Concentration of Baker's Yeast Suspension by Means of Membrane Enhanced Drying – Rheological Approach*

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This paper relates effectiveness of membrane enhanced drying process to rheology of yeast suspension. It describes relations of suspension viscosity with respect to the cell concentration, temperature, and shear rate. The collected data prove that the rheological behaviour is very complicated and depends on the three variables studied. It is demonstrated that transition from shear-thinning to shear-thickening phenomenon is mostly temperature-controlled and attributed to highly concentrated suspension only. At 30 °C, a suspension with unexpectedly low viscosity was found which triggered the search for process parameters that allow keeping low values of suspension viscosity.

Concentration of microorganism suspensions by means of a new method, membrane enhanced drying (MED), has been studied for the last two years [1, 2]. The goal of the MED process is to enlarge the liquid-vapour contact area and thus accelerate the evaporation process. For this purpose, capillary membranes were applied successfully. The contact throughout membrane pores allowed water to vaporize. It is suspected that the viscosity of remaining suspension raised inevitably. Such a viscosity increase should affect the operation process parameters and might turn the membrane drying to an unstable mode. Hence the variation of the suspension viscosity was assumed to have a critical impact on the process control. For this reason, the present studies were focused on the important factors governing rheological behaviour of microorganism suspensions. To simplify the study, baker's yeast suspension was selected as the medium.

When yeast suspension is processed by means of membranes, the cells are dragged towards the membrane surface and there concentrated. The following phenomena accomplish raising the cell contents: concentration polarization [3] as well as adsorption and deposition of cell in a cake layer [4—6]. To counterbalance the particle convection towards the membrane, cells back-diffusion and their movement induced by electrostatic or shear field was reported [7]. Finally, when convection reaches not so high extent, the forces are balanced and the process takes place under the conditions of the critical flux [8, 9]. Here, the membrane is not fouled by deposited cells [8]. For this goal, the recognition of the role of suspension rheology should help to understand and handle the MED process, too.

The literature survey of yeast suspension rheology leads to mostly ambiguous conclusions. Some authors have stated that the yeast suspension behaved as Newtonian liquid [10]. Others have pointed rheological behaviour to be dependent on share rate (γ), temperature (T), and cell concentrations (c) [11]. It was found that when yeast cells formed clusters [12] the suspension viscosity resulted from a large number of physicochemical and microbiological factors [13, 14]. Thus, the baker's yeast suspension appears to be a system with very complicated structure that should affect vitally the medium rheology. In the present paper, the effects of temperature and cell concentration on suspension viscosity were studied and used to interpret the efficiency of the membrane enhanced drying.

EXPERIMENTAL

One batch of flocculating baker's yeast, *Saccharomyces cerevisiae*, was used throughout this study. Prior to each measurement the appropriate suspensions were prepared by gentle mixing of cells in distilled water. The suspension was thermostated and mixed for 20 min outside of a rheometer.

A dynamic stress rheometer AR-1000N (TA Instruments) equipped with concentric cylinders (21.44 and 19.94 mm of inside-cup and outside-bob radius and 64 mm of bob height) was used for rheological measure-

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ments. During the experiments, the suspension temperature was kept constant (± 0.5 °C) by an external thermostat. The cell sedimentation between the rheometer cylinders was reduced by mixing the suspension for 5 min at 0.1 s^{-1} shear rate, and then left without agitation for another 5 min. Each run was repeated three times with freshly prepared suspension. The collected data were averaged with an 8 % accuracy level. Viscosity *vs.* shear rate courses were gathered for suspension containing 20 mass %, 40 mass %, 60 mass %, and 80 mass % of yeast cell at four different temperatures, 25 °C, 30 °C, 35 °C, and 40 °C. The concentration of cells in a yeast-bar was assumed to be 100 mass %.

The drying process was evaluated as described elsewhere [1]. Suspensions of baker's yeast were pumped through the membrane capillary system for 24 h, replaced by new medium and fed the system for another 24 h. The operation was repeated in a two-week period. After each day, water loss was noted. Microfiltration polypropylene membranes (AKZO K1800, pore diameter of 0.4 μm) were applied throughout the study. The capillaries had inside diameter of 1.2 mm and 50 cm length. Suspension was pumped with linear flow rate of 1.5 cm min^{-1} or 3.0 cm min^{-1}. The air, 60—65 % of relative humidity and 20—22 °C, was moved outside the capillaries with the average speed of 6 m s^{-1}.

RESULTS AND DISCUSSION

Rheological responses of suspended baker's yeast are shown in Figs. 1—4. The shape of obtained curves allows to assume that suspensions exhibit shear-thinning and shear-thickening behaviours.

