EXPERIMENTAL INVESTIGATION OF CONVECTIVE HEAT TRANSFER FOR A GAS MOVING IN THE INITIAL SECTION OF A CYLINDRICAL TUBE

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Results are presented of a generalization of the data of an experimental investigation of convective heat transfer for a gas moving in the initial section of a tube at subsonic and supersonic velocities.

In spite of the quite large number of experimental papers [1, 3, 4–6] devoted to investigation of convective heat transfer for air moving in a cylindrical tube at subsonic and supersonic tube inlet velocities, a number of questions have not been sufficiently elucidated. In the majority of the investigations, the usual parametric reduction of the test data was used, bringing in the supplementary parameter x/D. This method gives satisfactory results, however, only for the region of relatively low heating intensity [1]. Under intense heat flux the velocity of the gas in the potential flow core may be appreciably altered, the law of velocity change along the length being dependent on the heat flux intensity and the law of heat supply. In this case the introduction of the single supplementary parameter x/D will not be enough to allow calculation of the development of the thermal boundary layer along the channel [5]. An even greater difficulty arises in generalizing the test data for supersonic gas velocity at the tube inlet. In these conditions it is also necessary to take account of the influence of compressibility on the heat transfer coefficient.

In [3, 4, 6], devoted to an experimental investigation of heat transfer in tubes with supersonic gas velocities at the tube inlet, the temperature factor $\overline{T}_W < 1$. This stabilizes the boundary layer, as is known [9], and so some of the experimental points in these papers are located in the transition zone.

In order to exclude the stabilizing influence of cooling on the boundary layer, the present investigation was carried out with temperature factor $\overline{T}_W > 1$.

Reduction of the test data was carried out according to the method described in [7, 11]. An advantage of the method used, in comparison with others [5, 6], is the possibility of excluding the influence of the parameter x/D, which mainly determines the distribution of heat transfer coefficients along the tube, and thereby of establishing the influence of the nonisothermal state and of compressibility on the heat transfer in pure form. Knowing the heat transfer law, we may calculate the distribution of heat transfer coefficients along the initial section of the tube, by the method described in [10].

The experimental investigations were conducted on the setup shown schematically in Fig. 1. Air from a compressor passes through a metering disk 7 and filter 8, reaches the experimental section 13, and, being cooled in the coolers 17, is pumped out by vacuum pumps 19 to the atmosphere. Flowrate control is accomplished by valve 3.

The experimental section consisted of a stainless steel tube of external diameter 34, internal diameter 24.3, and length 1052 mm. For technical reasons the section was made of two identical tubes of length 500 mm each, joined by a transition tube. A detachable nozzle was fastened to the front end of the tube by means of a bushing. The subsonic nozzle had a conical inlet, and the supersonic nozzle was contoured for a Mach number of M = 3. To measure the static pressure distribution along the tube there were 33 orifices of diameter 0.75 mm, 30 mm apart in the direction of the longitudinal axis. Each successive tapping was displaced relative to the preceding one by an angle of 22° 30' (around the tube). Lead-out of pressures from the tube was effected by means of steel fittings screwed into the main tube. The tappings were connected to a manometer by brass tubes brazed to the fittings. Measurement of pressure was done on a multitube water manometer, with tubes of diameter 10 mm and length 2200 mm.

Measurement of absolute static pressures was performed on mercury manometers, at the same time as the measurement on the water manometer. The stagnation pressure ahead of the working section was measured on a reference manometer.

The tube was heated by an alternating electric current passing through a nichrome ribbon of width 5 mm and thickness 0.5 mm, wound on the tube. To avoid possible contact between the nichrome ribbon and the tube surface, a reliable gap was maintained. For this purpose eight porcelain tubes of diameter 3 mm were laid along the tube, and the nichrome ribbon was wound on these. To reduce heat loss to the surrounding medium, the working section was enclosed in a steel jacket of diameter 280 mm, supported on flanges mounted at the ends of the experimental section.

To avoid thermal gradients in the jacket, two thermal compensators were provided. The jacket was pumped down, which reduced heat leakage to the surrounding medium. To take account of heat loss in the calculations, a calibration of the equipment without air flow was performed.

