Journal of Engineering Physics and Thermophysics, Vol. 69, No. 3, 1996

ABOUT TEMPERATURE DEPENDENCE OF THE RHEOLOGICAL PROPERTIES OF HUMAN BLOOD AT LOW SHEAR RATES

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UDC 612.13

Measurements of the human blood flow curve as a function of temperature are reported. The blood was sampled from healthy donors. The measurements were made at the shear rates from 0.2 to 5.0 sec^{-1} in the temperature range 30–45°C. The blood flow curve was investigated by the nonstationary measurement method using a specially designed viscosimeter. An experimental study of the human blood flow curve at low shear rates allowed investigation of the temperature dependence of the Casson's model parameters describing it. It is shown that these parameters have a complicated temperature dependence that exhibits a specific feature at 42°C.

In conducting hyperthermia treatment, the heat transfer in healthy and affected tissues that is related, in turn, with the rheological factor of blood flow and, consequently, with the temperature dependence of rheological properties of blood, plays an important role.

It is known that blood represents a concentrated suspension formed by red and white blood corpuscles and platelets in plasma. The latter is a colloidal suspension of proteins with a different molecular weight.

Among the corpuscles the erythrocytes prevail in blood. In the free state they represent biconcave discs with the diameter of 8 μm and constitute approximately 93% of the total amount of corpuscles ($\sim 5 \cdot 10^6$ cells/cm^3) and 40–45% of blood volume. Proteins also exert a substantial influence on blood rheology [1]. As a rule such systems involve spontaneous development of spatial structures that substantially dictate the structural-rheological properties of these suspensions. Brownian movement is hindered in these systems. Surface forces of the particle–particle interaction are substantial, which causes structurization as in the case of ordinary colloid systems. The aggregates formed by the surface forces do not break down under gravity. In rheological measurements, this is manifested by the nonlinear dependence of shear stress on a shear rate. A suspension flow curve obtained from such measurements can be split into several parts corresponding to different flow mechanisms. At low shear stresses the system undergoes deformation without destruction of its structure. At high shear stresses the system fails, which entails a drastic decrease in viscosity, a change in which can be several orders of magnitude [2].

For some systems the part of the flow curve with an undestroyed structure corresponds to high values of the observed viscosity, and therefore it is not detected in experiments at all. In such cases, the system is considered to have a yield strength.

It would make sense that blood pertains to such systems. Figure 1 shows the typical plot for the stabilized healthy donor's blood obtained in a conventional rotary viscosimeter. It is evident that the curve originates from some positive limiting shear stress.

In modeling the rheological behavior of blood the Casson law is very often used [3]

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_c \dot{\gamma}} \ . \tag{1}$$

It is known that in blood a certain balance sets up between aggregation and disaggregation processes. The data [1] show that this balance can be violated at the shear rate gradient more than 100 sec^{-1}; at high shear rates the formed structure can be destroyed completely.

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute, Academy of Sciences of Belarus," Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 69, No. 3, pp. 386-389, May-June, 1996. Original article submitted March 20, 1996.

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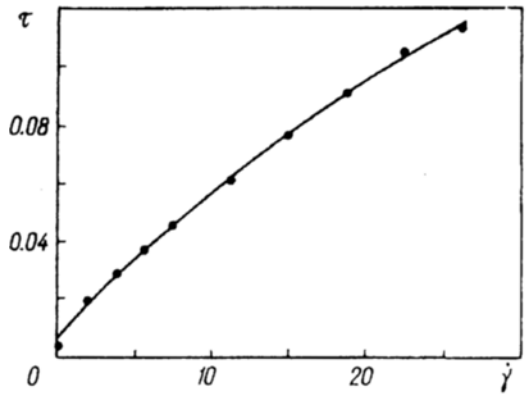

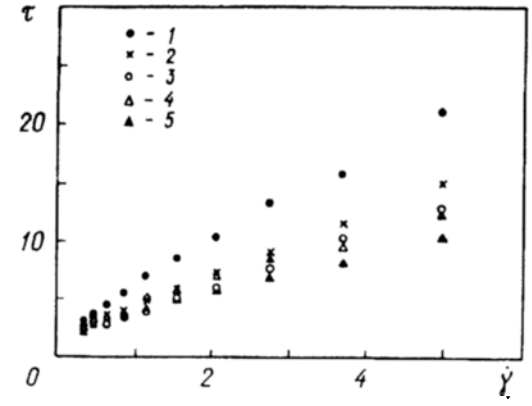

Fig. 1. Human blood flow curve measured in a rotary viscosimeter at 25°C [3]. τ, Pa; $\dot{\gamma}$, sec^{-1}.

Fig. 2. Human blood flow curves as a function of temperature: 1) 30.5; 2) 34.5; 3) 41; 4) 43; 5) 45°C. τ, mPa; $\dot{\gamma}$, sec^{-1}.

