CONVECTIVE HEAT TRANSFER IN RESPONSE TO A SONIC FIELD IN SATURATED SAND

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A liquid or gas may flow in a porous medium in response to a sound wave. Consideration has been given [1] to the dynamic density of the aggregate produced by relative displacement of the fluid and solid, which causes viscoinertial dispersion and attenuation of the sound. It has also been shown [2] that sound waves and vibration accelerate heat and mass transfer in liquids and gases.

We have examined the effects of waves of 12–100 kHz on the effective thermal conductivity of quartz sand saturated with outgassed petroleum, distilled water, or air. The sand is denoted by (0) and had a mean grain size of 0.16–0.25 mm. The other materials were as follows: (1) heavy petroleum from the Pavlova deposit, (2) light petroleum from Zyrya, (3) distilled water, (4) air. The following are the physical properties of the fluids at 20° C:

	ρ, g/cm³	μ, CP	c, m/sec	C_p, kcal/kg-deg
(1)	0.949	540	1475	0.5
(2)	0.872	9	1360	0.5
(3)	1.0	1.002	1490	1.9
(4)	0.0012	0.00018	330	0.27

Table 1 gives the characteristics of the specimens, which were 50 mm in diameter and 70 mm high, in which δ is the weight of a component, η is porosity, and S is degree of filling with liquid or gas.

Figure 1 shows the apparatus for examining the thermal parameters: the calorimeter 8, chromal-alumel thermocouple 3, EPP-0.7 recorder 6, TS-15 thermostat 7, Dewar vessel 9, pulse generator 4, IPA-59 oscilloscope 5, wave source 1, and detector 2. The last two were disks of TsTS-19 lead zirconate-titanate. Disks of different thicknesses (1, 5, and 10 mm) were used in order to obtain vibrations with different predominant frequencies. The pulse generator produced square pulses with durations from 5 to 30 μsec at a repetition rate of 25 sec^{-1}. The output voltage was 1600 V.

The thermal conductivity was determined with regular conditions of the first kind [3].

The filled calorimeter was heated to 45–50° C and was then allowed to cool in the thermostat for 15–30 min with continuous temperature recording. When the generator was used, the pulses began to be applied as soon as the calorimeter was placed in the thermostat. The pulse shape and instants of emission and reception were recorded photographically from the oscilloscope. The calorimeter was first isolated thermally and exposed to the pulses for 3 hr, with temperature recording. No temperature rise was detected within the 0.3° C limit of detection, so the attenuation in the specimen did not affect the temperature.

Table 2 gives the observed and calculated results, in which k_0 is the thermal conductivity without the pulses, k is the same with the pulses, λ is incident wavelength, f is frequency, and H/λ is the length of the specimen in wavelengths. The effective thermal conductivity of a porous medium (not acted on by pulses) is determined by the thermal conductivities of the skeleton and fluid. The pulses cause mixing of the fluid within the pores, which accentuates the heat transfer by forced convection, so the effective thermal conductivity is also dependent on the filtration resistance and on the specific heat and density of the fluid. The heat transport by forced convection increases with the heat content of unit volume, and so the effective thermal conductivity increases, whereas increase in filtration resistance tends to reduce the

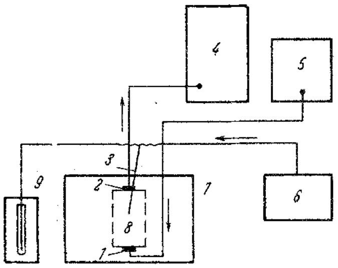

Fig. 1

Table 1

Mixture	δ_0, g	δ_{1-4}, g	δ, g	η, %	S, % liquid	S, % air
(0)+(3)+(4)	214.3	32.0	246.8	39.5	60	40
(0)+(3)	214.3	53.4	267.7	39.5	100	0
(0)+(2)+(4)	231.0	9.59	240.6	35.0	23	77
(0)+(2)	231.0	47.0	278.0	35.0	100	0
(0)+(1)+(4)	230.0	7.64	237.6	35.2	17	83
(0)+(1)	230.0	47.3	277.3	35.2	100	0
(0)+(4)	234.5	—	234.5	34.0	100	0

Table 2

Mixture	C_p, kcal/kg-deg	ρ, kg/m³	k_0, k, kcal/m-hr-deg		λ, см	$\frac{H}{\lambda}$	f, sec^{-1} $\cdot 10^3$	c, m/sec
(0)+(3)+(4)	0.295	1843	1.7	1.9				
(0)+(3)	0.351	2000	1.7	2.1	2.3	3.2	20	470
(0)+(2)+(4)	0.202	1798	0.87	0.93				
(0)+(2)	0.242	2077	0.87	1.1	2.4	2.9	14	456
(0)+(1)+(4)	0.200	1776	0.7	0.9				
(0)+(1)	0.243	2072	0.7	0.9	4.8	1.45	14	568
(0)+(4)	0.19	1751	0.24	0.31	2.0	3.5	19.2	474

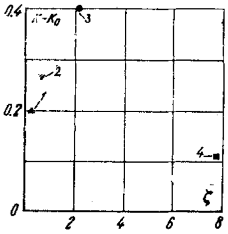

Fig. 2

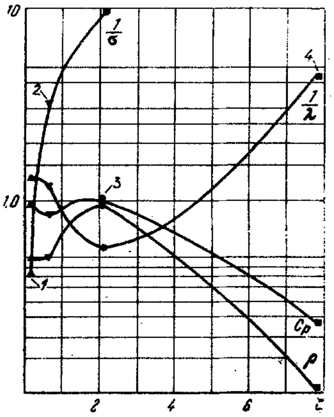

Fig. 3

effective thermal conductivity. Let z be the ratio of the transfer by forced convection to the transfer by normal conduction:

$$z=\frac{C_p\rho\eta V(T_2-T_1)}{k_0(T_2-T_1)}=\frac{C_p\rho\eta V}{k_0}\qquad\left(V=\frac{\operatorname{grad}p}{\sigma}\right).$$

Here grad p is the pressure gradient set up in the sound field [6] (this was taken as constant in processing the results), V is the filtration rate set up by this gradient, and σ is the specific resistance to flow within the pores. The following empirical formula has [5] been proposed for the last for a medium with grains of equal diameter d:

$$\sigma=\frac{1}{0.12\,\eta d}(2\,\rho\mu\omega)^{1/2},$$

in which ω is the angular frequency of the waves.

Figure 2 shows $k - k_0$ as a function of $\zeta = z/\operatorname{grad} p$ for these media, which is positive in all cases, being largest for water-filled sand and least for air-filled sand. Figure 3 shows the effects of each parameter on ζ for the various mixtures. The increase is least for air-filled sand because ρC_p for air is so low, while that for water-filled sand is largest because C_p and ρ take the largest values for water, while σ is quite low.

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