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SCIENTIFIC PAPER

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OPTIMIZATION OF THE MIXING IN STIRRED BIOREACTORS

1. Comparative analysis of the mixing efficiency with different radial impellers for simulated broths

Although radial impellers, especially the Rushton turbine, are widely used in stirred bioreactors, their applicability is limited by the high apparent viscosities of the broth. Beside the intensification of broth circulation, the energetic efficiency and the shear effects on biocatalysts must be taken into account to select the optimum impeller or impellers combination.
In this context, the paper presents a comparative study on the efficiency of seven different radial impellers for simulated broth mixing in a stirred bioreactor. The analysis was made by means of the mixing time values obtained by vertically changing the position of the pH–sensor in the broths, in correlation with the energy consumption needed for a certain level of mixing time or for the uniform distribution of the mixing intensity into the bulk volume of the broths.

Key words: Radial impeller, Rushton turbine, Disperser sawtooth, Smith turbine, Pumper mixer, Curved bladed turbine, Paddle with six blades,

The simplest and most suggestive definition of mixing was given by Hiby (1981), who affirmed that mixing is a process through which the inhomogeneity of a system is decreased [1]. A the completely mixed system corresponds to a perfectly uniform distribution of its components.

Mixing could be characterized by means of the mixing scale and/or mixing intensity [2]. The mixing scale represents the smallest dimension (volume, mass) of the analyzed system in which inhomogeneity is allowed. This parameter is always smaller than the dimension of the system itself and larger than the smallest component of the system.

The mixing intensity is defined as the deviation from complete mixing. Because perfect mixing is reached after an infinite period of time, the mixing intensity could be defined as the deviation from complete mixing after a prescribed finite amount of time [2].

Mixing can also be analyzed from the viewpoint of the homogenization level. Thus, three homogenization levels could be identified: macromixing, mesomixing and micromixing [3]. Macromixing consists of the uniform distribution of the content in the whole bulk of the considered system by means of liquid movement induced by stirrer agitation. Mesomixing occurs when the feed rate of a certain component is high and leads to its accumulation in the feed region, inducing a local inhomogeneity. Due to internal circulation, this region is perfectly mixed inside [4]. Micromixing consists of mixing at a molecular scale and is controlled by molecular diffusion. Regardless of the flow regime induced in the whole system, the flow is laminar at the micromixing scale. Micromixing is achieved by a coherent flow structure, such as vortex sheets and vortex tubes [5]. Meso– and micromixing become important especially for systems in which phase transformations or chemical/biochemical reactions occur.

One of the most useful criteria for the characterization of mixing intensity is the mixing time, tm, defined as the time needed to reach a given mixing intensity at a given scale, when starting from a completely segregated situation [2,6]. This parameter offers specific information concerning bulk mixing in the system (macromixing), as well as the flow inside the whole studied system, but it cannot allow rigorous quantification of the meso– and micromixing [3]. It can indicate the optimum hydrodynamic regime, the stirrer type that must be used, or can predict the modification of mixing efficiency induced by scaling–up [7,8].

The analysis of mixing in bioreactors is based on the same principles as the previously mentioned ones. However, in fermentation systems, biomass accumulation, the shear stress sensitivity of the biocatalysts (free or immobilized cells and/or enzymes), high viscosity or the non–Newtonian rheology behavior of the broths, the presence of the gaseous phase, as the result of aeration or cell respiration, considerably increase the difficulty of the analysis of mixing. Due to the complexity of the rheological behavior and inevitably induced the high viscosity of broths and, consequently, due to the flow patterns, a non–uniform mixing distribution with the appearance of stagnant regions in bioreactors.

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Although radial impellers, especially the Rushton turbine, are widely used in large–scale stirred bioreactors, their use is limited by the high viscosity and non–Newtonian behavior of the broths. For example, in the case of filamentous fungus cultures with high apparent viscosity a double stirrer, is recommended provided on the same shaft with a Rushton turbine in the lower region and a paddle with plane blades in the upper region [9]. The lower stirrer promotes high turbulence and, therefore, avoids biomass deposition, and the upper one creates a high flow velocity of the broth.

For these reasons, a comparative analysis of the mixing efficiency induced by different impellers types for different broths is required. But, beside the intensification of broth flow, for selecting a certain impeller or impeller combination, the energetic efficiency and the shear effects on biocatalysts must be taken into account.

In this context, the aim of our experiments was to comparatively study the efficiency of simulated and real broth mixing in a stirred bioreactor equipped with different radial impellers. This analysis will be made by means of the mixing time values obtained by vertically changing the position of the pH–sensor in the broth, in correlation with the energy consumption. Using the experimental data, the most efficient impeller or impeller combination will be selected for a certain fermentation broth.

This paper presents the results obtained for non–aerated simulated fermentation broths with different apparent viscosities.

MATERIALS AND METHOD

The experiments were carried out in a 5 l (4 l working volume, V, ellipsoidal bottom) laboratory bioreactor (Biostat A, B. Braun Biotech International), with computer–controlled and recorded parameters. The bioreactor characteristics and operating parameters have been presented in previous papers [10,11].

The mixing system consists of a double stirrer and three baffles. Six types of radial impellers were used (Figure 1), the experimental data being compared with previous data obtained for a Rushton turbine [12].

In all cases the impeller diameter, d, was 64 mm. The lower stirrer was placed 64 mm from the bioreactor bottom. The upper stirrer was placed on the shaft at a distance of 128 mm from the lower one, this being the optimum distance form the Ruston turbine, as demonstrated in previous work [11]. The rotation speed was maintained between 100 and 600 rpm, a domain that avoids "cave" formation at the broth surface (for rotation speeds greaten than 700 rpm in the case of highly viscous broths).

Water and simulated fermentation broths were used in the experiments. The simulated broths consisted of carboxymethylcellulose sodium salt solutions having

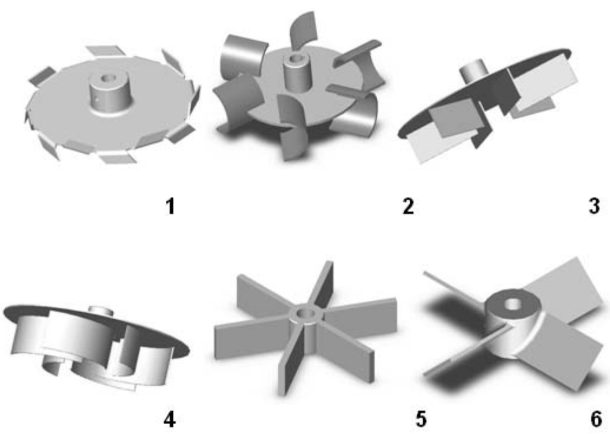


Figure 1. The radial impellers used in the experiments (1 – Disperser sawtooth, 2 – Smith turbine, 3 – Pumper mixer, 4 – Curved bladed turbine, 5 – Paddle with 6 blades, 6 – Pitched bladed turbine)

are apparent viscosity, η_a, in the range 15–96 cP. The owing to the difficulty of the *in situ* measurement of viscosity during the experiments, the viscosity was measured before and after each experiment using an Ostwald type viscometer. Both the experiments and viscosity measurements were carried out at a temperature of 24^{o}C. Any viscosity change was recorded during the experiments.

The values of the mixing time were determined for different positions in the broths. For this purpose, a solution of 2M KOH was used as a tracer, and the time needed for the mean pH–value to reach a value corresponding to the considered mixing intensity recorded. In this case, the following homogeneity criteria for mixing were considered [2,3,6,8,10–12]:

$$I = \frac{pH_\infty - 0.5\,\Delta pH}{pH_\infty} \times 100 = 99\% \text{ where } \Delta pH = 0.02.$$

The tracer volume was 0.5 ml, the tracer being injected opposite to the pH electrode, at 65 mm from the stirrer shaft and 10 mm from the liquid surface. Because the tracer solution density was similar to the liquid phase density, the tracer solution flow follows the liquid flow streams and there are no errors due to tracer buoyancy.

The pH electrode was introduced at four different positions, placed vertically from the bioreactor bottom as follows:

- position 1: at 20 mm
- position 2: at 70 mm
- position 3: at 120 mm
- position 4: at 170 mm.

The pH variations were recorded by the bioreactor computer–recorded system and were analyzed for the mixing time calculation. For calculating the power consumption for mixing, P, the correlations for the Power number for each impeller were considered [2,6]. The VisiMix® (VisiMix Ltd.) and MixerCalc® (Philadelphia Mixing Solutions) programs were used for this purpose.

RESULTS AND DISCUSSION

The accumulation of biomass or biosynthesized product (extracellular polysaccharides, protein molecules etc.) in fermentation processes leads to continuous modification of the medium rheological properties, producing the appearance of heterogeneous regions in the bioreactor. In some circumstances, the biomass concentration and morphology could exhibit a more pronounced influence of the mixing efficiency compared with the broth viscosity. Therefore, one of the most important problems which must be solved is to establish the optimum hydrodynamic regime for the stirred bioreactor and, implicitly, the optimum combination of impellers.

For increasing the efficiency of the mixing process, bioreactors are provided with multiple agitator systems which consist of two or more identical or different stirrer types assembled on the same shaft, the number of stirrers being a function of the broth height in the vessel. Among the main factors which control the mixing efficiency in systems with multiple impellers, the capacity to generate high turbulence and intense circulation in the whole fermentation broth is the most important.

The correct position of the stirrers on the shaft also represents a determinant factor for the mixing efficiency in these systems. The distance between the stirrers controls the interactions with other stirrers, its optimum value depending on the nature and viscosity of the fermentation broths. For an impeller with two Rushton turbines, previous studies have indicated that the optimum distance between two stirrers is $(1 \div 2)d$. An incorrect position can generate inefficient mixing, due to the following phenomena [6,10,11]:

– the interference of flow streams created by adjacent stirrers, especially for small distances between the stirrers,

– the formation of non– or low–agitated regions between the adjacent stirrers, as a result of the too long distances between them,

– biomass deposition at the bioreactor bottom.

These could lead to different values of the mixing time for different regions in the broths, increasing the difficulty to reach an uniform distribution of the optimum intensity of mixing.

As observed from previous experience for simulated fermentation broths, carried out in the same manner, but using a double impeller of the Rushton turbine type, the stagnant regions are mainly situated between the stirrers. The appearance of stagnant regions is the result either of the longer distance between the stirrers on the shaft, or of the interference of the flow lines between the stirrers if the distance becomes smaller. These phenomena were amplified by increasing the apparent viscosity of the broths. For certain values of the rotation speed, the recorded mixing times for the four considered positions in the bioreactor were almost equal, thus creating the conditions required for a uniform distribution of the mixing intensity in the bulk volume of the fermentation broth. For an apparent viscosity up to 60 cP, the optimum rotation speed was 250–300 rpm, increasing for higher viscosity at 400 rpm [12].

On the basis of the previous results, the mixing intensity distribution and the energy consumption for were comparatively studied for six different double stirrers, each consisting of two identical radial impellers placed on the same shaft. The aim of these studies was to select the optimum pair of impellers that could be used to mix broths with high apparent viscosity.

1. Mixing intensity distribution

1.1. Disperser sawtooth

Regardless of the apparent viscosity of the broth, Figure 2 indicates that in the case of a disperser sawtooth, the mixing time decreases with the increasing rotation speed.

In the case of water or simulated broths having an apparent viscosity below 25 cP, the superior region of the broth is the most efficiently mixed one (positions 3 and 4 of the pH electrode). The values of the mixing time obtained for the two positions are similar. With values of the apparent viscosity increasing above 25 cP, the agitation in position 2 becomes more intense related to the other positions. Consequently, for 96 cP, the most intense mixing is reached in this region.

