HEAT TRANSFER DURING THE FLOW OF RARE GAS THROUGH POROUS BODIES

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A study was made of the heat transfer during the flow of rare gas through porous bodies with various geometries and various thermal conductivities.

Transpiration cooling (by injection through a capillary-porous body) is now widely used in modern technology. One of its main advantages is the effective removal of heat from the porous surface under small temperature gradients. Many studies have dealt with the heat transfer during gas filtration [1-10], but so far no consensus has been arrived at concerning the nature of this heat transfer, nor has a reliable method been developed yet for calculating the internal heat transfer in porous bodies. This is understandable if one considers the complexity of this process.

In this study the authors deal with the heat transfer during filtration of rare gas through porous bodies. The experiments were performed with bodies having various different porosities and permeabilities as well as different geometries and thermal conductivities. Air served as the gaseous coolant. The characteristics of the specimens are listed in Table 1. The values of λ_{eff} had been determined experimentally [11, 12].

The permeability of a porous material increases as the gas filtrating through it becomes rarer. This is explained by the slide effect, i.e., by the weakening interaction between gas and pore walls. It is quite logical, therefore, to surmise that the heat transfer during filtration of rare gas may be affected by a temperature jump resulting in less heat transfer between gas and pore walls than during filtration of dense gas.

The experiment was designed to conform to the theoretical formulation of the problem, the latter having been solved in [2, 3]. The problem had been formulated as follows: one surface (outside) of a porous plate is heated to a constant temperature t_2, while the opposite surface remains exposed to a cooling gas. This gas becomes denser in the positive direction x and its temperature at $x \to \infty$ is t_0. The temperature field inside the plate is assumed uniform.

Our test data on the filtration of dense and rare gas have been compared with analytical results. The degree of correlation could thus be established between the physical model of heat transfer and the actual process taking place in bodies during filtration of rare gas.

In the test apparatus shown here (Fig. 1) rare gas oozed through porous bodies at certain velocities and under certain pressure drops. The filtrating air was taken from the atmosphere through a model VN-4G vacuum pump 1. The air was then purified of solid particles in an air filter 5 and driven through diffuser 4 into the active porous specimen 3. The high-pressure region was separated from the vacuum region by this specimen and a ring seal 8. The flow rate of the filtrating air and its pressure on the inlet side before entering the porous body were regulated by means of a vacuum check valve 2 and a needle throttle 6. The gas pressure on the inlet side and the pressure drop across the body were measured, depending on the range of magnitude, with a vacumeter and a mercury-type or an oil-type differential manometer. The flow rate of filtrating air was determined by the volumetric method [13]. The experiment was performed with the mass flow rate of coolant varying over a wide range and under inlet pressures from 0.0532 to $1 \cdot 10^5$ N/m^2, with the Reynolds number Re < 1.

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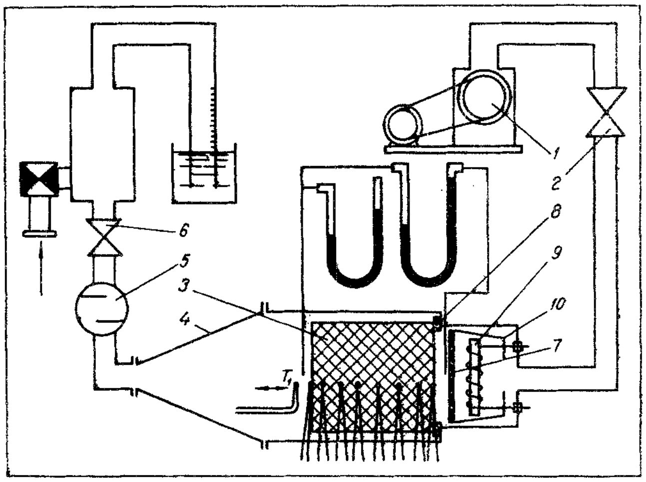

Fig. 1

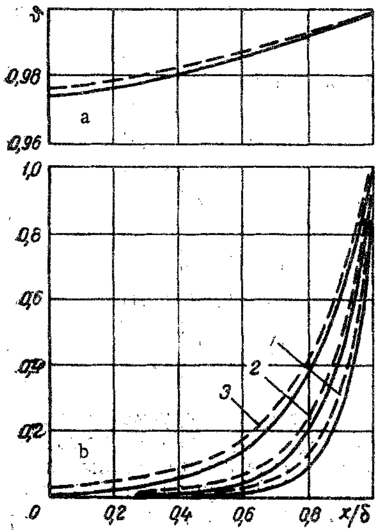

Fig. 2

Fig. 1. Schematic diagram of the test apparatus.