The maximum value of the losses was 6%. Measurement of tube wall temperature was done with chromel-kopel thermocouples located in annular grooves machined on the outer surface of the tube. The hot thermocouple junctions were welded electrically to the tube. To monitor the uniformity of temperature distribution

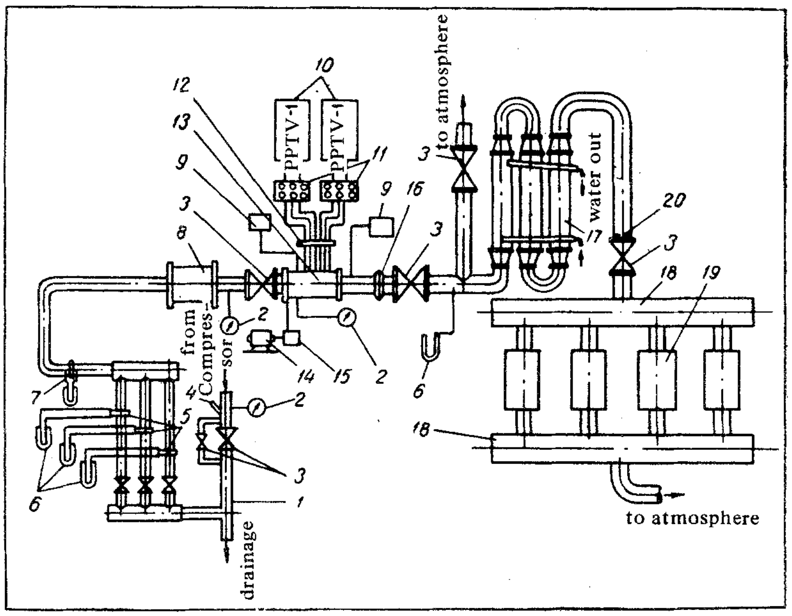

Fig. 1. Schematic of experimental setup: 1) tubing; 2) manometers; 3) valves; 4) thermometers; 5) measuring disks; 6) mercury manometers; 7) measuring disk; 8) filter; 9) EPP-09 potentiometers; 10) PPTV-1 potentiometer; 11) switches; 12) thermostat; 13) experimental section; 14) motor; 15) vacuum pump; 16) compensator; 17) cooler; 18) collector; 19) VN-6 pump; 20) mesh.

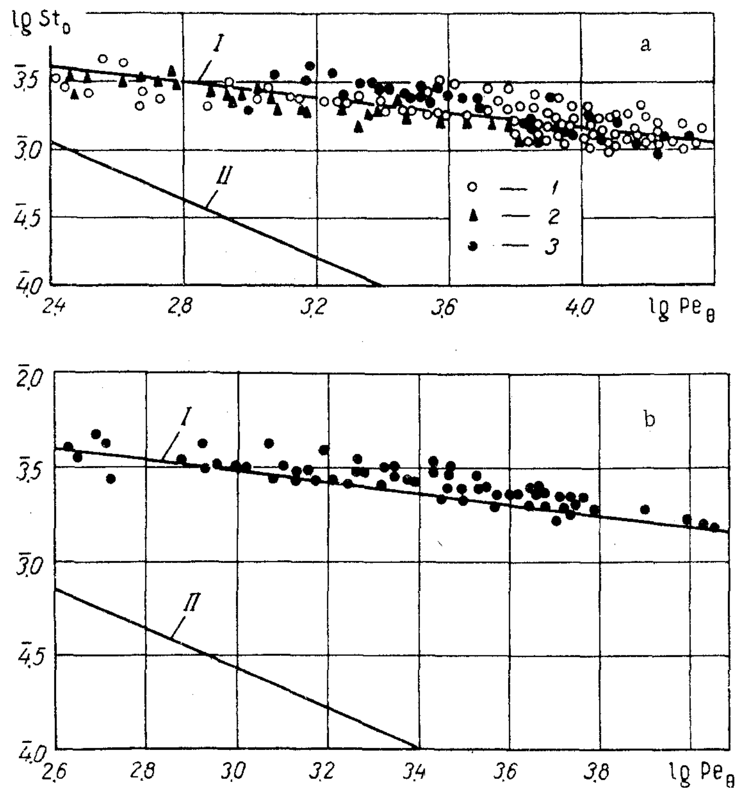

Fig. 2. Heat transfer law for the initial section of a cylindrical tube at (a) subsonic and (b) supersonic speeds at the tube entrance: I – $St_0 = 0.914/Pe_\theta^{0.25} Pr^{0.5}$; II–$St_0 = 0.22/Pe_\theta Pr^{1/3}$ for a laminar boundary layer according to [13]; 1) according to the authors' data; 2) from [14]; 3) from [5].

