Stirring Characteristics in Bioreactors

J. J. Vanags
M. A. Rikmanis
E. J. Ushkans
August Kirchenstein Institute of Microbiology
Latvian Academy of Sciences

U. E. Viesturs
Institute of Wood Chemistry
Latvian Academy of Sciences
Riga, Latvian Republic, USSR 226006

Distribution data of local values of specific kinetic energy of medium flow in the bioreactor volume made it possible to determine some integral criteria. The relationship of these criteria, microorganism growth and biosynthesis characteristics was studied in 5-5,000-L bioreactors. Energy-efficient stirring systems that ensure a minimum damage of cells have been also studied.

Introduction

Efficiency of state-of-the-art processes depends greatly on the choice of equipment and the reactor construction and regime. Hence, once a bioreactor is selected and constructed, it is important to evaluate the process specificity and properties of biological agents.

Various criteria are available that evaluate and compare reactors (Viesturs et al., 1986), yet their application is usually limited to geometrically similar constructions and reaction media of the same type. Methods of mathematical modeling (Viesturs et al., 1986) offer a complete theoretical concept of the processes in reactors; however, since a number of parameters have to be replaced (as it is virtually impossible to determine their real values) by theoretical suggestions, the calculations are rather unreliable.

Mass transfer characteristics of bioreactors have earned popularity, since they characterize the fitness of a given reactor for a specific process. Measurements in model media, such as Na_2SO_3, however, do not quite correspond to the results obtained in actual processes. Mass transfer characteristics determined during actual processes (Viesturs et al., 1986) are more reliable. Yet the range of their applications is limited, because it is not possible for the producers of fermentation equipment to test their reactors for all possible processes. Likewise, technologists cannot experimentally select the most suitable equipment. Hence, to solve the problem of stirring in biotechnology it is important to study the relationship of local stirring characteristics and other characteristics of the process. Quite often it is difficult to determine the distribution of local stirring characteristics in bioreactor volume because of the specific properties of the medium (in multiphase, disperse, inhomogeneous, etc. media) and complicated construction of the reactor itself.

Thermoanemometry was used to study flow characteristics during fermentation (Lippert et al., 1983), whose use in complex multiphase media is very complicated (Schugerl et al., 1987).

Local stirring characteristics in multiphase media should be studied by methods based on the mechanical and electrical transduction of the medium flow effect, since fluctuations of the gas content and density of the medium as well as the turbulent eddies of the flow in this case can be regarded as fluctuations of medium flow kinetic energy. This type of transducer is used to study turbulence in air flows (Siddon and Ribner, 1965; Cheng, 1974). According to Siddon and Ribner (1965), these transducers are reliable, cost less, and require comparatively simple equipment to treat the measured signal.

Chemical and biotechnological processes demand that primary transducers offer sealing, time and temperature stability, as well as chemical and biological stability of the medium. These requirements can be met by properly selecting construction and sealing materials.

Experimental Studies

Fermentation equipment FU-8 (Viesturs et al., 1986) was used for the experimental studies of this paper. The equipment consists of two systems:

1. Reactors with impeller drives and technological vessels
2. Panel for the control, measurement and monitoring of the main parameters of fermentation.

Reactors (Figure 1) of FU-8 in their basic variant (there are four interreplaceable stirring systems) are equipped with a double-tier turbine impeller. Each reactor, with its volume of 5 L (working volume, 2-3 L) is equipped with three baffle plates, nozzle bubbler, mechanical foambreaker, and a thermostatting system. The diameter of the fermentor $D = 145$ mm, that of the turbine impeller $d = 67.7$ mm ($d/D = 0.47$). The impeller shaft is magnetically sealed (Figure 2), and a special magnetic liquid fills the space between the shaft and ring-shaped poles. Magnetic sealing is advantageous because it can seal the shaft more reliably, is simple to apply, and the energy loss caused by friction in the sealing is insignificant.

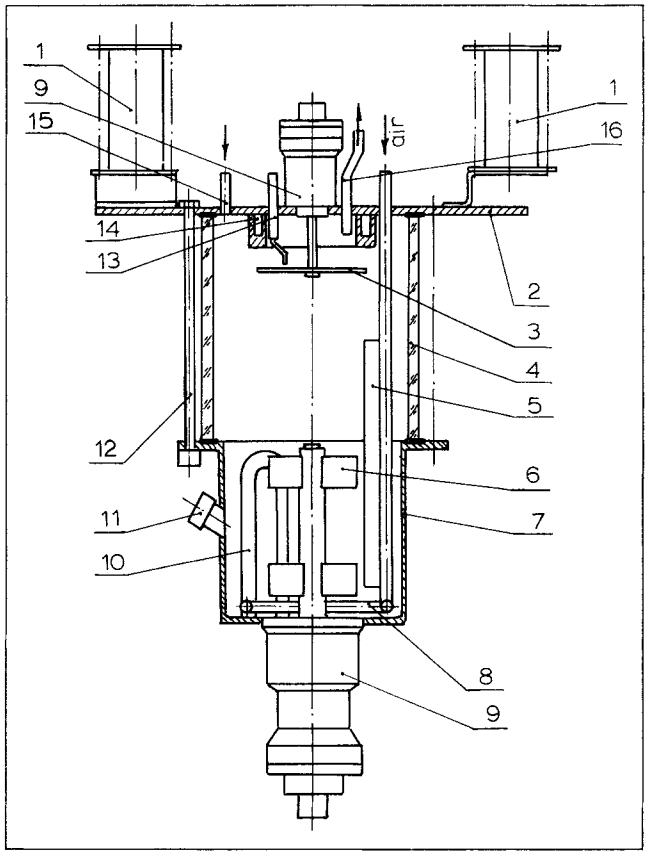

Figure 1. Basic reactor of the equipment FU-8.