The recorded evolution could be explained by the increase of the relative importance of the favorable cumulated contributions of the "bottom effect" [6] and presence of the baffles on the intensification of mixing at higher viscosities. This assertion is sustained by the following experimental information:

– the "bottom effect" itself cannot assure mixing intensification in the studied systems. Thus, due to the interference of the flow streams, which is amplified by the ellipsoidal geometry of the vessel, the least intense mixing was obtained for all viscosities in region 1, near the bioreactor bottom. By increasing the apparent viscosity, the circulation velocity of the broth is reduced, therefore the stream interference phenomena become less important and the "bottom effect" more pronounced. Consequently, the values of the mixing time obtained for position 1 become closer to those recorded for positions 3 and 4 (due to the flat geometry of the broth free surface, in the upper region of the bioreactor the "bottom effect" does not occur),

– the baffles promote the intensification of mixing, especially at lower apparent viscosities, this affirmation being sustained by the lowest values of the mixing time obtained for the upper positions 3 and 4. But, at higher levels of the apparent viscosity, the effect induced by the baffles is cumulated with the "bottom effect", in the absence of flow stream interference. That leads to an

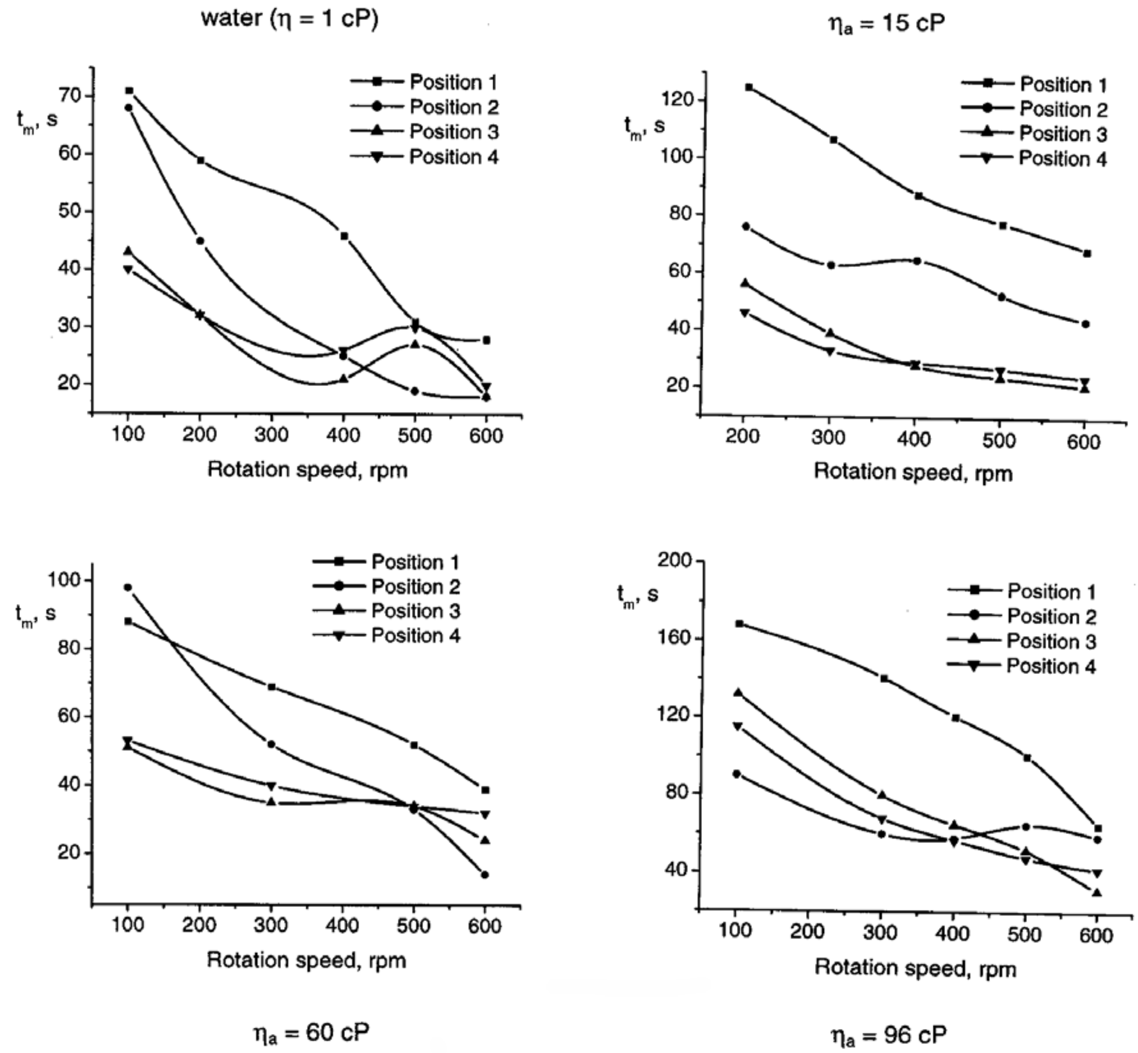


Figure 2. The influence of rotation speed and apparent viscosity on the mixing time at different sensor positions for a disperser sawtooth

increase of the mixing efficiency and, therefore, region 2 becomes the most intensely mixed region in the broth.

For water, by comparatively analyzing the influence of the rotation speed on the mixing intensity and on its distribution in these systems for two double stirrers, the former of the Rushton turbine type [12] and the second of the disperser sawtooth type, it was found that the values of the mixing time were similar for rotation speeds below 150 rpm. At higher rotation speeds, the Rushton turbine becomes more efficient for all the considered positions of the pH electrode. For rotation speeds greater than 150 rpm, the impeller of the disperser sawtooth type induces a mixing intensity similar to that generated by the Rushton turbine only in the upper region of the bioreactor.

In the case of simulated broths significant differences were observed between the two types of stirrers from the viewpoint of the mixing intensity distribution:

- **position 1 (lower region)**: for rotation speeds lower than 200 rpm, the impeller of the disperser sawtooth type is more efficient, regerdless of the apparent viscosity of the broth; above 200 rpm, due to the negative influence of the "bottom effect" on the flow stream interference at higher values of the rotation speed for this stirrer, the impeller of the Rushton turbine type offers more intense agitation.

- **positions 2 and 3 (intermediary region)**: in the case of a Rushton turbine, the interference of the flow streams between the two stirrers on the shaft leads to their mutnal annihilation, and, therefore, in all cases the impeller of the disperser sawtooth type induces more efficient mixing. Moreover, contrary to the Rushton turbine [12], variation of the mixing time with rotation speed for a disperser sawtooth does not indicate any minimum value, due to its continuous decrease with increasing rotation speed.

- **position 4 (upper region)**: the impeller of the disperser sawtooth type promotes superior turbulence, for the entire considered domain of the apparent viscosity.

- in all cases, the increase of the broth viscosity exhibited a less pronounced influence on the mixing time recorded for the impeller of the disperser sawtooth type; thus, at 300 rpm, by increasing the apparent viscosity from 1 to 96 cP, the mixing time for this stirrer increased by about 2.2–2.8 times, compared with an increase of 8.5–25 times obtained for the impeller of the Rushton turbine type [12].

But, as may be observed in Figure 3, no rotation speed corresponding to a uniform mixing distribution in

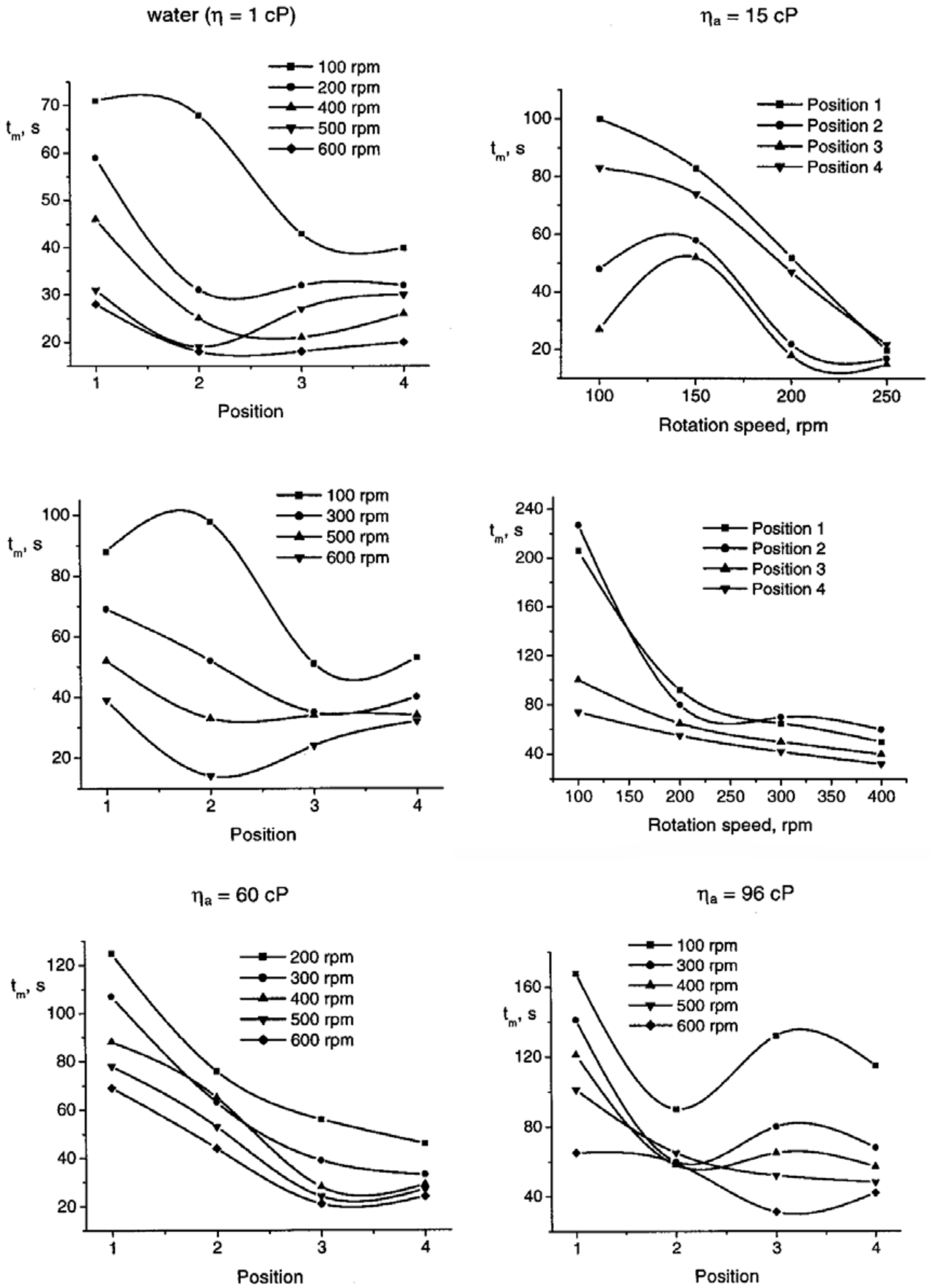


Figure 3. The influence of sensor position on the mixing time for a disperser sawtooth

the whole bulk of the broth has been recorded for the disperser sawtooth, as appored to the case of the Rushton turbine.

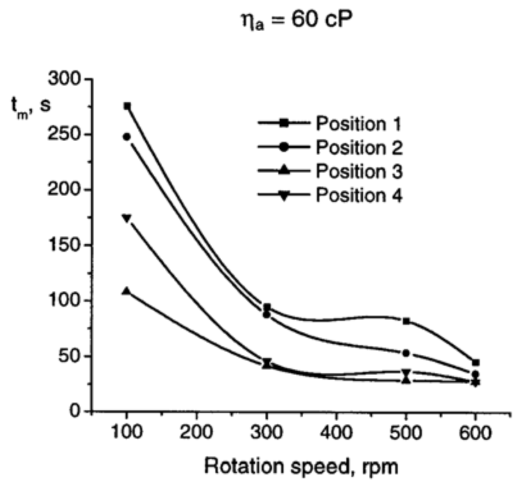
In conclusion, to attain a uniform distribution of the mixing intensity, the rotation speed of the disperser sawtooth must be different in different regions in the broths, that representing an important technical limitation of the use of this stirrer.

1.2. Smith turbine

This type of impeller disperses the gases better than the Rushton turbine, and is recommended for aerobic fermentation processes.

