$(\Sigma_{u1}\nu^5)^{1/4}$; $e_{\theta 2}(y) = E_{\theta 2}(k)/(\Sigma_{u1}\nu^{1/4})\Sigma_{\theta 1}$; b = 2.2, constant used in the calculation of turbulent dissipation for the flow of a gas in a pipe; u_+, dynamical velocity; R, radius of the pipe; $e_u^{(1)}(y)$, $e_v^{(1)}(y)$, $e_{\theta 1}^{(1)}(y)$, $e_{\theta 2}^{(1)}(y)$, one-dimensional normalized spectra of velocity and temperature fluctuations of the particles; Re, Reynolds number of the flow.

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GASDYNAMICS AND HEAT TRANSFER DURING AXISYMMETRIC TURBULENT JET INTERACTION WITH A NORMALLY DISPOSED AREA

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The influence of selecting the kind of turbulence model on the results of a numerical computation of turbulent jet interaction with an obstacle is analyzed.

At this time the investigation of turbulent jet interaction with different obstacles is of considerable practical interest. This paper is devoted to an analysis of certain results of numerical and experimental investigations of the flow and heat transfer during impingement of a submerged isothermal axisymmetric turbulent jet on a normally disposed heated area.

The method elucidated in [1] was used for the numerical solution of the time-averaged Navier–Stokes turbulent viscous fluid flow equations with constant thermophysical properties.

Closure of the system of differential equations in the vortex intensity ω, stream function ψ, and temperature T variables was realized by using the following two turbulence models: $K(L_\nu)$ and $K - \varepsilon$.

The one-parameter turbulence model $K(L_\nu)$ proposed in [2, 3] assumes dependence of the turbulent viscosity ν_T on energy of the turbulent fluctuations K and the turbulence scale L_ν:

$$\nu_T = C_\nu \sqrt{K} L_\nu.$$

The energy of turbulent fluctuations K is determined by solving the differential equation of the fluctuation energy balance. Far from a solid surface the turbulence scales are

*Deceased.

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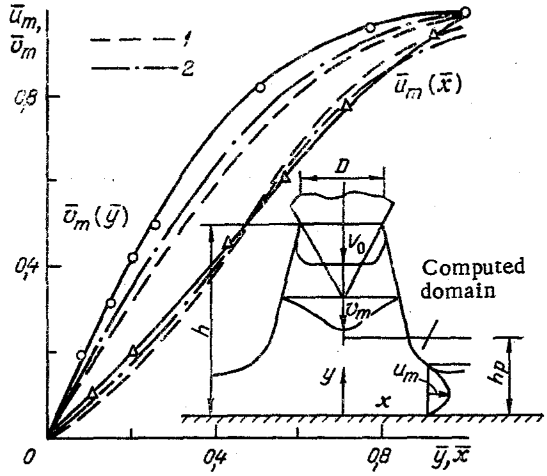

Fig. 1. Dependence of $\bar{v}_m$ and $\bar{u}_m$ on $\bar{y}$ and $\bar{x}$ for Re = 48,200, $\bar{h}$ = 2; computation: 1) K(L), 2) K − ε_{add}; points are experiment.

TABLE 1. Turbulence Models Utilized

Turbulence model	Variable φ_i	Schmidt number Sc_i	Source term S_i
One-parameter K(L)	K	1,53	$\nu_T F_k - C_D \frac{K^{\frac{3}{2}}}{L_D}$
Two-parameter K−ε	K	1,0	$\nu_T F_k - \varepsilon - 2\nu\left(\frac{\partial \sqrt{K}}{\partial y}\right)^2$
	ε	1,3	$C_{1\varepsilon}\nu_T F_k - C_2\frac{\varepsilon^2}{K} + 2\nu\nu_T\left(\frac{\partial^2 u}{\partial y^2}\right)^2$

assumed close to the Prandtl mixing path in a free jet $L_\nu = L_D = 0.03$ h. The expression for the scales near the wall and the empirical constants are borrowed from [2, 3]

$$\frac{L_\nu}{y} = 1 - \exp(-A_\nu R_T), \quad \frac{L_D}{y} = 1 - \exp(-A_D R_T),$$

where $R_T = \sqrt{K}y/\nu$; $A_\nu = 0.016$; $A_D = 0.263$; $C_\nu = 0.22$.