1 = Vessels for pH correction and antifoam liquids
2 = lid
3 = disc of mechanical foam breaker
4 = glass clyinder
5 = baffle plate
6 = turbine stirrer
7 = cylindric body of fermentor
8 = bubbler
9 = bearing case with magnetic sealing
10 = heater/cooler
11 = places for sensors
12 = tie
13 = chemical foam breaker supply
14 = cooling chamber of exhaust air
15 = medium supply
16 = exhaust air

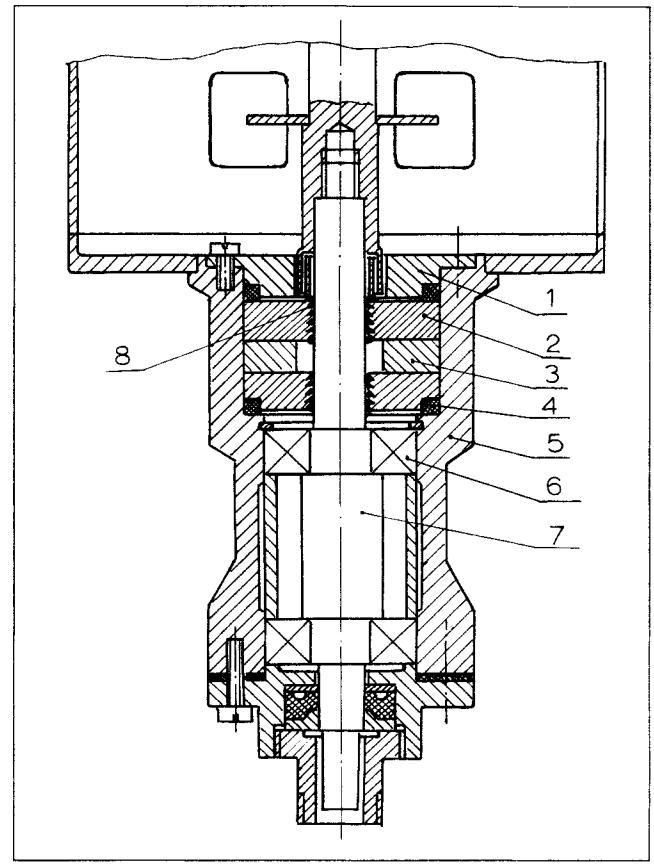

Figure 2. magnetic sealing of reactor shaft in FU-8 (item 9 in Figure 1).

1 = clamp
2 = pole
3 = permanent magnet
4 = sealing
5 = case
6 = bearing
7 = shaft
8 = magnetic liquid

Experiments in larger volumes were carried out in equipment FU-30 (Viesturs et al., 1986), comprising a 30-L fermentor and a control panel.

FU-8 and FU-30 are fermentors of intensive mass transfer with high values of the mass transfer coefficient—up to 25 $kg/m^3 \cdot h$ (determined by the sulfite method), and they are highly productive in cultivating various bacterial and yeast cultures. Yet submerged cultivation of mycelial fungi, using the standard turbine stirring system, did not yield the expected results. Acceleration of mass transfer rates by increasing the velocity of turbine impeller revolution produces locally intensive zones of stirring (in the zone of impellers and baffle plates), negatively affecting mycelial microorganisms and causing irreversible cell damages (Viesturs et al., 1984b; Zeltina et al., 1987).

To overcome this drawback a new stirring system was studied that ensures an intensive, yet sparing, regime of stirring. It was applied to fermentors FU-8 (Figure 3) and FU-30 by replacing the turbine impellers and foam breaker with conical discs with radial protrusions. During operation the discs revolve in opposite directions. The diameter of the impellers used in FU-8 $d = 100$ mm (the ratio of impeller and apparatus diameters was $d/D = 0.69$), and the maximum height of the radial protrusions = 15 mm. The efficiency of the stirring system is ensured by an interaction of counterflows produced by both impellers. In this case, the layer thickness in close proximity of the impellers, fixed construction elements and walls of the apparatus is so small that it can be assumed that the mass transfer process takes place mainly in the space between the impellers. During medium stirring by counterflows, the shear effects are determined only by the properties of the medium. In such conditions, free turbulence in the bulk liquid do not cause mechanical damage of microorganism hyphae. On the contrary, if medium stirring is ensured by the traditional methods, i.e., by an interaction of medium flow and the fixed construction elements (baffles, turbine impellers), gradients of medium flow rate appear to increase in the zone of interaction and the so-called locally intensive zones are formed.

In multiphase media (fermentation media included), the effects produced by the interaction of counterflows become remarkable: the homogenization of media, disruption of bubbles

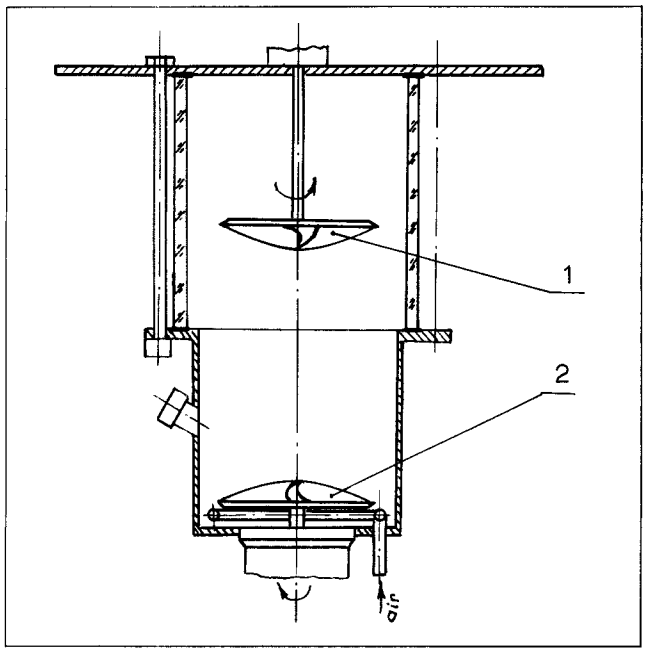

Figure 3. Modified reactor FU-8 with counterflow stirring system.

