EXPERIMENTAL STUDY CONCERNING THE THERMAL CONDUCTIVITY OF SATURATED MATERIALS IN AN ACOUSTIC FIELD OF VARIABLE INTENSITY

É. M. Simkin, O. L. Kuznetsov, and E. A. Filatova

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Results are shown of experimental estimates concerned with the effective thermal conductivity of capillary-porous and colloidal materials in an acoustic field of up to 2400 W/m^2 intensity. It is shown that the thermal conductivity of these materials becomes here accordingly 3.0-5.5 times higher.

In many thermophysical processes it becomes necessary to regulate the effective thermal conductivity of saturated materials by artificial means. Such a necessity arises, for example, during acoustic desiccation of materials, or where the combustion of solid fuels is to be improved, or where the thermal effects on porous petroleum collectors are to be boosted. Earlier studies have shown that one possible method of regulating the effective thermal conductivity is by means of an acoustic field [1].

In this article we will present the results of experimental estimates concerned with the effect of the acoustic field intensity in a capillary-porous and in a colloidal material on their effective thermal conductivity.

The tests were performed with an apparatus (Fig. 1) consisting of a three-layer cylindrical model of a capillary-porous and a colloidal material inside a thin-walled steel jacket (1), two model ÉPP-09M3 potentiometers (2), an audio-generator (3), two acoustic transmitters of different intensities (4), and an electric heater (5) with an LATR power supply (6) and a wattmeter (7). The model body was 300 mm in diameter and 400 mm thick. At the center along its axis was placed a copper tube 10 mm in diameter. Above and below the layer of capillary-porous material were layers of colloidal material, the upper one 150 mm thick and the lower one 130 mm thick. The thickness of the capillary-porous layer between was 120 mm. The tube was insulated from the housing with special rubber seals preventing the transmission of acoustic vibrations to the latter. The acoustic transmitter and the electric heater were placed in the tube together in such a way as to ensure a uniform radiation of both acoustic and thermal energy over the entire tube length.

In the capillary-porous and in the colloidal layers were installed altogether 15 thermocouples feeding the two potentiometers. The capillary-porous layer consisted of carefully washed and dried quartz sand medium smooth. The diameter of the grains was within the 0.2-0.4 mm range, the porosity was 34%. This sand was completely (to 100%) saturated with transformer oil having a viscosity of 0.024 kg/m·sec. The colloidal layers were made of concrete-grade clay powder with a density of 1440 kg/m^3, a 5% porosity, and a 15.6% water saturability, containing distilled water.

Voltage pulses of 400 V amplitude and 30 μsec width were sent from generator (3) to the electrodes of the piezo-transmitter at a 50 Hz repetition rate. The piezo-transmitter selected for this experiment was a parallelepiped (of grade TsTS-19 ceramic material) 300 mm high and 8.5 mm wide. The carrier frequency in the transmitted pulse spectrum was 21 kHz. The acoustic field intensity at the tube wall was varied from 1300 to 2400 W/m^2. The heater power was held constant throughout each test. It fluctuated between 150 and 175 W from test to test.

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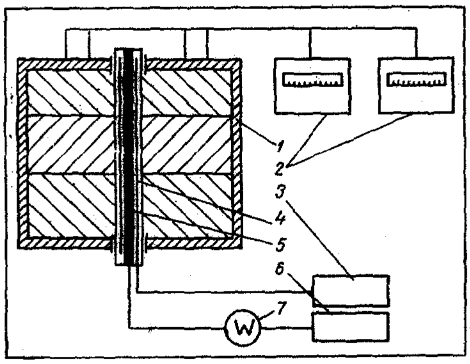

Fig. 1

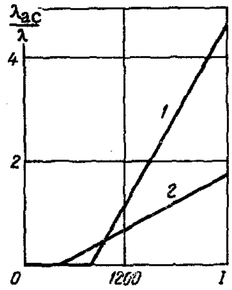

Fig. 2

Fig. 1. Schematic diagram of the apparatus: 1) housing for the radial model; 2) potentiometers; 3) audio-generator; 4) acoustic transmitter; 5) electric heater; 6) LATR power supply; 7) wattmeter.

Fig. 2. Relative effective thermal conductivity (λ_{ac}/λ) as a function of the acoustic field intensity (I, W/m^2) for: 1) the capillary-porous material; 2) the colloidal material.

