$$\left(\frac{\partial\lambda}{dt}\right)_p^{av} = 0.287\cdot 10^{-8}\,p^2 - 0.129\cdot 10^{-5}\,p + 0.151\cdot 10^{-3}.$$

The deviations of the experimental data from the values calculated according to Eq. (1) do not exceed the experimental error limits.

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THERMOPHYSICAL AND RHEOLOGICAL PROPERTIES OF CERTAIN BIOLOGICAL FLUIDS

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UDC 536.22+532.135

The dependence of the thermophysical properties of blood on its physicochemical composition and rheological properties is determined. Measurements are carried out by the probe technique.

The biological activity of the organism of man and animals is contingent upon the movement of various biological fluids in it. The most important such fluid is the blood. Knowledge of its thermophysical properties is not only of practical importance in connection with the design of heat exchangers needed for artificial circulation apparatus, it also has purely scientific implications insofar as those properties characterize the nature of the physiological thermal regulation system. The role of the blood in the thermal regulation system of the living organism is immense, because the poor heat conduction of the tissues renders heat conduction via heat transfer in the organism of little consequence in comparison with the convective heat transfer effected by the blood flow. Yet the thermophysical properties of the blood itself have been studied very little to date.

Research on the thermophysical properties of blood has been directed along the following lines:

1) determination of the influence of physicochemical composition and rheological properties of blood on its thermophysical characteristics;

2) determination of the variations of measurable quantities with age.

The thermophysical properties of blood have been studied experimentally by means of a relative probing technique [1] based on the comparison of thermograms for the investigated medium and a standard medium. This technique has been used with great effectiveness in determining the thermophysical characteristics of disperse materials [2]. Blood, of course, comprises a dispersoid of definite constituents (erythrocytes, leukocytes, and lymphocytes) in the plasma. The virtue of this technique is that it permits all the thermophysical coefficients of the medium to be calculated from one brief test with the use of simple experimental equipment.

The theoretical foundation of the method is the solution of the heat-conduction problem for heating of a finite cylinder (the probe) in an unbounded medium. The solution of this problem is described in [3] and represents complex functional dependences, which are exceedingly difficult to use for the derivation of analytical expressions describing the thermo-

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 33, No. 3, pp. 467-472, September, 1977. Original article submitted December 2, 1975.

0022-0841/77/3303-1063$07.50

physical characteristics. The following practical analytical expression for the thermal conductivity of the investigated medium has been derived under certain assumptions [4-6]:

$$\lambda = \lambda_s \frac{\Delta t_s}{\Delta t}. \tag{1}$$

The introduction of the ratio $\Delta t_s/\Delta t$ in Eq. (1) greatly facilitates the calculations in that it obviates the need to perform absolute measurements of temperature differentials.

The determination of the thermal diffusivity is based on a comparison of the temperatures for two multiple times τ and 2τ for the test medium and the standard. The temperatures are given by the expressions

$$t(\tau) = \frac{q}{4\pi\lambda}\left(\ln\frac{4a\tau}{R^2} + \gamma\right), \tag{2}$$

$$t(2\tau) = \frac{q}{4\pi\lambda}\left(\ln\frac{8a\tau}{R^2} + \gamma\right). \tag{3}$$

$$t_s(\tau) = \frac{q}{4\pi\lambda_s}\left(\ln\frac{4a_s\tau}{R^2} + \gamma\right), \tag{4}$$

$$t_s(2\tau) = \frac{q}{4\pi\lambda}\left(\ln\frac{8a_s\tau}{R^2} + \gamma\right) \tag{5}$$

(γ is the Euler constant).

We denote the temperature ratios for the standard and test media by θ_s and θ, which are given by the equations

$$\theta_s = \frac{t_s(\tau)}{t_s(2\tau)} = \frac{\ln\frac{4a_s\tau}{R^2} + \gamma}{\ln\frac{8a_s\tau}{R^2} + \gamma}, \tag{6}$$

$$\theta = \frac{t(\tau)}{t(2\tau)} = \frac{\ln\frac{4a\tau}{R^2} + \gamma}{\ln\frac{8a\tau}{R^2} + \gamma}. \tag{7}$$

From relations (6) and (7), knowing $t(\tau)$, $t(2\tau)$, $t_s(\tau)$, and $t_s(2\tau)$, we can calculate the thermal diffusivity a with reference to an auxiliary graph of the relation

$$\theta = \frac{\ln X + \gamma}{\ln 2X + \gamma} = f(X). \tag{8}$$

Then

$$a = \frac{a_s X}{X_s}, \tag{9}$$

where

$$X_s = \frac{4a_s\tau}{R^2};\ X = \frac{4a\tau}{R^2}.$$

To calculate the specific heat of the investigated medium we use the familiar relation

$$c = \frac{\lambda}{a\rho}, \tag{10}$$

where ρ is the density of the medium.