1 = top impeller 2 = bottom impeller

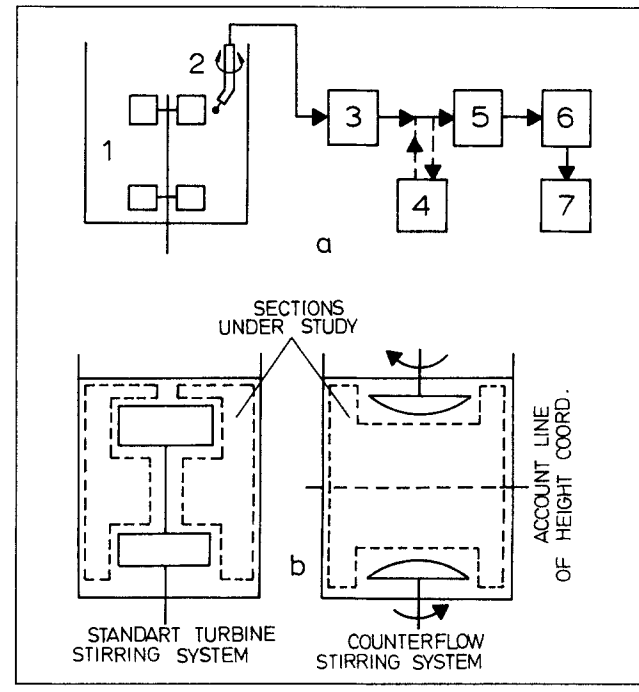

Figure 4. (a) System for determination of the stirring characteristics. (b) Sections available for measurements in both stirring systems.

1 = reactor
2 = primary piezoelectric transducer
3 = charge amplifier
4 = measuring tape recorder
5 = spectrum analyzer
6 = computer
7 = data output device

and agglomerates of microorganisms, and other disperse inclusions in the zone of flow interaction increase.

To determine the optimum stirring conditions for the cultivation of microorganisms, the comparative hydrodynamic investigations were carried out in bioreactors with the standard turbine impellers and counterflow stirring systems. The hydrodynamic investigations were compared with the results of microorganisms cultivation.

The hydrodynamic conditions in reactors were studied by our own system for the determination of stirring characteristics (Rikmanis et al., 1983; Rikmanis et al., 1987a) (Figure 4a).

It is necessary to note that our approach does not correspond to the classical theory of turbulence where the mass of a definite liquid particle set in a subdomain remains constant in the flow of time. This assumption allows us to consider the energetic process of turbulence as a velocity field, because the mass in the equation of kinetic energy $e = (mv^2)/2$ is assumed to be constant and changes in the energy are determined only by the changes in velocity (and *vice versa*). Unfortunately, in the case of a three-phase flow the mass constancy of the unit volume is not taken into account, therefore the application of the classical turbulence theory to a three-phase flow is not well founded. In our approach, which considers turbulence as a field of energy (corresponding to the physical status of the phenomenon), we could not help but use some general terms with new meaning making it more difficult to understand our approach.

The system consists of a piezoelectric transducer (of our construction), a charge amplifier (Bruel & Kjaer, type 2635), a measuring tape recorder (Bruel & Kjaer, type 7003), a spectrum analyzer (HP 3580A), and a computer (HP 9825S). The use of a piezoelectric mechanico-electrical transducer with a spherical receiver provides the isotropy of the transducer—the electric signal of the transducer depends on the energy and the scale of the eddies, not on the direction of the flow. The spectrum analyzer presents the signal in the form of amplitude frequency spectrum (AFS). On the basis of AFS, the following parameters are determined on a computer:

1. In the obtained AFS, the amplitudes are proportional to the kinetic energy of eddies of a definite scale, while the corresponding frequencies are inversely proportional to the scale of the eddies. Hence, the averaged kinetic energy of the flow patterns (in relative units) can be obtained as the integral area of the spectrum.

$$e = \int_{\Omega\min}^{\Omega\max} e(\Omega) \cdot d\Omega \qquad (1)$$

where

Ω = spectral frequency, Hz
Ω_{max} = minimal and maximum limit frequencies of the spectrum, Hz
$e(\Omega)$ = density distribution of the medium flow energy e in the frequency range used

2. In biotechnological processes, an important role is attached to microscale eddies, which ensure the restoration of the air bubble surface and the transport of substrates to the surface of microorganisms. Hence, for stirring efficiency it is important to take into account the energy distribution in AFS with a stress on high-frequency signals corresponding to microscale eddies. Multiplication of each AFS amplitude by its frequency provides a

modified estimation of the kinetic energy of medium flow fluctuations, which enhances the effect of microscale eddies:

$$e_m = \int_{\Omega\min}^{\Omega\max} \Omega \cdot e(\Omega) \cdot d\Omega \qquad (2)$$

Since the kinetic energy of turbulence dissipates from large- to small-scale eddies and the modified characteristics of energy e_m takes into account the distribution of energy in AFS, it can be suggested that e_m reflects both the total kinetic energy of eddies and its dissipation rate.

3. In considering the microstirring effect on the growth of microorganisms, it is important to single out the microstirring characteristics (vorticity) as a criterion, whose value does not depend on the total kinetic energy of flow patterns. The value of this criterion can be determined as the ratio of a modified characteristic e_m and the average kinetic energy e:

$$K_R = e_m/e = \int_{\Omega\min}^{\Omega\max} \Omega \cdot e(\Omega) \cdot d\Omega \Big/ \int_{\Omega\min}^{\Omega\max} e(\Omega) \cdot d\Omega \qquad (3)$$

During the development of bioreactor constructions it is important to determine the distribution of the introduced power across the volume of the stirred medium.

To determine the character of e distribution it must be measured in a number of spatial points in the reactor (the number of the points depends on the required precision of approximation), localized in the sections available for direct measurements (Figure 4b). During experiments on fermentor FU-8, the piezoelectric transducer was mounted in a tubular body vertically. The end of the transducer body was bent in a 35° angle. Changes in the height coordinate of the measurement point were ensured by moving the transducer vertically, while those of the radial coordinate by turning it round the axis. To study stirring characteristics, the following parameters were varied:

- Velocity of impeller revolution n (for the counterflow system—velocities of the top n_t and bottom n impeller) within 0 and 850 rpm
- Consumption of aerating gas Q (0–9 L/min)
- Concentration of insoluble substrate S (0–9%).