The two-parameter turbulence model K − ε is also based on the Kolmogorov–Prandtl turbulent viscosity hypothesis. It relates the turbulent viscosity ν_T to the turbulent fluctuations energy K and the turbulence energy dissipation rate ε by means of the relationship

$$\nu_T = C_\mu \frac{K^2}{\varepsilon}.$$

The differential equations for the quantities K and ε differ by source terms and have the following form in "stream function-vortex intensity" (ψ − ω) variables [1]:

$$\frac{\partial}{\partial y}\left(\varphi_i \frac{\partial \psi}{\partial x}\right) - \frac{\partial}{\partial x}\left(\varphi_i \frac{\partial \psi}{\partial y}\right) = \frac{\partial}{\partial y}\left[x\left(\nu + \frac{\nu_T}{Sc_i}\right)\frac{\partial \varphi_i}{\partial y}\right] + \frac{\partial}{\partial x}\left[x\left(\nu + \frac{\nu_T}{Sc_i}\right)\frac{\partial \varphi_i}{\partial x}\right] + xS_i.$$

The source terms and constants in the equation are presented in the table depending on the turbulence model [1, 4], where

$$F_k = 2\left[\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{u}{x}\right)^2\right] + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2;$$

$$C_D = 0{,}416; \quad C_{1\varepsilon} = 1{,}65 \ [5]; \quad C_2 = 1{,}92(1 - 0{,}3\exp(-R_T^2));$$

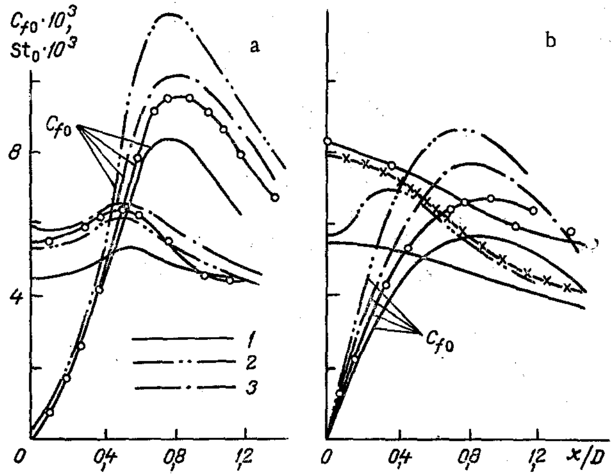

Fig. 2. Dependence of the number St_0 and the friction coefficient C_{f0} on the distance $\bar{x}$ to the jet axis of symmetry: a) $\bar{h}$ = 2 and b) $\bar{h}$ = 8: 1) K(L); 2) K − ε; 3) K − ε_{add}; points are experiment, Re = 48,200.

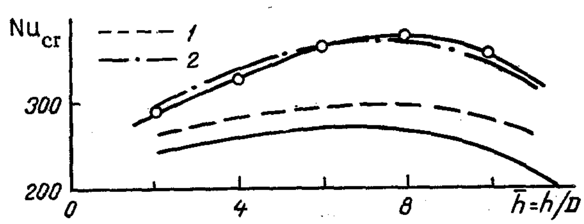

Fig. 3. Dependence of the number Nu_{cr} at the stagnation point on $\bar{h}$: computation: 1) K(L), 2) K − ε_{add}; Re = 48,200; points are experiment. Solid curve is a laminar theory computation.

