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HEAT TRANSFER FOR TURBULENT FLOW IN A CIRCULAR TUBE WITH UNIFORM SUCTION OR INJECTION

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Abstract—The results of calculations of mean and fluctuating heat transfer characteristics in a turbulent flow of liquid through a circular tube with permeable walls are presented. The results were obtained with the use of six differential equations for the description of turbulent momentum and the heat transfer mechanism. The calculations were conducted for air ($Pr = 0.7$) over the range of Reynolds numbers $Re_0 = 10^4$–4×10^5 and suction (injection) rates $m_0 = -0.2$–0.02. The effect of suction and injection on the velocity and temperature distributions, temperature fluctuations, turbulent heat flux, and turbulent Prandtl number is shown. It has been established that the effects of strong suction (injection) on the hydrodynamic and thermal characteristics are different—the fact being due to the appearance of high positive (for suction) and negative (for injection) pressure gradients. In the case of strong suction, a substantial change in Pr_t over the tube cross-section is observed. The results of Stanton number calculations for the region far from the inlet cross-section are well correlated to give a relative heat transfer law.

NOMENCLATURE

a	thermal diffusivity
b_T	suction or injection parameter, m/St_0
E	turbulent energy, $(\langle u_x'^2\rangle + \langle u_r'^2\rangle + \langle u_\phi'^2\rangle)/2$
F	dissipation function, $E^{3/2}/L$
L, L_T	scales of velocity and temperature fluctuations
$\bar{L}$	L/r_w
$\bar{L}_T$	L_T/r_w
m	local rate of suction or injection, V/U
m_0	suction or injection rate at tube inlet, V/U_0
P	pressure
Pr	Prandtl number, ν/a
Pr_t	turbulent Prandtl number, $(\sigma \cdot \partial T/\partial r)/(q \cdot \partial u_x/\partial r)$
q	turbulent radial heat flux, $\langle u_r' T'\rangle$
$\bar{q}$	$q/U(T_b - T_w)$
r_w	tube radius
Re	local Reynolds number, $2r_w U/\nu$
Re_0	Reynolds number at tube inlet, $2r_w U_0/\nu$
Re_E	turbulent Reynolds number, $E^{1/2}L/\nu$
St	Stanton number, $-a(\partial T/\partial r)_{r=r_w}/U(T_b - T_w)$
St_0	Stanton number in tube with impermeable walls
T	temperature
T_b	local bulk temperature
T_w	wall temperature
T_*	friction temperature, $-a(\partial T/\partial r)_{r=r_w}/u_*$
$\bar{T}$	$(T - T_w)/(T_b - T_w)$
$\bar{u}$	u_x/U
u_*	friction velocity, $[-\nu(\partial u_x/\partial r)_{r=r_w}]^{1/2}$
u_x, u_r	longitudinal and radial velocity components
u_x', u_r', u_ϕ', T'	fluctuations of longitudinal, radial, and azimuthal velocity components, and of temperature
U	local mean velocity, $U_0 - 4V \cdot \bar{x}$
U_0	mean velocity at tube inlet
V	suction or injection velocity
x, r	longitudinal and radial coordinates
$\bar{x}$	dimensionless longitudinal coordinate, $x/2r_w$
y	transverse coordinate, $r_w - r$
$\bar{y}$	dimensionless transverse coordinate, y/r_w.

Greek symbols

η	distance from the wall in universal coordinates, yu_*/ν
θ	intensity of temperature fluctuations, $\langle T'^2\rangle$
$\bar{\theta}$	$\theta/(T_b - T_w)^2$
ν	kinematic viscosity
ξ	friction coefficient, $-8\nu(\partial u_x/\partial r)_{r=r_w}/U^2$
ρ	density
σ	turbulent shear stress, $\langle u_x' u_r'\rangle$
Φ	thermal dissipation function, $E^{1/2}\theta/L_T$
Ψ_T	relative heat transfer coefficient, St/St_0.

1. INTRODUCTION

THEORETICAL investigation of the hydrodynamics of a turbulent flow in a tube with steady suction or injection through porous walls was the concern of a number of publications [1–9]. In refs. [2–4], a hydrodynamically developed flow with suction has been calculated on the basis of different modifications of the van Driest damping model, while in refs. [5, 6] this has been done with the use of the fluctuation energy balance equation. As a result, it has been found that, just as in the case of flow past a plate, an increase in the rate of suction results in a greater fullness of the axial velocity profile and in a higher surface friction. According to the model suggested in ref. [2], the turbulent transfer increases with suction, while following refs. [3, 4] it decreases by analogy with external flow. A low rate of suction has been shown [5, 6] to result in a lower turbulence level of the flow. The hydrodynamics over the inlet stretch of the tube with suction in the presence of a long preinserted impervious segment has been calculated [7] on the basis of a three-equation model of turbulence. As a result, a hydrodynamically developed flow is shown to be actually realizable only in the case of weak suction, with the velocity profiles becoming fuller and fluctuation intensity decreasing in conformity with the experimental [10–12] and predicted [2–6] evidence. In the case of strong suction, the flow parameters change dramatically along the tube, high positive pressure gradients appear, the profiles of axial velocity become steeper at the axis, and the laminarization effect of mass outflow is replaced by the turbulazation one, which agrees well with the experimental data [13]. A numerical analysis of the transitional and turbulent flow regimes in a tube with injection has been performed in refs. [8, 9]. It follows from the results of theoretical and experimental [14] investigations that a quasi-developed flow is set up at some distance from the tube entrance when the flow parameters in each cross-section of the tube correspond to the local value of the suction rate and are virtually independent of the upstream flow characteristics.