Insoluble substrate was obtained from thermochemically treated straw (Zeltina et al., 1987). It was chosen because the goal of our studies is to elaborate a stirring system for the growth of mycelial fungi, which is able to utilize both soluble (glucose, sucrose, etc.) and insoluble (cellulose) substrates. The shape of the insoluble substrate particles is practically spherical with their average diameter 0.1 mm.

Rheological properties were determined with the rotational viscosimeter REOTEST-2 (GDR). The effect of insoluble substrate concentration on the rheological properties is shown in Figure 5.

Combinations of variable parameters were chosen by the mathematical planning method of the experiment (Audze and Eglajs, 1977). The subsequent measurements of the multifactor regressive modeling (Eglajs, 1980) established the correlative dependences of the local stirring characteristics e, e_m, and K_R on both spatial coordinates and regime parameters, as well as dependence of integral criteria K_D and e_p on regime parameters alone.

In both construction variants, we determined also the distribution of insoluble substrate concentration along the height of the bioreactor, using in-line turbidity and suspended solids transmitter MEX-2 (Eur-Control).

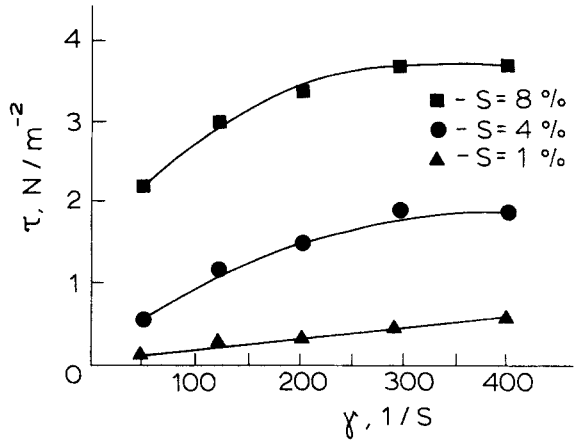

Figure 5. Rheological media characteristics: shear rate effect on the stress vs. concentrations of insoluble substrate S

Power introduced by impellers was determined with the help of the rotational viscosimeter REOTEST-2 (Rehrer, 1969).

Results and Analysis

Distribution characteristics

Local stirring characteristics (e, e_m, K_R) are multiargument functions. This paper analyzes two-coordinate curves with the values of other parameters being fixed.

Typical for a standard turbine system is the plane of the most intensive stirring, i.e., horizontal sections in the mid-height of the top and bottom impellers. It is just on these planes that changes in aeration rate and the rheological properties of media influence the distribution of $e(r, h)$ most markedly (Figure 6).

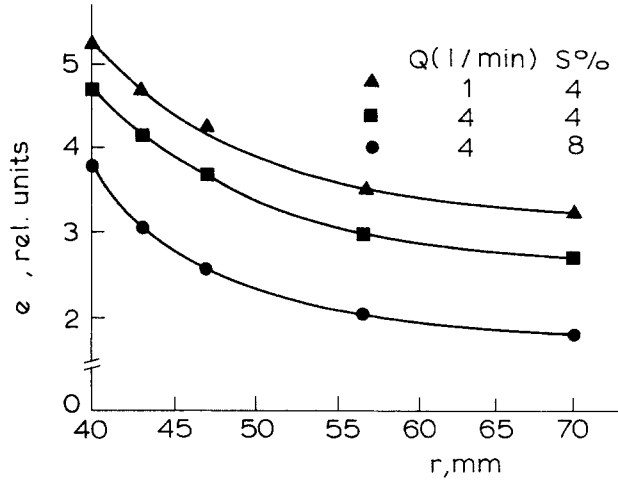

Figure 6. Distribution of kinetic energy e along radius in a standard turbine reactor vs. values of aerating air Q and concentration of insoluble substrate S.

Velocity of stirrer revolution n = 300 rpm.

For the counterflow system cylindrical surfaces (r = const) are more informative. Analysis of $e(r, h)$ distribution along the height reveals the characteristics of the counterflow system (Figure 7). The space between the stirrers is the place where the flows generated by oppositely revolving impellers interact. As the distance between the point of measurement and the stirrer increases, the kinetic energy of the flows decreases and the middle zone of the apparatus reaches its minimum. Since the tangential and axial components of the toroid vortical flows generated by the top and bottom impellers are oppositely directed, the vorticity (the degree of turbulence) in the zone of their interaction reaches the maximum. Figure 7 confirms this and shows that on the zone of interaction K_R assumes its maximum and e its minimum value. The location of the zone of interaction depends on the ratio of disc revolution velocity n_t/n, while its volume (thickness) depends on the regime of work (n, n_t, Q) and rheological properties of the medium.

At comparatively low velocities of impeller revolution (up to 220 rpm), the gradient of insoluble substrate concentration along the height h tends to zero. In the counterflow system, the power introduced for a complete homogenization of the concentration is up to 1.8 times less than that in the turbine reactors (Figure 8). The advantages of the counterflow system become more marked with high insoluble substrate concentrations ($S > 8\%$), when medium viscosity and pseudoplasticity are increased.

