Eqs. (17') and (17''). Into account is also taken here that the tensors $\mathbf{B}_\beta$ can depend on the flow characteristics.

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INTERRELATIONSHIP OF RHEOLOGICAL AND BIOLOGICAL CHARACTERISTICS IN COMPLEX SYSTEMS

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The interrelationship of rheological properties and quantitative indices of fluids of biological origin is analyzed. Possible variants of the use of the viscosity for estimating the state of the system are presented.

In studying labile systems, whose properties depend greatly on the parameters of the external medium (t, P, φ) or the state of the system itself (t, W), it is necessary to choose a characteristic physical indicator, which reflects to a certain extent the state of the substance, as well as the kinetics and dynamics of its variation. Typical representatives of such materials are heterogeneous systems of biological origin – microbe biomasses. It is well known that the presently existing methods of microbiological analysis are imperfect and are distinguished by their long duration, measured in days, and high degree of error. The effect of the error can be eliminated by multiple repetition of the experiment and statistical analysis of the results obtained, as is customary in studying probabilistic processes. However, in this case, the duration of the analysis increases even more, which can be eliminated only by developing and applying new improved methods, based on the interrelationship of physical and biological properties of the system.

It is well known that microbiological materials of different nature are characterized by a wide range of rheological properties from Newtonian to plastic [1], which can serve as qualitative and quantitative indices of heat and mass transfer in bioengineering and biotechnology processes. Thus, the viscosity of the starting feed media exceeds by not more than a factor of 1.5-2 the viscosity of water, while during the growth of life of microorganisms, this quantity increases by one to two orders of magnitude. The increase in the viscosity of the

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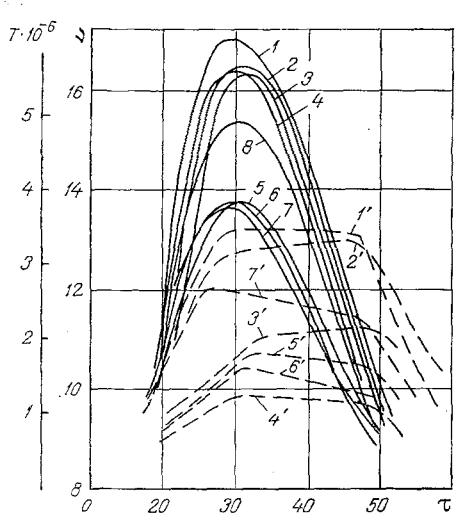

Fig. 1

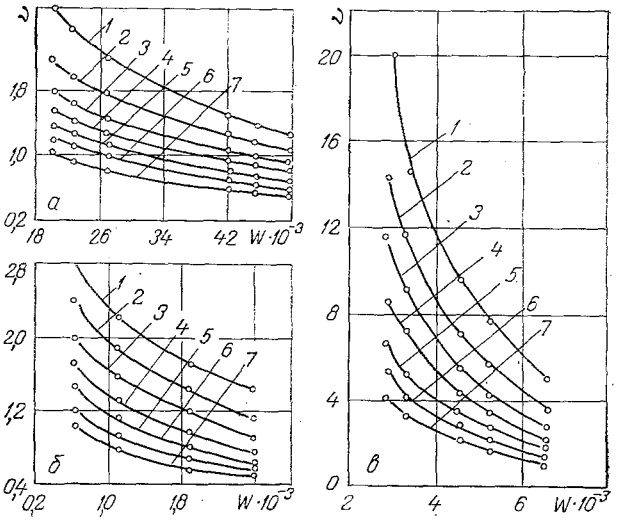

Fig. 2

Fig. 1. The change in the viscosity of the biomass (Az. chroococcum) and concentration of microorganisms in time: continuous lines indicate the viscosity, the dashed lines the concentration (titer); 1-7, 1'-7' enumerate the experiments; 8 is the average viscosity. τ, r; ν, cSt; T, kl/ml.

Fig. 2. The dependence of the viscosity of biological fluids on moisture content (W) and temperature (T): a) entobacterin; b) cormogrizin; c) azotobacterin; 1) t = 20; 2) 30; 3) 40; 4) 50; 5) 60; 6) 70; 7) 80°C. W, %.

biomass with time is due to the change in the properties of the dispersed medium, which is a complicated complex of organic and inorganic compounds, and an increase in the quantity and size of solid dispersed inclusions. This is especially sharply manifested in cultivating certain actinomyces, molds, and yeasts, as well as cap-forming vegetative cultures. The fluids obtained in this case have sharply manifested non-Newtonian properties [1, 2].