Theoretical studies of heat transfer for turbulent flow in a tube with suction or injection are carried out in refs. [2, 5, 15]. The flow was assumed to be thermally developed and the turbulent Prandtl number was regarded as constant over the cross-section and independent of the transverse mass flow rate. It has been found that the effects of suction and injection exerted on the nature of velocity and temperature distribution deformations are qualitatively similar, though the temperature profiles undergo stronger deformations than the velocity ones; the changes in heat transfer and surface friction coefficients have also tended to be similar.

The present paper reports the results of calculations of the mean and fluctuating heat transfer characteristics of flow in a permeable circular tube which were obtained with the use of six differential equations for the description of turbulent momentum and heat transfer mechanisms.

2. STATEMENT OF THE PROBLEM

The equations, which in the boundary layer theory approximation describe the velocity and temperature distributions for a steady-state axisymmetric flow of fluid with constant physical properties in a circular tube, are

$$\frac{\partial(ru_x)}{\partial x}+\frac{\partial(ru_r)}{\partial r}=0, \tag{1}$$

$$u_x\frac{\partial u_x}{\partial x}+u_r\frac{\partial u_x}{\partial r}=-\frac{1}{\rho}\frac{dP}{dx}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu\frac{\partial u_x}{\partial r}-\sigma\right)\right], \tag{2}$$

$$u_x\frac{\partial T}{\partial x}+u_r\frac{\partial T}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(a\frac{\partial T}{\partial r}-q\right)\right]. \tag{3}$$

The fluctuating motion is described with the aid of a three-equation model of turbulence [7, 9] consisting of the fluctuation energy balance and Reynolds shear stress equations and also of the equation for the dissipation function to average the scale of velocity fluctuations

$$u_x\frac{\partial E}{\partial x}+u_r\frac{\partial E}{\partial r}=-\sigma\frac{\partial u_x}{\partial r}-C\frac{E^{3/2}}{L}-C_{1E}\nu\frac{E}{L^2}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\nu+\alpha_E E^{1/2}L)\frac{\partial E}{\partial r}\right], \tag{4}$$

$$u_x\frac{\partial \sigma}{\partial x}+u_r\frac{\partial \sigma}{\partial r}=-K_1[1-\exp(-\gamma\, Re_E)]E\frac{\partial u_x}{\partial r}-K\frac{E^{1/2}\sigma}{L}-C_{1\sigma}\frac{\sigma}{L^2}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\nu+\alpha_\sigma E^{1/2}L)\frac{\partial \sigma}{\partial r}\right]-\frac{(\nu+\alpha_\sigma E^{1/2}L)\sigma}{r^2}, \tag{5}$$

$$u_x\frac{\partial F}{\partial x}+u_r\frac{\partial F}{\partial r}=-a_F\frac{\sigma\cdot F}{E}\frac{\partial u_x}{\partial r}-2C\frac{E^{1/2}F}{L}-C_{1F}\nu\frac{F}{L^2}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\nu+\alpha_F E^{1/2}L)\frac{\partial F}{\partial r}\right]. \tag{6}$$

The factor $1-\exp(-\gamma\, Re_E)$ has been introduced into equation (5) in order to reduce the resulting contribution of turbulence production into the turbulent stress balance near the wall. The scale of velocity fluctuations is so normalized that in the boundary layer on an impervious surface the value of L is coincident with the Prandtl mixing length, i.e. $L = 0.4y$ at $y \to 0$. The terms which dominate in equations (4)–(6) closer to the wall (in a viscous sublayer) are those which describe molecular diffusion and dissipation. The balance of the dominant terms and the conditions that $E \sim y^2, \sigma \sim y^4$ and $F \sim y^2$ at $y \to 0$ give the values of constants $C_{1E} = C_{1F} = 0.32$; $C_{1\sigma} = 1.92$. The other constants were found by comparison with the experimental data on the distribution of hydrodynamic characteristics of flow in impervious tubes: $C = 0.13$; $K = 0.35$; $K_1 = 0.2$; $a_F = 1.7$; $\alpha_E = \alpha_\sigma = \alpha_F = 0.2$; $\gamma = 0.06$.