around the tube, two or three equally spaced thermocouples were placed in each groove. The thermocouple leads were led into a common thermostat, consisting of a massive copper cover fastened to a wooden support. The junctions located in the thermostat were joined by copper wires to the switches of a PPTV potentiometer. The simultaneous readings of the 24 thermocouples were recorded on electronic 12-point EPP-09 potentiometers. Lead-out of the thermocouples, pressures, and electrical wires was effected through the rear flange of the section by means of special fittings. Before the tests were conducted, the system was pressurized both in the cold and in the hot condition.

All the measurements were taken after the system had reached a steady state. Tests were done with three M values at the tube entrance: 0.28, 0.36, and 3. The temperature factor $\bar{T}_W$ was varied from 1 to 2.05 with q_W = const.

During the tests the following parameters were measured: p_0—the stagnation pressure at the tube entrance; p—the distribution of static pressure along the tube; T_W—the wall temperature distribution along the tube; T_0—the stagnation temperature at the tube entrance; G—the mass flowrate; Q—the power supplied to the experimental section.

The original test data are shown in Tables 1 and 2.

As preliminary tests showed, the chief error in wall temperature measurement arose from possible unsteadinesss in conditions during the test. The steadiness of conditions during the measurement was controlled from the readings of the 12-point EPP-09 potentiometric recorders, to which the 24 thermocouples were connected.

The magnitude of the specific thermal flux was determined from the formula

$$q_w = (Q - Q')/\pi D l. \qquad (1)$$

Subsequent processing of the test data was carried out according to the method described in [11]. Local values of the Stanton number were calculated from the formula

$$\mathrm{St} = q_w \sqrt{T_0}/m p_0 q(\lambda) c_p (T_w - T_l), \qquad (2)$$

where m = 0.3965 (for air). Values of q(λ) were found from the static pressure distribution $\tau = p/p_0$, according to a table of gasdynamic functions [12]. The Peclet number, based on energy thickness, was determined from the equation

$$\mathrm{Pe}_\theta = q_w x/\lambda_0 (T_w - T_l). \qquad (3)$$

Figure 2a shows the results of generalizing the test data in the subsonic velocity region. The Stanton number is referred to thermally insulated conditions according to Kutateladze's formula [2]. It may be seen from the graph that the test points fall on a single curve which may be described by the formula [11]

$$\mathrm{St}_0 = 0.014\, \mathrm{Pe}_\theta^{-0.25} \mathrm{Pr}^{-0.5}. \qquad (4)$$

The same graph shows the test data of [6] and [5], reduced according to the method described. These tests also confirm formula (4). It was shown in [7] that in Lel'chuk's tests at a distance of about x/D < 6, the channel entrance conditions had an appreciable influence on the heat transfer, and these points are therefore not shown in Fig. 2a.

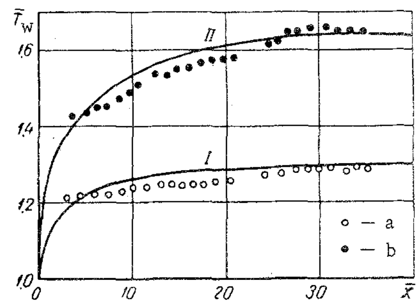

Fig. 3. Comparison of theoretical calculation of $\bar{T}_W$ distribution along the tube with q_W = const according to the method described in [10], with the authors' test data: I and II) theoretical calculation [10] according to the original data of the first (Table 2) and third regimes, respectively; a and b) test data of the first and third regimes.

Figure 2b presents the test data on heat transfer for supersonic gas flow in the tube. The test values of Stanton number are reduced to incompressible fluid flow conditions according to the limit formula [8]. For a small range of variation of M and $\bar{T}_W$, the relative influence of compressibility and nonisothermal state may be represented approximately by the formula

$$\mathrm{St}/\mathrm{St}_0 = [(1-\beta^2)/\bar{T}_w]^{0.5}. \qquad (5)$$

It may be seen from the graph that the test points in reduced form are located around curve I. Therefore, the general heat transfer law which describes turbulent transfer of heat in the boundary layer of the initial section of the tube has the form [11]

$$\mathrm{St} = \frac{0.014}{\mathrm{Pe}_\theta^{0.25}} \left(\frac{1-\beta^2}{\bar{T}_w \mathrm{Pr}} \right)^{0.5}. \qquad (6)$$

The heat transfer law obtained (6) was used for solving the integral energy equation. The result is a comparatively simple and quite effective method of calculating heat transfer in the initial section of a tube [10]. Figure 3 shows a comparison of the results of a calculation of wall temperature by the method described in [10] with the authors' test data.

