OPTIMIZATION OF THE GEOMETRY OF A RECTANGULAR DUCT FOR LOW-GRADIENT FLOW GENERATION

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A numerical experiment is carried out to determine the feasibility of generating low-gradient flow around samples of materials in a rectangular duct.

An apparatus designed for the investigation of high-temperature materials in a tangentially impinging gas flow is described in detail in [1]. It is shown in that paper that the conditions of external flow around models in the form of plates can be adequately reproduced on a low-specific-power apparatus if the models are heated in a rectangular duct.

On the basis of rough calculations, a working section for low-gradient material testing has been constructed in the form of rectangular duct of cross section 100 × 10 mm and length 110 mm. However, in order to optimize the geometrical dimensions of the duct for low-gradient flow generation at a given specific power of the apparatus, it is advisable to carry out a preliminary numerical experiment aimed at assessing the feasibility of creating zero-gradient flow in plane ducts and the degree of approximation to that condition.

On the basis of the results of such an experiment, in the present article we propose the simplest procedure for updating the indicated apparatus by variation of the half-height of the duct h.

Assuming that the mass flow of the heat-transfer agent $G = \rho_B u_B 2h_i$ and the flow temperature at the beginning of the duct (duct inlet) T_B remain constant as h is varied, we obtain

$$\mathrm{Re}_B = \frac{\rho_B u_B h_i}{\mu_B} = \mathrm{const}; \tag{1}$$

the velocity coefficient at the duct inlet $\xi_B = u_B/\sqrt{2c_pT_{sB}}$ and the relative wall temperature $\Theta_w = T_w/T_{sB}$ for various values of h_i are determined from the equations

$$\xi_{Bi} = 1 \Bigg/ \sqrt{\left(\frac{1}{\xi_{B0}^2} - 1\right)\frac{h_i^2}{h_0^2} + 1}, \tag{2}$$

$$\Theta_{wi} = \frac{\Theta_{w0}}{1 + \xi_{B0}^2\left(\frac{h_0^2}{h_i^2} - 1\right)}. \tag{3}$$

The initial value of the duct height $2h_0 = 10$ mm. The values of the parameters ξ_{Bi}, Θ_{wi} and the Mach number M_{Bi} calculated according to Eqs. (2) and (3) for various values of h_i are given in Table 1 for the four flow regimes discussed in [2], which differ in the values of Re_B, ξ_B, and Θ_w. The procedure described in [2] is used to determine the fundamental flow and heat-transfer parameters for the plane duct configurations represented in Table 1. The method of estimating the approximation to zero-gradient flow and the results of such an estimation on the basis of the indicated calculations can be used by researchers in experimental studies of a similar nature with limited mass flow of the heat-transfer agent.

Figures 1-3 give some results of calculations pertaining to the gradients and differential pressures in plane ducts. It is evident from Fig. 1 that a significant reduction of the pressure gradient along the duct takes place when h is varied from 4 mm to 4.5 mm (curves 5 and 4). Each subsequent 0.5-mm increment of h creates a diminishing difference in the pressure gradient, because the relative increase in the half-height of the duct in every

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TABLE 1. Values of the Flow Parameters at the Duct Inlet

Regime No.	Re_B	i	1	2	3	4	5
		h_i/h_0	1,2	1,1	1,0	0,9	0,8
1	$8\cdot10^2$	ξ_{Bi}	0,224	0,243	0,266	0,293	0,326
		Θ_{wi}	0,202	0,201	0,200	0,198	0,197
		M_{Bi}	0,547	0,594	0,651	0,716	0,798
2	$1,27\cdot10^3$	ξ_{Bi}	0,226	0,245	0,268	0,295	0,328
		Θ_{wi}	0,237	0,236	0,234	0,232	0,230
		M_{Bi}	0,553	0,600	0,656	0,721	0,803
3	$2,36\cdot10^3$	ξ_{Bi}	0,243	0,264	0,288	0,317	0,352
		Θ_{wi}	0,241	0,240	0,238	0,236	0,233
		M_{Bi}	0,594	0,646	0,704	0,775	0,862
4	$3,65\cdot10^3$	ξ_{Bi}	0,273	0,295	0,322	0,354	0,391
		Θ_{wi}	0,319	0,316	0,313	0,309	0,305
		M_{Bi}	0,667	0,721	0,788	0,865	0,956

