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DETERMINATION OF THE RHEOLOGICAL PROPERTIES OF WHOLE BLOOD BY THE NONSTATIONARY METHOD OF PULSED CHANGING OF THE RATE OF SHEAR

Z. P. Shul'man and V. A. Mansurov

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Problems associated with the use of the nonstationary method of pulsed changing of the rate of shear for the measurement of important viscoplastic properties of whole blood — the critical shear stress τ_0 and the plastic viscosity μ_p — are considered. The indicated method was compared to the method of stationary rheometry. It is shown that the blood-flow curve obtained by this method, unlike that obtained by the stationary method, characterizes a viscoplastic medium. To calculate the parameters of this medium exactly, it is necessary to take into account the dependence of the rate of shear on the above-indicated parameters.

The study of the rheological properties of whole blood, considered as a macroscopic system, and the relation between these properties and other parameters is of considerable importance in the solution of important medical problems. By way of example we refer to the pathological processes in an organism that significantly influence the rheological properties of the blood and plasma and, as a result, cause the so-called hemorheological disturbances. These disturbances manifest themselves markedly in the case of cardiovascular diseases, such as myocardial ischemia, diabetes, and sepsis, and in the case of long physical loads [1, 2].

An increase in the blood viscosity, caused by a decrease in the deformability and the aggregation ability of erythrocytes, is typical of the majority of cardiovascular diseases. The ischemic diseases of other organs are also accompanied by a deterioration of the hemorheological parameters. In the case of certain diseases, these changes can be considered as an indication of an insufficiency of the circulatory functions and, therefore, can be used for diagnostic purposes [2].

It is difficult to investigate blood circulation experimentally because, in this case, the measuring methods influence the investigation object. This is explained by the fact that, along with the problems associated with the complex hydrodynamics of the flow in rheometers, there arise problems caused by the physicochemical processes in colloidal systems. For example, some experimental schemes give no way of taking into account the nonstationary processes occurring in the blood flow in an organism [2].

Evidently, the classical notion of the viscosity of liquids as their constant coefficient of internal friction loses its meaning for microdisperse liquids. The rheological properties of these liquids can be characterized by the consistency measured under viscosimetry conditions. This characteristic is a function of the shear viscosity and is determined from the relation between the rate of shear $\dot{\gamma}$ and the shear stress τ. The odd material function $\tau = \tau(\dot{\gamma})$ or $\dot{\gamma} = \dot{\gamma}(\tau)$, i.e., the viscosity function, should be reproducible under the conditions of any viscosimetry experiment and, consequently, should define any rheological property of a given microdisperse liquid at a definite temperature, pressure, and aggregate dispersion state. In this case, in the majority of publications devoted to the rheometry of microdisperse media, a flow in the measurement unit of a viscosimeter is assumed to be steady even though scientifically substantiated estimates of the measurement time are, as a rule, absent in these works.

In actuality, blood flow in an organism is pulsed; therefore, there is a need for investigating the features of the instantaneous running resistance to it, caused by a sharp change in the rate of shear. Hemorheological measurements [1–3] have shown that blood flow is characterized by (1) visco- or pseudoplasticity, (2) viscoelasticity manifesting itself as a nonstationary change in the rate of shear, and (3) thixotropy related to the initial running resistance caused by the orientation and disaggregation of erythrocytes. It should be noted that measurements of the viscosity of

A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus; email: v-man@hmti.ac.by. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 78, No. 5, pp. 176–179, September–October, 2005. Original article submitted November 1, 2004.

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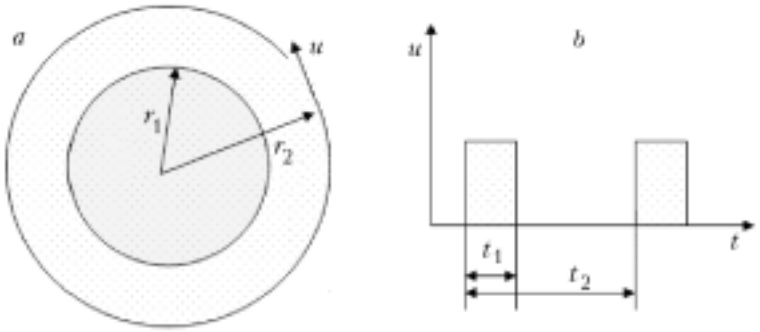


Fig. 1. Scheme of the nonstationary method: a) measuring unit; b) change in the velocity of a flow in the measuring unit.

blood *in vivo* give rheological parameters differing from those measured using a viscosimeter (*in vitro*). This is explained by the fact that stationary measurement methods that are usually used for measuring blood *in vitro* give no way of exactly determining its rheological properties; more reliable data on these properties can be obtained using a nonstationary measurement method that reproduces the actual conditions more adequately [4].

