HEAT EXCHANGE AND HYDRAULIC RESISTANCE IN MICRONOZZLE GRIDS

A. A. Basovskaya and V. A. Reisig

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We give the results of an experimental investigation of heat exchange and hydraulic resistance when air flows through micronozzle grids.

The study of the kinetics of physicochemical processes in stationary flow-through systems is carried on by means of hardening devices, one of which is a Laval nozzle or a nozzle grid [1, 2]. The hardening device makes it possible to increase the time scale of the process under study, whose duration is usually measured in tens or hundreds of microseconds. This is achieved by increasing the gradients of the gasdynamics parameters of the medium under investigation through a reduction of the geometric dimensions of the hardening device. Thus, for a critical cross section height of 10^{-3} m the rate of cooling of a gas heated to 1500-3000°K is $4\cdot10^{8}$-10^{9} deg/sec [3], and the characteristic gasdynamic time is

$$t_* = \left|\frac{1}{T}\ \frac{dT}{dt}\right|^{-1} \sim 3\cdot 10^{-6}\ \text{sec}. \tag{1}$$

According to [4], such time values ensure a freezing of many physicochemical processes which satisfy the condition

$$t_* \leqslant \tau. \tag{2}$$

As a rule, the media investigated have fairly large values of dissociation energy or excitation energy of the internal degrees of freedom, which necessitates their thermal pumping to temperatures higher than the maximum values for stability of the structural materials. Consequently, the elements of the hardening device must be cooled.

Attempts to miniaturize the nozzle or the elements of the nozzle grid lead to increase in the hydraulic resistance and to intensification of the heat transfer from the gas to the wall. However, there are no available data concerning heat exchange and hydraulic resistance in such devices with elements having characteristic geometric dimensions of the order of 10^{-3} m, and this is the reason for our investigation.

If the working medium used is argon with a small amount of the investigated component added, the Reynolds criterion in the 1500-3000°K range will be 10^{3}-10^{4}. These conditions can be simulated in air at a temperature of up to 400°K.

The procedure and the test stand we used are described in [5]. Here we shall mention only the characteristic of the elements of the micronozzle grid and the results of the investigations.

The micronozzle grid was a collection of profiled copper blades arranged in a single row; the blades had a semicylindrical frontal part and a shaft in the shape of an equilateral triangular prism with a vertex angle of $\alpha = 30°$. The sides of the prism were in planes tangent to the cylindrical surface. The height of the blades was $H = 5\cdot10^{-3}$ m, the diameter of the cylindrical part was $D = 10^{-3}$ m, the spacing of the blades (the throat of the micronozzle) in the grids investigated was $s = 10^{-4}$ m and $2\cdot10^{-4}$ m. The blades were in good thermal contact with the heated frame of the grid.

Table 1 shows the results of one of the experiments conducted with two types of grids. The value of the coefficient of heat transfer from the elements of the grid to the air corresponds to its value for the movement of water in pipes [6]. Such large values of the specific heat flux and heat-transfer coefficient must inevitably affect the characteristics of the investigated medium beyond the hardening device. From this it follows that heat exchange must be taken into account when we calculate the parameters of working media.

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TABLE 1. Values of the Parameters and Thermal Characteristics of Micronozzle Grids for Different Air Flow Rates

Notation	Blade grid									
	$s=0.1\cdot10^{-3}$, m, $H=5\cdot10^{-3}$, $n=18$, $B=742.5$ mm Hg, $T_{amb}=298$ K, $T_{therm}=333.5$ K					$s=0.2\cdot10^{-3}$ m, $H=5\cdot10^{-3}$ m, $n=16$, $B=764$ mm Hg, $T_{amb}=293$ K, $T_{therm}=333$ K				
$G\cdot10^3$ kg/sec	2,35	1,85	1,402	0,994	0,253	2,202	1,759	1,342	0,964	0,25
$P\cdot10^{-4}$ N/m^2	3,72	2,50	1,559	0,892	0,147	2,30	1,549	0,833	0,49	0,098
ΔT, deg	14,2	14,2	14,5	16,2	20,2	8	8,5	9,5	10,5	15
T_W, K	325,2	326	326,6	327,3	328,8	325	325,5	326,5	327	329
T_2, K	306,2	308,2	310,15	312,4	322	301,5	303	304,5	306	313
$q\cdot10^{-6}$ W/m^2	0,55	0,433	0,335	0,266	0,084	0,327	0,278	0,237	0,188	0,069
α, W/m$^2\cdot$deg	2506	2088	1553	1372	901,6	1412	1232	1071	850	351
$\overline{\mathrm{Nu}}$	95	78	58,4	51,5	33	54	47	40,6	32	13
Re	14171	11097	8366	5931	1471	7489	6232	4626	3253	830