The relation between the change in the viscosity of the biomass and the dynamics of the development of the culture of microorganisms is used as a method for controlling the duration of the process of accumulating the biomass [3]. The principle of determination is based on the following: The quantity of vital cells (the titer) increases during the first 30 h of culture development (Fig. 1), and simultaneously the kinematic viscosity of the biomass also increases. This period corresponds to the logarithmic phase in the growth of bacteria, and then the stationary phase begins. The maximum value of the titer corresponds to the maximum viscosity of the biomass, which then begins to decrease exponentially. Thus, the process of development can be assumed to be completed at a time when a decrease in viscosity is observed relative to its maximum value.

In connection with the fact that biotechnological processes occur primarily in an isothermal regime, it is interesting to observe the degree to which moisture content affects the viscosity of different microbiological materials. Figure 2 shows that a decrease in the moisture content causes a significant increase in the kinematic viscosity of the materials. The temperature dependence of the viscosity has an analogous character.

For Newtonian type fluids, a generalized empirical expression is obtained that permits determining the viscosity as a function of the nature and state of the fluid [4]:

$$\nu = \exp(a + bt + cW), \tag{1}$$

where a, b, and c are empirical factors, whose values, determined by the nature of the substance, for a number of materials studied in the temperature range 20-80°C and moisture content 7-67 kg/kg, are presented in Table 1.

Therefore, a physical parameter such as viscosity not only characterizes the state of the substance, but also with other physical parameters of the medium and of the system itself remaining constant, can be used as an indicator of specific properties of the object being studied for analysis and control of the kinetics and dynamics of biotechnological processes.

TABLE 1. Values of the Coefficients in Eq. (1)

Object	Empirical Coefficients			Remarks
	a	b	$c \cdot 10^4$	
Entobacterin	1,6	—0,015	—2,0	Titer of biomass $(1\text{-}2) \cdot 10^9$ kl/ml
Cormogrizin	1,6	—0,018	—3,6	Activity of biomass 500-1000 units/ml, grainy structure of mycelia
Bacitracin	1,9	—0,018	—5,0	Activity of biomass 200-5500 units/ml
Azotobacterin	4,7	—0,026	—4,0	Titer of biomass $(1.5\text{-}3.5) \cdot 10^9$ kl/ml

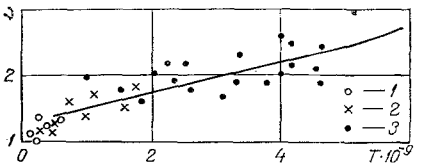

Fig. 3. The interrelationship of the viscosity and concentration of viable cells of the Bac. thuringiensis biomass: 1) suspension of cells; 2) biomass obtained under laboratory conditions; 3) biomass obtained under commercial conditions.

An important distinguishing feature of microbiological fluids is their inadequacy. Metabolic processes between microorganisms and the medium lead to the formation of a complex multicomponent system, including, aside from the basic components of the concentration (active component), many additional fluids and solid products of metabolism. This stems from the instability of the processes of development and life processes of the microorganisms and often has a large effect on the physical, including also rheological, properties of the materials. In this connection, in developing physical methods for analyzing and controlling the system, the specific arrangement of the experiment, which permits observing the direct effect of the determining parameters (in a given specific case, the concentration of microbe cells) on the indicator characterizing the physical properties of the system, namely, the viscosity, plays an important role.

Figure 3 presents the calibration curves constructed based on the experimentally studied interrelationship $\nu = f(T)$ for a microbiological preparation, widely used in the economy as a means for protecting plants (Bac. thuringiensis and Bac. dendrolim culture). The properties of the fluid have a sharply manifested Newtonian character. Not only the biomass, but also the suspension of microbe cells, not containing the products of metabolism accompanying metabolic reactions (Fig. 3, group of experimental points in the region $T = 2 \cdot 10^9$ kl/ml), was also studied. The mathematical analysis of the experimental data, measured over a wide range of variation of the quantity of viable cells with multiple repetition of experiments (not less than 7-10), yielded a linear correlation $\nu = f(T)$ in the form

$$\nu = 0.24\,T + 1.2. \tag{2}$$

The disagreement between the experimental data and the computed dependence does not exceed 10-15%, which, compared to the generally accepted accuracy of microbiological analyses (±30%), gives a clear positive effect. The calibration curve was constructed based on a microbiological analysis of the material conducted in parallel with the measurement of the kinematic viscosity and shows that the increase in the quantity of viable cells by a factor of 5-6 increases the viscosity of the fluid by 300%, in spite of the extremely insignificant change in density (not more than 1%). Therefore, by measuring the viscosity of the fluid, it is possible to determine with sufficient reliability the concentration of the active source — live cells. If we also take into account that the duration of the viscosity measurements with the instrumentation used on the whole does not exceed several minutes, the expedience of using the interrelationship of biological and rheological properties of a system of this type, as a rapid method for measuring the concentration of the active component, is obvious.

NOTATION

Here ν is the kinematic viscosity; T, concentration (titer); t, temperature; W, moisture content; P, pressure; and φ, relative humidity of air.

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