Uneven flow kinetic energy distribution

Our earlier studies (Viesturs et al., 1984b) have demonstrated that to exceed a definitive level of stirring intensity is detrimental not only for mycelial cultures, but for yeasts and bacteria as well, especially in media of increased viscosity. It is caused mainly by mechanical stresses on the cell wall as well as drastic

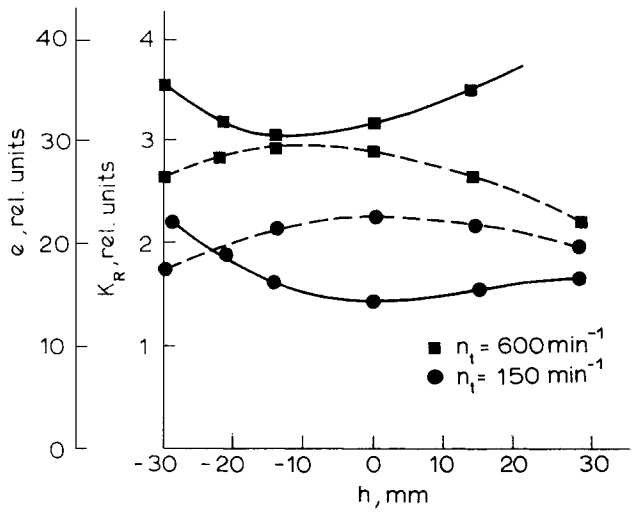

Figure 7. Distribution of kinetic energy e along the height in a counterflow stirring system with various velocities of the top impeller revolution n_t.

Velocity of bottom impeller revolution n = 450 rpm; aerating air uptake Q = 4 L/min; concentration of insoluble substrate S = 4%; coordinate of radius r = 40 mm
K_R -----; e — — —

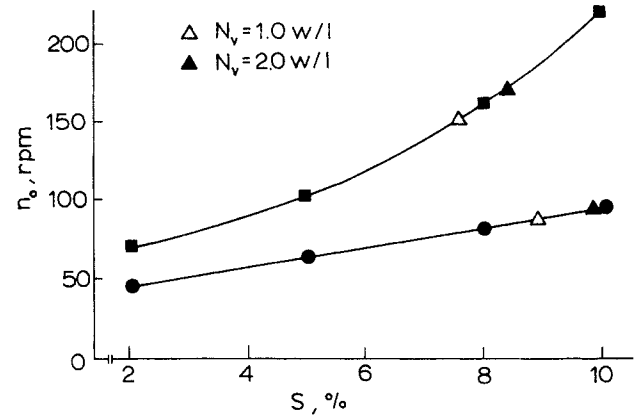

Figure 8. Dependence of the minimum velocity of impeller revolution n_o, ensuring a full equalization of insoluble substrate S along bioreactor height, on substrate concentration S.

Velocity of top impeller revolution in the counterflow stirring system n_t = 100 rpm
■ STMS; ● CFMS.

pressure gradients due to cavitation. On the basis of the average velocity distribution, Oldshue (1966, 1983) determined the maximum and the average shear rate to characterize shear effects in reactors, which depend on reactor construction and stirring regime. By first approximation, the effect of medium flow on microorganism cell structure would be proportional to the gradient of medium flow energy e. The averaged spatial gradient of the energy e characterizes also the unevenness of energy distribution in the reactor. Since the distribution of energy e in the apparatus is not even, the cells have to pass through zones of various conditions for the transport of nutrient substances, which has a negative effect on their growth (Cleland and Enfors, 1987; Larsson and Enfors, 1988; Moes et al., 1985; Oosterhuis and Kossen, 1983). Thus, along with other characteristics, criterion K_D of uneven energy distribution in bioreactor volume (Rikmanis et al., 1987b) is an important parameter, determined as the averaged gradient of the local values of e in the following way:

$$K_D = 1/V \iiint_{(V)} \sqrt{|\delta e/\delta r|^2 + |\delta e/\delta h|^2 + |\delta e/r\delta\phi|^2}\, r \cdot dr \cdot dh \cdot d\phi \quad (4)$$

where

K_D = criterion of uneven energy distribution in bioreactor volume
V = volume of the zone under study
r, h, ϕ = spatial coordinates

In keeping with Eq. 4, the determined unevenness K_D quantitatively characterizes the sum of results of all microbial cell and stirred medium interactions (damages and deformations of cells, inhomogeneity of transport in various zones of the reactor and other phenomena), which resulted from an uneven distribution of energy e in bioreactor volume.

Since $\delta e/\delta\phi$ for axially-symmetric apparata is 0, we obtain a

simplified expression for K_D:

$$K_D = 2\pi/V \int_{r0}^{r}\int_{h0}^{h} \sqrt{|\delta e/\delta r|^2 + |\delta e/\delta h|^2}\, r \cdot dr \cdot dh \quad (5)$$

With similar power introduction K_D in a counterflow system is notably less than that in the apparatus with turbine impellers, and with acceleration of impeller revolution (i.e., with power introduction) this difference tends to grow (Figure 9).

An increase of the concentration of insoluble substrate S, giving rise to the corresponding changes in rheological properties of media, increases K_D sharply in the apparatus with turbulent impellers (Figure 10). Decrease of K_D in $S > 4\%$ is imaginary, as in this case not the difference between the energy flows in various zones of the apparatus decreases, but the total set of locally intensive zones with the growth of the viscosity in the zone, increases the energy dissipation rate in the turbine as well as the zone nearby (not accessible to direct measurements).

The increase of S actually does not affect the energy distribution of the counterflow system much, since medium turbulence takes place mainly in the bulk liquid, not only in the zone of a direct impact of the impellers. Changes in the flow of aerating gas Q makes an insignificant influence on K_D.

Enegy dissipation in the zone

It has been reported that the bulk of the introduced power dissipates in close proximity to the impeller (Cutter et al., 1966; Gunkel and Weber, 1975; Tojama et al., 1981). Tojama et al. (1981) have demonstrated using thermoanemometry that the turbulent dissipation energy convecting in the zone out of contact with turbine impellers in a reactor without baffle plates is approximately 20% of the introduced power (reactor diameter $D = 58.5$ mm; ratio of impeller and reactor diameters $d/D = 0.5$; rate of impeller velocity = 80 rpm).