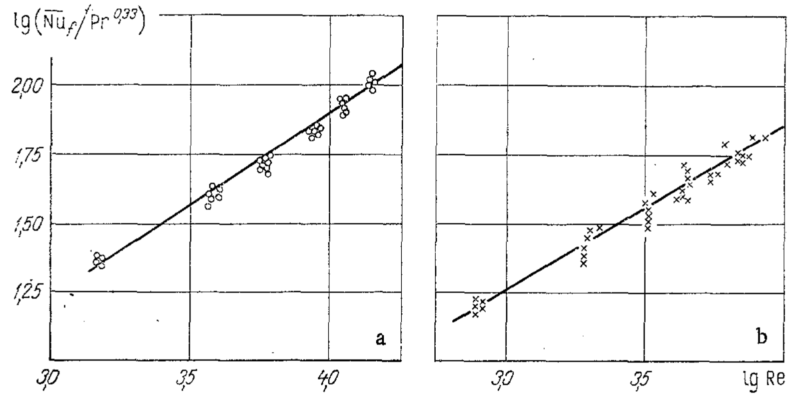

Fig. 1. Variation of $\overline{\mathrm{Nu}}_f/\mathrm{Pr}^{0.33}$ as a function of the Reynolds criterion for a nozzle grid with $s = 10^{-4}$ m (a) and $s = 2\cdot10^{-4}$ m (b).

The most convenient form for using the experimental data in the calculations is a criterion equation. Figure 1a and b shows the variation of $\overline{\mathrm{Nu}}_f/\mathrm{Pr}^{0.33}$ as a function of the Reynolds criterion in logarithmic coordinates. The corresponding criterion equations have the form:

for $s = 10^{-4}$ m

$$\overline{\mathrm{Nu}}_f = 0.15\,\mathrm{Re}_f^{0.68}\mathrm{Pr}^{0.33}\,; \tag{3}$$

for $s = 2\cdot10^{-4}$ m

$$\overline{\mathrm{Nu}}_f = 0.3\,\mathrm{Re}_f^{0.59}\mathrm{Pr}^{0.33}\,. \tag{4}$$

As in [5], in determining the Reynolds number Re the velocity was taken at the minimal cross section, the equivalent diameter was $D_{eq} = 10^{-3}$ m, and as the determining temperature we took the arithmetic mean of the air temperatures at the grid inlet and outlet. In processing the experimental data, we took the temperature of the wall of a grid element to be constant and equal to the temperature of the frame. A calculated check of the temperature distribution along the height of an element, using the data obtained, confirmed the validity of this assumption. The dispersion of the experimental data for a given air flow rate was no more than ±15%.

The coefficient of hydraulic resistance of the grid, in accordance with [7], was determined from the air parameters at the inlet to the grid. Figure 2 shows the variation of ξ as a function of the numbers Re and Re_0, in which the quantity used as the equivalent diameter was the diameter at the middle section and the ratio of the quadrupled minimal section to the wetted perimeter at the minimal cross section, respectively.

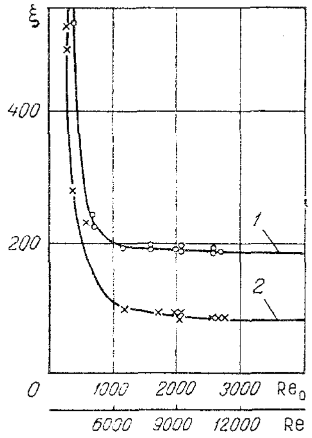

Fig. 2. Total coefficient of hydraulic resistance as a function of the numbers Re_0 and Re for grids with: 1) $s = 10^{-4}$ m; 2) $s = 2 \cdot 10^{-4}$ m.

As a result of the investigation, we obtained the average Nusselt criterion for grids with profiled blade elements and the value of the coefficient of hydraulic resistance in the range $1000 \leqslant Re \leqslant 10{,}000$.

NOTATION

t, time; τ, relaxation time of the physicochemical process; t_*, characteristic time scale for the gasdynamic process; T, temperature; T_2, air temperature behind the grid; ΔT, temperature drop across the grid; T_w, temperature of the wall (grid frame); B, barometric pressure; ΔP, pressure drop across the grid; G, air mass flow rate; q, specific heat flux through one of the bases of a profiled grid element; α, heat-transfer coefficient from wall to air; H, height of grid elements; D, D_{eq}, diameter of elements at the middle section and equivalent diameter; s, spacing between grid elements; $\overline{Nu}_f$, Pr, Nusselt and Prandtl criteria; Re, Re_0, Reynolds criteria; ξ, coefficient of hydraulic resistance of the grid; T_{amb}, air temperature; T_{therm}, temperature of water in the thermostat.

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