In order to describe the fluctuating thermal characteristics of the flow, use is also made, by analogy with the set of equations (4)–(6), of the three-equation model of turbulent heat transfer consisting of the balance equations for temperature fluctuations and turbulent heat flux and of the equation for thermal dissipation function to determine the scale of temperature fluctuations

$$u_x\frac{\partial \theta}{\partial x}+u_r\frac{\partial \theta}{\partial r}=-2q\frac{\partial T}{\partial r}-C_\theta\frac{E^{1/2}\theta}{L_T}-C_{1\theta}a\frac{\theta}{L_T^2}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(a+\alpha_\theta E^{1/2}L_T)\frac{\partial \theta}{\partial r}\right], \tag{7}$$

$$u_x \frac{\partial q}{\partial x} + u_r \frac{\partial q}{\partial r} = -K_1[1-\exp(-\gamma\, Re_E)]E\frac{\partial T}{\partial r} - K_q \frac{E^{1/2}q}{L^{1/2}L_T^{1/2}} - C_{1q}(\nu+a)\frac{q}{LL_T} + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{\nu+a}{2} + \alpha_q E^{1/2}L^{1/2}L_T^{1/2}\right)\frac{\partial q}{\partial r}\right] - \left(\frac{\nu+a}{2} + \alpha_q E^{1/2}L^{1/2}L_T^{1/2}\right)\frac{q}{r^2}, \quad (8)$$

$$u_x \frac{\partial \Phi}{\partial x} + u_r \frac{\partial \Phi}{\partial r} = -a_\Phi \frac{q\Phi}{\theta}\frac{\partial T}{\partial r} - C_\Phi \frac{E^{1/2}\Phi}{L_T} - C_{1\Phi} a \frac{\Phi}{L_T^2} + \frac{1}{r}\frac{\partial}{\partial r}\left[r(a+\alpha_\Phi E^{1/2}L_T)\frac{\partial \Phi}{\partial r}\right]. \quad (9)$$

The scale of temperature fluctuations, L_T, is normalized in the same way as the scale of velocity fluctuations, L. The approximate equations used to bring about closure of equations (7)–(9) are similar to those described in ref. [16]. The dominant terms in equations (7)–(9) at $y \to 0$, as in equations (4)–(6), are those which describe molecular diffusion and dissipation. The balance of these terms and the conditions $\theta \sim y^2, q \sim y^4$, and $\Phi \sim y^2$ at $y \to 0$ yield the constants $C_{1\theta} = C_{1\Phi} = 0.32$; $C_{1q} = 0.96$. The remaining constants are found by comparison with the experimental data on thermal characteristics of flows in impervious tubes: $C_\theta = 0.4$; $C_\Phi = 0.8$; $K_q = 0.32$; $a_\Phi = 3.8$; $a_\theta = \alpha_q = \alpha_\Phi = 0.2$.

The boundary conditions for equations (1)–(9) on the axis and wall of the tube are written as

$$r = 0,$$

$$\frac{\partial u_x}{\partial r} = \frac{\partial T}{\partial r} = \frac{\partial E}{\partial r} = \sigma = \frac{\partial F}{\partial r} = \frac{\partial \theta}{\partial r} = q = \frac{\partial \Phi}{\partial r} = 0,$$

$$r = r_w, \quad u_x = E = \sigma = F = \theta = q = \Phi = 0,$$

$$T = T_w, \quad u_r = V.$$

The inlet boundary conditions ($x = 0$) are chosen to be the distributions typical of the hydrodynamically and thermally developed flow in the absence of suction (injection), i.e. it is assumed that a porous tube has a sufficiently long preinserted impervious segment.

The set of equations (1)–(9) was solved by using the factorization method with iterations. Equations (2)–(9) were approximated with the aid of a double-layer implicit six-point scheme, and a four-point scheme was used to approximate equation (1).

3. CALCULATION RESULTS

The calculations were carried out for air ($Pr = 0.7$) over the range of Reynolds numbers $Re_0 = 10^4$–4×10^5 and suction (injection) rates $m_0 = -0.02$–0.02. The distributions of temperature, Stanton number, temperature fluctuations and turbulent heat flux in a tube with impervious walls agree quite well with the well-known experimental data. A comparison between the

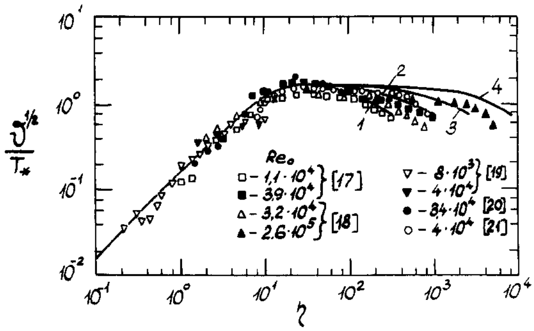


FIG. 1. Distribution of temperature fluctuations over the cross-section of an impervious tube: 1, $Re_0 = 10^4$; 2, $Re_0 = 4 \times 10^4$; 3, $Re_0 = 10^5$; 4, $Re_0 = 4 \times 10^5$.

predicted distributions of temperature fluctuations over the tube cross-section and the experimental data of different authors [17–21] is shown in universal coordinates in Fig. 1. A comparison of the predicted hydrodynamic characteristics of flows in tubes with suction and injection with the experimental data of refs. [11, 13, 14] is presented in refs. [7, 9].

