MEASUREMENT OF GAS CONCENTRATION ON WALL IN CASE OF LOCAL INJECTION OF ARGON AND HELIUM IN INITIAL SECTION OF TUBE

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Film cooling can be used to protect surfaces from the effects of high-temperature and chemically aggressive gas streams. In this case the cooling gas (liquid) is injected through a slot or porous section into the boundary layer on a surface.

Most film-cooling investigations have been concerned with the injection of a gas of the same kind (air into air). It is only in a few works [1-4] that the injection of a foreign gas on an adiabatic flat wall has been considered.

It is known that porous cooling is more effective when a gas of lower molecular weight is injected [5].

A recent investigation of film cooling [4] showed that the effectiveness of helium injection on an adiabatic wall is a little greater than that of Freon 12 (with the same coolant flow rates the weight concentration of the injected component on the wall is a little higher for gases with lower molecular weight). For the same value of the ratio $w =$ const of the injection velocity through a slot W_s and the mainstream velocity W_0 the weight concentration of coolant on the wall is higher for a gas with higher molecular weight.

It was shown in [6] that the transverse curvature of the surface had a substantial effect on the rate of heat and mass transfer in a submerged ($w \to \infty$) wall jet in the case of longitudinal flow over the external surface of a cylinder.

The aim of the present work was to determine the effectiveness of local injection of argon and helium in the initial section of a tube.

The experiments were conducted on the apparatus described in detail in [7]. In this case we used special working sections, which are shown schematically in Fig. 1. The gas concentration on the wall was measured when argon or helium was injected through a tangential slot (Fig. 1a) and when helium was injected through an initial porous section (Fig. 1b). When argon or helium was injected through the tangential slot (Fig. 1a), the working section consisted of two coaxial shaped nozzles 3 and 4, which ensured uniform velocity profiles of the air and injected gas at the entrance to the duct 1.

The mainstream (air) entered the duct from an air system through the inner nozzle 3. The injected gas (argon or helium) flowed into the duct from cylinders through the slot formed by nozzles 3 and 4. The diameter of the outlet section of nozzle 4 was 41 mm. The slot width s was constant (2.08 mm) in all the experiments. The thickness of the outlet lip of nozzle 3 was not more than 0.3 mm. The mainstream and the injected gas entered the duct with the same temperature $t_0 = t_s = 20°C$. The gas was discharged from the duct into the atmosphere. The air flow rate was measured with an orifice meter and was 150-200 g/sec. The flow rates of helium (0.49-3.34 g/sec) and argon (6-43 g/sec) were measured with RS-5 and RS-7 rotameters. The cylindrical duct with internal diameter 41 mm and length 400 mm was made of ebonite. Sixteen holes of diameter 0.2 mm were drilled in the wall along the duct for the removal of gas samples for analysis. These holes were in a helical line to ensure that the samples were not affected by the preceding samples.

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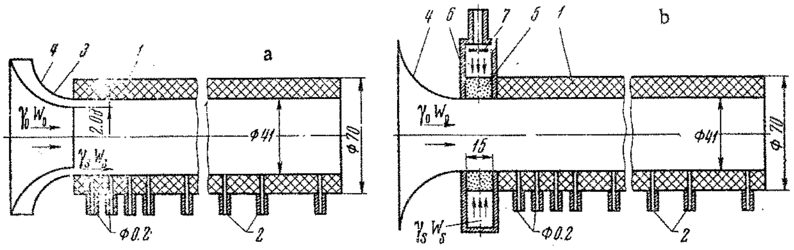