The dependence of the mixing time on the rotation speed for a double stirrer of the Smith turbine type is plotted in Figure 4 and indicates important differences between the agitation of water and of simulated broths with superior apparent viscosities.

In the case of water, the highest values of the mixing time were obtained for the marginal positions, namely 1 and 4. For the intermediary positions, 2 and 3, the mixing time initially decreaseal with increasing rotation speed, reaching a maximum value corresponding to 150 rpm, followed by a new decrease. This variation is due to the interference of the flow streams created by the two Smith turbines for rotation speeds lower than 150 rpm, the magnitude of this phenomenon being diminished with acceleration of the stirrer velocity.



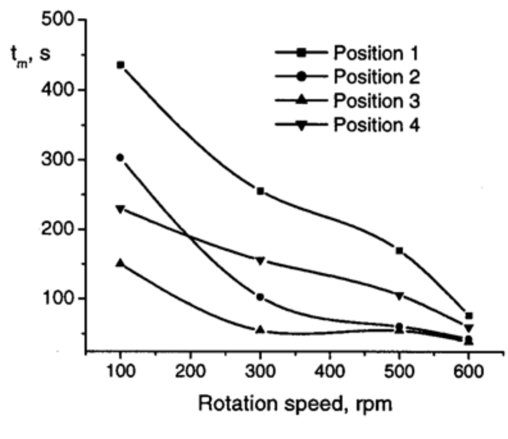


Figure 4. The influence of rotation speed and apparent viscosity on the mixing time at different sensor positions for a Smith turbine

In the domain of rotation speeds greaten than 300 rpm, it is possible to attanin an uniform distribution of the mixing intensity in the broth, the values of the mixing time for positions 1, 2, 3 and 4 becoming similar.

The results obtained for simulated broths indicated continuous reduction of the mixing time with increasing rotation speed, regardles of the pH electrode position. For the same apparent viscosity, the relative magnitude of the mixing intensity for a certain region depends on the rotation speed. Thus, in all the studied cases, below a certain level of the rotation speed, which depends on the apparent viscosity, the less agitated region is the lower one (positions 1 and 2), above this rotation speed mixing becoming uniform in the whole broth. The minimum value of the rotation speed needed for uniform mixing increases from 300 to 600 rpm by increasing the apparent viscosity from 15 to above 60 cp.

For apparent viscosities lower than 60 cP, the values of the mixing time are rather similar for positions 1 and 2, respectively 3 and 4. Unlike the disperser sawtooth, for which the values of the mixing time differed from one position to another, the previous results suggest the appearance of two independent regions of mixing for the rotation speed domain lower than the one corresponding to uniform mixing. At high viscosities, due to the limitation of broth circulation, four independent regions can be distinguished. Moreover, with increasing viscosity, the most intense mixed region becomes the one indicated by position 3 of the pH electrode, probably due to the favorable cumulated influences of the baffles and the "bottom effect", similar to the above studied impeller.

A comparative analysis of the mixing efficiency of a double stirrer of the Rushton turbine type and one of the Smith turbine type, from the viewpoint of the influence of rotation speed, indicated that the Rushton turbine was more efficient in the case of water, but without recording significant differences between the two stirrers. Moreover, no maximum value of the mixing time was recorded for the intermediary positions for the Rushton turbine, as in the case of the Smith turbine.

The differences between the two stirrers are amplified by increasing the apparent viscosity of the simulated broths:

- **position 1 (lower region)**: regardlen of the apparent viscosity value, the Rushton turbine is more efficient.
- **positions 2 and 3 (intermediary region)**: the mixing time values obtained for the Rushton turbine have a similar variation with rotation speed for both

positions, but different evolutions for the Smith turbine. The efficiency of the Smith turbine is superior to that of the Rushton turbine for apparent viscosities up to 60 cP; at higher viscosities, except the values obtained around 400 rpm, the efficiency of the Smith turbine remains superior (the mixing time recorded for the Rushton turbine reaches a minimum at 400 rpm [12]).

- **position 4 (upper region)**: the impeller of the Rushton turbine type induces more intense mixing.

- in all cases, the increase of the broth viscosity exhibited a less pronounced influence on the mixing time recorded for the impeller of the Smith turbine type. Thus, at 300 rpm, by increasing the apparent viscosity from 1 to 96 cP, the mixing time for this stirrer increased by about 2.2–5.8 times, compared with an increase of 8.5–25 times obtained for an impeller of the Rushton turbine type [12].

Figure 5 suggests that the mixing intensity could be uniformly distributed into the bioreactor by using a stirrer with two Smith turbines if the rotation speed ranged from 250 to 600 rpm, the higher values being required for higher apparent viscosities.

The values of the rotation speed corresponding to uniform mixing are higher compared with those established for the Rushton turbine (for apparent viscosities below 60 cP, the optimum rotation speed for the Rushton turbine was of 250–300 rpm, increasing to 400 rpm for higher viscosities [12]).

1.3. Pumper mixer

This impeller represents the component part of some equipment used for liquid–liquid extraction, due to its superior capacity to disperse two liquid phases by promoting intense circulation. The induced flow is similar to the radial flow created by the Rushton turbine, but the amplitude of the streams depends on the ratio between the blade diameter, d, and the disc diameter, d_D. Thus, for $d/d_D < 2$, the stirrer promotes intense circulation in the region under the disc plane, similar to the flow stream from the lower region of the radial circulation induced by the Rushton turbine. In this case, the impeller acts as a centrifugal pump. For $d/d_D \geq 2$, the flow is identical to that generated by the Rushton turbine [13].

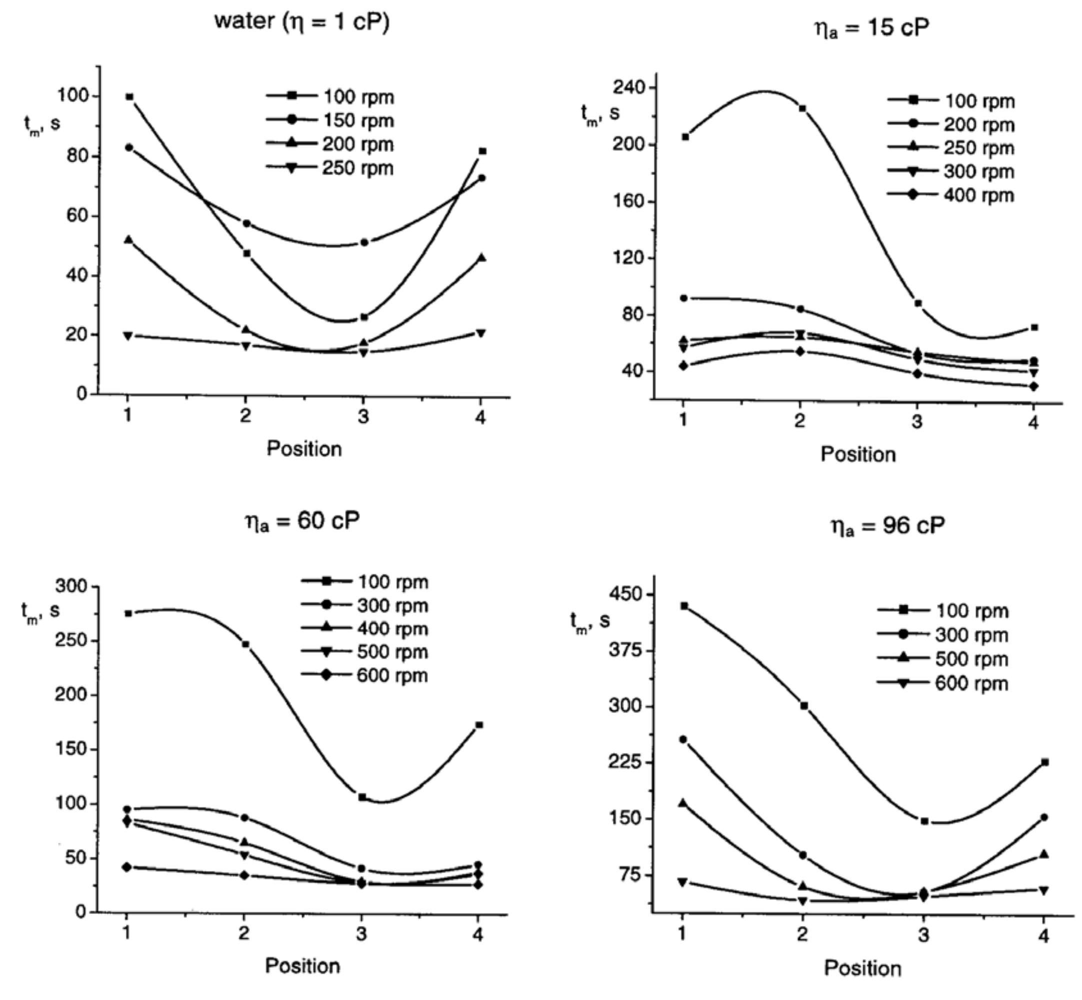


Figure 5. The influence of sensor position on the mixing time for a Smith turbine

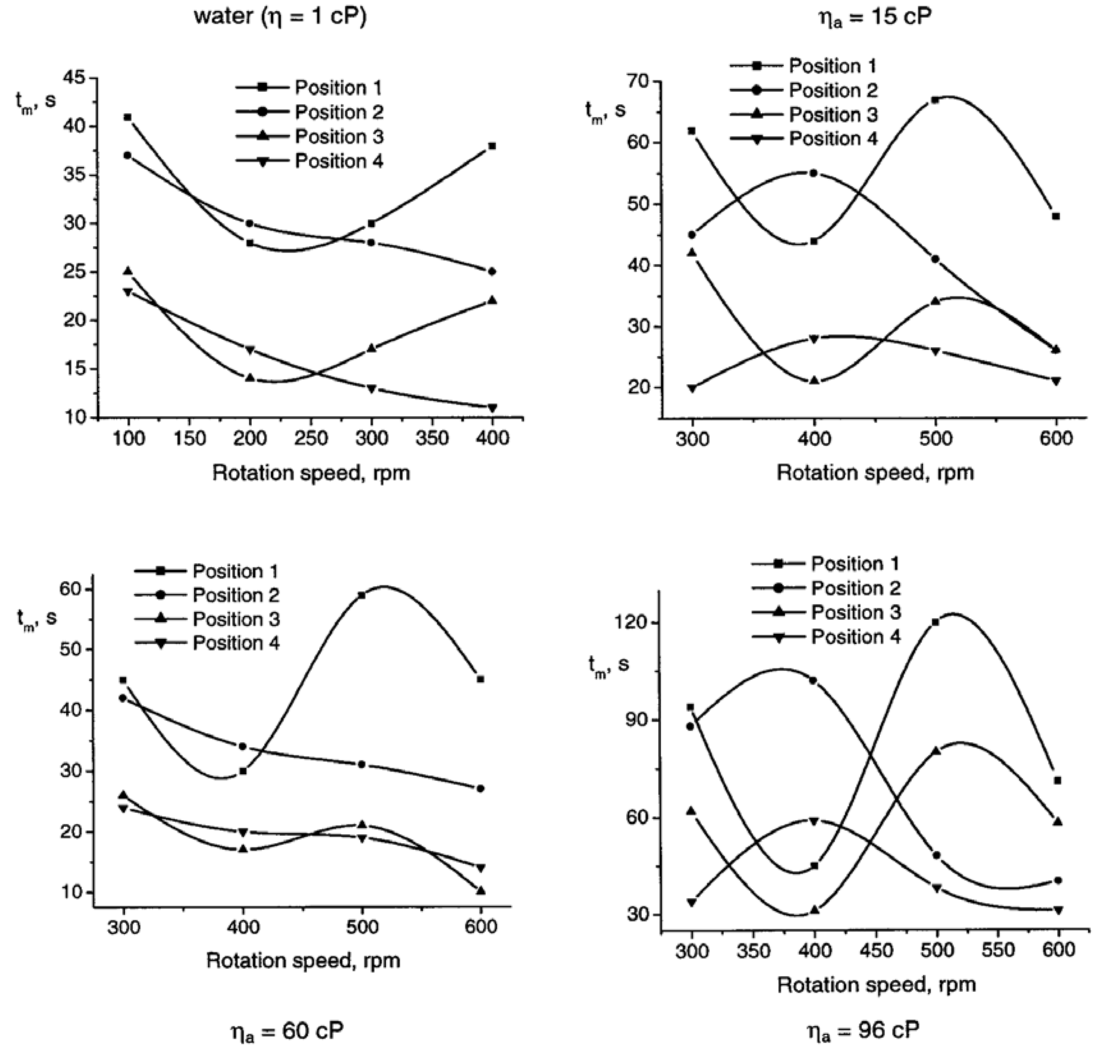


Figure 6. The influence of rotation speed and apparent viscosity on the mixing time at different sensor positions for a pumper mixer

Compared with the above studied impellers, the increase of the pumper mixer rotation speed does not lead to the continuous reduction of the mixing time (Figure 6).

