2. I. I. Gogonin and O. A. Kabov, "Film condensation of vapor in finned tube bundles," in: Heat Transfer and Hydrodynamics in Boiling and Condensation Processes [in Russian], Inst. Teplofiz. Sib. Otd., Akad. Nauk SSSR, Novosibirsk (1985), pp. 81-98.
3. S. S. Kutateladze, Basic Theory of Heat Transfer [in Russian], Atomizdat, Moscow (1979).
4. I. I. Gogonin, V. I. Sosunov, S. I. Lazarev, and O. A. Kabov "Heat transfer with condensation of motionless vapor in bundles of horizontal tubes of different geometry," Teploenergetika, No. 3, 33-36 (1982).
5. I. I. Gogonin, O. A. Kabov, and I. V. Padyukov, "Film condensation of motionless vapor on a finned surface," Inzh.-Fiz. Zh., 49, No. 5, 709-717 (1985).
6. V. F. Rifert, P. A. Barabash, and A. B. Golubev, "Intensity of condensation of water vapor on horizontal tubes with surface wires," Izv. Vyssh. Uchebn. Zaved., Energetika, No. 7, 106-110 (1980).
7. D. G. Thomas, "Enhancement of film condensation heat-transfer rates on vertical tubes by vertical wires," Ind. Eng. Chem., 6, 97-103 (1967).
8. G. F. Smirnov and I. I. Lukanov, "Investigation of heat transfer with condensation of Freon 11 on a bundle of finned tubes" Kholod. Tekh., No. 5, 31-33 (1971).
9. O. P. Ivanov, S. T. Butyrskaya, and V. O. Mamchenko, "Heat transfer with condensation of moving Freon 12 vapor in bundles of smooth and finned tubes," Kholodn. Tekh., No. 9, 24-27 (1971).
10. V. F. Chaikovskii, R. A. Bakhtiozin, I. I. Lukanov, and B. V. Puchkov, "Investigation of heat and mass transfer with condensation of mixtures of Freon 12 and 22 in horizontal finned tubes," Kholodn. Tekh., No. 2, 24-28 (1973).
11. D. L. Katz and J. M. Geist, "Condensation of six finned tubes in a vertical row," Trans. ASME, 70, No. 8 (07-914 (1948).
12. N. V. Zozulya, V. P. Vorovkov, I. Ya. Skuratov, et al., "Increase of efficiency of low-pressure regenerative superheaters and condensers by the use of low-finned tubes," Tr. TsKTI, No. 121, Leningrad (1973), pp. 132-139.
13. V. G. Rifert, A. I. Butuzov, G. G. Leont'ev, et al., "Intensification of heat transfer in the condensers of vacuum and water-distillation equipment," Sudostroenie, No. 7, 28-30 (1974).
14. G. G. Shklover, O. O. Mil'man, V. A. Baskov, and G. A. Ankudinov, "Some special features of heat transfer with vapor condensation in horizontal finely corrugated tubes", in: Heat Transfer and Hydrodynamics [in Russian], Nauka, Leningrad (1977), pp. 174-180.

HEAT EXCHANGE AT THE BOTTOM OF A DEAD END BATHED BY A LAMINAR IMPINGING JET

A. I. Abrosimov and A. V. Voronkevich

UDC 536.242:532.525.6

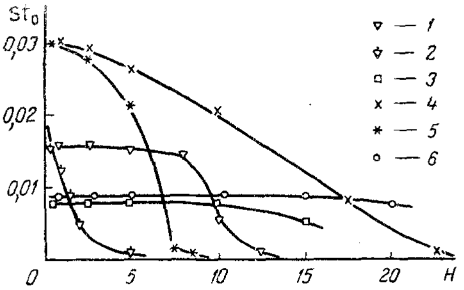
The local and average heat exchange of a round laminar jet flowing perpendicularly onto the center of the bottom of a dead-end chamber are investigated numerically.

The cathodes of plasmatrons and the elements of powerful electronic instruments are often cooled by a liquid which flows, in the form of a round laminar jet, coaxially into a cylindrical chamber and impinges perpendicularly on the flat bottom located opposite to the nozzle.

Certain aspects of the hydrodynamics and heat exchange of a round laminar jet in a dead end are considered in [1, 2]. The investigations were made by integrating the complete Navier–Stokes and energy equations for constant physical properties and incompressibility of the medium. In [1] only initial data are given on local heat exchange at the bottom of a dead end bathed by a jet with a rectangular initial velocity profile. From them one can judge that the degree of constriction b of the stream vitally affects both the intensity of heat exchange and the character of its distribution. For relatively small b, in particular, there are regions with enhanced heat exchange in the corners of the dead end, which does not occur when a jet impinges on a barrier. The influence of the determining parameters on the dispersion of the

All-Union Scientific-Research Institute of Electromechanics, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 51, No. 1, pp. 23-26, July, 1986. Original article submitted April 1, 1985.