Fig. 1

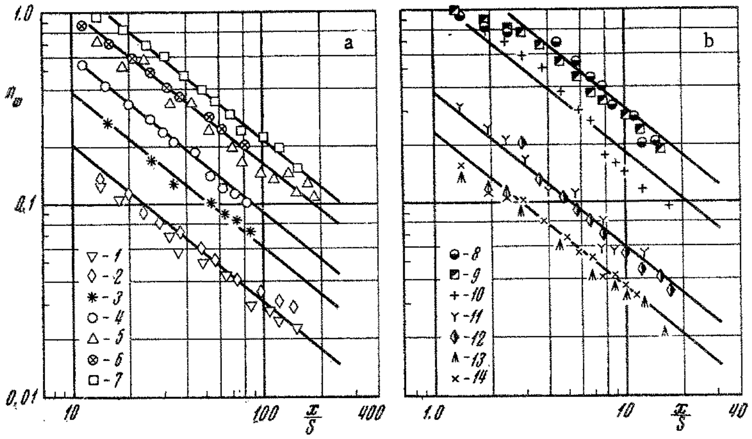

Fig. 2

When helium was injected through a porous insert, we used the working section shown schematically in Fig. 1b. The inner nozzle 3 was removed, and the air flowed into the duct through nozzle 4. The helium flowed in through a cylindrical porous insert 5, made of PG-50 graphite, with a porosity of 50%; a reflector 7 was mounted in the collector 6.

The concentration measurements were made with a GSTL laboratory chromatograph, which has a bridge-type measuring circuit. One arm of the measuring bridge is situated in the chamber through which the investigated gas mixture passes. The instrument readings depend on the thermal conductivity of the gas mixture, which depends on the concentration of the individual components. The instrument was calibrated by the volume method. The gas samples were obtained through branches 2 on the wall. These branches were fitted with rubber tubes, which were filled with distilled water before the experiment and closed with clamps. Injection needles were inserted in the other ends of the tubes, and the water was forced out through these when the gas samples were taken. When the particular regime had been established, all the clamps were opened simultaneously, and the gas samples were taken. The volume of a sample was 30 ml.

If the samples are taken rapidly, the gas may be drawn not only from the surface but also from the core of the boundary layer, which may lead to significant errors. Hence, we first investigated the effect of sampling time on the accuracy of measurement of the helium concentration on the wall. In these experiments the helium slot injection conditions were the same. The ratio of the velocity in the slot to the mainstream velocity $w = 0.1$ was kept constant, and the sampling time was varied. The gas samples were taken at two points on the wall at distances of 30 and 60 mm from the slot mouth. As these experiments showed, with sampling times from 14 to 110 sec the results of measurement of the gas concentration on the wall were the same in the considered conditions. This can be attributed to the fact that the concentration gradient on an impermeable wall is zero, i.e., $\partial k_i / \partial y = 0$.

In the subsequent experiments the gas sampling time was one minute. The main experimental conditions are given in Table 1.

Figure 2 shows the result of measurement of the volume concentration of helium (a) and argon (b) on the wall of the tube in the case of injection through a tangential slot. The numbering of the points in this figure and also in Figs. 3 and 5 corresponds to the experiments characterized in Table 1.

TABLE 1

Points	W_0, m/sec	w	$R_s \cdot 10^{-3}$	Points	W_0, m/sec	w	$R_s \cdot 10^{-3}$
tangential injection of He				tangential injection of Ar			
1	123.0	0.096	0.222	8	133.0	0.787	19.4
2	119.0	0.105	0.227	9	128.0	0.705	17.0
3	128.0	0.174	0.425	10	128.0	0.62	14.65
4	118.5	0.29	0.653	11	131.0	0.223	5.42
5	161.0	0.492	1.5	12	129.0	0.153	5.42
6	153.0	0.51	1.48	13	146.8	0.098	2.72
7	122.0	0.656	1.52	14	146.8	0.098	2.72
He injected through porous section							
15	120.6	0.0153	0.254	17	120.6	0.0448	0.743
16	120.0	0.0252	0.416	18	121.6	0.0558	0.93