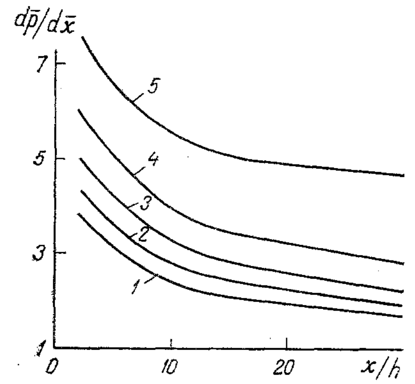

Fig. 1

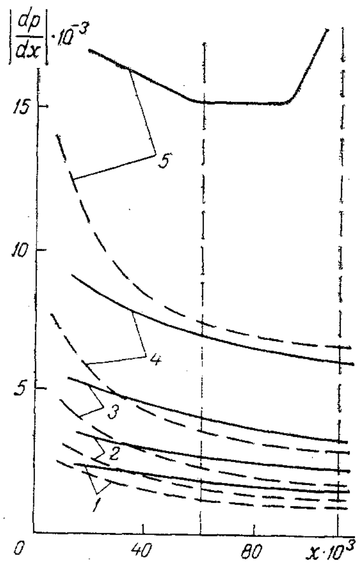

Fig. 2

Fig. 1. Variation of pressure gradients along the length of the duct at $Re_B = 1.27\cdot10^3$. 1) h = 6 mm; 2) 5.5; 3) 5; 4) 4.5; 5) 4 mm.

Fig. 2. Variation of pressure gradients dp/dx (Pa/m) along the length x (m) of the channel for $Re_B = 8\cdot10^2$ (dashed curves) and $Re_B = 2.36\cdot10^3$. The numbers 1-5 have the same significance as in Fig. 1, and the vertical dashed lines indicate the boundaries of the zone occupied by the tested sample.

such increment of h decreases, and the Mach number at the duct inlet gradually decreases. It must be emphasized that intense cooling of the duct walls ($\Theta_{wi} < 0.25$; see Table 1) ensures comparatively low pressure gradients in the zone of the investigated sample ($12 \leq \bar{x} \leq 22$) for all h_i. Indeed, the following equation can be derived for incompressible fluid flow in the stabilized section of a plane duct:

$$\frac{d\bar{p}}{d\bar{x}} = \frac{1}{2} c_f \mathrm{Re}_B, \qquad (4)$$

where the dimensionless quantities $\bar{p} = (p_B - p)/\rho_B u^2_B$; $\bar{x} = x/h\mathrm{Re}_B$.

If we use the Blasius equation obtained on the basis of experimental fluid friction data for the stabilized sections of ducts [3]:

$$c_f = 0.079\,\mathrm{Re}'^{-0.25}_B, \quad 5\cdot10^3 \leqslant \mathrm{Re}_B \leqslant 3\cdot10^4, \qquad (5)$$

where the number Re'_B involves the hydraulic diameter 4h rather than the half-height of the duct, then for

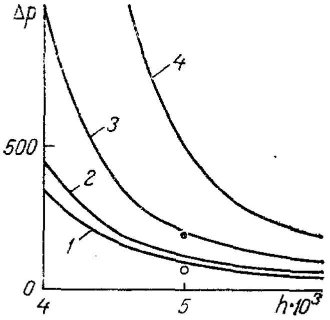

Fig. 3 Differential pressure Δp (N/m²) on the tested sample vs half-height of the duct h (m). 1) $Re_B = 8\cdot10^2$; 2) $1.27\cdot10^3$; 3) $2.36\cdot10^3$; 4) $3.65\cdot10^3$; the dots represent the experimental values.

$$Re'_B = 4\,Re_B = 5.08\cdot10^3$$

we obtain from Eq. (4)

$$\frac{d\bar{p}}{d\bar{x}} = 5.87.$$

This pressure gradient is attained only for two values of h (curves 4 and 5 in Fig. 1), and then only at the duct inlet.

In Fig. 2 the |dp/dx| curves for regime 3 (see Table 1) are naturally situated above the curves for regime 1 for equal values of h. Consequently, if it is required to maintain the same pressure gradients in the zone of the investigated sample of heat-shielding material for different regimes in an experiment, this can be accomplished by varying h_i. For example, it follows from Fig. 2 that approximately the same gradient |dp/dx| can be attained in regime 3 for h_i = 5.5 mm (solid curve 2) as in regime 1 for h_i = 5 mm (dashed curve 3). The same situation is observed for curves 3 and 4 and regimes 3 and 1, respectively. Curve 5 for regime 3 is in a somewhat unique position. The appreciable increase of the pressure gradient observed for this case after x ≥ 90 mm is attributable to the large subsonic velocity at the inlet (M_{Bi} = 0.862) and the subsequent rapid approach to sonic velocity. In fact, the velocity coefficient in the flow core ξ = 0.390 in the cross section x = 104 mm (right end of the solid curve 5) varies only 5% up to the critical point ξ_c = 0.408. High gradients are unacceptable in this case for experiments simulating low-gradient flow. For regime 4 (the pressure gradient curves are not shown here), according to calculations, the same situation can occur in the case M_{Bi} = 0.865, and in the case M_{Bi} = 0.956 the approach to sonic velocity near the inlet is accompanied by an even higher pressure gradient, as is customary in this case.