Fig. 2. Temperature profiles of porous bodies: a) porous graphite $\delta = 21$ mm; b) close-packed glass balls, 1 mm in diameter; 1) $G = 2.81 \cdot 10^{-2}$ kg/m^2 · sec; 2) $G = 7.95 \cdot 10^{-2}$ kg/m^2 · sec; 3) $G = 12.7 \cdot 10^{-2}$ kg/m^2 · sec; G) mass flow rate of gas.

TABLE 1. Characteristics of Test Specimens

Porous material	λ_{eff}, W/m · °C	P (porosity)	$\delta \cdot 10^2$, m	$S \cdot 10^2$, m^2	$\delta \cdot 10^{-4}$ kg/m^3
Fireclay ceramic	0,65	0,31	1,25	0,58	0,188
Glass balls, 3 mm in diameter	0,25	0,4	2,5	0,385	0,182
Glass balls, 1 mm in diameter	0,25	0,4	2,5	0,385	0,191
Steel powder	0,4	0,6	2,5	0,385	0,341
Graphite	46	0,475	2,1	0,47	0,105
Graphite	46	0,475	1,09	0,47	0,105
Graphite	46	0,475	0,45	0,47	0,105

The temperature was measured with copper–constantan thermocouples. The thermocouples were located as shown in Fig. 1. The highest temperature of a porous plate was 363°K, the lowest temperature of the cooling gas was 289°K. The gas temperature on the inlet side was measured with a movable thermocouple T_1 so that the temperature field near the porous body could be plotted. The temperature of the opposite surface of a porous plate was held constant by means of a heat radiator also shown in Fig. 1. This heater consisted of a Nichrome coil would on a ceramic rod 9, a perforated copper disk 7 black coated on both sides, a reflector 10, and vacuum-sealed current leads.

The results of this experiment are shown in Fig. 2b, plotted in dimensionless coordinates, for a porous-body model consisting of close-packed glass balls 1 mm in diameter. These balls were poured into a special cylindrical tube of acrylic glass, with fine Nylon meshes closing it at both ends tightly stretched by a roller clamp. Thermocouples were installed at various heights of this column, also at the gas inlet and outlet. For comparison with the test data (dashed lines), we also show in Fig. 2a, b temperatures calculated according to the formula in [2] (solid lines). The comparison indicates a satisfactory agreement between both sets of values ($\Delta \leq 15\%$).

Temperature profiles based on the heat transfer data are shown in Fig. 3 for a porous-body model consisting of steel powder. According to the graph, the thermocouples read almost the same temperatures during filtration of rare gas under various inlet pressures but at the same mass flow rate G.

In the tests with a porous-body model consisting of glass balls 3 mm in diameter, the temperature differences between the solid phase and the filtrating gas were measured with copper–constantan differential thermocouples at various heights along the column. One junction of such a thermocouple was inserted in a pore, the other was fixed directly inside a glass ball. Under steady-state conditions of heat transfer and

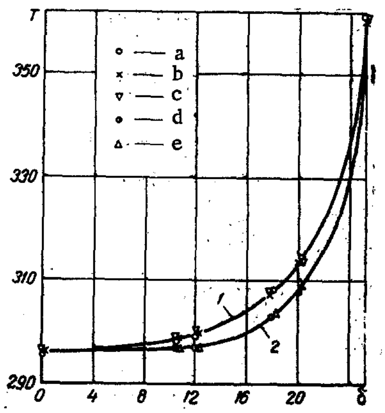

Fig. 3

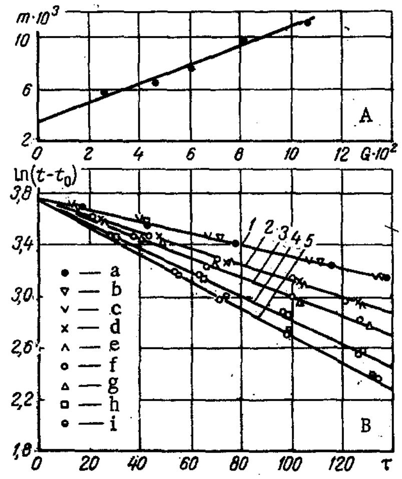

Fig. 4

Fig. 3. Temperature profiles across the specimen thickness: 1) $G = 3.98 \cdot 10^{-2}$ kg/m^2 · sec; 2) $G = 7.0 \cdot 10^{-2}$ kg/m^2 · sec; a) $p_1 = 0.328 \cdot 10^5$ N/m^2; b) $0.62 \cdot 10^5$ N/m^2; c) $0.85 \cdot 10^5$ N/m^2; d) $0.486 \cdot 10^5$ N/m^2; e) $0.785 \cdot 10^5$ N/m^2; thickness δ (mm).