Regardless of the apparent viscosity of the broths, the forms of graphical correlations between the mixing time and rotation speed are similar, on the one hand, for positions 1 and 3, and on the other, for positions 2 and 4. These pairs of pH electrode positions indicate two specific positions related to the two pumper mixers on the stirrer shaft: positions 1 and 3 are situated vicinal under the impeller disc, while positions 2 and 4 are above this disc.

For water, increase of the pumper mixer rotation speed to 200 rpm determines the intensification of mixing in regions 1 and 3, above this level of stirrer velocity the mixing time increases with increasing rotation speed. This variation could be explained by the appearance of the hindering effect against broth circulation at high rotation speeds. This effect is induced either by the baffles, or by the bioreactor wall, because the length of the flow streams is increased by accelerating the stirrer velocity. Region 1 is significantly less efficiently mixed, due to this region geometry (ellipsoidal bottom) which reduces the broth circulation velocity compared to region 3 with a cylindrical geometry.

The variation of the mixing time plotted for positions 2 and 4 is different from the above analyzed ones, this parameter being continuously reduced by increasing rotation speed. Except the rotation speed range of 150–250 rpm, which corresponds to the minimum level of mixing time for positions 1 and 3, the mixing efficiency for positions 2 and 4 was superior to that obtained for the other two positions.

The experimental data obtained for simulated broths indicated a sinusoidal variation of the mixing time with rotation speed acceleration, a devolopment that is more pronounced for positions 1 and 3 at higher apparent viscosities (Figure 6). For the entire domain of broth apparent viscosities, the mixing time for positions 1 and 3 is reduced to a minimum by increasing the rotation speed to 400 rpm. The mixing time then increases and reaches a maximum value at 500 rpm, followed by a new reduction. According to the above analyzed influences, the existence of the minimum is due to the hindering effect against the broth circulation induced either by the baffles or by the bioreactor wall. An increase of rotation speed above 500 rpm diminishes this negative effect, which explains the appearance of a maximum value for the mixing time.

This sinusoidal variation is accentuated at higher viscosities, especially for position 3, due to the absence of the "bottom effect" in this region (the maximum value of the mixing time for positions 1 and 3 could also be observed in the case of water, but an increase of the rotation sped above 400 rpm could lead to "cave" formation at the free surface, thus affecting the accuracy of the experiments).

For apparent viscosities lower than 25 cP the mixing efficiency from the positions 2 and 4 increases continuously with rotation speed. Similar to the case of water, except the rotation speed range of 300–400 rpm, the turbulence degree in these regions is higher than that generated in positions 1 and 3.

An increase of the apparent viscosity above 25 cP modifies the evolution of the mixing time with rotation speed for positions 2 and 4. Therefore, at 400 rpm a maximum value of the mixing time was recorded for positions 2 and 4, opposite to its minimum value obtained at positions 1 and 3. This contrary variation suggests that the intensification of mixing in the region placed under the impeller disc leads to a reduction of broth circulation above the disc. This phenomenon becomes more pronounced at higher viscosities, due to the decreasing of the broth circulation amplitude.

At rotation speeds greater than 400 rpm, the baffles and the bioreactor wall disperse the streams created by the pumper mixer in its lower region, the amplitude of broth circulation increases, thus inducing the penetration of the turbulence also in the region above the impeller and, consequently, the reduction of mixing time in this region.

Due to the sinusoidal variation of mixing time, it cannot be established the order of the mixing intensity magnitude on the broth height, as in the previously analyzed cases. Moreover, this order depends on the rotation speed level.

Beside the differences between the variations of the mixing time with rotation speed, by comparing the influence of the rotation speed on the mixing intensity for a double stirrer of the pumper mixer type and of the Rushton turbine type, the following conclusions were drawn:

- **position 1 (lower region)**: the pumper mixer is more efficient than the Rushton turbine for rotation speeds below 200 rpm for water, or 450 rpm for viscous broths.
- **positions 2 and 3 (intermediary region)**: in all cases, the pumper mixer is more efficient than the Rushton turbine.
- **position 4 (upper region)**: in all cases, the pumper mixer is more efficient than the Rushton turbine.
- although a sinusoidal variation of the mixing time amplifies the difficulty of the comparison between the two stirrers, it may be observed that an increase of the apparent viscosity exhibits a weaker influence on the mixing time for the pumper mixer. Thus, at 500 rpm, in the range of the apparent viscosities from 1 to 96 cP, the value which corresponds to the maximum of the mixing time at positions 1 and 3, the mixing time recorded for the pumper mixer increased by 2.2–4 times, compared with an increase of 8.5–25 times obtained for the impeller of the Rushton turbine [12].

However, the pronounced non–uniform distribution of the mixing intensity in the bulk volume of the broth, as a result of the opposite sinusoidal variation of mixing time in the studied regions, represents the most important limitation of the use of the a stirrer of the pumper mixer type. Thus, Figure 7 indicates that in this case a uniform distribution of the mixing time cannot be reached in the bioreactor.

1.4. Curved bladed turbine

Similar to the pumper mixer, this impeller is used for dispersing the liquid phases in the extraction process. The generated circulation streams depend in the same manner on the ratio between the blade diameter and the disc diameter [13].

Although its construction is quite similar to the pumper mixer one, the experiments indicated significant differences between the two impellers concerning the variation of the mixing time with the rotation speed, as in the case of the impellers of the Rushton turbine and the Smith turbine types. According to Figure 8, the mixing time initially decreases with the acceleration of rotation speed to a certain value depending on the pH of the electrode and the apparent viscosity and then, increases. Because the length of the broth circulation route increases with rotation speed, the existence of a minimum value for the mixing time could be the result of the hindering effect induced by the baffles and/or bioreactor wall. As in the case of a pumper mixer impeller, the graphical representations of the mixing time variations are rather similar for positions 1 and 3, respectively 2 and 4.

The least intense mixing war recorded for the lover region, position 1, as a result of the ellipsoidal geometry of this region that hinders the circulation of the broths on the route induced by the impeller. The best agitation was obtained for position 3, under the upper impeller, due to the positive cumulated influences of the mixing generated by the lower impeller and of the local cylindrical geometry.

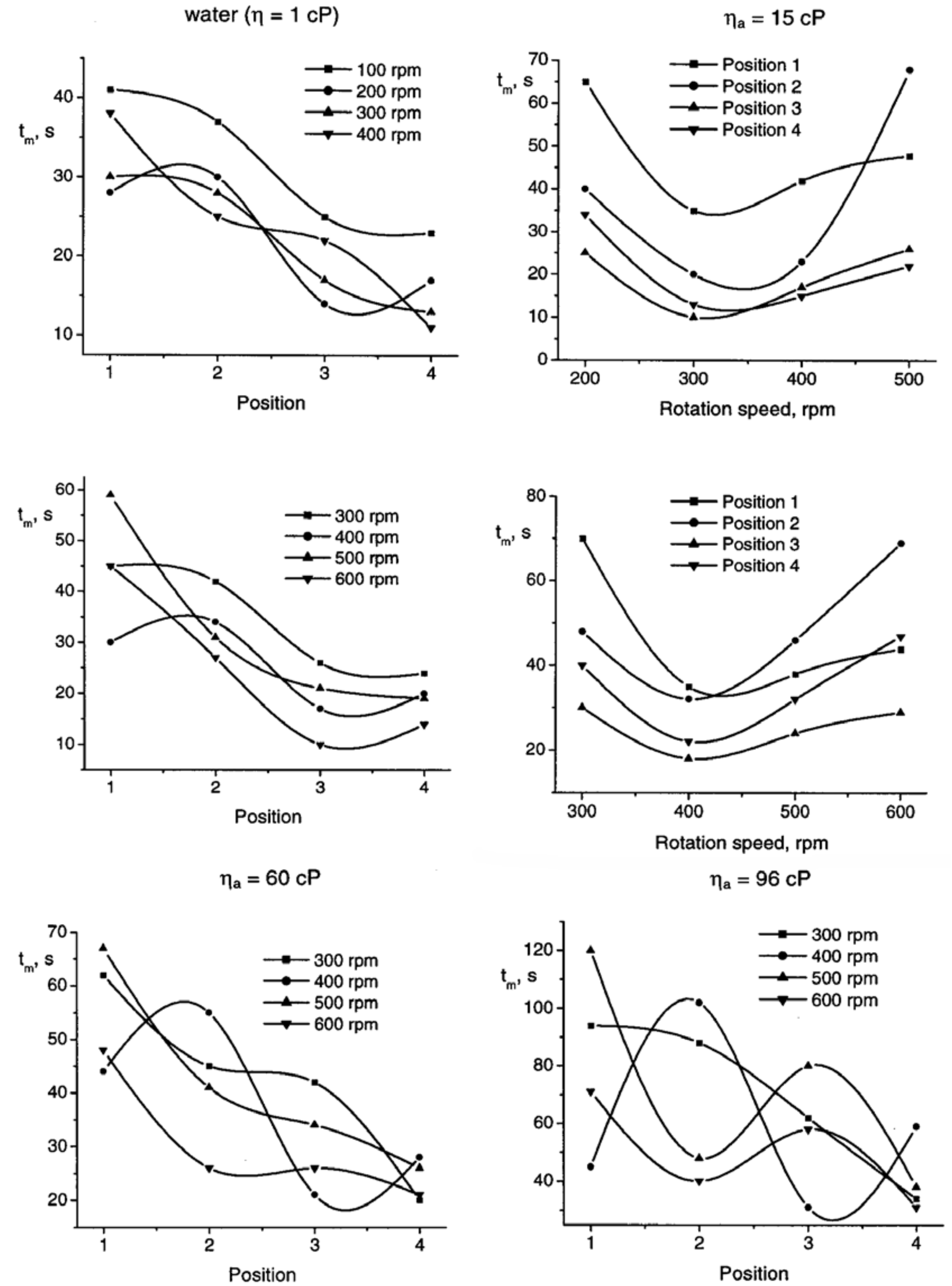


Figure 7. The influence of sensor position on the mixing time for a pumper mixer

For all positions of the pH electrode, the minimum value of the mixing time was reached at 300 rpm for water, respectively at 400 rpm for simulated broths with higher viscosities.

By analyzing the mixing intensity and its distribution in the bioreactor for the Rushton turbine and curved bladed turbine, it was found that the Rushton turbine is more efficient. In the case of simulated fermentation broths, the following comparative results concerning the influence of the rotation speed on the mixing efficiency were obtained:

- **position 1 (lower region)**: the Rushton turbine is more efficient, regardles of the apparent viscosity of the broth.