The curves with simplest courses were obtained at 25 °C and 30 °C for the whole range of yeast concentrations. At low and medium shear rate values a sigmoid shape of curves, so characteristic of the shear-thinning phenomenon, was observed. With the increase of shear rate the organized structure of cells was destroyed and the suspension became less viscous. For all temperatures under investigation, the expected effect of concentration was found. Any increase of cell concentration resulted in the increase of suspension viscosity. However, a careful observer might find some unusual phenomena.

In the region of low shear rate, the viscosity of suspensions with the lowest yeast cell content reached higher values than those obtained for suspensions with higher (40 mass %) yeast concentration. The second finding deals with the shape of curves obtained at higher temperatures for suspensions containing 60 and 80 mass % of yeast. Two sigmoid regions could be identified in the shape of these curves. Therefore, it seems that at least two yeast structures were gradually destroyed when the shear rate was increased. The third observation points at a shear-thickening character of the yeast suspensions. When the shear rate reaches the critical value, the viscosity of suspension increases. The estimated critical values of shear rate are juxtaposed in Table 1. Due to the fact that estimation has failed for suspension of 20 mass % and has given an unrealistic data for 40 mass % content, Table 1 contains entries for 60 mass % and 80 mass % yeast mass only.

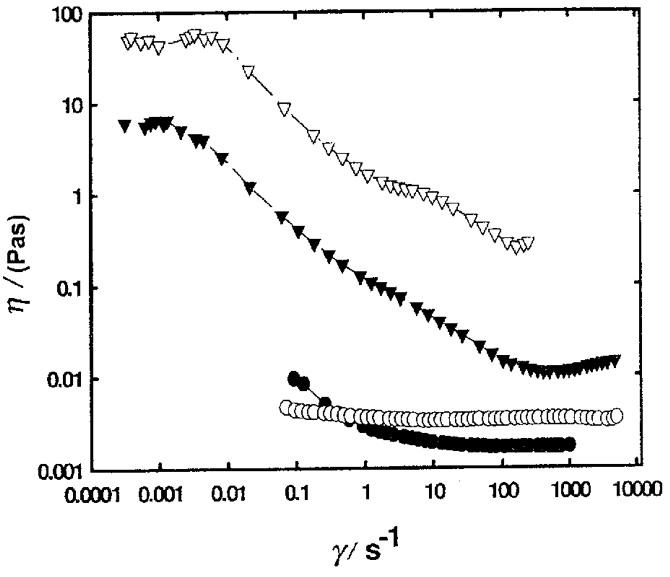

Fig. 1. Effect of shear rate on viscosity at 25 °C. Suspension containing 20 mass % (filled circle), 40 mass % (open circle), 60 mass % (filled triangle), and 80 mass % (open triangle) of cells.

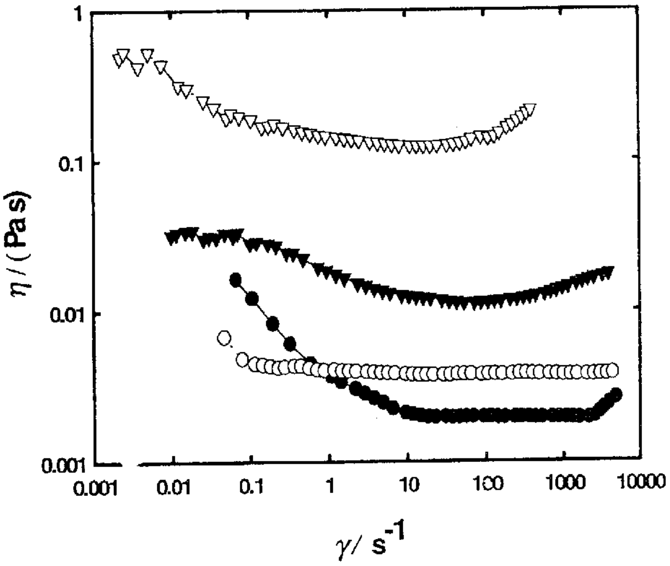

Fig. 2. Effect of shear rate on viscosity at 30 °C. Suspension containing 20 mass % (filled circle), 40 mass % (open circle), 60 mass % (filled triangle), and 80 mass % (open triangle) of cells.