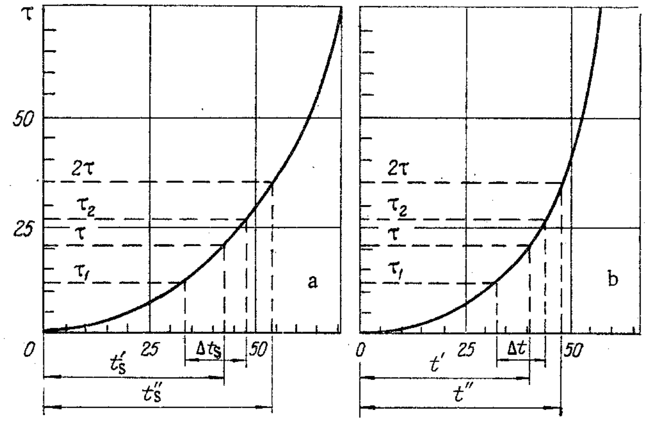

Fig. 1. Time (τ, sec) variation of probe temperature: a) in standard medium (glycerin); b) in blood.

The experimental arrangement is assembled on the scheme of [6-9]. The procedure is as follows. The sensitive probe is first placed in a cylindrical vessel containing the standard fluid, and thermograms are recorded at a constant temperature of 37°C. The experiment lasts about 30 to 60 sec. Thermograms are similarly recorded for the same constant electrical power input with the investigated blood. The thermograms provide a quantitative and a qualitative pattern of the time variation of the probe temperature (Fig. 1), making it possible to calculate the temperature differentials Δt and Δt_s and to determine the thermophysical characteristics of the investigated blood according to expressions (1), (9), and (10) above.

To ascertain how the rheological properties and individual physicochemical characteristics of blood influence its thermophysical properties we have determined separately the values of the specific heat, thermal conductivity, and thermal diffusivity for both young and mature dogs.

In the same blood sample we measured the following characteristics: the effective viscosity μ_{ef}, fluidity φ, and the degree D of gradient variation, using a capillary viscosimeter of our own design. We determined the relative viscosities η_{rel} of the blood and η_p of the plasma with a VK-4 capillary viscosimeter; the erythrocyte concentration EC by the conductometric technique; the hematocrit value Hct with a TsS-1 centrifuge; and the hemoglobin content Hb of the blood per 1 mm^3, using a photoelectrocolorimetric technique.

On the basis of the experimental data we have calculated the true total volume Ht of red blood cells; the total surface area ΣS_ε of erythrocytes per 1 mm^3 blood; the mean hemoglobin content CHb_e of the erythrocytes; the mean concentration KHb_e of hemoglobin in the erythrocytes; and the color index CI_e of the erythrocytes. For the investigation we used 1%-heparinized blood.

All the data obtained in the investigation were processed by the variational statistical method on a Minsk-22 digital computer.

As a result of the investigation we learned the dependence of the thermophysical characteristics of blood on its composition and other properties, as well as the age-dependent variations of those characteristics (Table 1). Thus, with an increase in the erythrocyte concentration, hematocrit value, true total volume of red blood cells, total surface area of erythrocytes per 1 mm^3, density, effective and relative viscosities of the blood, relative viscosity of the plasma, and degree of gradient variation of the blood, its thermal conductivity and thermal diffusivity decrease, while the specific heat increases.

The opposite dependence is observed with an increase in the average content and average concentration of hemoglobin in the erythrocytes, color index, and consistency of the blood. This behavior is attributable to the functional relationship of the specific heat, thermal conductivity, and thermal diffusivity of the erythrocyte suspension to the volume fraction [10] and, clearly, also to the variations in structure and chemical composition of the given suspension.

TABLE 1. Dependence of Thermophysical Properties of Blood on Its Physicochemical Composition and Rheological Properties for Dogs of Different Ages