The nature of the effect of suction and injection on the temperature distribution over the cross-section of the tube and along its length is shown in Figs. 2 and 3, where the axial velocity profiles are also given for comparison. In the case of suction, an increase in its rate results in a fuller temperature profile which agrees with the experimental data of ref. [22]. Thus, while the effect of weak suction ($m_0 < 0.005$) on deformation of velocity and temperature distributions is qualitatively similar, the effect of strong suction (as seen from Fig. 2) is different—at the wall the velocity profile clings to it and stretches out at the axis. The breakdown of the analogy between the velocity and temperature distributions is attributed to the appearance (in the case of strong suction) of high positive pressure gradients, which influences directly only the dynamic flow characteristics. With injection, the temperature profile becomes much more distorted than the velocity one,

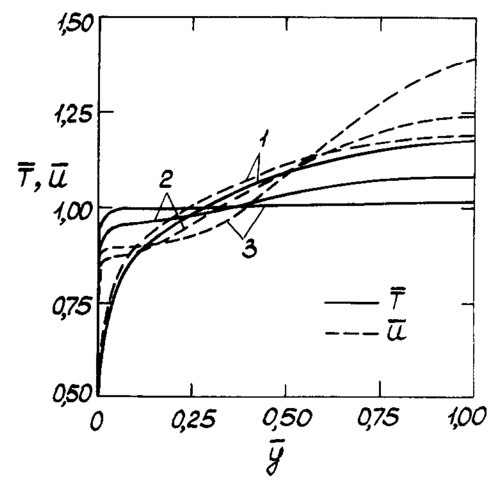


FIG. 2. Temperature and velocity profiles for suction ($Re_0 = 10^5$; $m_0 = 0.02$): 1, $\bar{x} = 0$; 2, $\bar{x} = 5$; 3, $\bar{x} = 10$.

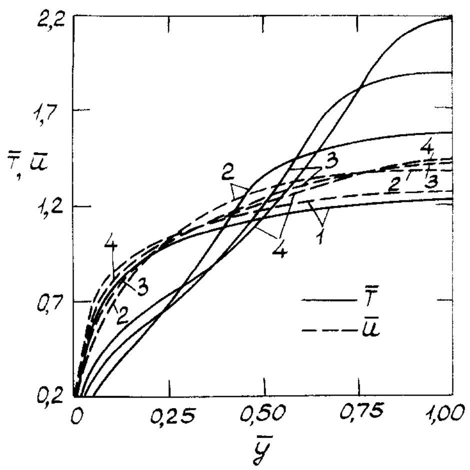


FIG. 3. Temperature and velocity profiles with injection ($Re_0 = 10^4$; $m_0 = -0.02$): 1, $\bar{x} = 0$; 2, $\bar{x} = 5$; 3, $\bar{x} = 10$; 4, $\bar{x} = 15$.

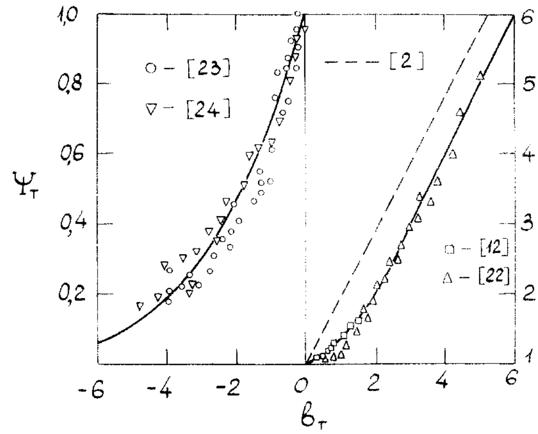


FIG. 5. Relative heat transfer coefficient.

which is displayed in its strong displacement from the wall and extension in the axial zone. A weaker influence of injection on the dynamic characteristics as compared to the thermal ones is explained by the appearance of a substantial mass inflow-induced negative pressure gradient, which exerts a stabilizing effect on the flow and prevents the velocity profile displacement from the wall. Subsequent to initial strong displacement, the fullness of the velocity and temperature profiles at the wall becomes greater with an increase of x due to a drop in the injection rate m caused by a rise of the mean velocity U. However, the flow in the central part of the tube possesses a higher degree of relaxation (in the sense that it responds much more slowly to the changes in the external attacks on the flow), so that the velocity, and especially temperature, profiles still continue their extension in the axial zone.

The effect of suction or injection on the behaviour of

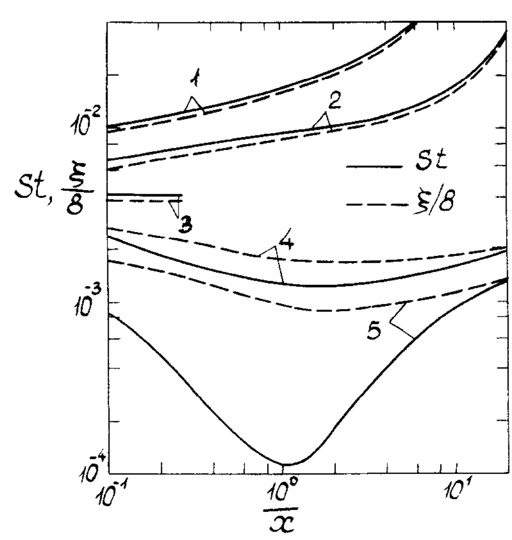


FIG. 4. Variation of friction coefficient and Stanton number along the tube ($Re_0 = 10^4$): 1, $m_0 = 0.02$; 2, $m_0 = 0.01$; 3, $m_0 = 0$; 4, $m_0 = 0.01$; 5, $m_0 = -0.02$.