The obtained results show the phenomenon to be temperature-dependent according to the Arrhenius re-

Table 1. Estimated Critical Shear Rates (γ_c/s^{-1})

Temperature/ °C	Yeast concentration	
	60 mass %	80 mass %
25	40	20
30	70	40
35	150	70
40	350	150

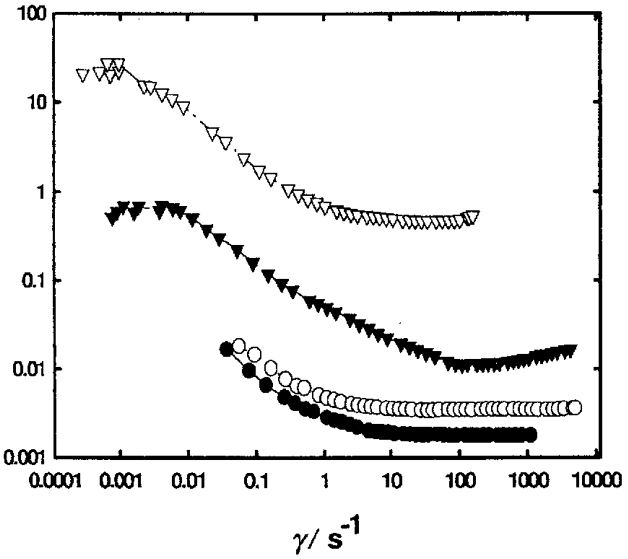

Fig. 3. Effect of shear rate on viscosity at 35 °C. Suspension containing 20 mass % (filled circle), 40 mass % (open circle), 60 mass % (filled triangle), and 80 mass % (open triangle) of cells.

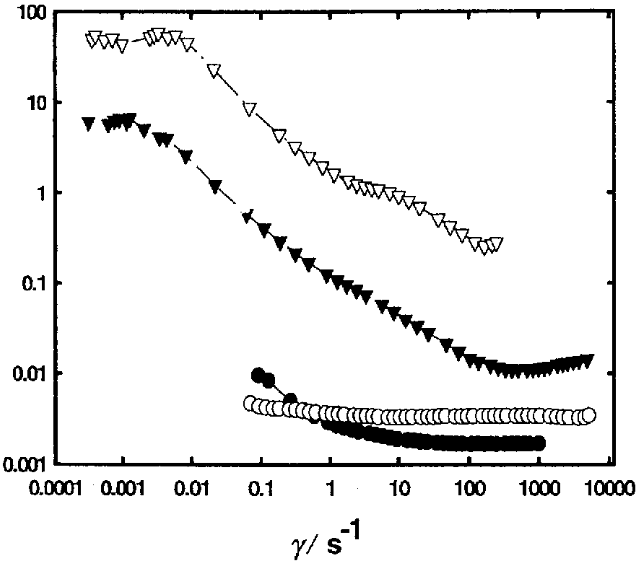

Fig. 4. Effect of shear rate on viscosity at 40 °C. Suspension containing 20 mass % (filled circle), 40 mass % (open circle), 60 mass % (filled triangle), and 80 mass % (open triangle) of cells.

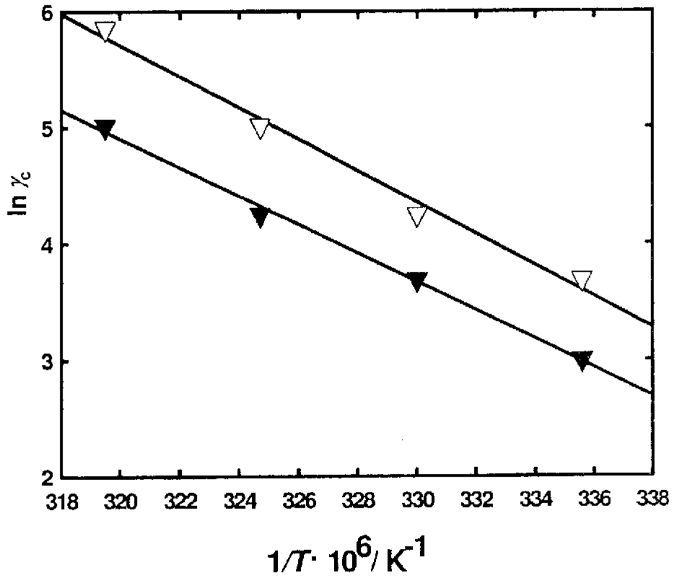

Fig. 5. Arrhenius relationship of shear-thinning to shear-thickening transition. 60 mass % (filled triangle) and 80 mass % (open triangle) of cells.

lationship

$$\gamma_c \propto \exp\left(\frac{1}{T}\right) \tag{1}$$

The linear relationship of $\ln \gamma_c$ *vs.* $(1/T)$, presented in Fig. 5, allows us to note that the transition is weakly related to the cell content for concentrated suspension. Both lines, representing relationship for 60 and 80 mass % of cells, have almost the same slope.