Fig. 4. Transient cooling curves for porous graphite ($\delta = 4.5$ mm), based on the experiment: A) cooling rate m as a function of the gas filtration rate G (kg/m^2 · sec); B) temperature difference as a function of time, presented in a semilogarithmic anamorphosis; 1) $G = 2.84 \cdot 10^{-2}$ kg/m^2 · sec; 2) $G = 4.53 \cdot 10^{-2}$ kg/m^2 · sec; 3) $G = 6.05 \cdot 10^{-2}$ kg/m^2 · sec; 4) $G = 8.25 \cdot 10^{-2}$ kg/m^2 · sec; 5) $G = 10.85 \cdot 10^{-2}$ kg/m^2 · sec; a) $p_1 = 0.26 \cdot 10^5$ N/m^2; b) $p_1 = 0.518 \cdot 10^5$ N/m^2; c) $p_1 = 0.69 \cdot 10^5$ N/m^2; d) $p_1 = 0.348 \cdot 10^5$ N/m^2; e) $p_1 = 0.492 \cdot 10^5$ N/m^2; f) $p_1 = 0.98 \cdot 10^5$ N/m^2; g) $p_1 = 0.42 \cdot 10^5$ N/m^2; h) $p_1 = 0.505 \cdot 10^5$ N/m^2; i) $p_1 = 0.56 \cdot 10^5$ N/m^2.

under various pressures p_1 the differential thermocouples did not record any temperature difference between the solid phase and the filtrating gas, indicating that the temperatures of both had equalized.

In order to establish any effect of a temperature jump on the heat transfer during filtration of rare gas through a porous body, we performed an experiment where the preheated porous body was cooled in a transient manner. The porous specimen was first heated up to a temperature, constant in each test, then the heater was turned off and the specimen was cooled by filtering gas through it at some mass flow rate G and under an inlet pressure p_1. During the cooling process we recorded the time till the temperature at the outside surface had dropped to some definite level. If a temperature jump had an appreciable effect, then the cooling rate during gas filtration at some constant mass flow rate G but under a variable pressure p_1 should have decreased with the pressure p_1. An evaluation of test data (Fig. 4B), however, indicated an almost the same cooling rate m during transient cooling of porous graphite ($\delta = 4.5$ mm) under various pressures p_1 – this cooling rate being equal to the slope of the temperature–time curve. An analysis of the test data (Figs. 3 and 4B) reveals no effect of a temperature jump on the heat transfer during filtration of rare gas through porous materials, as long as the Knudsen number remained $\mathrm{Kn} \leq 0.26$.

The physical process of heat transfer is in this case determined by the number of heat carriers (Fig. 4A), i.e., by the mass flow rate of gas filtrating through porous media, where a complete exchange of energy occurs between gas molecules and pore walls as a result of multiple collisions and with a subsequent equalization of their temperatures. Thus, the theory of heat transfer proposed in [1-3] is in satisfactory agreement with the experimental evidence obtained in this study concerning the heat transfer during filtration of rare gas with the Knudsen number $\mathrm{Kn} \leq 0.26$.

It is to be noted that the closeness between test data and theoretical values depends essentially on the reliability of the thermal conductivity values given for the tested materials and on the accuracy of thermocouple readings after steady state has been reached.

NOTATION

G	is the mass flow rate of gas, $kg/m^2 \cdot sec$;
p_1	is the gas inlet pressure before entering a porous specimen, N/m^2;
δ	is the thickness of a porous specimen, m;
x	is the length coordinate, m;
λ_{eff}	is the effective thermal conductivity of a porous material, $W/m \cdot deg$;
$\nu = (t-t_0)/(t_2-t_0)$	is the dimensionless temperature;
τ	is the time, sec;
T	is the temperature of a porous specimen, °K.

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