Age in years	Statistical characteristic	$\rho \cdot 10^{-3}$, kg/m^3	λ, W/m·°K	$a \cdot 10^7$, m^2/sec	$c \cdot 10^{-3}$, J/kg·°K	EC·10^6/mm^3	Hct, vol.%	Ht, vol.%	$\Sigma S_\varepsilon \cdot 10^8$/mm^3, μ^2	μ_{ef}, cP	η_{rel}·cP	η_p, cP	φ, cm^2/dyn·sec	D	CHb_e, pg	KHb_e, %	CI_e
4,2	$\overline{X}$	1,053	0,424	0,675	0,590	7,96	37,8	23,3	5,61	4,23	4,67	1,33	23,3	2,02	18,7	37,7	0,56
	S	0,003	0,029	0,116	0,101	3,01	7,73	9,17	1,62	0,52	1,38	0,14	2,74	0,27	6,60	10,9	0,20
	$S_{\overline{X}}$	0,001	0,009	0,037	0,032	0,95	2,44	2,90	0,51	0,17	0,44	0,04	0,87	0,09	2,08	3,45	0,06
0,99	$\overline{X}$	1,050	0,465	0,766	0,582	6,06	37,2	16,5	4,08	3,37	4,36	1,29	30,3	1,50	27,7	38,9	0,81
	S	0,003	0,055	0,089	0,078	2,51	2,85	7,45	1,55	0,54	0,80	0,18	4,39	0,21	10,5	7,34	0,31
	$S_{\overline{X}}$	0,001	0,018	0,028	0,025	0,79	0,90	2,35	0,49	0,17	0,25	0,06	1,38	0,07	3,33	2,32	0,09

TABLE 2. Interrelationship of the Specific Heat of Blood and Its Physicochemical Composition and Rheological Properties

Characteristic	Statistical characteristic					
	r	t^*	T			
			R^*XY	R^*YX	TXY	TYX
ρ	+0,96	+10,4	+30,8	+ 0,03	+10,4	+10,4
λ	+0,93	+ 7,65	+ 3,24	+ 0,27	+ 7,65	+ 7,65
a	+0,96	+10,9	+ 0,84	+ 1,11	+10,9	+10,9
EC	+0,97	+12,9	+ 0,03	+ 29,0	+12,9	+12,9
Hct	+0,95	+ 9,63	+ 0,01	+ 73,3	+ 9,63	+ 9,63
Ht	+0,93	+ 7,48	+ 0,01	+ 84,7	+ 7,48	+ 7,48
ΣS_ε	+0,98	+13,9	+ 0,06	+ 15,7	+13,9	+13,9
μ_{ef}	+0,97	+12,0	+ 0,18	+ 5,04	+12,0	+12,0
η_{rel}	+0,88	+ 5,37	+ 0,06	+ 12,1	+ 5,37	+ 5,37
η_p	+0,96	+11,0	+ 0,69	+ 1,35	+11,0	+11,0
D	+0,96	+10,9	+ 0,36	+ 2,60	+10,9	+10,9
KHb_e	+0,99	+21,0	+ 0,009	+107	+21,0	+21,0
CHb_e	+0,96	+10,8	+ 0,01	+ 63,1	+10,8	+10,8
CI_e	+0,97	+11,6	+ 0,49	+ 1,92	+11,6	+11,6

It is also known that heat transfer takes place in flowing blood mainly by convection, while the heat-transfer coefficient depends on the properties of the medium in which convection takes place [13].

It is also essential to take account of the thermal effects of chemical reactions, in particular, the oxidation of hemoglobin.

A correlation and regression analysis carried out to determine the degree to which the specific heat depends on the other characteristics of the composition and properties of blood shows that a strong positive correlation and quantitative interdependence exists between the specific heat of blood and its rheological and functional parameters (Table 2).

It follows from the results of our experiments that the values of the thermal conductivity and thermal diffusivity of blood decrease with age, while the specific heat simultaneously increases.

In the case of mature animals the thermal regulation of the organism is more efficient than for young specimens, because the latter have a higher rate of heat production per unit mass, so the specific heat of the blood is lower [14]. This fact complicates the physiological problem of maintaining a constant body temperature [11]. Blood with a high specific heat is characterized by the fact that the quantity of heat transmitted to it increases substantially as a result of latent heat [12].

The foregoing investigations demonstrate the considerable value of determining the thermophysical properties of blood in relation to the thorough analysis of its functions.

The probe method for determining the thermophysical characteristics could eventually, in later studies, become an integral method for characterizing the physicochemical composition and rheological properties of blood.

NOTATION

t, temperature, °C; τ, time, sec; R, probe radius; a, thermal diffusivity, m^2/sec; λ, thermal conductivity, $W/m\cdot°K$; c, specific heat, $J/kg\cdot K$; q, specific heat flux, W/m; ρ, density of medium, kg/m^3; μ_{ef}, effective viscosity, cP; φ, fluidity, $cm^2/dyn\cdot sec$; η_{rel}, relative viscosity of blood, cP; η_p, relative viscosity of plasma, cP; EC, erythrocyte concentration; Hct, hematocrit value, vol. %; Hb, gemoglobin content, mass %; Ht, true volume of red blood cells, vol. %; KHb_e, hemoglobin concentration in the erythrocytes, %; CI_e, color index of the erythrocytes; X, arithmetic mean; S, standard deviation; S_X, mean error; t*, confidence; r, correlation coefficient; R*, regression coefficient; T, correlating factor.

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