The experimental runs, shown in Figs. 1—4, allow us to monitor the effect of temperature on the rheology of the yeast suspension, too. The medium containing 20 mass % of cells shows almost the same character for all temperatures considered in this study. When the yeast content was increased to 40 mass %, a significant viscosity increase was observed in the region of low shear rates. Suspension comprising 60 mass % of cells exhibits the highest viscosity at 40 °C meanwhile it is less viscous at 30 °C. This behaviour is more pronounced for the suspension containing 80 mass % of yeast. It may be noted that viscosity increases with the temperature increase for the region of small γ values while for the highest shear rates applied the opposite relation is noticed. The exception was the course carried out at 30 °C when the lowest values of viscosity were obtained for the whole range of shear rates. This phenomenon could be explained considering the yeast suspension as an agglomerate system in which different aggregation mechanisms are activated at various temperatures and to the different extent. As a consequence of the above discussions, the model of yeast cell organization is postulated (Fig. 6).

The yeast cell structuring can be divided into three groups. At low shear rates, cells form large enough agglomerates (region A) organization of which de-

Table 2. Concentration of Yeast Suspensions. Average Water Flux, J, in g m^{-2} h^{-1}. Process Parameters: Membrane AKZO K1800, Room Temperature, Air Relative Humidity 60—65 %, Air Speed 6 m s^{-1}

Yeast concentration	Flow rate of suspension			
	3 cm/min		1.5 cm/min	
%	Without wind	With wind	Without wind	With wind
0*	274 ± 6	481 ± 7	272 ± 8	471 ± 4
20	162 ± 5	263 ± 9	168 ± 6	263 ± 4
40	146 ± 8	285 ± 4	171 ± 7	304 ± 9
60	153 ± 12	291 ± 10	153 ± 4	296 ± 13

*Pure water as the feed medium.

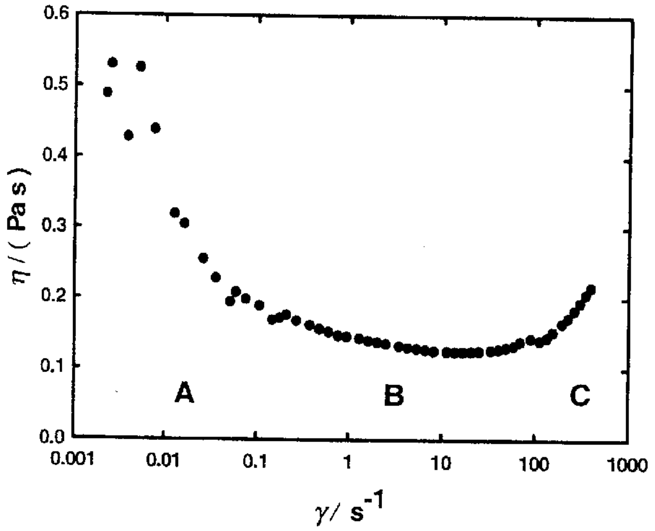

Fig. 6. Effect of shear rate on the structure of yeast suspension. A, B, C denote the regions of the existence of different structures. More detailed explanation is in the text.

pends on the temperature. Both aggregates and flocs may form such structures. When the suspension is exposed to larger shear force (region B), the weakest forms of cell organization are destroyed. As a consequence, a suspension viscosity decreases. Once the primary aggregates are broken, sometimes in more than one step, the yeast cells start to move in an ordered way. The freely moving cells can meet each other and form short-living aggregates (region C). Thus, the suspension viscosity increases and shear-thickening effect is observed. When suspension is pumped in a capillary membrane, the important processes appear in the vicinity of the membrane surface where cells are concentrated. Diffusional back movement and rheological lifting do not allow cells to foul the membrane. Hence, the yield of MED process should not be related to the content of yeast in the suspension. This hypothesis is verified below.

The flux of vapour, that expresses the amount of water evaporated from unit area per unit time, is considered here as a yield of the membrane drying process. Its values are juxtaposed in Table 2. After comparing the obtained vapour fluxes one notes that water removal is not affected by yeast cell concentration. Hence, the shear-induced removal of yeast cells from the membrane surface must play a critical role in keeping the membrane surface unfouled. Different flux rates for pure water and yeast suspensions are the findings coming from the obtained data. They show that yeast cells are deposited on the surface. The deposited layer, however, shows some properties independently of bulk cell concentration. When one assumes that shear forces act also within the deposit layer, it is clear that shear-thinning phenomenon should keep the surface not so dangerously fouled. Such situation allows us to believe that the MED process should be easy to control.

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SYMBOLS

γ	shear rate	s^{-1}
γ_c	critical shear rate	s^{-1}
η	suspension viscosity	Pa s
J	water flux	g m^{-2} h^{-1}
T	temperature	K
c	yeast concentration	mass %

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