There are a number of nonstationary measurement methods that can be used for investigating suspensions similar to blood. We now consider some of them. A Couette viscosimeter, described in [5], includes a step-by-step motor controlled by a computer, which makes it possible to change the rate of shear by a definite law and investigate a nonstationary blood flow at moderate rates of shear (from 1 to 100 sec^{-1}). It has been established in this work that the viscosity of a suspension substantially decreases and its thixotropic properties strengthen with increase in the rate of shear.

In the computer-controlled viscosimeter described in [6], a pulsating shear stress is applied to the measuring unit. A step change in the shear stress generates a pulsating flow with a rate of shear oscillating with a period of about 0.7 sec. It was shown that, in the region of large rates of shear, the aggregation of a suspension is independent of the pulsating rate of shear. This allows the conclusion that the viscoplastic Bingham model can be used for mathematical simulation of a flow pulsating in accordance with the rheological law.

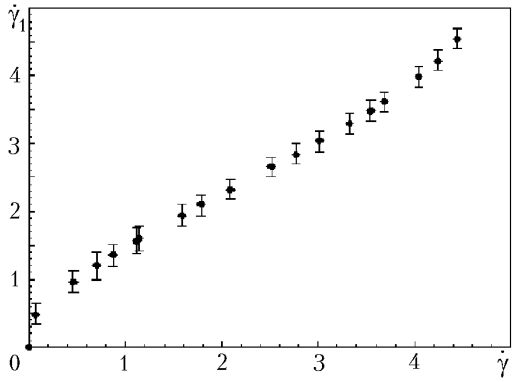
However, the above-described methods have a number of disadvantages that, above all, cause difficulties in the calculation of the effective (acting) rate of shear. In [7], a nonstationary Couette flow was investigated on the assumption that a measuring unit is filled with a Bingham medium. The calculations have shown that the effective rate of shear is proportional to the off-duty ratio of the stop pulse and the pulse accelerating the rotating element of the measuring unit. Blood can be considered under certain assumptions as such a liquid.

The nonstationary measurement method used for investigating the rheological properties of blood and suspensions similar to it with the use of viscosimeters in which the working unit moves discontinuously was described in [8, 9]. The cycle of movement of the working unit of the viscosimeter presented in Fig. 1 consists of two phases including (1) a sharp displacement of the movable part of the working unit to a small angle ($\sim 5^{\circ}$) with a rotational velocity of up to 1 sec^{-1} for the time $t_1 \approx 40 \cdot 10^{-3}$ sec, which, for the given measuring units, corresponds to the maximum linear velocity u = 0.02 m/sec or the rotational velocity ω = 1 sec^{-1}, and (2) a pause lasting for the time t_2, ranging from several tens of seconds to several hundreds of milliseconds. Since the outer part of the measuring unit rotates, there are no reasons for development of a Taylor vortex and the pulsating Couette flow is stable.

On the assumption that the flow in the unit changes with a period t_2, the initial velocity profile $u(r)$ will be the same for the instants of time t = 0 and $t = t_2$. For a viscoplastic liquid investigated under these conditions, the following formula was obtained [10]:

$$\dot{\gamma} = \frac{t_1}{t_2}\left(\frac{2u}{r_2}\left(\frac{2}{1-\zeta^2} - \frac{\text{Sen}}{2}\left(1 + \frac{\ln \zeta^2}{1-\zeta^2}\right)\right)\right), \quad \text{Sen} = \frac{2r_2\tau_0}{u\mu_p}, \quad \zeta = \frac{r_1}{r_2}. \tag{1}$$

Note that, at Sen = 0, i.e., τ_0 = 0, this equation is transformed into the known relation for the rate of shear of a Couette flow of a Newton liquid, proportional to the off-duty ratio t_1/t_2.



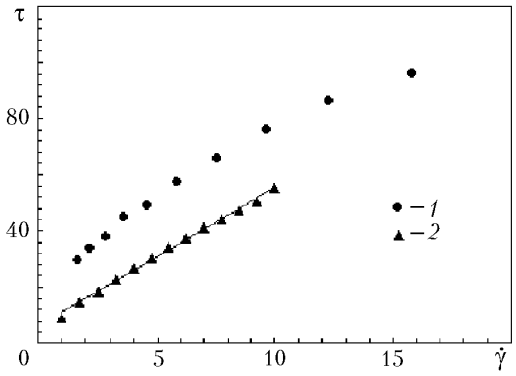


Fig. 2. Dependence of the effective rate of shear on the given rate of shear (the ordinate is determined from Eq. (2) and the abscissa is determined experimentally).

Fig. 3. Comparison of the whole-blood flow curves measured by the stationary (1) and nonstationary (2) methods; the line represents the nonstationary-measurement data fitted to the Bingham model.