$$C_\mu = 0{,}09\exp\left(-\frac{2{,}5}{1+R_\tau/50}\right), \quad R_\tau = \frac{K^2}{\nu\varepsilon}.$$

The boundary conditions for the stream function ψ, vorticity ω, and turbulence energy K at the input to the computed domain (Fig. 1) are obtained from experimental profiles of the averaged and fluctuation components of the longitudinal velocity in a free jet approximated by piecewise-smooth functions [3], where the quantity h_p was selected equal to h_p = (1 + 0.05 $\bar{h}$)D_C in conformity with the recommendations in [5]. Adhesion conditions were used at the wall, the vortex intensity was computed by an approximate formula of second order accuracy [6]. The system of linear algebraic equations was solved by the Gauss–Zeidel method.

The computed and experimental data [7] are represented in Fig. 2 in the form of the dependences St = St($\bar{r}$) and C_{f0} = C_{f0}($\bar{r}$). Comparison of these data shows that satisfactory agreement is observed for distances from nozzle to obstacle of $\bar{h}$ = 2 (Fig. 2a) and $\bar{h}$ = 8 (for $\bar{x}$ > 0.5, Fig. 2b) when the K − ε turbulence model is utilized in the computation. A computation by the K − L turbulence model yields a somewhat smaller value of the friction and heat transfer as compared with the experiment. For $\bar{h}$ = 8 in the neighborhood of the stagnation point at $\bar{x}$ < 0.5 the computed dependence St = St($\bar{r}$), obtained by the K − ε turbulence model, has a peripheral maximum which is not qualitatively in agreement with the experiment. As analysis of the computations showed, the reason for this is the exaggerated value of the turbulent viscosity in the domain from $\bar{x}$ = 0 to $\bar{x}$ = 0.5 D. This deduction is confirmed by computations performed under the assumption that the turbulent viscosity value for each value of y within boundary layer limits (from $y = 0$ to $y = \delta_m$) is independent of $\bar{x}$ and equal to the value of ν for $\bar{x} = 0.5$ D (these results are denoted by $K - \varepsilon_{add}$ on the graphs). This artificial method permitted obtaining better agreement between the computations and experiment for $\bar{h} = 2...10$ in the $Re = 10^4...10^6$ Reynolds number range.

Shown in Fig. 1 are velocity profiles on the jet axis $\bar{v}_m = v_m/V_0$ and on the outer boundary of the near-wall boundary layer $\bar{u}_m = u_m/V_0$ as a function of the distance to the area surface $\bar{y} = y/D$ and the axis of symmetry $\bar{x} = x/D$, respectively.

The dependence of the Nusselt number Nu_{cr} at the stagnation point on $\bar{h}$ is shown in Fig. 3. Both in the experimental data and in the numerical solution a maximum of the number Nu_{cr} is observed for $\bar{h} \cong 8$, which is characteristic for jets with a natural initial turbulence.

The comparison showed that the numerical solution of the problem of jet interaction with an area by using a two-parameter turbulence model and taking account of the additions mentioned in the paper is in better agreement with experimental data on the friction and heat transfer coefficients as compared with the one-parameter turbulence model. This permits utilization of two-parameter turbulence models to describe more complex nonisothermal turbulent flows.

NOTATION

y, distance from the wall; x, distance from the axis of symmetry; v, longitudinal velocity; u, transverse velocity; V_0, velocity at the nozzle exit; h, distance between nozzle and area; K, kinetic energy of fluctuation motion (kinetic energy of turbulent fluctuations); ε, rate of turbulence energy dissipation; L_ν, turbulence scale; L_D, scale of viscous turbulence energy dissipation; ν_T, kinematic turbulent viscosity coefficient; R_T, turbulent Reynolds number; ω, vortex intensity; ψ, stream function; Sc, Schmidt number; St, Stanton number; Nu, Nusselt number; C_{f0}, friction coefficient; and δ_m, near-wall boundary layer thickness.

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