EFFECTIVENESS OF GAS-FILM COOLING IN A CIRCULAR TUBE WITH ADIABATIC WALLS

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The effectiveness of gas-film cooling in the presence of a turbulent air flow in an adiabatic circular tube with an initial porous section is discussed in relation to the experimental results.

The results of an experimental investigation of gas-film cooling effectiveness in a turbulent air flow through a circular tube with adiabatic walls were reported in [1]. The empirical relations proposed differed from the known formulas of Kutateladze and Leont'ev [2], Goldstein et al. [3], and Nishiwaki et al. [4] for a gas film on a plate in a longitudinal flow.

In the range of injection parameters that we investigated, application of the Kutateladze-Leont'ev theory to the gas film in a tube leads to the following relation:

$$\theta = (15.6 - 23.9)\left(\frac{X}{ml}\right)^{-0.8}. \tag{1}$$

When analyzed in accordance with the usual formula $\theta = A(X/ml)^{-0.8}$, the experimental data give the relations presented in Table 1.

As may be seen from Table 1, the correlation of all the data in a single formula requires an additional parameter. Goldstein [3] proposed that the data be correlated by a relation having the form

$$\theta = A\,\mathrm{Re}_{\delta^*}^{p}\left(\frac{X}{ml}\right)^{n}. \tag{2}$$

Here, A, p, and n are constants, and $\mathrm{Re}_{\delta^*} = U_a\delta^*/\nu$ is the Reynolds number based on the displacement thickness.

However, an analysis of our data revealed considerable stratification with respect to the injection parameter m. The discrepancy between the data of various investigators on film effectiveness is usually attributed to differences in the hydrodynamic and thermal conditions immediately beyond the secondary-gas injection point. According to Kutateladze and Leont'ev [2], the film effectiveness can be represented in the generalized form

$$\theta = \frac{\mathrm{Re}_{t_a}^{**}}{\beta\,\mathrm{Re}^{**}}; \tag{3}$$

$\beta = \delta_t^{**}/\delta^{**}$ is treated as an integral characteristic of the hydrodynamic conditions and the thermal state of the flow; $\mathrm{Re}_{t_a}^{**} = U_a\delta_{t_a}^{**}/\nu$ and $\mathrm{Re}^{**} = U_a\delta^{**}/\nu$ are the Reynolds numbers based on the energy thickness at the outlet from the porous section and the momentum thickness in the given section, respectively.

Our measurements in a circular tube with an initial porous section enabled us to calculate δ^*, δ^{**}, δ_t^{**}, and β for various Re_d, m, $\bar{X}$, l. It was found that the dynamic characteristics δ^*, δ^{**} start by increasing with increase in $\bar{X}_1$, reach a maximum at $\bar{X}_1 = 1$–2, and then gradually fall to a value determined by the power-law velocity profile of the steady-state turbulent flow in the circular tube. The energy thickness δ_t^{**} increases with $\bar{X}$, reaching a limiting value in the section where complete adiabatic mixing of the flows

Table 1

Relations for the Effectiveness of a Gas Film in a Circular Tube

l/d	$\frac{X}{ml}$	Formula
5.2	50—1000	$(14.1\text{–}24.5)\left(\frac{X}{ml}\right)^{-0.8}$
2.74	50—1000	$(15.3\text{–}24)\left(\frac{X}{ml}\right)^{-0.8}$
0.94	50—1000	$(16\div 20)\left(\frac{X}{ml}\right)^{-0.8}$

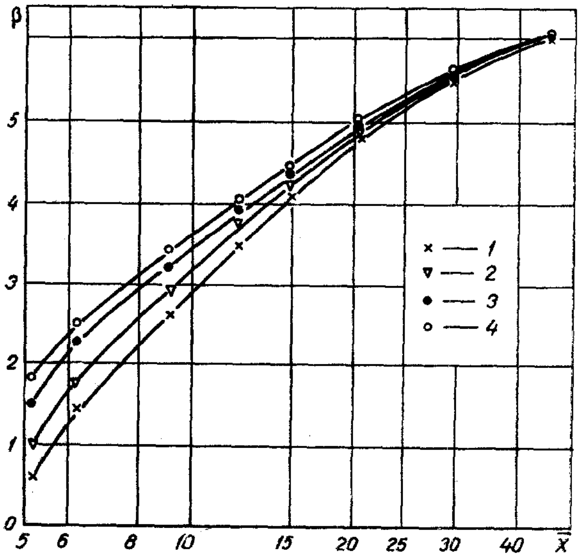

Fig. 1. The parameter β as a function of the dimensionless distance $\bar{X}$ and the injection parameter at $l/d = 5.2$: 1) $m = 1.8\cdot 10^{-3}$, $\mathrm{Re}_d = 41.7\cdot 10^3$; 2) $10.06\cdot 10^{-3}$ and $41.7\cdot 10^{-3}$; 3) $21.13\cdot 10^{-3}$ and $15.3\cdot 10^3$; 4) $43.84\cdot 10^{-3}$ and $9.4\cdot 10^3$.