the friction coefficient and of the Stanton number along the tube is qualitatively similar, as seen from Fig. 4. With suction applied, the values of $\xi/8$ and St turn to be nearly the same (the Reynolds analogy is approximately valid) and increase monotonically downstream with the suction rate, approaching m. In the case of injection, the values of ξ and St first decrease with an increase of x, which is due to the rearrangement of velocity and temperature profiles under the action of mass inflow, and then increase as a result of a decrease in the rate of local injection. In the case of suction and weak injection, just as in an impervious tube, the St number takes on higher values than the ratio $\xi/8$ does. With strong injection, the reverse is the case, i.e. $\xi/8 > St$, as a result of a much stronger displacement of the temperature profile (especially in the initial section of the tube).

The results of the calculation of the St number in the region of $\bar{x} > 5$ are correlated in the form of a relative heat transfer law $\Psi_T(b_T)$, where $\Psi_T = St/St_0$, $b_T = m/St_0$, St and St_0 are the Stanton numbers in permeable and impervious tubes, respectively, at the same value of local Reynolds number Re. The function $\Psi_T(b_T)$ turns to be universal enough in the sense that the effect of the parameters Re_0 and $\bar{x}$ is practically absent. It gives an adequate description of the experimental data [12, 22–24] (Fig. 5). Figure 5 also contains a curve, which correlates the results of calculations presented in ref. [2].

Figures 6 and 7 show the deformation in the distributions of temperature fluctuations and turbulent heat flux downstream of the tube under the action of injection and suction. In the case of injection, like in boundary layer flow along a permeable plate [25], the temperature fluctuations and turbulent heat flux increase and the maxima of their distribution shift from the wall to the flow core. Unlike the turbulent kinetic energy E [9], the temperature fluctuations, despite a decrease in the local injection rate m, keep growing over the entire range of $\bar{x}$ studied. This is due to an increase of temperature gradient in the flow core (Fig. 3), which is much in excess of the axial velocity gradient, thus leading to an additional generation of temperature

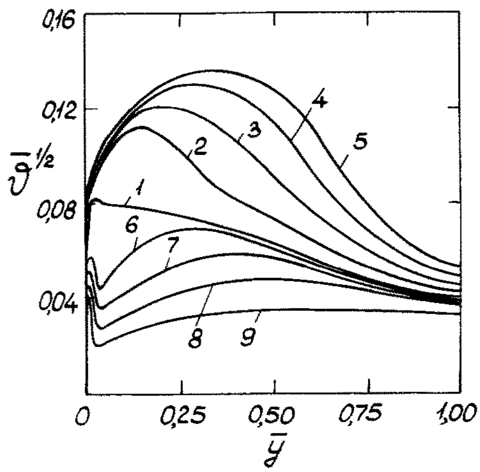


FIG. 6. Distribution of temperature fluctuations over the tube cross-section with suction and injection ($Re_0 = 10^5$): 1, $m_0 = 0$; 2–5, $m_0 = -0.005$; 6–9, $m_0 = 0.005$; 2, 6, $\bar{x} = 5$; 3, 7, $\bar{x} = 10$; 4, 8, $\bar{x} = 15$; 5, 9, $\bar{x} = 20$.

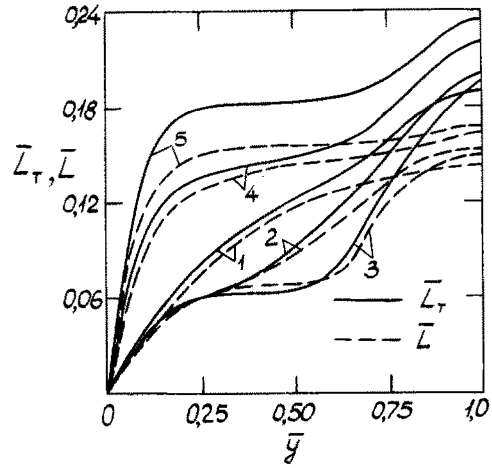


FIG. 8. Distribution of the scales of temperature and velocity fluctuations over the tube cross-section with suction and injection ($Re_0 = 10^5$; $\bar{x} = 10$): 1, $m_0 = 0$; 2, $m_0 = -0.005$; 3, $m_0 = -0.01$; 4, $m_0 = 0.005$; 5, $m_0 = 0.01$.

fluctuations as compared to the velocity fluctuations. With a further increase of $\bar{x}$, the temperature fluctuations $\bar{\vartheta}$, like those of temperature $\bar{T}$ at the axis of the tube, decrease. In the case of suction, the distributions of temperature fluctuations and turbulent heat flux, just as the profiles of turbulent energy and Reynolds shear stresses [7], feature two maxima—one in the vicinity of the wall and the other in the flow core. With an increase in the rate of suction, the level of fluctuations of θ and q decrease in average over the cross-section, which is consistent with the experimental data of ref. [12]. Thus, the effect of low suction on the hydrodynamic and thermal fluctuations turns out to be similar. However, in the case of strong suction, when the velocity gradient in the flow core takes on high values and conversely the temperature profile approaches a uniform shape, the qualitative correspondence breaks down. In contrast to a sharp growth of velocity fluctuations, with the exception of the wall region, the temperature fluctuations continue to decrease—the fact which is due to a lesser production of temperature fluctuations in the flow core as a result of the temperature profile evolution into a uniform shape.