For the Newton media, $\mu_p = 0$. In this case, $\frac{Sen}{2}\left(1+\frac{\ln\zeta^2}{1-\zeta^2}\right) = 0$ and the following formula can be used as the first approximation for the effective rate of shear of the flow considered:

$$\dot{\gamma}_w = \frac{t_1}{t_2}\left(\frac{2u}{r_2}\left(\frac{2}{1-\zeta^2}\right)\right). \qquad (2)$$

For the purpose of verification of these calculations, the rate of shear was experimentally determined with the use of a nonstationary viscosimeter realizing the above-described pulsating flow. It is known that 96% ethanol is a Newton liquid with a rate of shear changing in a wide range, whose dynamic viscosity at a given temperature is a reliable table quantity. Let us assume that formula (2) is true for this case. The measuring unit of the viscosimeter was filled with ethanol, the viscosimeter drive was energized, the shear stress corresponding to a given effective rate of shear was measured, and the effective rate of shear was calculated as $\dot{\gamma}_1 = \tau/\eta_e$. The results are presented in Fig. 2. It is seen that, within the limits of the measurement error, the rate of shear calculated by (2) corresponds to the measured one.

The results of nonstationary measurements of the rheological properties of whole blood, stabilized by the anticoagulant heparin, with a hematocrit $H_e = 40\%$ at a temperature of 37°C are presented in Fig. 3. For comparison, this figure gives the results of measuring the rheological properties of the same blood by the stationary method (VIR-78ME rheometer) with the use of an analogous measuring unit. It is seen that the blood-flow curve obtained by the nonstationary method is viscoplastic in character and is defined by the Bingham equation with parameters $\mu_p = 4.9$ mPa·sec and $\tau_0 = 6.2$ mPa. These results correspond well to the results obtained in [6]. We call attention to the fact that the stationary method gives the critical Caisson shear stress equal to 11 mPa, i.e., the critical shear stresses determined by the two indicated measurement methods coincide in order of magnitude.

For the case considered, the parameter Sen = 0.22. The contribution of the viscoplasticity to Eq. (1) is $\frac{Sen}{2}\left(1+\frac{\ln\zeta^2}{1-\zeta^2}\right) = 0.048$. This means that the rate of shear should be corrected, for which purpose we calculated its new value in accordance with (1) using the already determined parameters τ_0 and μ_p. The results are presented in Fig. 4. This procedure gives a value of $\mu_p = 4.9$ mPa·sec instead of the value of $\mu_p = 5.2$ mPa·sec obtained from formula (1), i.e., it shows that the plastic viscosity changes substantially, which should be taken into account when μ_p is determined by the nonstationary method.

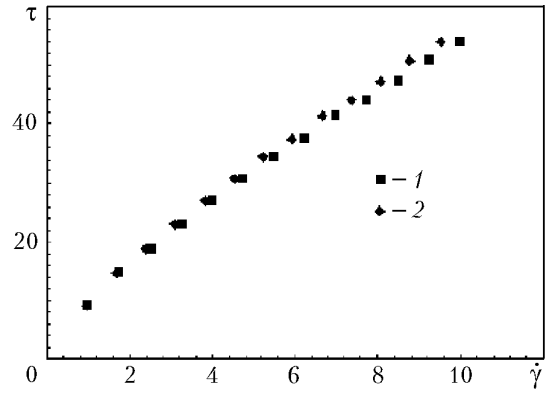


Fig. 4. Result of correction of the rate of shear: 1) by (1); 2) by (2).

In conclusion, it may be said that the use of the nonstationary measurement method has made it possible to develop a simple and reliable viscosimeter for medical purposes. Since the data obtained by the nonstationary method are closer to the actual data on blood flow, it may be suggested that, using this method, one can investigate the rheological properties of blood more exactly. The data obtained by the method proposed for calculating the rate of shear can be simply processed, which makes this method suitable for use in medical practice.

NOTATION

H_e, hematocrit, %; r_1 and r_2, radii of the inner and outer cylinders of the measuring unit, m; Sen, Saint Venant number; t, running time, sec; t_1, time of movement with a maximum velocity, sec; t_2, period of change in the rotational velocity of the measuring unit, sec; u, maximum linear velocity of movement, m/sec; $u(r)$, profile of the rate of shear in the measuring unit, m/sec; $\dot{\gamma}$, rate of shear, $\sec^{-1}$; $\dot{\gamma}_1$, effective rate of shear, $\sec^{-1}$; ζ, ratio between the radii of the inner and outer cylinders of the measuring unit; η_e, viscosity of ethanol, mPa·sec; μ_p, plastic viscosity, mPa·sec; τ, shear stress, mPa; τ_0, limiting shear stress, mPa; ω, angular rotational velocity, $\sec^{-1}$. Subscripts: e, ethanol; p, plastic deformation; w, wall.

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