ends. At the outlet from the porous section, the quantities δ^*, δ^{**}, δ_t^{**}, and β increase with increase in the injection parameter. However, the dependence of these quantities on m, $\overline{X}$, l cannot be generalized by any simple function capable of serving as a correlation formula relating the effectiveness with the experimental parameters in the range of variation investigated. In Fig. 1, β is shown as a function of $\overline{X}$ and m at $l/d = 5.2$. The increase is sharpest up to the section $\overline{X}_1 = 10$; the effect of the injection parameter m declines as $\overline{X}_1$ increases. In our opinion, the best correlation of the experimental data is offered by a formula of the type

$$\theta = C\beta_a^p\left(\frac{X}{ml}\right)^q \tag{4}$$

or

$$\theta = 15.2\left(\frac{l}{d}\right)^{0.1}\left[\beta^p\left(\frac{X}{ml}\right)\right]^{-0.8}. \tag{5}$$

The quantity β_a is calculated from the corresponding values of T and U in the section at the outlet from the porous region, while the exponent p depends on m, l, and X:

$$\beta_a = 4.17\left(\frac{l}{d}\right)^{0.54} m^{0.5}. \tag{6}$$

Figure 2 is convincing evidence of the suitability of formulas (5) and (6). The empirical relations obtained for porous sections of different lengths are presented in Table 2.

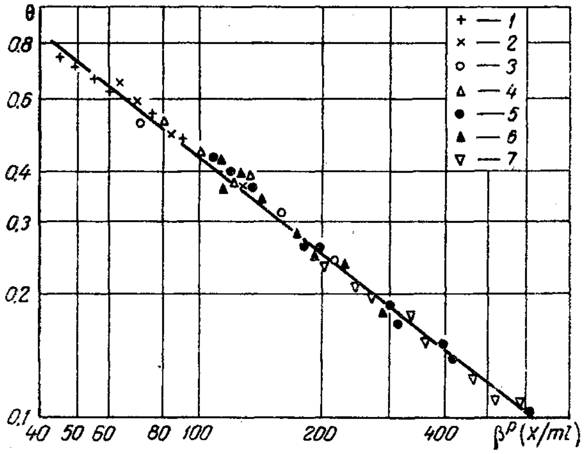

Fig. 2. Effectiveness of gas film at $l/d = 5.2$ as a function of $\beta^p X/ml$: 1) $m = 44.83 \cdot 10^{-3}$, $Re_d = 10.2 \cdot 10^3$; 2) $31.17 \cdot 10^{-3}$ and $15.3 \cdot 10^3$; 3) $19.44 \cdot 10^{-3}$ and $24.1 \cdot 10^3$; 4) $14.54 \cdot 10^{-3}$ and $36.2 \cdot 10^3$; 5) $10.6 \cdot 10^{-3}$ and $41.7 \cdot 10^3$; 6) $8.743 \cdot 10^{-3}$ and $41.7 \cdot 10^3$; 7) $1.951 \cdot 10^{-3}$ and $41.7 \cdot 10^3$.

Table 2

Relations for the Effectiveness of a Gas Film in a Circular Tube Obtained on the Basis of the Experimental Data

l/d	$\frac{X}{ml}$	$m \cdot 10^3$	$\overline{X}$	p
0.94	>60	—	—	0.25
2.74	—	>20	>4	1
			<4	0
		<20	>10	1
			<10	0.8
5.2	—	>9	>10	1
			<10	0
		<9	>6	1.8
			<6	1

NOTATION

$\theta = (T_a - T_{ad}^w)/(T_a - T_{in})$ is the effectiveness of the gas film; X is the longitudinal coordinate from the beginning of the porous section, m; $\overline{X} = X/d$; l is the length of the porous section, m; $m = \rho_w V_w/\rho_a \overline{U}_a$ is the injection parameter; $\delta^* = \int_a^R (1 - \rho_i U_i/\rho_a U_a)(1 - y/R)dR$ is the displacement thickness, m; $\delta^{**} = \int_a^R (1 - U_i/U_a) \times \rho_i U_i/\rho_a U_a(1 - y/R)dR$ is the momentum thickness, m; $\delta_t^{**} = \int_a^R [1 - (T_a - T_i)/(T_a - T_w)]\rho_i U_i/\rho_a U_a(1 - y/R)dR$ is the energy thickness, m; $\overline{U}_a$ is the mean-mass velocity at the inlet to the porous section, m/sec; U_a is the velocity on the channel axis, m/sec; $\overline{X}_1$ is the dimensionless distance from the beginning of the impermeable wall; δ_{ta}^{**} is the energy thickness at the outlet from the porous section. Subscripts: w refers to parameters at the wall; a, to parameters on the axis; i, to parameters at a given point of the cross section; ad represents adiabatic; in represents secondary flow.

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