 0022-0841/86/5101-0764$12.50



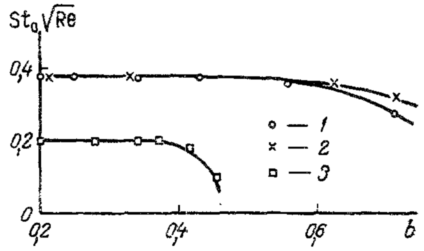


Fig. 1 Fig. 2

Fig. 1. Influence of the initial velocity profile, Reynolds number, b, and H on heat exchange in the vicinity of the critical point (Pr = 9.6): 1-3) rectangular velocity profile: 1) Re = 200, b = 0.2; 2) 200, 0.455; 3) 740, 0.2; 4-6) parabolic velocity profile; 4) Re = 200, b = 0.2; 5) 200, 0.455; 6) 2040, 0.2.

Fig. 2. Heat exchange in the vicinity of the critical point as a function of the initial velocity profile and b (Pr = 9.6): 1, 2) parabolic velocity profile, H = 2.5: 1) Re = 200; 2) 2680; 3) rectangular velocity profile, H = 5, Re = 2680.

inflowing jet and the coefficient of friction on the bottom of the dead end was studied in [2].

The flow scheme presumed the evacuation of spent liquid through the annular gap between the nozzle and the cylindrical wall of the dead end. The numerical experiments were carried out by the method presented in [1, 2].

In the calculations the Reynolds number was varied from 68 to 2680, the length H of the dead end from 0.5 to 22.5, and the quantity b from 0.1 to 0.715, and the velocity profile at the nozzle cut was rectangular and parabolic.

Heat transfer in the vicinity of the critical point (Fig. 1) depends in a complex way on the Reynolds number, the degree of constriction of the stream, the quantity H, and the initial velocity profile of the jet. We only note that an increase in the Reynolds number, as well as a transition from a rectangular to a parabolic velocity profile at the nozzle cut, lead to intensification of heat transfer and a shift in the boundary between "long" and "short" dead ends into the region of larger values. The length of the dead end for which $St_0 = 0.01(St_0)_{H=0.5}$, other determining parameters being equal, served as this boundary.

The calculations showed that for each Re, H, and shape of the initial velocity profile (Fig. 2), there exists a region of variation of the degree of stream constriction in which $St_0 \approx$ const. Starting with a certain value $b = b_b$, a further increase in the degree of stream constriction is accompanied by a decrease in St_0. Dead ends for which $b \leqslant b_b$ will arbitrarily be called "broad" dead ends.

Data on heat exchange in the vicinity of the critical point for "broad" dead ends with $H \leqslant 5.0$ are generalized, with an error not exceeding ±6%, by the relation

$$St_0 = A\,Re^{-0,5}\,Pr^{-0,62}, \tag{1}$$

where A = 1.61 for a parabolic initial velocity profile and A = 0.813 for a rectangular one. We note that the relation (1), to within the indicated error, generalizes calculated [3] and experimental [4] data obtained at the critical point of a barrier bathed by a laminar jet with a parabolic initial velocity profile.

In the dispersing part of the flow, the local heat exchange at the bottom of a dead end can be described by the expression

$$St_l = 0{,}813\,Re_l^{-0,5}\,Pr^{-0,62}. \tag{2}$$

It is characteristic that deviation from this relation already begins at the end of the indicated region. The flow is gradually transformed into a semibounded fan jet, and the similarity relation takes the form

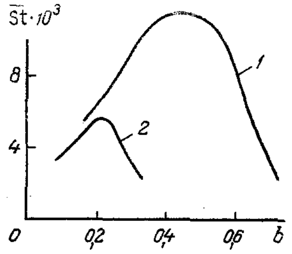


Fig. 3. Average heat exchange as a function of the initial velocity profile and b (Re = 200, Pr = 9.6, H = 5): 1) parabolic velocity profile; 2) rectangular profile.

$$St_{l.j} = 0{,}575\,Re_l^{-0,5}\,Pr^{-0,62}. \tag{3}$$

The data of the numerical solution are generalized by the relations (2) and (3) with an error not exceeding ±10%. In the predetachment zone the scatter increases, and the calculated points lie below the relation (3).

The variation of heat exchange averaged over the bottom of the dead end as a function of the degree of stream constriction for "short" dead ends (Fig. 3) is characterized by the presence of a maximum for jets with both rectangular and parabolic initial velocity profiles. Two factors operate with an increase in b: the increase in the relative area of the dead end occupied by the dispersing part of the flow, characterized by the highest heat-transfer coefficient, and the speedup of dispersion of the jet under the action of the opposite stream of heat-transfer agent being evacuated, the velocity of which grows as the dead end narrows. The first factor predominates when the degree of stream constriction is low. With an increase in b, the role of the second factor grows, and it finally becomes decisive.