The effect of injection and suction on the scales of velocity and temperature fluctuations (Fig. 8) is qualitatively similar, though in the case of strong injection this similarity becomes violated. The injection causes a decrease of turbulence scales in the flow core, while in the wall region the scales vary insignificantly. A similar effect of injection on the distribution of the transverse scale of velocity fluctuations and on the mixing length has been observed experimentally in refs. [26–28]. The scales over the entire cross-section of the tube increase with the rate of suction.

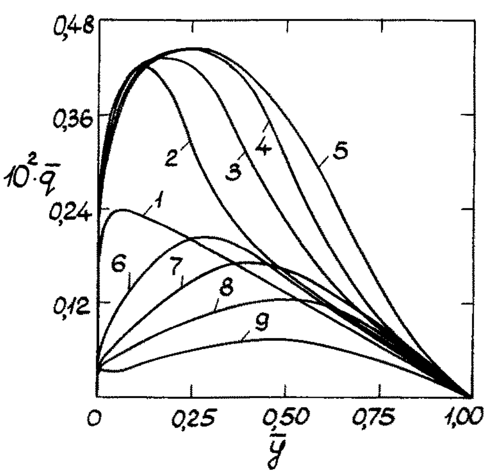
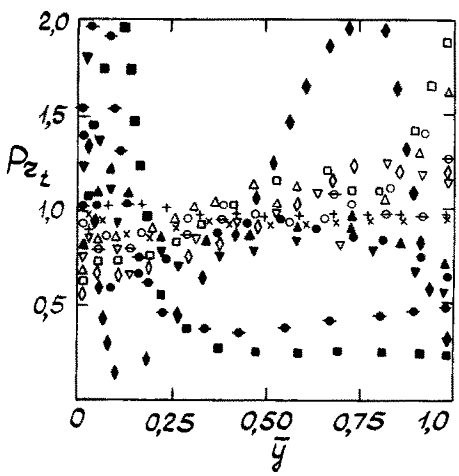


FIG. 7. Distribution of a turbulent flux over the tube cross-section with suction and injection. The symbols are the same as in Fig. 6.



m_0	-0,02		-0,01		-0,005		0		0,005		0,01		0,02	
Re_0	10^4		10^4		10^5		10^4	10^5	10^5		10^4	10^5	10^4	10^5
$\bar{x}$	10	20	10	20	10	20	0	0	10	20	10	10	10	10
	□	◇	△	▽	○	⊖	+	×	●	♦	▲	▼	■	-●-

FIG. 9. Turbulent Prandtl number.

Figure 9 gives the results of calculations of the turbulent Prandtl number. It is seen that the effect of moderate injection ($|m_0| < 0.01$) is not very significant, and the values of Pr_t, like in impervious tubes, are close to 1. The results obtained for injection agree well with the experimental data of ref. [29], where it has been established that the distributions of Pr_t over the cross-section of a boundary layer on an impervious and a permeable plate differ only slightly in the cases of moderate injection and suction. However, as seen from Fig. 9, in contrast to ref. [29], the suction turns out to exhibit a marked effect, and a substantial change of Pr_t over the tube cross-section is observed. Thus, the calculations carried out allow a conclusion that the turbulence models, which fail to take into account the effect of mass outflow and inflow on Pr_t, are of limited use for the calculation of heat transfer in tubes with permeable walls.

In order to check the possible effect of the production of turbulent fluctuations by axial velocity and temperature gradients, the calculations were carried out using additional terms (similar to those introduced in ref. [30]) in equations (4) and (6)–(9). It has been found that even at $m_0 = \pm 0.02$ the difference of all the hydrodynamic and thermal characteristics from those predicted without these additional terms is insignificant (<2–3%), i.e. the contribution of the additional terms into the production of fluctuations is unimportant.