In total we performed 5 series of tests. In the preliminary two series we measured the ambient temperature field at various acoustic field intensities with the heater off. No significant temperature rises were recorded then, indicating that an acoustic field of these intensities did not affect the thermocouple readings and, therefore, produced no heating.

In the third series we measured the temperature field of the layers without an acoustic field. We then measured the temperature field with an acoustic field intensity of 2400 W/m^2 at the tube wall in the fourth test series, and with an acoustic field intensity of 1300 W/m^2 at the tube wall in the fifth test series.

The heater power and the temperatures at the various points of the model were continuously recorded during the tests. Each test lasted till a quasisteady temperature level had been reached.

The results have been evaluated in terms of $T(r, \tau)$ relations.

The effective thermal conductivity of the materials was determined from measurements of the temperature field which the heater had produced in the layers. The effective thermal conductivity was calculated by the following procedure. On a model BSM-6 computer we solved the equation of heat conduction

$$C \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial r}\left(\frac{\lambda}{r} \cdot \frac{\partial T}{\partial r}\right) \tag{1}$$

with boundary conditions of the second kind

$$\lambda \frac{\partial T}{\partial r} = q_0 \quad (r = r_0) \text{ and } \lambda \frac{\partial T}{\partial r} = 0 \quad (r = R)$$

and zero initial conditions.

The thermal conductivity in an acoustic field was expressed as a function of the acoustic field intensity:

$$\begin{aligned} \lambda &= \lambda_0 + AI_{ac}(r) \quad \left(I_{ac}(r) \geqslant 300 \text{ W/m}^2 \text{ for clay, and } I_{ac}(r) \geqslant 840 \text{ W/m}^2 \text{ for sand}\right), \\ \lambda &= \lambda_0 \quad \left(0 \leqslant I_{ac}(r) < 300 \text{ W/m}^2 \text{ for clay and } 0 \leqslant I_{ac}(r) < 840 \text{ W/m}^2 \text{ for sand}\right). \end{aligned} \tag{2}$$

The acoustic field intensity is

$$I_{ac}(r) = I_0 \frac{\exp[-\alpha(r-r_0)]}{(r/r_0)^{0,5}}. \quad (3)$$

The equation of heat conduction was solved on the computer by the method of finite differences, with various values of the coefficient A and with one-dimensional elimination. In order to improve the accuracy of the computation scheme, the radial intervals were selected so as to make their endpoints fall on the breaks in the thermal conductivity curve [4]. The approximation error was $0\ (\Delta\tau + \Delta r_{max}^2)$. A computed temperature field was then compared with a measured one and coefficient A was thus determined. The effective thermal conductivity of a material was then calculated according to formulas (2) and (3), on the basis of values obtained for A. This procedure was also checked against direct measurements of the thermal conductivity in the absence of an acoustic field. These measurements were made in the regular heating mode of the first kind [5]. The described procedure has yielded an effective thermal conductivity of 1.28 W/m · deg for the capillary-porous material and 0.589 W/m · deg for the colloidal material. The thermal conductivity based on the regular heating mode of the first kind was 1.26 W/m · deg and 0.580 W/m · deg, respectively. The discrepancies between these two sets of values, based on two different methods of measurement, did not exceed 1.5%. In Fig. 2 is shown the relative variation in the thermal conductivity of each material, as a function of the field intensity. According to Fig. 2, then, as the acoustic field intensity increases to 2400 W/m^2, the effective thermal conductivity of the capillary-porous material increase up to 5.5 times and that of the colloidal material increases up to 3 times.

NOTATION

$T(r, \tau)$	is the temperature
τ	is the time;
r	is the radial coordinate in the cylindrical system;
r_0	is the radius of tube;
R	is the radius of model;
$\Delta\tau$	is the time interval;
Δr_{max}	is the maximum radial interval;
C	is the heat capacity per volume;
q_0	is the thermal flux at tube wall;
λ	is the effective thermal conductivity of a material;
λ_0	is the effective thermal conductivity of a material without an acoustic field;
I_0	is the acoustic field intensity at the tube wall;
$I_{ac}(r)$	is the acoustic field intensity at radius r;
α	is the acoustic absorptivity;
A	is the empirical coefficient.

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