Thus, it can be concluded that the rheological characteristics obtained in the shear rate range 0.1–100 sec^{-1} sec^{-1} are mainly related with the aggregation processes of red blood cells. From this viewpoint it is very difficult to elucidate a temperature dependence of rheological properties of the whole blood. To simplify the problem, it is necessary to use such a method that could prevent aggregation of red blood cells. This method and related equipment have been developed in [4]. It consists in ensuring the interrupted motion of the working unit of a viscosimeter. A motion cycle involves two phases; first, abrupt displacement of the movable part of the working unit for a small angle (1–2°) at a shear rate up to 500–1000 sec^{-1}; second, controllable exposure from ten milliseconds to several seconds. The mean shear rate can change from 0.1 to 100 sec^{-1} in the gap of the working unit.

Works are known in which it is asserted that the temperature dependence of the apparent blood viscosity corresponds to that for water [1, 5]. However, investigations of these properties by the given method have revealed a much more complicated dependence that has some specific features at the temperature 42°C [4, 6].

Experiments were conducted with donor's blood anticoagulated with glugitsir sampled at the Belarusian Republican Community Blood Center. As samples, use was made of whole blood with the natural packed cell volume. For this, some portion of the whole blood was centrifuged for 10 min at 1000 g in a desk-mounted OPN-2 unit with a bucket rotor to take off plasma by removing the supernatant. Then an erythrocyte paste was suspended in plasma up to the prescribed Ht = 30%. The prepared samples were kept in a cooler for no more than 1 h (a measurement run) at 12°C; measurements in the viscosimeter were accomplished at a preset temperature.

Investigations were carried out using a Rheomed RM-010 viscosimeter (with coaxial working units having the 1 mm gap) at temperatures ranging from 30 to 45°C. The data of one of the experiments are shown in Fig. 2. The measurement time of the flow curve at the shear rate ranged from 0.2 to 5 sec^{-1} was 2 min. The temperature in the measuring cell of the viscosimeter was controlled with an accuracy of 0.2°C. To obtain the Casson's equation parameters, experimental data were processed by the least squares method. The accuracy of determining the parameters varied from 5 to 10%. Figure 3 shows these parameters as a function of temperature. Because of the lack of the investigated material, we could not obtain statistical estimates. The results of different experiments were similar but slightly differed in numerical values.

The physical meaning of the limiting shear stress in Casson model (1) for blood lies in the fact that red blood cells form a continuous structure through its whole mass. Depending on their orientation and position, separate aggregates will be involved in the structure to a different extent but as for their size, it depends on a blood temperature. On the other hand, the amount of aggregates also changes under heating conditions but in reverse. Thus, it can be assumed that the above parameter insignificantly depends on the temperature, as observed in Fig. 3. Small changes in the low temperature region are within the error limits. A behavior of the Casson viscosity depending on temperature is most pronounced. As already mentioned, in some investigations it is shown that the temperature dependence of the apparent blood viscosity is approximately the same as for water. It is inferred that

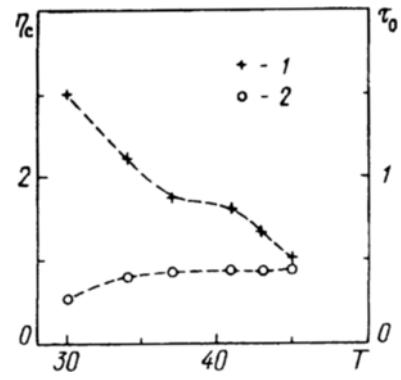

Fig. 3. Parameters of the Casson model as a function of temperature: 1) η_c; 2) τ_0; η_c, mPa·sec; τ_0, mPa; T, °C.

a change in a blood viscosity with temperature is attributed to plasma properties but not to bonds between red blood cells [7]. However, this statement is based on the data obtained for temperature variation at substantial intervals. But in the case of smooth change in temperature, the temperature dependence of the apparent blood viscosity in Arrhenius coordinates is found [5] to have three regions with different activation energies of the viscous flow. The phenomenological description of this dependence suggested in that work has the characteristic temperature of 42°C.

Investigation of the whole blood heated in the temperature range 34–44°C by optical methods has also demonstrated that the blood properties undergo drastic changes [8]. This means that at this temperature the complicated biochemical processes take place whose nature is unclear.

The authors thank the Fundamental Research Fund of Belarus (grant B94-009) for financial support and Prof. H. Schramm (HAAKE, Karlsruhe) for providing the measurement data on rheological blood properties.

NOTATION

τ, shear stress, mPa; $\dot{\gamma}$, shear rate, sec^{-1}; τ_0, limiting shear stress, mPa; η_c, Casson viscosity, mPa·sec; Ht, packed cell volume, %; T, temperature, °C.

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