REFERENCES

1. S. W. Yuan and E. W. Brogren, Turbulent flow in a circular pipe with porous wall, *Physics Fluids* **4**, 368–372 (1961).
2. R. B. Kinney and E. M. Sparrow, Turbulent flow, heat transfer and mass transfer in a tube with surface suction, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **92**, 117–125 (1970).
3. L. Merkine, A. Solan and Y. Winograd, Turbulent flow in a tube with wall suction, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **93**, 242–244 (1971).
4. M. R. Doshi and W. N. Gill, Turbulent flow in a tube with wall suction, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **96**, 251–252 (1974).
5. V. M. Yeroshenko, A. V. Yershov and L. I. Zaichik, Calculation of momentum and heat transfer for a turbulent flow of fluid in tubes with permeable walls, in *Heat Mass Transfer—VI*, Vol. 1, Pt. 1, pp. 78–82. Minsk (1980).
6. V. M. Yeroshenko, A. V. Yershov and L. I. Zaichik, Calculation of developed turbulent flow in a tube with injection and suction, *Teplofiz. Vys. Temp.* **19**(1), 102–108 (1981).
7. V. M. Yeroshenko, A. V. Yershov and L. I. Zaichik, Calculation of turbulent flow of incompressible fluid in a circular tube with suction through porous walls, *Izv. AN SSSR, Mekh. Zhidk. Gaza* No. 4, 87–93 (1982).
8. A. A. Sviridenkov and V. I. Yagodkin, On the flow in entrance sectors of channels with permeable walls, *Izv. AN SSSR, Mekh. Zhidk. Gaza* No. 5, 43–48 (1976).
9. V. M. Yeroshenko, A. V. Yershov and L. I. Zaichik, Turbulent flow of fluid in a circular tube with uniform injection through porous walls, *Inzh.-Fiz. Zh.* **41**(5), 791–795 (1981).
10. H. L. Weissberg and A. S. Berman, Velocity and pressure distributions in turbulent pipe flow with uniform wall suction, *Proc. Heat Transfer Fluid Mech. Inst.* **14**, 1–30 (1955).
11. A. Brosh and Y. Winograd, Experimental study of turbulent flow with wall suction, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **96**, 338–342 (1974).
12. M. Elena and R. Dumas, Champs dynamique et thermique d'un écoulement turbulent en conduite avec aspiration à la paroi, *6th Int. Heat Transfer Conf.*, Vol. 5, pp. 239–244, Toronto (1978).
13. J. K. Aggarwal, M. A. Hollingsworth and Y. R. Mayhew, Experimental friction factors for turbulent flow with suction in a porous tube, *Int. J. Heat Mass Transfer* **15**, 1585–1602 (1972).
14. R. M. Olson and E. R. G. Eckert, Experimental studies of turbulent flow in a porous circular tube with uniform fluid injection through the tube wall, *J. Appl. Mech.* **33**, 7–17 (1966).
15. S. W. Yuan, *Turbulent Flows and Heat Transfer* (edited by C. C. Lin), Vol. 5. Princeton, New Jersey (1959).
16. B. E. Launder, *Turbulence* (edited by P. Bradshaw). Springer, Berlin (1978).
17. S. Tanimoto and T. J. Hanratty, Fluid temperature fluctuations accompanying turbulent heat transfer in a pipe, *Chem. Engng Sci.* **18**, 307–311 (1963).
18. M. Kh. Ibragimov, V. I. Subbotin and G. S. Taranov, Fluctuations of velocity, temperature and their correlations for turbulent air flow in a tube, *Inzh.-Fiz. Zh.* **19**(6), 1060–1069 (1970).
19. B. S. Petukhov, A. F. Polyakov, Yu. L. Shekhter and Yu. V. Tsypulev, Statistical characteristics of temperature fluctuations and turbulent heat transfer in viscous sublayer, in *Wall Turbulent Flow*, Pt. 2, pp. 162–177. Novosibirsk (1975).
20. M. Elena, Etude experimentale de la turbulence au voisinage de la paroi d'une tube légérement chauffé, *Int. J. Heat Mass Transfer* **20**, 935–944 (1977).
21. M. Hishida and Y. Nagano, Structure of turbulent velocity and temperature fluctuations in fully developed pipe flow, *Trans. Am. Soc. Mech. Engrs*, Series C, *J. Heat Transfer* **101**, 15–22 (1979).
22. J. K. Aggarwal and M. A. Hollingsworth, Heat transfer for turbulent flow with suction in a porous tube, *Int. J. Heat Mass Transfer* **16**, 591–609 (1973).
23. G. Lombardi, E. M. Sparrow and E. R. G. Eckert, Experiments on heat transfer to transpired turbulent pipe flows, *Int. J. Heat Mass Transfer* **17**, 429–437 (1974).
24. T. F. Bekmuratov, Experimental study of porous and combined cooling for turbulent air flow in a circular tube. *Inzh.-Fiz. Zh.* **16**(3), 417–422 (1969).
25. M. Senda, K. Suzuki and T. Sato, Turbulence structure related to the heat transfer in a turbulent boundary layer with injection, *Turbulent Shear Flows*, Vol. 2, pp. 143–157. Springer, Berlin (1980).
26. V. M. Polyaev, I. V. Bashmakov, D. I. Vlasov and I. M. Gerasimov, On some special features of flow in turbulent boundary layer on a permeable plate with injection, in *Wall Turbulent Flow*, Pt. 2, pp. 43–57. Novosibirsk (1975).
27. M. Senda, Y. Kawaguchi and K. Suzuki, Study of a turbulent boundary layer with injection. Turbulent scales, *Bull. J.S.M.E.* **24**, 1748–1775 (1981).
28. R. J. Baker and B. E. Launder, The turbulent boundary layer with foreign gas injection—I. Measurements in zero pressure gradient, *Int. J. Heat Mass Transfer* **17**, 275–291 (1974).
29. R. L. Simpson, D. G. Whitten and R. J. Moffat, An experimental study of the turbulent Prandtl number of air with injection and suction, *Int. J. Heat Mass Transfer* **13**, 125–149 (1970).
30. K. Hanjalić and B. E. Launder, Sensitizing the dissipation equation to irrotational strains, *Trans. Am. Soc. Mech. Engrs*. *J. Fluids Engng* **102**, 34–40 (1980).