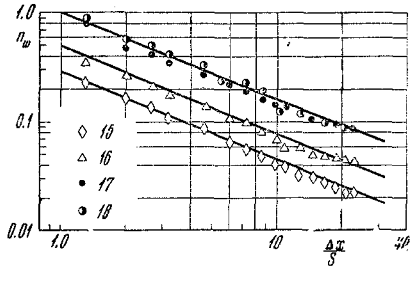

Fig. 3

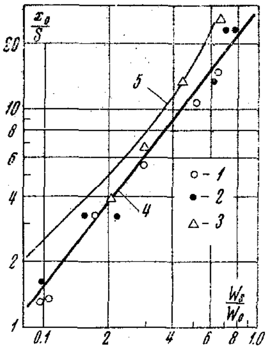

Fig. 4

In these experiments the mainstream velocity was 120-160 m/sec, and the ratio of the velocity in the slot to the mainstream velocity lay in the range $0.1 \leq w \leq 0.7$. As the graph shows, with increase in distance x from the slot the volume concentration of injected gas n_w on the wall decreased exponentially.

Figure 3 gives the results of measurements of the volume concentrations of helium on the wall of the tube when the helium was injected through a porous section of width s (taken as a characteristic length; the coordinates are expressed as fractions of this length). In this case the longitudinal coordinate $x = \Delta x$ was measured from the trailing edge of the porous insert. The change in the volume concentration along the wall in this case was again exponential: $n_w \sim (\Delta x)^{-0.8}$.

Experiments in which helium ($w = 0.5$) or argon ($w = 0.7$) was injected through a tangential slot clearly showed the existence of an initial section in which the gas concentration on the wall is unity. In experiments with lower injection rates the length of this section was determined, as in [8], by extrapolation of the obtained dependence to the point where the concentration of the injected gas on the wall was unity.

Figure 4 shows the length of the initial section as a function of the relative injection velocity w. The experimental results obtained for tangential injection of helium (points 1) and argon (points 2) into air can be approximated by the simple dependence

$$x_0 = 28\, w^{1.25} \tag{1}$$

The same figure shows the length of the initial section determined by Seban [8] for the case of injection of air into air (points 3) on a plate. Curve 4 corresponds to calculation from Eq. (1), and curve 5 to calculation from Abramovich's formula [9] for a free plane jet with $w < 1$:

$$x_0 = \frac{W_0 + W_s}{W_0 - W_s} \left[0.112 + 0.036 \frac{W_0}{W_s} \right]^{-1} \tag{2}$$

It is clear that the length of the initial section in the case of injection of helium or argon through a slot is practically the same as the length of the initial section when air is injected into air.

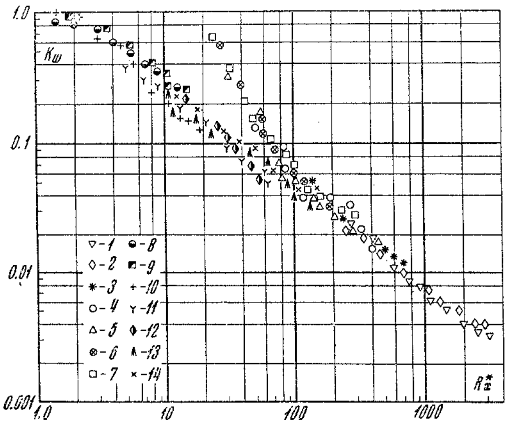

Fig. 5

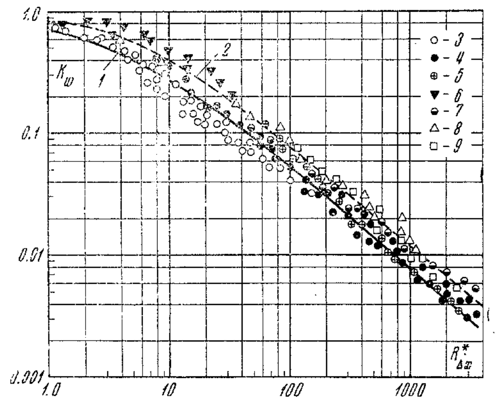

Fig. 6

In most investigations of film cooling [1, 4, 8] the experimental data are correlated by the dimensionless group

$$\frac{x}{ms}\left(R_s\frac{\mu_0}{\mu_s}\right)^{-0.25}=\frac{R_x}{R_s^{1.25}}\left(\frac{\mu_0}{\mu_s}\right)^{1.25}=R_x^* \tag{3}$$

Treatment of the volume-concentration data shows pronounced stratification of the experimental data in relation to the molecular weight of the injected gas. In Fig. 5 the experimental results for the injection of argon and helium through a tangential slot are shown in the form of a plot of the weight concentration of the injected gas on the wall against R_x^*. The main experimental conditions are given in Table 1.