Dissipation of the mechanically introduced power depends on both the apparatus design and the rheological properties of the medium stirring and aeration regime. Hence, the dissipation characteristics should be experimentally determined for each case. Because it is impossible to determine the efficient viscosity

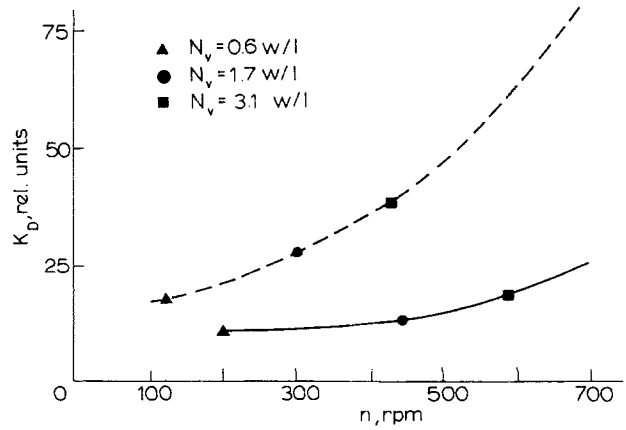

Figure 9. Dependence of stirring unevenness K_D on the velocity of impeller revolution n.

$Q = 4$ L/min, $S = 4\%$, $n_i = 300$ rpm
----- STMS; — — — CFMS

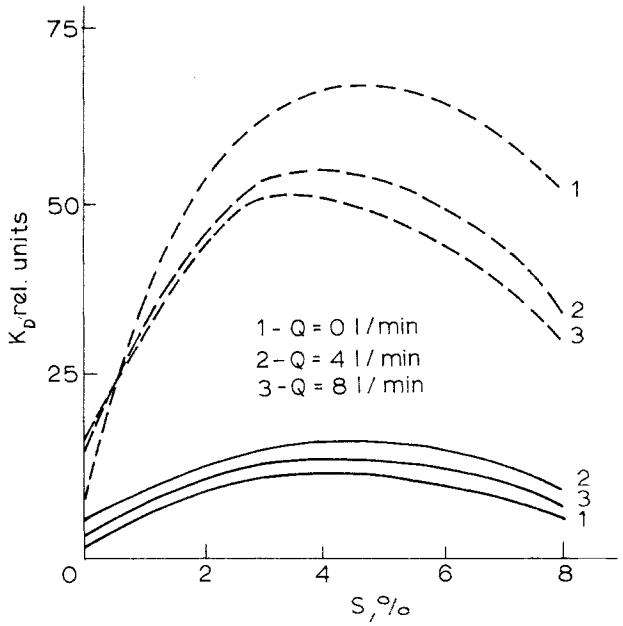

Figure 10. Dependence of stirring unevenness K_D on the concentration of insoluble substate S.

Velocity of impeller revolution in a turbine stirring system n = 700 rpm and in a counterflow system n = 700 rpm (n_i = 400 rpm)
----- STMS; — — — CFMS

of the aerated liquid (even more complicated due to an uneven distribution of the gas across the volume of the apparatus), the routine methods of determining the local energy dissipation rates in bioreactors are useless. Considering that all the flow energy dissipates into heat and the parameter e_m (according to 2) reflects the character of the energy distribution along the eddies of different scales, which in turn reflects the dissipation rate, we can arrive at the medium energy to be dissipated in the research field of the apparatus by integrating the measured value of e_m:

$$e_D = 1/V \iiint_{(V)} e_m \cdot r \cdot dr \cdot dh \cdot d\phi \quad (6)$$

where

e_m = stirring intensity of energy dissipation
V = volume
r, h, ϕ = spatial coordinates

To compare the character of dissipaton of both systems, we studied the zones of practically similar volume (68% of the working volume).

Figure 11 shows that the energy dissipated in a turbine reactor is smaller than that in a counterflow reactor, and it tends to increase with the increase of the introduced power.

The ratio of the relative part of the dissipated energy e_D to the specific power N_v characterizes the real energy distribution between the bulk volume of reactor and the zone not available for direct measurements. An estimation of the dependence of this ratio on the concentration of insoluble substrate (Figure 12) shows that, upon an increase in the viscosity intensity (with an increase in the S value), the relation of the dissipated energy and

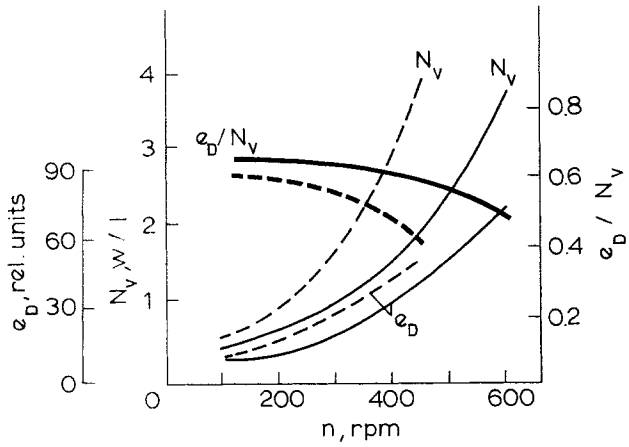

Figure 11. Dependence of the mechanically introduced specific power N_v and energy e_p dissipated on the velocity of impeller revolution.

Q = 4 L/min; S = 4% (n_i = 300 rpm)
----- STMS; — — — CFMS

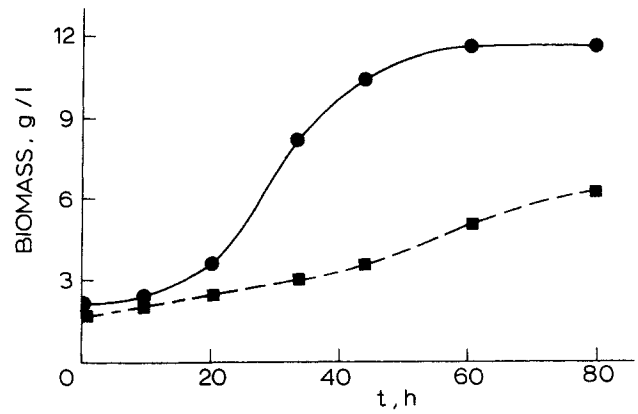

Figure 13. Comparative dynamics of the mycelial fungus Trichoderma viride growth (measured as protein yield) on insoluble substrate—straw in the fermentor FU-8.