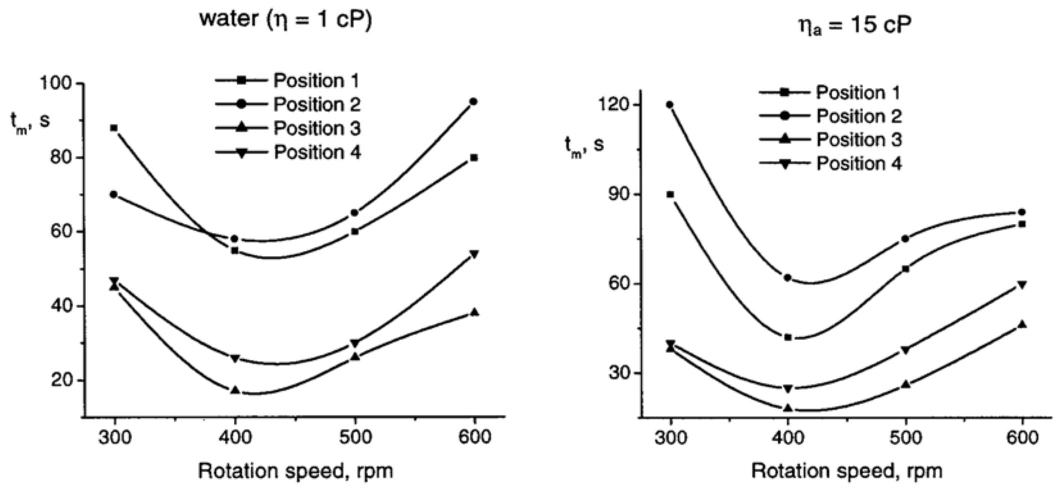


Figure 8. The influence of rotation speed and apparent viscosity on the mixing time at different sensor positions for a curved bladed turbine

- **positions 2 and 3 (intermediary region)**: the curved bladed turbine is more efficient, regardles of the apparent viscosity of the broth.
- **position 4 (upper region)**: in all cases, the curved bladed turbine is more efficient than the Rushton turbine.

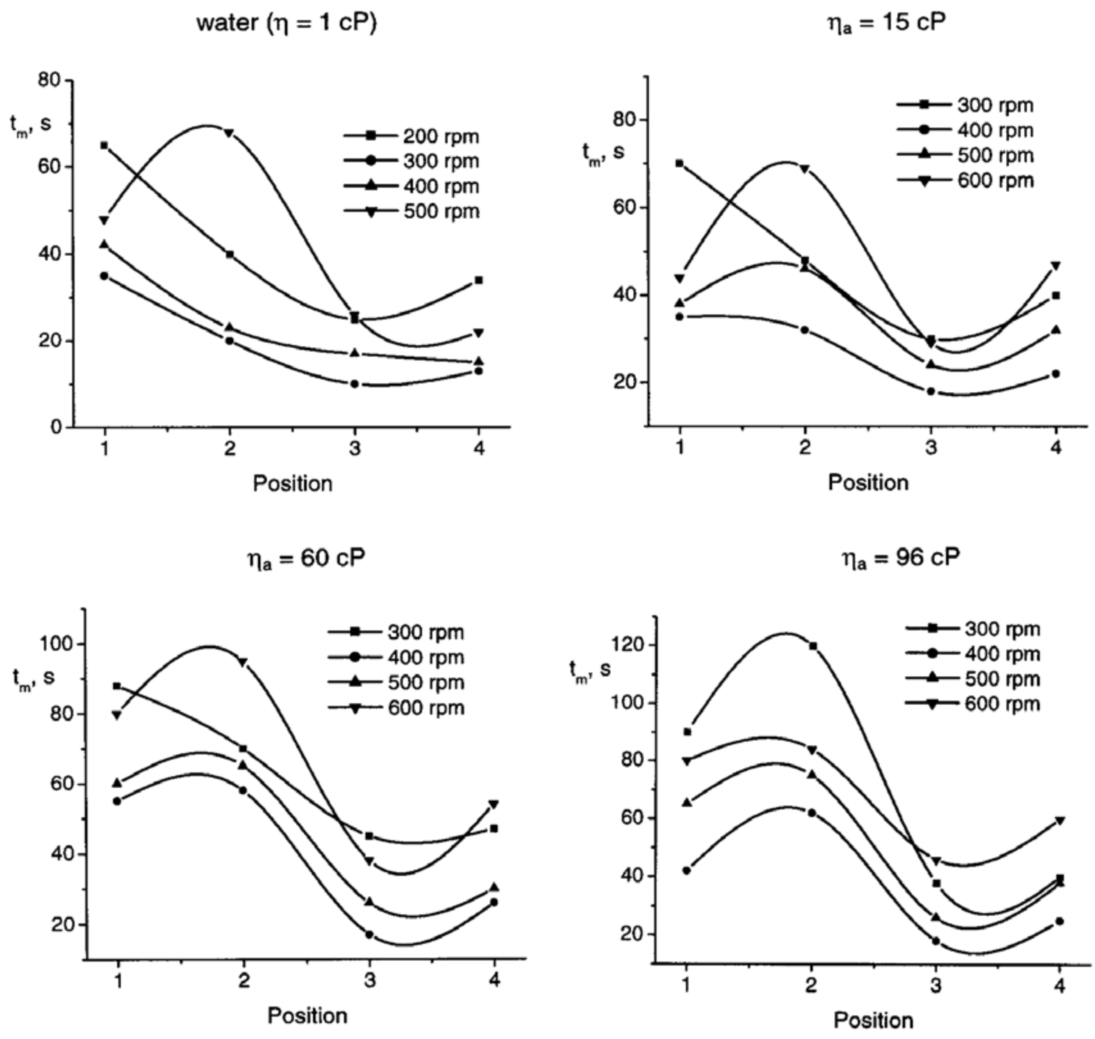


Figure 9. The influence of sensor position on the mixing time for a curved bladed turbine

• an increase of the apparent viscosity exhibits a weaker influence on the mixing time in the case of the curved bladed turbine. Thus, for 300 rpm, in the considered range of the apparent viscosity, the recorded mixing time increased by 1.5–2.4 times for this impeller, compared with an increase of 8.5–25 times for the Rushton turbine [12].

Although the values of the mixing time for the four positions of the pH electrode are more similar than those recorded for the pumper mixer, no value of the rotation speed that could induce a uniform distribution of the mixing intensity in the bulk volume of the broths was observed (Figure 9).

1.5. Paddle with six blades

A similar variation of the mixing time with the rotation speed regardlen of the apparent viscosity of the broth may be observed in Figure 10.

Therefore, up to a certain value of the rotation speed, which depends on the apparent viscosity, the mixing time increases with increasing rotation speed, reaches a maximum, and then decreases. The initial increase of the mixing time could be the result of the amplification of the interactions between the flow streams induced by the impeller and the bioreactor wall or baffles at lower stirrer velocity. Above a certain level of the rotation speed, which increases with increasing apparent viscosity (100 rpm for water, 300 rpm for simulated broths with an apparent viscosity lower than 25 cP, 400 rpm for apparent viscosities higher than 25 cP), these negative effects diminish and, therefore, a reduction of the mixing time was recorded.

In all the studied cases, weaker mixing was obtained for the lower region, position 1, indicating that for this impeller the "bottom effect" exhibits an important negative influence. The most intense mixing was recorded for the upper region, position 4, due both to the geometry of the vessel, and to the presence of baffle. The values of the mixing time corresponding to positions 2 and 3 are intermediary between the above limits, as a result of the appearance of a stagnant region

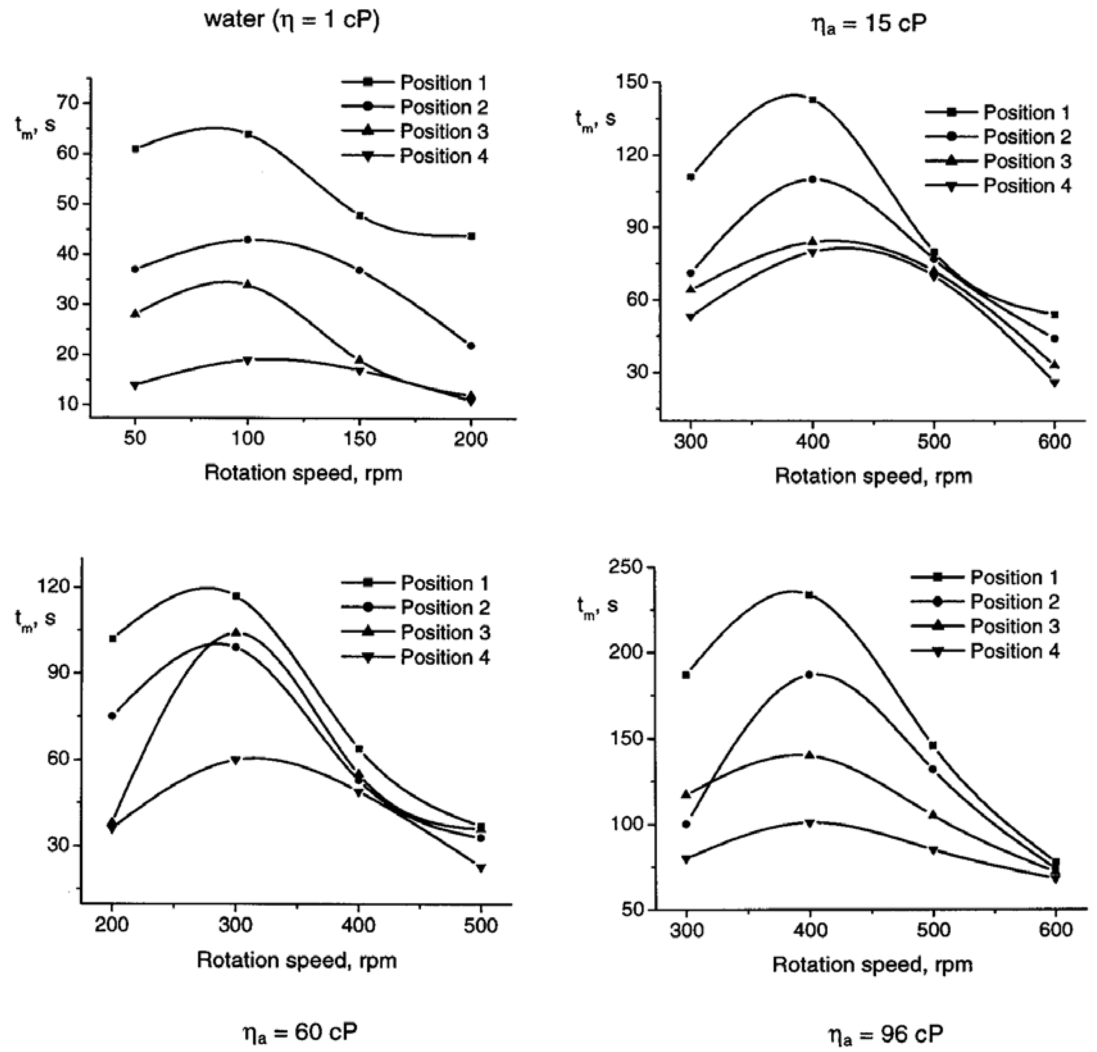


Figure 10. The influence of rotation speed and apparent viscosity on mixing time at different sensor positions for a paddle with six blades

between the impellers, at lower rotation speed, and of the interference of the flow streams, at higher rotation speed.

Except the inferior region, compared with the Rushton turbine, a paddle with six blades offers more efficient mixing for water. The same values of the mixing time can be reached at lower rotation speeds. Regarding the influence of the rotation speed in the case of simulated broths, the results of the comparative analysis between the two impellers could be presented as follows:

- **position 1 (lower region)**: the Rushton turbine is more efficient, regardles of the apparent viscosity of the broth.
- **positions 2 and 3 (intermediary region)**: except for the two ranges of the rotation speed, around 300 rpm for apparent viscosities below 60 cP, and around 400 rpm above this level of the apparent viscosity, a double stirrer with a paddle with six blades is the more efficient. The mentioned range of the rotation speed correspond to the maximum of the mixing time for a paddle with six blades and to the minimum for the Rushton turbine [12].
- **position 4 (upper region)**: in all cases, a double stirrer with a paddle with six blades is more efficient than the stirrer of the Rushton turbine type.
- an increase of the apparent viscosity exhibits a weaker influence on the mixing time for the paddle with six blades. Thus, for 300 rpm, in the considered range of the apparent viscosity, the mixing time increased by 1.2–2.0 times for this impeller, compared with an increase of 8.5–25 times for the Rushton turbine [12].