NOTATION

x—coordinate along tube; D—internal diameter of tube; $\bar{T}_W = T_W/T_0$—temperature coefficient; T_W—wall temperature; T_0—stagnation temperature outside boundary layer; Q'—power, equivalent to heat losses to surrounding medium; l—length of heated section of tube; q_W—specific heat flux; q(λ)—gasdynamic function; T_l —

Table 1

Original Test Data on p/p_0 Distribution Along the Tube

	Subsonic nozzle								Supersonic nozzle			
G, kg/sec	0.0872	0.0872	0.0862	0.0866	0.149	0.1415	0.147	0.147	0.0651	0.0656	0.0723	0.0798
$(Q-Q')$, kW	2.28	3.4	4.52	6.8	1.315	2.6	4.1	2.56	2.56	2.85	3.0	3.84
p_0, kN/m_2	169	169	169	169	284	284	286	284	269	269	300	330
T_0, K	289.8	289.8	292	291.1	288.9	288.5	288.5	288.5	293.5	294.0	298.0	292.0
	p/p_0											
For $\bar{x}$ = 2.915	0.922	0.922	0.922	0.922	0.948	0.950	0.948	0.950	0.037	0.039	0.038	0.0381
4.140	0.920	0.920	0.920	0.920	0.947	0.947	0.947	0.948	0.0451	0.0465	0.0428	—
5.370	0.919	0.919	0.919	0.918	0.946	0.947	0.946	0.945	0.0419	0.0324	0.0341	0.0373
6.620	0.918	0.916	0.917	0.916	0.945	0.945	0.943	0.944	0.0368	0.0394	0.0393	0.037
7.85	0.915	0.915	0.915	0.913	0.943	0.942	0.942	0.942	0.0369	0.039	0.0398	0.0388
9.100	0.914	0.914	0.912	0.912	0.943	0.942	0.942	0.341	0.0385	0.039	0.0752	—
10.3	0.912	0.912	0.910	0.909	0.942	0.9415	0.941	0.940	—	—	—	—
11.65	0.910	0.909	0.909	0.907	0.940	0.940	0.938	0.938	0.043	0.0307	0.0322	0.0452
12.9	0.909	0.908	0.908	0.905	0.939	0.938	0.937	0.937	0.0426	0.044	0.0441	0.0439
14.05	0.907	0.905	0.904	0.902	0.936	0.937	0.935	0.936	0.044	0.0469	0.0458	0.0449
15.3	0.905	0.904	0.903	0.900	0.935	0.936	0.933	0.935	0.0507	0.0552	0.0555	0.051
16.45	0.904	0.903	0.902	0.898	0.935	0.935	0.932	0.933	0.051	0.0495	0.0528	0.0529
17.75	0.903	0.902	0.899	0.897	0.934	0.934	0.932	0.932	—	0.0571	0.0565	0.0531
19.0	0.902	0.899	0.897	0.894	0.932	0.933	0.930	0.931	—	—	—	0.0536
20.1	0.900	0.898	0.896	0.892	0.932	0.931	0.929	0.929	—	0.0894	—	0.0616
21.4	0.898	0.896	0.895	0.890	0.930	0.930	0.928	0.928	—	—	—	0.0582
22.52	0.897	0.895	0.892	0.888	0.920	0.895	0.927	0.927	—	—	—	—
23.65	0.895	0.893	0.890	0.885	0.927	0.928	0.925	0.926	—	0.156	0.0958	—
25.1	0.894	0.892	0.889	0.884	0.926	0.927	0.924	0.924	—	—	—	—
26.4	0.892	0.890	0.886	0.880	0.925	0.925	0.922	0.922	—	—	—	—
27.3	0.891	0.888	0.885	0.879	0.924	0.922	0.920	0.921	—	—	—	—
28.8	0.890	0.886	0.883	0.876	0.922	0.922	0.918	0.920	—	—	—	—
30.1	0.887	0.884	0.880	0.874	0.922	0.921	0.917	0.918	—	—	—	—
31.3	0.885	0.882	0.878	0.871	0.920	0.920	0.916	0.917	—	—	—	—