■ STMS; ● CFMS

introduced power in the zones of potential measuring diminishes with partial energy dissipated inside and in close proximity of the turbine impeller increasing, while the counterflow system is practically indifferent to the changes of S (within the limits under discussion).

Biotechnological studies

The efficiency of the counterflow stirring system was confirmed in both laboratory- and industrial-scale apparatus in the presence and the absence of the insoluble substrate.

Figure 13 shows the comparative dynamics of the growth of mycelial fungus Trichoderma viride on insoluble substrate—milled straw in a laboratory equipment FU-8. Taking into account the possible shortening of the process length, it can be well seen that the biomass yield in a counterflow reactor can be about three times higher than that in a turbine reactor.

Comparative experiments were carried out also in a 5-m^3 industrial fermentor by cultivating mycelial fungus Trichoderma viride on a liquid medium, molasses (without insoluble substrate). In this case, another construction variant of the counterflow stirring system was used, which made it possible to use only one drive and one shaft for both impellers. Comparative results are presented in Figure 14 and Table 1. The counterflow system is not only more productive, but more economical as well. In the given case, the specific air consumption was five times and power consumption by the impeller was 2.5 times lower than that in the turbine reactor. The economy of the consumed energy is achieved by efficiently using the evenness of its distribution across the volume of the apparatus and by decreasing the duration of the batch process. The economy of the aerating air is achieved due to a notable increase of the dispersion degree (i.e., the interface area) and an increase of the

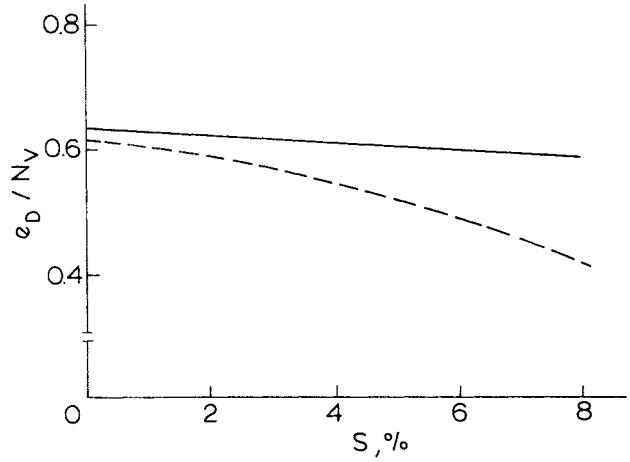

Figure 12. Dependence of the ratio of dissipated (e_D) and mechanically introduced specific power (N_v) on the concentration of insoluble substrate S.

Velocity of impeller revolution in a turbine system n = 300 rpm and in a counterflow system n = 400 rpm (that of top impeller n_i = 300 rpm)
----- STMS; ——— CFMS

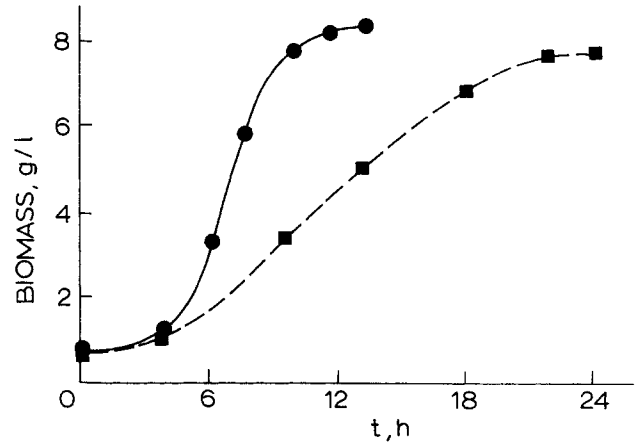

Figure 14. Comparative dynamics of the mycelial fungus Trichoderma viride growth on a liquid nutrient medium—molasses in a 5 m^3 fermentor.

■ STMS; ● CFMS

Table 1. Counterflow Stirring System vs. Standard Turbine Stirring System

Parameters	5-m^3 Apparatus: Basic Equip.	5-m^3 Apparatus: Modified with Counterflow Stirring	Changes Made to Basic Equip.
Process Time, H	24	13	− 46
Biomass, g/L	7.5	7.8	+4
Specif. Productivity, $kg/m^3 \cdot h$	0.31	0.60	+94
Specific Air Consumption, $nm^3/m^3 \cdot min$	0.5	0.1	− 80
Total Air Consumption during Process, nm^3	2,160	234	− 89
Power Consumed by Impeller, kW	13	5.2	− 60
Energy consumed for Stirring during Process, $kW \cdot h$	312	67.8	− 78

gas residence time in the cultivation medium. These phenomena jointly contribute to a more efficient use of the oxygen introduced by air.

The counterflow system does not require a new fermentor construction. The existing industrial-scale reactors with mechanical impellers can be modified by equipping them with the counterflow system.

Conclusions

The counterflow stirring system is not just for the cultivation of cells sensitive to mechanical effects. The economy of the energy consumed for stirring does not depend on the character of the process taking place in the apparatus. The advantages of the counterflow system against turbine impellers increase with the growth of medium viscosity or with the presence of the solid phase.

The decrease of the aerating gas uptake reduces the expenses of its compression and purification (sterilization), ensures a more economical use of the air during any gas—liquid mass transfer process, and helps solve the problems of ecology decontamination of the treated gas residues.

The system of the quantitative estimation of the local stirring intensity is useful not only for the evaluation and development of bioreactor designs, but also for the monitoring of the stirring system during industrial processes. It ensures an economical energy uptake and compensates for the changes in the rheological properties of the reaction medium.

A joint use of the stirring intensity determination system and the counterflow stirring system, which ensures even hydrodynamic conditions in all the volume of the cultivation medium, makes it possible to study the effect of hydrodynamic conditions (stirring intensity) on the vital activity of the cultivated cells.