Figure 11 indicates the existence of a certain value of the rotation speed, the optimum value, which allows obtaining uniform mixing in the bulk volume of the broths.

For the simulated fermentation broths, the value of the optimum rotation speed increases gradually with apparent viscosity, from 450 rpm for viscosities lower than 15 cP, to 600 rpm, for 96 cP.

1.6. Pitched bladed turbine

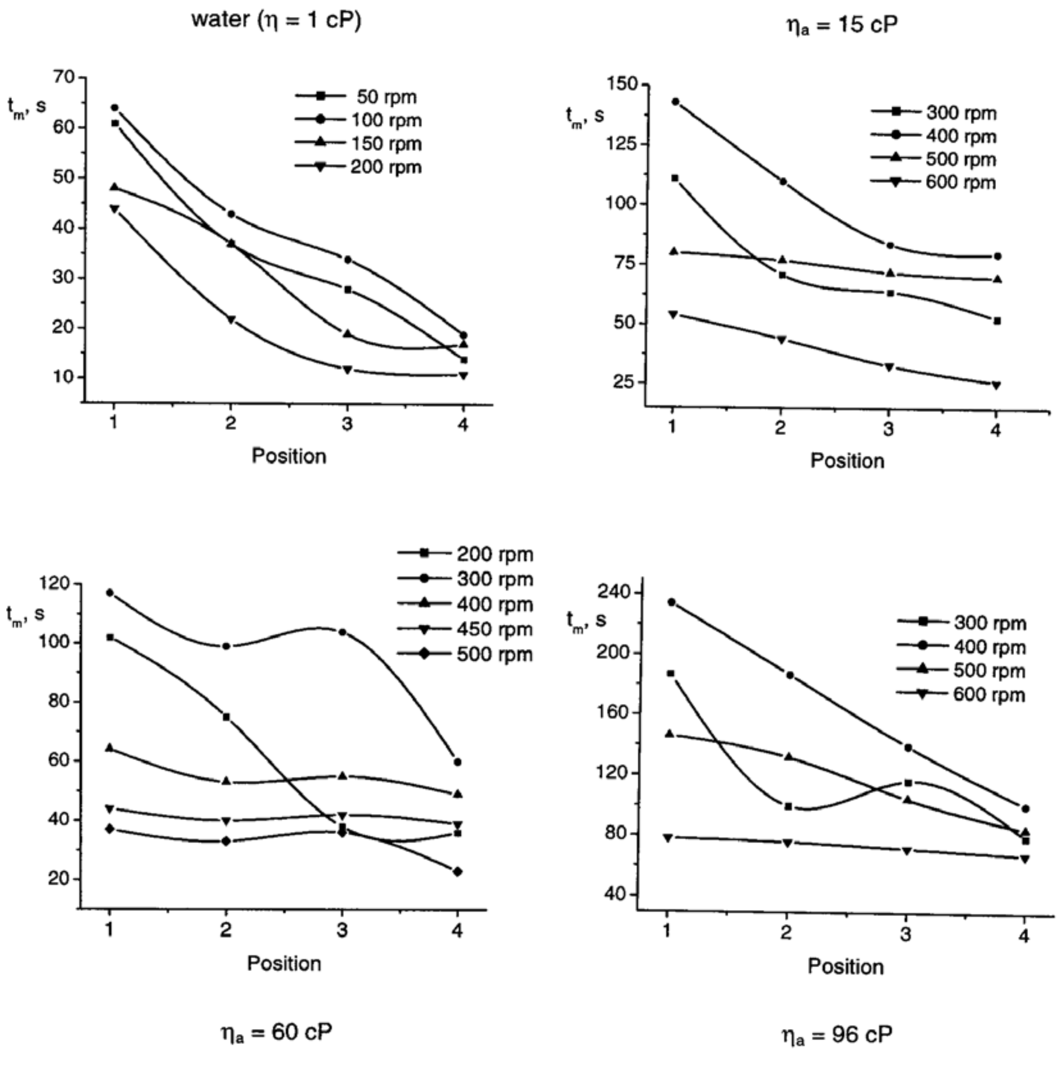


Figure 11. The influence of sensor position on the mixing time for a paddle with six blades

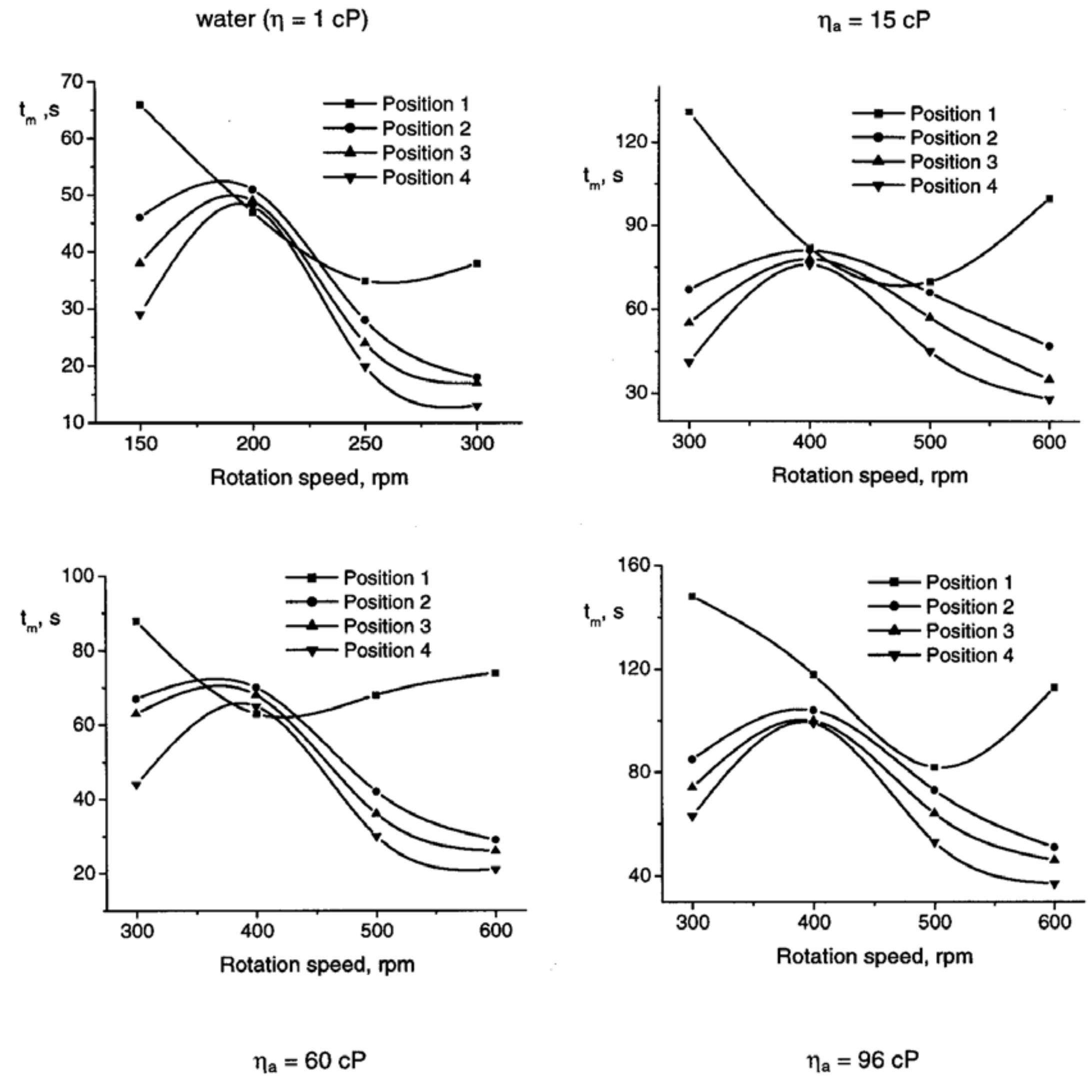


Figure 12. The influence of rotation speed and apparent viscosity on the mixing time at different sensor positions for a pitched bladed turbine

Although this impeller generally induces an axial flow, in certain conditions it could generate a radial flow, similar to the above impellers. Thus, for a ratio between the impeller diameter, d, and the bioreactor diameter, D, greater than 0.2 and a higher rotation speed, the broth circulation changes from axial flow to radial [14]. Because of the experimental equipment used, the ratio d/D is 0.36, it could be assumed that the conditions for a radial circulation of the agitated liquid are respected.

Compared with the above analyzed impellers, Figure 12 indicates the most pronounced similarity between the curves that describe the variation of the mixing time with the rotation speed at a certain apparent viscosity. Consequently, this impeller can offer the most uniform distribution of the mixing intensity in the bioreactor.

Furthermore, except for the lower region, the form of the graphical dependence between the mixing time and the rotation speed is similar for all of the studied broths. Thus, for the upper and intermediary positions, the mixing time initially increases with acceleration of the stirrer velocity, reaches a maximum value and then decreases. The value of the rotation speed corresponding to the maximum one could represent the point of the flow changing from axial, less extended and which induces the flow stream interferences in the vertical direction, to a radial one, more intense and extended. This rotation speed value is about 180 rpm for water, increasing to 400 rpm for broths with higher apparent viscosities.

For the lower region, position 1 of the pH electrode, for the entire range of the viscosity, an initial decrease of the mixing time with increasing rotation speed was observed. Above a certain value of the rotation speed, depending on the apparent viscosity (250 rpm for water, 400 rpm for simulated broths with an apparent viscosity below 60 cP, 500 rpm for more viscous broths), the mixing time begins to increase, due to the hindering effect of the bioreactor bottom ("bottom effect").

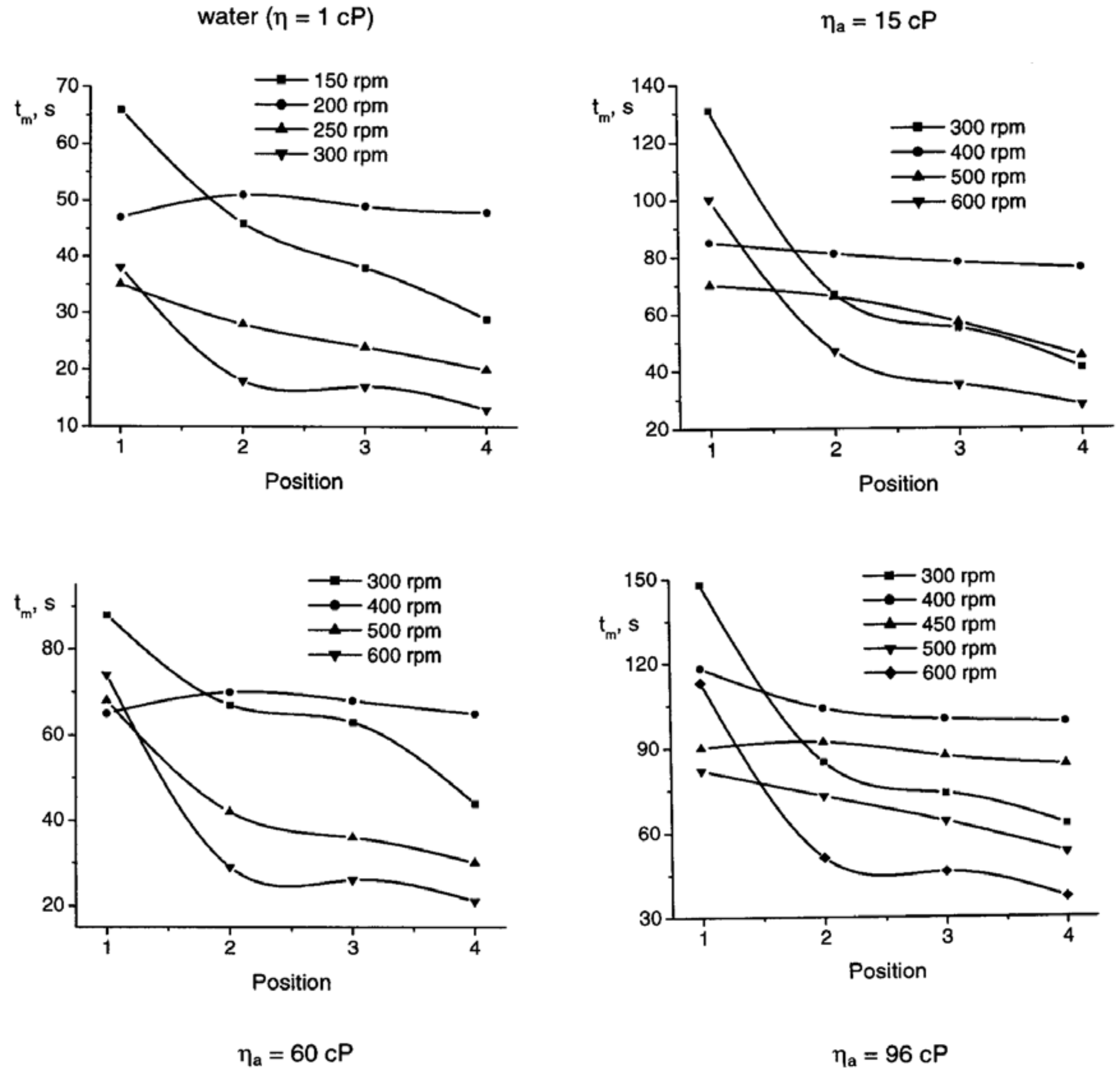


Figure 13. The influence of sensor position on the mixing time a the pitched bladed turbine

Due to the absence of both the "bottom effect", as in position 1, and of the mutnal annihilation of the flow streams by their interference, as in regions 2 and 3, the most efficient mixing is reached at position 4.