The quantity b_{max}, corresponding to $\overline{St}_{max}$, was determined for H = 2.5 and 5.0. In the range of Re = 200-2680, the data obtained for b_{max} are generalized, to within ±5%, by the following relations:

for a parabolic initial velocity profile

$$b^{**}_{max} = (0{,}35 - 0{,}01H)\,Re^{0,077}, \tag{4}$$

for a rectangular initial velocity profile

$$b^{*}_{max} = (0{,}31 - 0{,}033H)\,Re^{0,077}. \tag{5}$$

The relations for calculating the maximum average heat exchange can be recommended in the form

$$\overline{St}^{*}_{max} = 0{,}338Re^{-0,44}\,Pr^{-0,62}, \tag{6}$$

$$\overline{St}^{**}_{max} = 0{,}536Re^{-0,44}\,Pr^{-0,62} \tag{7}$$

for rectangular and parabolic velocity profiles at the nozzle cut, respectively.

In the region of $b > b_{max}$, an increase in the degree of stream constriction is accompanied by a sharp drop in $\overline{St}$. This region of variation of b is of practical interest in the case of a considerable decrease in the coolant flow rate, such as in emergency situations.

In the known installations, $b < b_{max}$ at the nominal coolant flow rate. For $b \leqslant 0.85b_{max}$, the similarity relation for calculating the average heat exchange is obtained in the form

$$\overline{St} = B\,Re^{-0,44}\,Pr^{-0,62}\,b^{0,5}, \tag{8}$$

where B = 0.573 for a rectangular velocity profile and B = 0.775 for a parabolic one at the nozzle cut. The influence of the distance H was insignificant in the investigated regimes.

If the principle of pseudolocal similarity [5] is used, then when a surface with an effective diameter D is cooled by a system of n uniformly distributed, round jets, having rectangular initial velocity profiles, the expression for the average heat exchange is written, using Eq. (8), in the form

$$\overline{\mathrm{St}}_c^* = 0{,}573\mathrm{Re}^{-0{,}44}\,\mathrm{Pr}^{-0{,}62}\left(\frac{d}{D}\right)^{0{,}5} n^{0{,}25}. \qquad (9)$$

Calculations through Eq. (9) for $\mathrm{Re} \leqslant 3.10^3$ and $H \leqslant 5.0$ are in satisfactory agreement with test data [6, 7] obtained under the conditions of evacuation of the spent coolant through channels located between the jet orifices.

NOTATION

$b = d/D_d$, degree of stream constriction; d, nozzle diameter; D_d, diameter of dead-end chamber; $\mathrm{Re} = dv/\nu$, $\mathrm{Re}_l = ru_m/\nu$, Reynolds numbers; v, average-mass velocity at the nozzle cut; r, radial distance from the axis; u_m, velocity at the outer limit of the wall boundary layer; ν, kinematic viscosity; $H = h/d$, h, distance between the nozzle cut and the bottom of the dead end; $\mathrm{St}_0 = \alpha_0/\rho c_p v$, $\mathrm{St}_l = \alpha/\rho c_p U_m$, $\overline{\mathrm{St}} = \overline{\alpha}/\rho c_p v$, Stanton numbers in the vicinity of the critical point, in the dispersing part of the flow, and average Stanton number; α, $\overline{\alpha}$, local and average heat-transfer coefficients; ρ, density; c_p, specific heat; $\mathrm{Pr} = \mu c_p/\lambda$, Prandtl number; λ, thermal-conductivity coefficient.

LITERATURE CITED

1. A. I. Abrosimov, "On the internal peak in the coefficient of heat transfer to a plate bathed by a perpendicular jet," Teplofiz. Vys. Temp., 22, No. 3, 512-516 (1984).
2. A. I. Abrosimov and A. V. Voronkevich, "Some characteristics of the flow of a round laminar jet in a dead end," Dept. No. 5672-84, VINITI, Aug. 3 (1984), Inzh.-Fiz. Zh., 48, No. 1, 146 (1985).
3. N. R. Saad, W. J. M. Douglas, and A. S. Mujumdar, "Prediction of heat transfer under an axisymmetric laminar impinging jet," Ind. Eng. Chem., Fundam., 16, No. 1, 148-154 (1977).
4. M. T. Scholtz and O. Trass, "Mass transfer in a nonuniform impinging jet," AIChE J., 16, No. 1, 82-96 (1970).
5. P. Krötzsch, "Wärme- und Stoffübergang bei Prallströmung aus Düsen- und Blendenfeldern," Chem.-Ing.-Tech., 40, No. 7, 339-344 (1968).
6. A. I. Abrosimov, A. I. Paramonov, and G. M. Rozhina, "Experimental investigation of heat transfer in the jet cooling of semiconducting power equipment," Stabilized Converter Cells, Tr. Vses. Nauchno-Issled. Inst. Elektromekh., 50, 92-97 (1977).
7. H. Ott, "Wärmeübergang an einer durch Luftstrahlen gekühlten Platte," Schweiz. Bauztg., 79, No. 46, 834-840 (1961).