Notation

e = average specific kinetic energy of medium flow, relative units
e_D = integral criteria reflecting average efficient energy dissipation, r.u.
e_m = efficient energy dissipation, r.u.
h = coordinate of height, mm
k = coefficient of proportionality
K_D = unevenness of energy distribution, r.u.
K_R = criterion of microstirring, r.u.
n = velocity of turbine and bottom impeller revolution in a counterflow stirring system, stirring, rpm
n_o = minimum velocity of impeller revolution ensuring a full equalization of insoluble substrate along the height, rpm
n_t = velocity of top impeller revolution in a counterflow stirring system, rpm
N = power generated by impellers, W
N_v = specific power generated by impellers, W/L
Q = aerating gas uptake, L/min
r = spatial coordinates of radius, mm
S = concentration of insoluble substrate—straw, %
t = the running time of fermentation, h
V = volume of the stirred medium, L
X = biomass concentration, g/L
Y = biomass yield, $g/L \cdot h$

Greek letters

γ = shear rate, L/s
τ = shear stress, N/m^2
ϕ = coordinate of angle, grad
Ω = frequency, Hz

Others

STMS = standard turbine mixing system
CMFS = counterflow mixing system

Literature Cited

Audze, P. P., and V. O. Eglajs, "A Novel Approach to the Planning of Multifactor Experiments," *Voprosi Dinamiki i Prochnosti*, RPI, No. 35, 104 (in Russian) (1977).

Cheng, D. Y., "Introduction of the Viscous Force Sensing Fluctuating Probe Technique," AIAA Paper, No. 73–1044 (1974).

Cleland, N., and O. Enfors, "A Biological System for Studies on Mixing Bioreactors," *Bioprocess Eng.*, **2**, 115 (1987).

Cutter, A. L., "Flow and Turbulence in a Stirred Tank," *AIChE J.*, **12**, 35 (1966).

Eglajs, V. O., "Synthesis of a Regression Model of an Object on the Basis of Table Data," *Izv. AN LatvSSR, Ser. Phiz. i Tekhn. Nauk*, **4**, 107 (in Russian) (1980).

Gunkel, A. A., and E. M. Weber, "Flow Phenomena in Stirred Tanks," *AIChE J.*, **21**, 931 (1975).

Larsson, G., and S. O. Enfors, "Studies of Insufficient Mixing in Bioreactors: Effects of Limiting Oxygen Concentrations and Short-Term Oxygen Starvation on Penicillum chrysogenum," *Bioprocess Eng.*, **3**, 123 (1988).

Lippert, J., I. Adler, H. D. Meyer, A. Lubbert, and K. Schugerl, "Characterization of the Two-Phase Systems in Airlift Tower-Loop Bioreactors During the Cultivation of *E. coli*," *Biotechn. and Bioeng.*, **25**, 437 (1983).

Moes, J., M. Griot M, J. Keller, E. Heinzle, I. J., Dunn, and J. R. Bourne, "A Microbial Culture with Oxygen-Sensitive Product Distribution as a Potential Tool for Characterizing Bioreactor Oxygen Transport.," *Biotechnol. and Bioeng.*, **27**, 482 (1985).

Oldshue, J. Y., "Fermentation Mixing Scale-Up Techniques," *Biotechnol. and Bioeng.*, **8**, 3 (1966).

Oldshue, J. Y., *Fluid Mixing Technology*, McGraw-Hill, New York (1983).

Oosterhuis, N. M. G., and N. W. F. Rosser, "Dissolved Oxygen Concentration Profiles in a Production-Scale Bioreactor," *Biotechnol. and Bioeng.*, **26**, 546 (1984).

Rehrer, E. O., "Stirring of non-Newtonian Fluids," *Chemie-Ing.-Techn.*, **21**, 14 (in German) (1969).

Rikmanis, M., I. Neilande, and U. Viesturs, "Energy and Flow Structure Characteristics in Bioreactors," Abstr., *Symp. Soc. Countries on Biotechnol.*, Bratislava, 44 (1983).

Rikmanis, M.A., J. J. Vanags, and U. E. Viesturs, "Determination of Stirring Characteristics in Bioreactors," *Biotekhnologiya*, **3**, 72 (in Russian) (1987a).

Rikmanis, M. A., J. J. Vanags, E. J. Ushkans, and U. E. Viesturs, "Distribution of Energy Introduced into Bioreactors with Various Constructions of Stirrers and Rheological Properties of the Liquid," Abstr., *Cong. on Biotechnol.* **1,** Amsterdam, 110 (1987b).

Schugerl, K., A. Lubber, and Th. Schlepper, "On-Line Prozessanalyse in Bioreaktoren," *Chemie-Ing.-Techn.*, **59,** 701 (in German) (1987).

Siddon, T. E., and H. S. Ribner, "An Aerofoil Probe for Measuring the Transverse Component of Turbulence," *AIAA J.*, **3,** 747 (1965).

Tojama, S., M. Sogame, and T. Anemo, "Ratio between the Consumed Energy and Dissipation Energy Convecting Liquids in Stirring Devices without Partitions," *Kagaku Kogaku Rombunsju,* **7,** 524 (in Japanese) (1981).

Viesturs, U. E., M. A. Rikmanis, and J. S. Levitan, "Energy Consumption and Distribution in Bioreactors," *Proc. Eur. Cong. on Biotechnol.*, Munchen, **2,** Dechema, Verlag Chemie 263 (1984a).

Viesturs, U. E., A. J. Berzins, M. K. Toma, and M. A. Rikmanis, "Mass Transfer and Shear Effects in Bioreactors at Increased Concentration of Solids," *Proc. Eur. Cong. on Biotechnol.*, Munchen, Dechema, Verlag Chemie, 293 (1984b).

Viesturs, U. E., A. M. Kuznetsov, and V. V. Savenkov, *Fermentation Systems,* Zinatne, Riga (in Russian) (1986).

Zeltina, M. O., M. P. Leite, J. J. Vanags, A. A. Apine, and U. E. Viesturs, "Submerged Fermentation of Cellolignin Materials (Compared with Solid-State Fermentation and Other Alternatives)," *Acta Biotechnol.*, **7,** 157 (1987).

Manuscript received Sept. 8, 1988, and revision received June 21, 1990.