The double stirrer of the Rushton turbine type induces more intense mixing of the water. Howerer, regarding the influence of the rotation speed on the mixing efficiency for simulated broths, the following differences between the two stirrers were observed:

- **position 1 (lower region)**: the Rushton turbine is more efficient, regardles of the apparent viscosity of the broth.
- **positions 2 and 3 (intermediary region)**: the double stirrer of the pitched bladed turbine generates more intense mixing.
- **position 4 (upper region)**: for apparent viscosities below 60 cP, the efficiencies of the two stirrers are similar. Above this level of the viscosity, the double stirrer of the pitched bladed turbine type becomes more efficient,
- an increase of the apparent viscosity exhibits a weaker influence on the mixing time for the pitched bladed turbine. Thus, for 300 rpm, in the range domain of the apparent viscosity from 1 to 96 cP, the mixing time recorded for the pitched bladed turbine increased by 1.8–2.3 times, compared with an increase of 8.5–25 times for the Rushton turbine [12].

At certain rotation speed values, the use of the double stirrer of a pitched bladed turbine type offers the possibility to reach uniform mixing in the bioreactor. Thus, it can be seen in Figure 13, that the optimum rotation speed is 200 rpm for water, 400 rpm for simulated broths with an apparent viscosity below 60 cP, respectively 450 rpm for higher apparent viscosities. These values are similar but higher than those recorded for the Rushton turbine [12].

2. Energetic efficiency of mixing

The comparative analysis of the influence of the rotation speed on the mixing time and its distribution in the fermentation broths offers information concerning the turbulence degree that must be generated by a certain impeller to reach a certain level of mixing intensity in a certain region in the bioreactor. Therefore, this analysis allows selecton the of most efficient impeller for a certain level of rotation speed, without taking into account the power consumption needed for a certain level of mixing intensity which is generated locally or in the whole broth.

The dependences between the specific power input, P/V, and the mixing time for the studied stirrers are plotted in Figures 14–17 for the four positions of the pH electrode and the experimental range of the apparent viscosity.

For water, mixing times below 80 s can be reached with minimum energy consumption using the disperser sawtooth, for positions 1 and 2, respectively the paddle with six blades, for positions 3 and 4 (Figure 14). Consequently, for obtaining this level of mixing time with the lowest power consumption, the double stirrer must equipped at the lover part with a disperser sawtooth, and at the upper part with a paddle with six blades.

But, if it is taken into account concomitantly the criteria of the uniform distribution of mixing intensity, for positions 1 and 2 a pitched bladed turbine is recommended. Under these circumstances, to reach a mixing time below 80 s with the lowest power consumption and a uniform distribution of mixing, a double stirrer must be provided with a pitched bladed turbine at the lower region, and a paddle with six blades at the upper one.

For values of the mixing time above 80 s, the power consumptions of the impellers become more similar. Therefore, each of the studied impellers could be used, except the Smith turbine for lower positions.

It can be observed in Figure 15 that the most energetically efficient impeller for the extreme positions, 1 and 4, is the pumper mixer. For the intermediary positions, the most efficient is the pitched bladed turbine. By combining these results with the previous

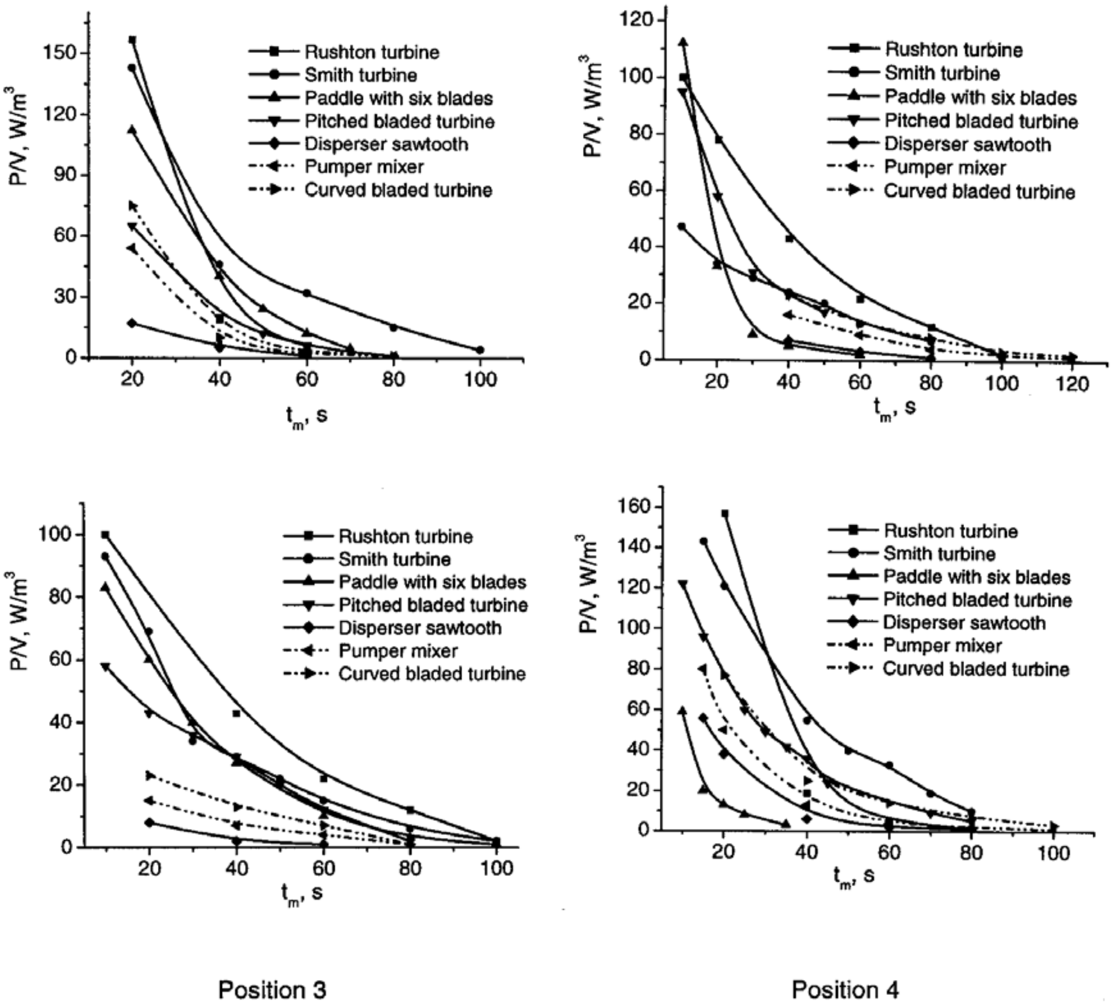


Figure 14. The dependence between the stirrer power consumption and mixing time for water

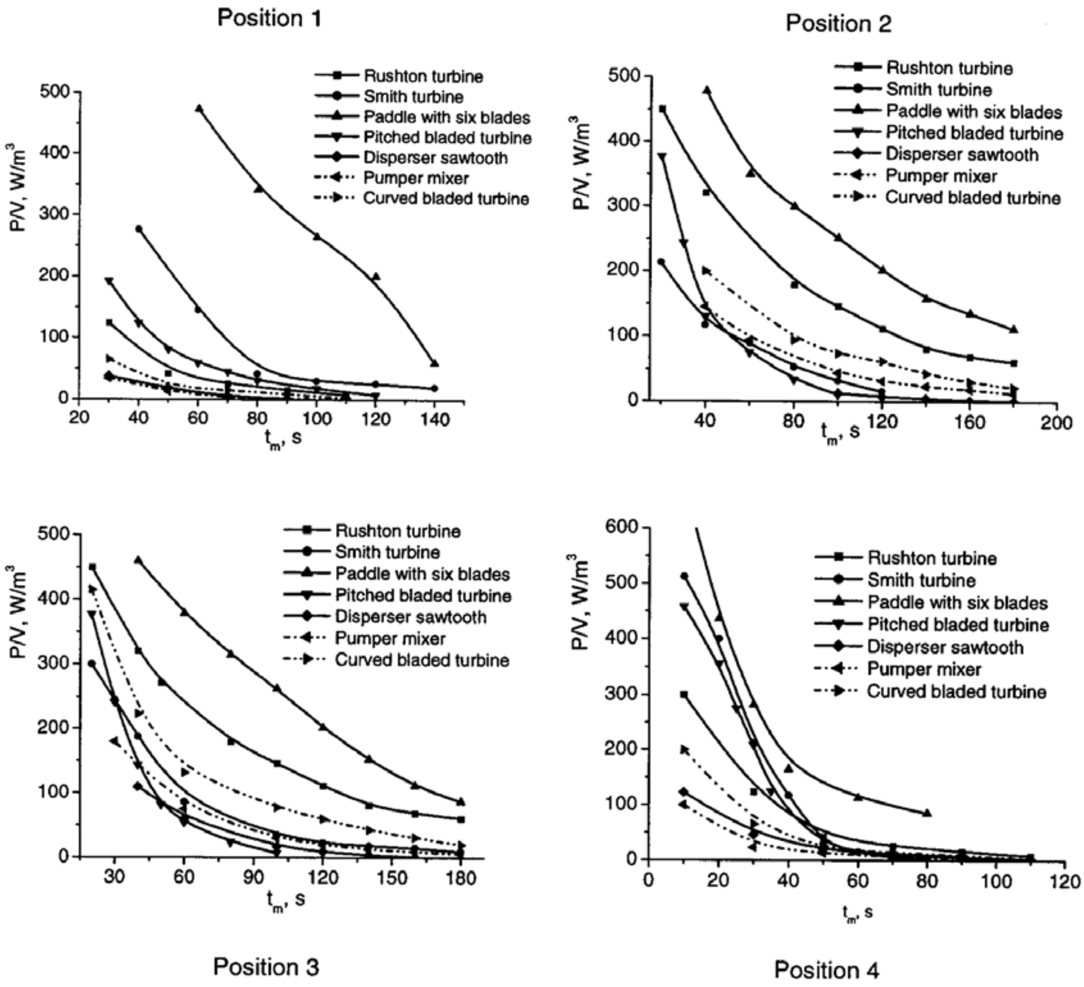


Figure 15. The dependence between the stirrers power consumption and mixing time for simulated broths with an apparent viscosity of 15 cP

ones regarding the distribution of the mixing intensity, it may be concluded that for mixing simulated broths with viscosity up to 15 cP, a double stirrer with a pumper mixer at the lover part and a pitched bladed turbine at the upper part could be recommended.