Table 2

Original Test Data on $\overline{T}_w$ Distribution Along the Tube

	Subsonic nozzle								Supersonic nozzle			
G, kg/sec	0.0872	0.0872	0.0862	0.0866	0.149	0.1415	0.147	0.147	0.0651	0.0656	0.0723	0.0798
$(Q-Q')$, kW	2.28	3.4	4.52	6.8	1.315	2.6	4.1	2.56	2.56	2.85	3.0	3.84
P_0, kN/m_2	169	169	169	196	284	284	286	284	269	269	300	330
T_0, °K	289.8	289.8	292	291.1	288.9	288.5	288.5	288.5	293.5	294.0	298.0	292.0
	$\overline{T}_w$											
For $\overline{x}$ = 3.51	1.205	1.322	1.438	1.700	1.066	1.14	1.209	1.148	1.239	1.306	1.297	1.381
4.77	1.207	1.328	1.450	1.740	1.067	1.148	1.222	1.154	1.284	1.359	1.333	1.424
6.0	1.212	1.337	1.462	1.749	1.072	1.16	1.245	1.168	1.327	1.407	1.371	1.469
7.25	1.215	1.342	1.470	1.755	1.079	1.173	1.257	1.178	1.347	1.437	1.388	1.492
8.5	1.225	1.358	1.491	1.786	1.083	1.182	1.269	1.189	1.357	1.443	1.392	1.51
9.7	1.232	1.365	1.500	1.800	1.084	1.181	1.268	1.189	1.359	1.464	1.388	1.504
10.95	1.235	1.374	1.512	1.836	1.087	1.188	1.2799	1.195	1.3604	1.439	1.386	1.504
12.2	1.242	1.386	1.530	1.860	1.086	1.189	1.283	1.196	1.361	1.436	1.384	1.202
13.4	1.244	1.386	1.531	1.862	1.088	1.190	1.284	1.196	1.354	1.419	1.374	1.491
14.65	1.250	1.396	1.544	1.880	1.091	1.192	1.289	1.201	1.364	1.428	1.385	1.492
15.9	1.252	1.392	1.548	1.878	1.092	1.24	1.306	1.211	1.354	1.418	1.378	1.494
17.1	1.254	1.405	1.560	1.900	1.092	1.2044	1.309	1.212	1.352	1.411	1.373	1.494
18.4	1.262	1.424	1.574	1.915	—	1.203	1.305	1.212	1.351	1.411	1.371	1.495
19.7	1.261	1.415	1.575	1.920	1.102	1.208	1.315	1.215	1.353	1.373	1.357	1.488
20.8	1.265	1.426	1.578	1.920	1.134	—	—	—	1.248	1.273	1.276	1.352
24.5	1.279	1.441	1.612	1.989	1.102	1.226	1.345	1.231	—	1.256	—	1.326
25.7	1.280	1.450	1.622	2.001	1.112	—	1.556	1.23	—	1.211	—	1.288
28.2	1.286	1.452	1.636	2.020	1.1102	1.228	1.3507	1.23	—	1.247	—	1.333
29.4	1.289	1.460	1.638	2.019	1.1075	1.249	1.378	1.252	—	—	—	—
30.6	1.291	1.465	1.648	2.045	1.104	1.243	1.3756	1.245	—	—	—	—
33.2	1.296	1.470	1.650	2.050	1.107	1.234	1.359	1.234	—	—	—	—
35.6	1.290	1.462	1.640	2.030	1.104	1.23	1.352	1.236	—	—	—	—
38.0	1.290	1.460	1.637	2.027	—	1.231	1.353	1.234	—	—	—	—
38.0	1.286	1.459	1.636	2.028	—	1.227	1.348	1.227	—	—	—	—

adiabatic wall temperature [6]; c_p—specific heat at constant pressure; λ_0—thermal conductivity at stagnation temperature; β—dimensionless velocity in the relation $p/p_0 = (1 - \beta^2)^{k/(k+1)}$; k—adiabatic exponent.

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