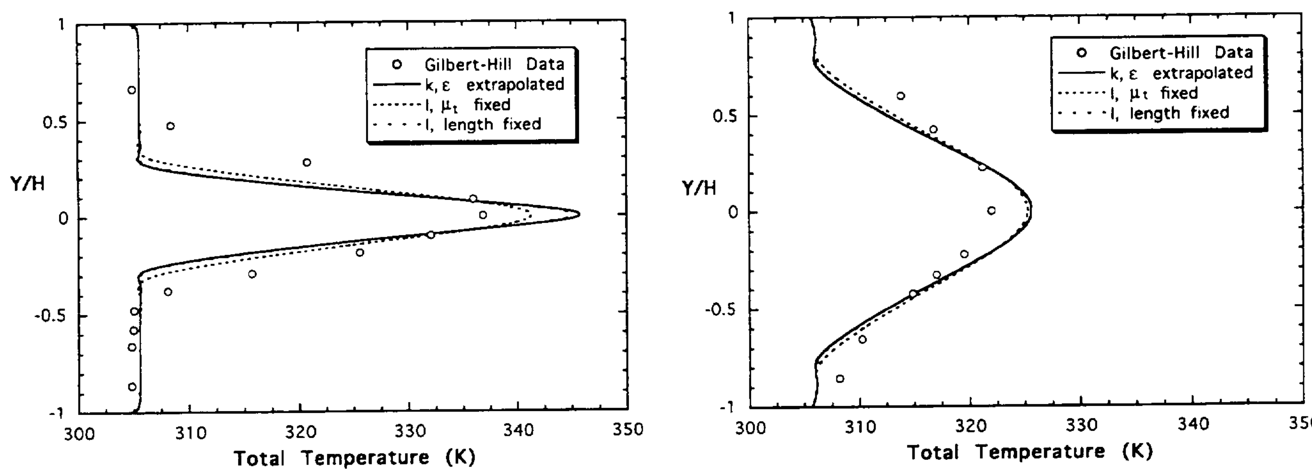


(c) x =17.8 cm.



(d) x = 26.7 cm.

Figure 7. Velocity profiles for the 2D ejector nozzle flow using different inflow boundary conditions.



(a) x = 7.6 cm. (b) x = 26.7 cm.

Figure 8. Total temperature profiles for the 2D ejector nozzle flow using different inflow boundary conditions.

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13. ABSTRACT *(Maximum 200 words)*

This report documents the changes that were made to the two-equation k-ε turbulence model in the NPARC (National-PARC) code. The previous model, based on the low Reynolds number model of Speziale, was replaced with the low Reynolds number k-ε model of Chien. The most significant difference was in the turbulent Prandtl numbers appearing in the diffusion terms of the k and ε transport equations. A new inflow boundary condition and stability enhancements were also implemented into the turbulence model within NPARC. The report provides the rationale for making the change to the Chien model, code modifications required, and comparisons of the performances of the new model with the previous k-ε model and algebraic models used most often in PARC/NPARC. The comparisons show that the Chien k-ε model installed here improves the capability of NPARC to calculate turbulent flows.

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