The uniform distribution of the mixing intensity in the bulk volume of the broths with the lowest power consumption can be reached if a double stirrer with a pitched bladed turbine is used at the lower region and a Rushton turbine at the upper one.

For simulated broths with an apparent viscosity between 15 and 60 cP, the most energetically efficient impeller is the pumper mixer for positions 1 and 4, respectively, the disperser sawtooth for positions 2 and 3 (Figure 16). Therefore, by means of these results and of the previously obtained, ones the stirrer formed by a lower impeller of the pumper mixer type and an upper one of the disperser sawtooth type is recommended for obtaining low mixing time values with the lowest power input.

But, in this case the double stirrer of the Rushton turbine type allows to uniformly distribute the intensity in the bulk volume of the broths with the minimum power consumption.

The graphical correlations plotted in Figure 17 suggested that the most efficient stirrer for broths with an apparent viscosity over 60 cp, from the viewpoint of the power consumption needed for low mixing time, is that the previously proposed, respectively, that consisting from a lower pumper mixer and an upper disperser sawtooth.

Uniform mixing could be insured by using a stirrer containing at the lower part a Smith turbine, and at the upper part a Rushton turbine, this combination resulting from the concomitant analysis of the energy consumption and mixing time distribution.

CONCLUSIONS

By comparatively analyzing the mixing intensity and its distribution into a stirred bioreactor using seven radial impellers, for simulated fermentation broths with different apparent viscosities, the following conclusions can be drawn:

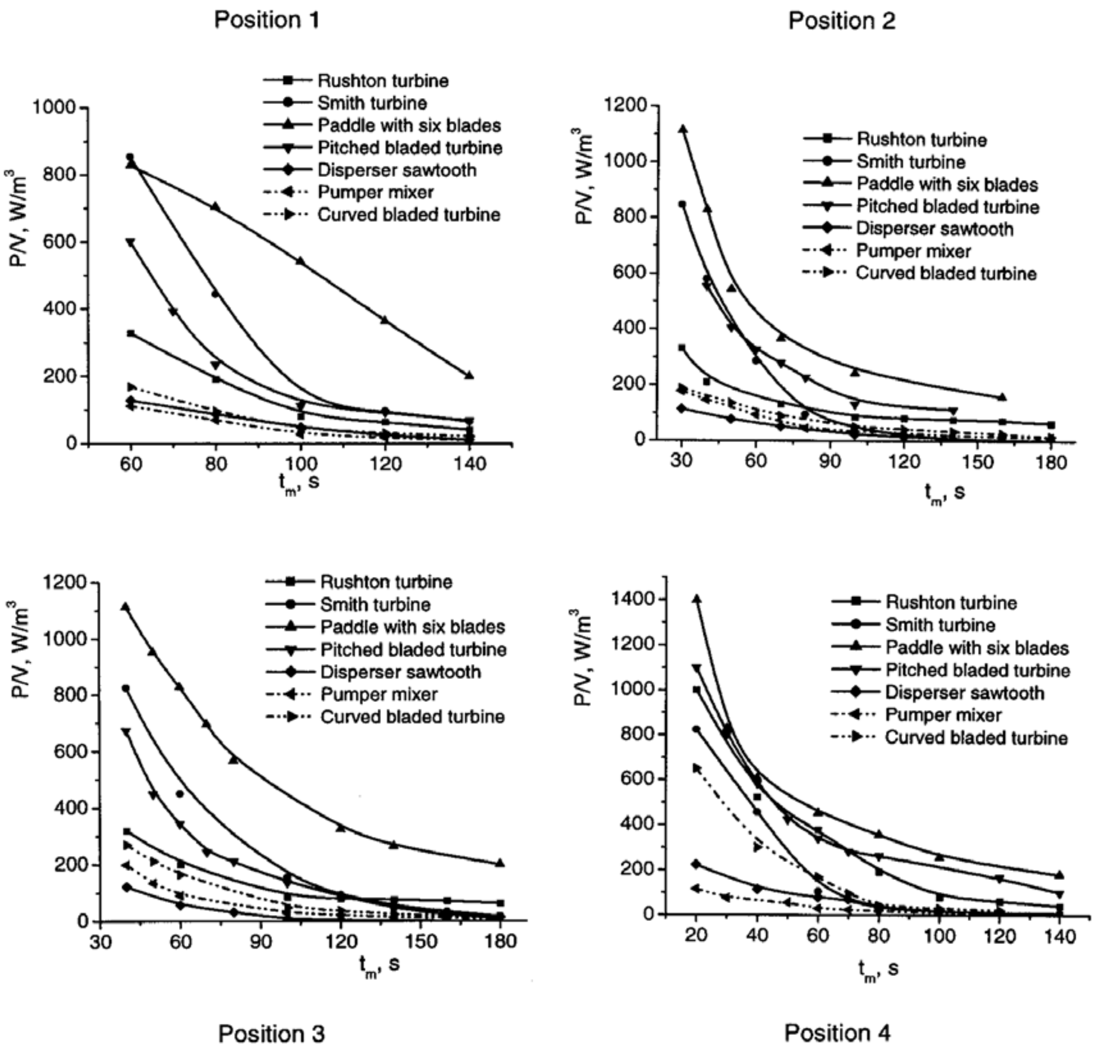


Figure 16. The dependence between the stirrer power consumption and mixing time for simulated broths with an apparent viscosity of 60 cP

1. Taking into account the criteria of the rotation speed needed to reach a certain value of the mixing time, it was demonstrated that the pumper mixer is the most efficient impeller for lower apparent viscosities, regardles of the sensor position, followed by a paddle with six blades (except the upper region) and the Rushton turbine.

At higher apparent viscosities of the simulated broths, the pumper mixer offers also the most intense mixing, except the lower region for a rotation speed range above 450 rpm. In this case, to reach a certain level of the mixing time, the Rushton turbine rotation must be greater than that of the other impellers.

2. For the considered range of the rotation speed, the impellers that can generate a uniform distribution of the mixing intensity in the bulk volume of the fermentation broths are the Rushton turbine, the Smith turbine, a paddle with six blades and a pitched bladed turbine. The optimum rotation speeds needed for the Rushton turbine for promoting the uniform distribution of mixing are 250–300 rpm for an apparent viscosity below 60 cP, 400 rpm for an apparent viscosity above 60 cP, this impeller being the most efficient impeller from this viewpoint. The optimum values of the rotation speed for a pitched bladed turbine are similar to those for the Rushton turbine: 200 rpm for water, 400 rpm for simulated broths with an apparent viscosity lower than 60 cP, 450 rpm for more viscous broths. The optimum rotation speeds for the other two mentioned impellers are higher, increasing to 600 rpm for an apparent viscosity of 96 cP.

3. The analysis of the energetic efficiency, regarding of the power consumption needed for a certain value of the mixing time, underlined that the most efficient mixing of water can be obtained with a double stirrer equipped at the lower part with a disperser sawtooth, and at the upper part with a paddle with six blades. But, to reach uniform mixing with low power input, the disperser sawtooth has to be replaced with the pitched bladed turbine.

The selected combinations of the impellers could be changed in the case of simulated broths with higher apparent viscosities. Thus, considering only the power consumption, the most efficient double stirrers have a

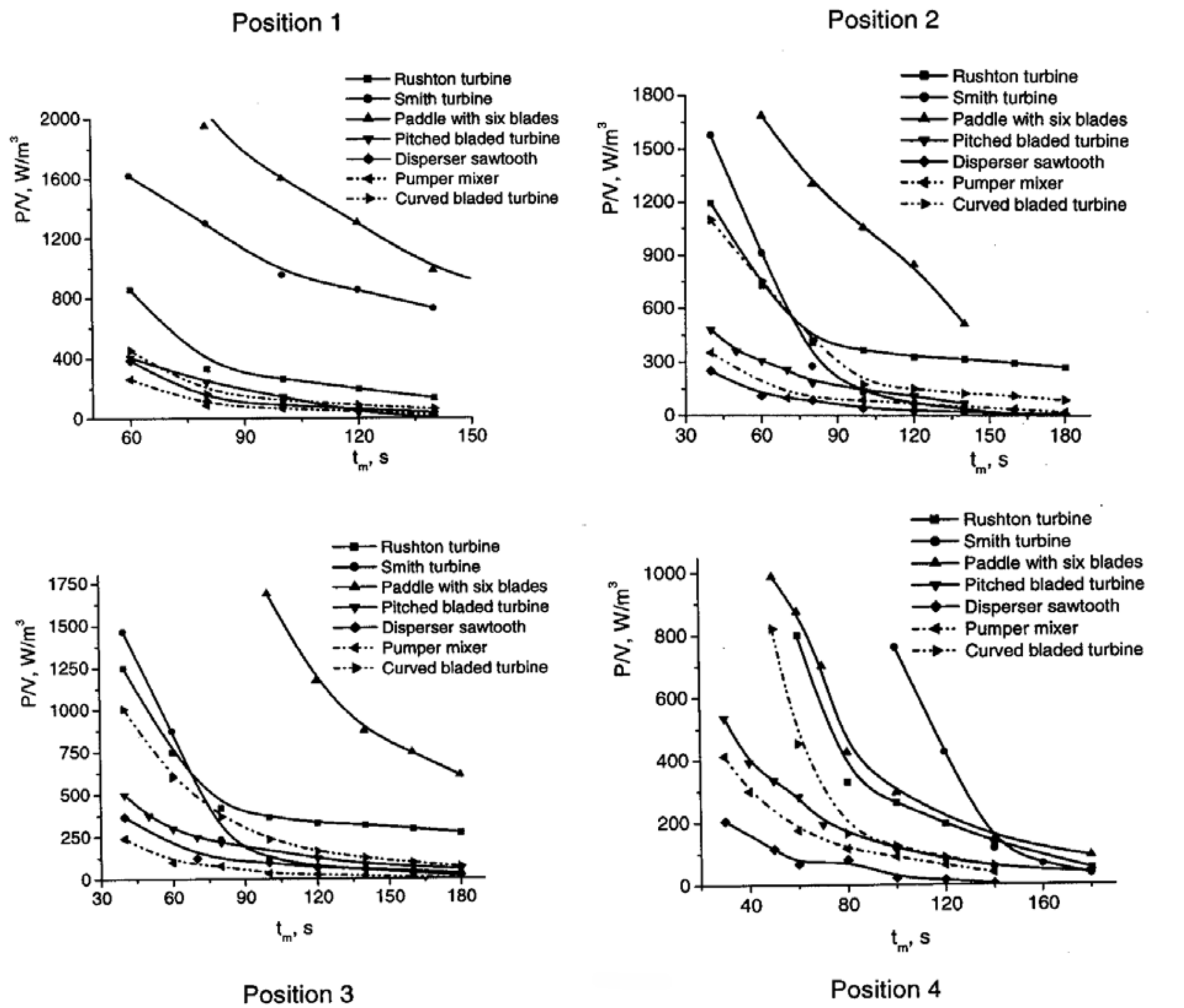


Figure 17. The dependence between the stirrers power consumption and mixing time for simulated broths with an apparent viscosity of 96 cP

pumper mixer at the lower region in all cases. The superior impeller can be of pitched bladed turbine type, for apparent viscosities below 60 cP, or of disperser sawtooth type, for more viscous liquids.

The stirrer that can offer uniform mixing with lower energy consumption consists of a superior Rushton turbine and different inferior impellers, a function of the apparent viscosity of the broth. Therefore, the lower impeller is of pitched bladed turbine for a viscosity up to 25 cP, a Rushton turbine for an apparent viscosity between 25 and 96 cP, a Smith turbine for higher viscosities.

In all the studied cases, the optimum impeller combination for a certain fermentation broth can be selected only by concomitantly analyzing the experimental data regarding the mixing intensity, mixing distribution and energetic efficiency, that being the aim of future experiments.

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