The calculated data are generalized in Fig. 3, which shows the differential pressure for all four flow regimes in the zone of the tested sample as a function of the half-height of the duct. For pressures of the order of $7\cdot10^{-3}$ N/m² at the duct inlet, the differential pressure remains less than 3% of that value for regimes 1-3 at h_i ≥ 5 mm. In the case of regime 4 such a limitation on the differential pressure forces the experimenter to change to h_i ≥ 6 mm. Curve 4 in Fig. 3 suffers a discontinuity as h_i = 4 mm is approached because it is impossible to estimate the differential pressure according to the procedure of [2] as sonic velocity is approached.

All the experiential points in this figure were obtained with correct measurements of the static pressure along the duct in the experiments [1]. The spectrum of such curves for the most disparate regimes can be calculated and provides the experimenter with a diagram for estimating the degree of approximation to low-gradient flow; it also serves as a guide for selecting the height of a rectangular duct or the range of variation of that height in an apparatus capable of implementing such a variation.

The reported data are also of theoretical significance in the study of the special characteristics of flow in the least-investigated inlet section of a duct (see [4, 5], etc.).

NOTATION

c_p, specific heat at constant pressure; c_f, friction coefficient; G, mass flow rate; 2h, duct height; M, Mach number; p, pressure; Re, Reynolds number; T, temperature; u, longitudinal velocity component; x, longitudinal coordinate; ρ, density; μ, dynamic viscosity coefficient; ξ, velocity coefficient; Θ, relative temperature. Indices; s, stagnation parameters; B, duct inlet; w, duct wall; 0, initial value; i, instantaneous value.

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HEAT PIPES BASED ON NAPHTHALENE

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The authors describe an experimental investigation of heat pipes for the mean temperature range. Data for tests of a heat exchanger of air–air type are given.

Heat pipes, thermosiphons, and heat exchangers based on them are finding wider application as efficient heat-transfer devices, offering intensification of heat-transfer processes and also good heat energy economy [1].

The temperature region in which heat pipes operate is very wide, from low cryogenic to very high temperatures. The temperature range of stable operation of heat pipes is determined mainly by the wall material and the properties of the heat-transfer agent. Heat-transfer agents include water, liquefied gases, organic liquids, and fusible metals. Liquid metal heat-transfer agents, which give large specific heat-transfer flux, operate, as a rule, at high temperatures, not spanning the mean temperature range (150-600°C). Therefore, it is an urgent matter to find, investigate, and apply practically to heat pipes a rather inexpensive and reliable heat-transfer agent capable of long-term stable operation in the above temperature range. In the use of sulfur with iodine additives [2-4], a number of problems arise, connected with the high reactivity of the sulfur–iodine mixture and also the strong dependence of the viscosity of sulfur on temperature, leading to instability of the characteristics of these heat pipes. Therefore, it is more promising to use naphthalene as a heat-transfer agent.

Naphthalene is a product of oil production, its chemical formula is $C_{10}H_8$, and its molecular weight 128.16. At ordinary temperature it is a white-colored solid with a fusion temperature of 80.3°C and a boiling temperature of 218°C. Liquid naphthalene has very low viscosity, which decreases considerably with increase of temperature. Thus, its basic properties are quite suitable for use as a heat-transfer agent in heat pipes and heat exchangers of the mean temperature range.

The aim of this paper is to investigate heat-transfer equipment with naphthalene as heat-transfer agent in long-term operation, to explore the desirability and the promise of creating heat exchangers in heat pipes with naphthalene. Tests were made with two types of two-phase thermosiphons with steel and tantalum walls and with a vapor-dynamic thermosiphon. The geometric parameters of the thermosiphons and the naphthalene mass in them are given in the legend of the appropriate figures. The experimental equipment contained traditional nodes and elements necessary to investigate heat pipes: a test thermosiphon with an ohmic heater, a source of stabilized and regulated power, and instruments for measuring the electrical power and the thermal emf, and thermocouples. Chromel–Alumel thermocouples were welded along the generator of the thermosiphon at equal distances. The experimental technique and the facility were described in detail in [5].

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