We use the following relationship between the weight and volume concentrations of the injected component:

$$K_w=\frac{n_w M_s}{M_0-n_w(M_0-M_s)} \tag{4}$$

where M_0 and M_s are the molecular weights of the mainstream and the injected gas. As the graph shows, for the same helium and argon flow rates close to the slot, injection of a gas with lower molecular weight is more effective. At a large distance from the slot the results of the experiments converge asymptotically and merge into a single curve. This is due to the fact that for equal flow rates of the injected gas the velocity ratio w in the slot will be greater in the case of a lighter gas. As Fig. 4 indicates, the length of the initial section, where $K_w = 1$, will be greater.

In Fig. 6 the same experimental data are plotted against the group

$$R_{\Delta x}^*=\frac{R_{\Delta x}}{R_s^{1.25}}\left(\frac{\mu_0}{\mu_s}\right)^{1.25} \tag{5}$$

in which the Reynolds number is determined with the initial section ($\Delta x = x - x_0$) taken into account. This figure sums up the experimental data on the effectiveness of film cooling. Curves 1 and 2 are obtained from Eqs. (6) and (7). Points 3 and 4 (tangential injection of argon and helium) and points 5 (injection of helium through a porous section) are the results of our experiments. The other points are taken from [4] and correspond to tangential injection of Freon 12 into air (points 6), hydrogen into air (points 7), and helium into air (points 8). Points 9 are the results of measurements of helium concentration on a wall in the case of injection through a porous section [2]. In this case the longitudinal coordinate Δx is measured from the trailing edge of the porous section. It should be borne in mind, however, that at high (supercritical) injection rates there may be a region beyond the porous section in which the concentration of the injected component $K_w = 1$.

In this treatment the experimental data for tangential injection of argon and helium are in good agreement with one another and with the results obtained for injection of helium through a porous section. The obtained results can be approximated by the following dependence:

$$K_w=[1+0.4R_{\Delta x}^*]^{-0.8} \tag{6}$$

The same graph shows the experimental data of other authors for the concentration of hydrogen, helium, and Freon 12 after a tangential slot [4] and helium after a porous section [2]. These investigations were made in a boundary layer on a flat plate. We consider only experiments in which the velocity of the gas injected through the slot is less than the mainstream velocity (w < 1). This condition corresponds to the physical model adopted in [3, 5, 10] for calculation of the effectiveness of a gas curtain.

Figure 6 also gives the calculated values of the effectiveness of a gas curtain from the formula obtained in [5]:

$$\theta = \frac{(K_i)_0 - (K_i)_w}{(K_i)_0 - (K_i)_s} = [1 + 0.24R_{\Delta x}^{*}]^{-0.8} \tag{7}$$

Here $(K_i)_0$, $(K_i)_s$, and $(K_i)_w$ are the weight concentrations of the i-th component in the mainstream, the slot, and the wall. If the concentration of the injected gas in the mainstream is zero $(K_i)_0 = 0$, its concentration on the wall determines the film-cooling effectiveness $\theta = K_w$. Practically all the experimental data lie between the two theoretical curves.

The results of the present work, obtained in the initial section of a tube ($x/d < 10$ and $s/d = 0.508$), lie a little below the results for a flat plate. The effect of transverse curvature of the surface may increase with increase in the ratio of the slot height s to the tube diameter d.

In the experimental data given in Fig. 6 the enthalpy factor in the slot i_s/i_0 varied from 0.51 for argon injection to 15 for hydrogen injection. They are all correlated, however, without consideration of the nonisothermality factor, which confirms the conclusion, made in [11], that nonisothermality has little effect on the effectiveness of film cooling of an adiabatic wall.

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