TRANSFERT THERMIQUE POUR UN ECOULEMENT TURBULENT DANS UN TUBE CIRCULAIRE AVEC UNE SUCCION OU UNE INJECTION UNIFORME

Résumé—On présente les résultats de calculs des caractéristiques moyennes et fluctuantes de transfert thermique pour un écoulement turbulent de liquide dans un tube circulaire. Les résultats sont obtenus à partir de six équations aux dérivées partielles pour la description du mécanisme turbulent de la quantité de mouvement et du transfert thermique. Les calculs sont menés pour l'air ($Pr = 0{,}7$ dans les domaines de nombres de Reynolds $Re_0 = 10^4$–4×10^5 et de flux de succion (injection) $m_0 = -0{,}2$–$0{,}02$. On montre l'effet de la succion, de l'injection, sur les distributions de vitesse et de température, les fluctuations de température, le flux thermique turbulent et le nombre de Prandtl turbulent. Les effets d'une forte succion (injection) sur les caractéristiques hydrodynamiques et thermiques sont différents, le fait étant dû à l'apparition de forts gradients de pression positifs (pour la succion) et nègatifs (pour l'injection). Dans le cas d'une aspiration forte, un changement sensible de Pr_t est observé dans la section droite du tube. Les résultats du calcul du nombre de Stanton pour la région éloignée de l'entrée sont assez bien corrélés pour donner un loi de transfert.

WÄRMEÜBERTRAGUNG BEI TURBULENTER STRÖMUNG IN EINEM KREISROHR MIT GLEICHFÖRMIGER ABSAUGUNG ODER EINBLASUNG

Zusammenfassung—Berechnungsergebnisse für den mittleren und den fluktuierenden Wärmeübergang in einer turbulenten Flüssigkeitsströmung durch ein Kreisrohr mit durchlässiger Wand werden vorgelegt. Die Ergebnisse basieren auf der Verwendung von sechs Differentialgleichungen, die den turbulenten Impuls- und Wärmeübertragungs-Mechanismus beschreiben. Die Berechnungen wurden für Luft ($Pr = 0{,}7$) im Bereich der Reynolds-Zahlen $Re_0 = 10^4$ bis 4×10^5 und Absaug-(Einblas-)Raten $m_0 = -0{,}2$ bis $0{,}02$ durchgeführt. Der Einfluß von Absaugen und Einblasen auf die Geschwindigkeits- und Temperaturverteilungen, die Temperaturschwankungen, den turbulenten Wärmestrom und die turbulente Prandtl-Zahl wird gezeigt. Es wurde nachgewiesen, daß die Einflüsse von starkem Absaugen (Einblasen) auf die hydrodynamischen und thermischen Eigenschaften unterschiedlich sind—dies aufgrund grosser positiver (bei Absaugung) und negativer (bei Einblasung) Druckgradienten. Im Fall starker Absaugung ergibt sich eine wesentliche Änderung von Pr_t über den Rohrquerschnitt. Die Berechnungsergebnisse für die Stanton-Zahl für das Gebiet in großer Entfernung vom Eintritts-Querschnitt sind gut korrelierbar und liefern eine relative Wärmeübergangsbeziehung.

ТЕПЛООБМЕН ПРИ ТУРБУЛЕНТНОМ ТЕЧЕНИИ В КРУГЛОЙ ТРУБЕ С РАВНОМЕРНЫМ ОТСОСОМ ИЛИ ВДУВОМ

Аннотация—Представлены результаты расчета осредненных и пульсационных характеристик теплообмена при турбулентном течении жидкости в круглой трубе с проницаемыми стенками, полученные с использованием шести дифференциальных уравнений для описания механизма турбулентного переноса импульса и тепла. Расчеты были проведены для воздуха ($Pr = 0{,}7$) в диапазоне изменения числа Рейнольдса $Re_0 = 10^4$–4×10^5 и интенсивности отсоса (вдува) $m_0 = -0{,}02$–$0{,}02$. Показано влияние отсоса и вдува на распределения скорости и температуры, пульсации температуры, турбулентный тепловой поток, турбулентное число Прандтля. Получено, что воздействие сильного отсоса (вдува) на гидродинамические и тепловые характеристики различно, что связано с появлением больших положительных (при отсосе) и отрицательных (при вдуве) градиентов давления. В случае сильного отсоса наблюдается существенное изменение Pr_t по сечению трубы. Результаты расчета числа Стентона вдали от входного сечения хорошо обобщаются в форме относительного закона теплообмена.