HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 34. pp. 35-39 (2006)

OPTIMIZATION PROBLEMS OF FERMENTOR AERATION-AGITATION SYSTEM

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After four decades of almost exclusive application of Rushton turbines a number of types of impellers were developed for the fermentation industry in the last 20 years which were proven to be more efficient despite their lower power requirements.

The efficiency of an impeller is affected strongly by the degree of their hydromechanical properties corresponding with the specific characteristics and requirements of a certain fermentation process. Evaluation in case of non-Newtonian broths cannot be carried out with proper accuracy, and their optimization becomes difficult.

An increase in yield even by a few percent can be of great importance in large-scale fermentation vessels. Consequently, the optimization of agitation system is a very important factor but it is only partially provided by scale-up using pilot plant data and similarity criteria. This is the reason why we need newer methods for optimization of aeration-agitation systems for large-scale fermentation vessels by agitators equipped with changeable flow modifying parts.

Keywords: power number, non-Newtonian broth, Rushton turbine, shear power, scale-up, flooding

Advantages and Disadvantages of Newer Agitation Systems

The disadvantages of flat-blade Rushton turbines – less axial circulation capability and large power requirement - applied in penicillin fermentation for many years due to their excellent dispersion capability became more and more obvious with the increase in size of fermentation vessels. Due to these disadvantages newer types of impellers and complex agitation systems were developed.

Turbines

The efficiency of Rushton turbines *(Fig. 1)* was increased by the application of impellers with parabolic profile instead of flat-blades in Scaba 6SRGT system *(Fig. 2)*. Their power number has decreased from 5,5-6,0 to 3,2. The number of higher energy peaks around the impeller endangering more sensitive microorganisms decreased and by increasing impeller's diameter larger volumes could be blended with the same power requirements. The impellers' sensitivity to "flooding" phenomenon and increased viscosity had decreased, but still they had lower circulation capability. In the event of applying more impellers compart-mentalization (inadequately blended areas) may occur. That is why in newer agitation systems these are used only at the lowest, dispersion level. (A. Baker et al. 1)

Closed turbines have better circulation capability but these are rarely applied due to their little dispersion capability.

Propeller agitators

Propeller agitators have excellent axial circulation properties but weak dispersion capability. Due to their little power number of 0,5-1,1 their diameter could be larger with the same power requirement and this facilitates full blending of viscous broths and filamentous microorganisms.

First EKATO has developed propeller type impellers with pitched blades called MIG and INTERMIG *(Fig. 3)*. Recently streamlined propeller agitators with twisted surface have been applied at the upper levels of complex agitation systems. Impellers with larger diameter ratios of 1:0,5-1:0,6 narrower blades such as Lightnin 310 are applied for blending of lower viscosity broths. Impellers with less diameter and diameter ratio of 1:0,45 and broader blades which have power number of 1,0-1,1 such as Lightnin A 315 and Prochem Maxflo (Fig. 4 and Fig. 5) are applied for blending of higher viscosity broths.

According to A.W. Nienow propeller agitators provide better blending efficiency for both the lower and higher viscosity broths and better mass and heat transfer than Rushton turbines. Other advantages of these agitators are their power number and indulgence with sensitive microorganisms (A.E. Nienow 2.)

Vacuum agitators

Vacuum agitators has low power requirement, good dispersion capability but lesser circulation properties. These types can be used for blending less air volumes.

They are used only in certain technological processes such as in flotation devices and in yeast production.

Newer Complex Agitation Sysems

Merely the last few decades the researchers and manufacturers have realized that the efficiency if agitation systems can be increased by development of complex systems including more agitators of different types and properties which satisfy better the requirements of the particular levels. Despite many published paper literature dealt not so much with the problems of agitation of large-scale fermentation vessels. Perhaps on the Symposium in Firenze in 1993 data on the mass transfer problems due to differences between the levels of large-scale fermentation vessels were published for the first time. These differences are stemming partially from the position of levels and partially from their different functions i.e. could be local or functional differences.

Local differences are mainly caused by the pressure differences due to 8-12 m height of fermentors and this may affect bubble size and the density of foaming broths, etc.

Functional differences are because the function of the lowest agitator is efficiently disperse air input, the function of the middle agitator(s) is the best intensity circulation of the broth-air mixture and the function of the upper agitator is recirculation of the foaming broths on the surface with less further foam formation possible.

In the nineties the increase in differences due to larger and larger-scale fermentation vessels had led to the development of complex agitation systems considering the differences between levels. 6SRGT modified turbine agitator with good dispersion capability is generally used on the lowest level, and high efficiency propeller agitators e.g. Lightnin, Prochem are applied on the highest level. (K. Myers, 3.) These complex systems have better energy dissipation, dispersion and circulation capabilities, they are more efficient and more sensitive to flooding than the older systems built from components of the same type and size.

Optimization Problems of Agitation Systems

Sizing and development of large-scale agitation systems is still based mainly on data from and experiences with pilot plant fermentors, and relations developed through the theory of similarity and dimension analysis. Lately industrial measurements have been used more and more often.

The application of the results of experimental measurements during scale-up is limited very much by the significant differences in the hydrodynamic fields and flow patterns of large-scale fermentors mainly due to the following reasons:

a) because of the nearness of the baffles and impellers the large velocity gradient between the flowing layers in the experimental device results in large shear velocity and shear power, while in large-scale devices the much less velocity gradient due to larger sizes results less values.
b) unlike in the large-scale vessels no free turbulence facilitating mass transfer is evolved because of the less Reynolds number value due to the less size of the experimental device.
c) flow of high viscosity broths can slow down so much in the large-scale vessels that inadequately mixed areas are formed even when newer agitation systems are applied. No secondary dispersion can occur along the baffles which may mask the deficiencies of the impeller type itself in pilot plant fermentors.
d) Due to the high pressure of large-scale fermentation vessels bubble size affecting oxygen transfer is decreased, solubility of gases, the density of liquid-gas mixture and coalescence of bubbles are increased.
e) In large-scale vessels the agitation time and cross-sectional air flow velocity are increased with the same specific air volume and v/v input.

Kipke's example can be cited for demonstration of the increase in agitation time, namely if a given agitation time can be produced in a laboratory fermentor of 5 liters with P/V = 1 kW/m^3 power/unit volume, in a large-scale fermentation vessel of 50 m^3 the same agitation time can only be achieved with 5000 kW power! The differences in magnitude show the problems of scale-up and the limitations of the application of experimental results.

The scales are changed considerably during scale-up even during entirely proportioned geometric scale-up. For example, if the size of a model is increased only by tenfold, its surface increases hundred-fold but its volume increases thousand-fold. That is why even the name of similarity criteria is false since their application provides merely partial similarity. Due to the unequal change in size and value ratios, physical, geometric, kinetic and dynamic similarity criteria cannot be selected simultaneously.

Due to the lack of a generally valid procedure many scale-up processes had been developed.

The most often is to rely on power requirement per volume (P/V), volumetric oxygen transfer coefficient (k_La), gas-holdup and shear stress (viscosity/velocity gradient).

The variation of chosen considerations may lead to great differences. That is why many researchers' opinion is that results do not comply with the technical and economical requirements of biotechnology and can only be informative data for developers of sizing procedures. According to M. Charles: "in practice, scale-up strategies tend to be »mixed bags« engendering art enpricism, conventional wisdom and (frequently) wishful thinking" (4).

For the optimization of fermentation process i.e. for the achievement of largest possible yields even distribution of the dissolved oxygen (DO), medium and ingredients added during fermentation and optimum mass transfer conditions should be provided besides application of high productivity microorganisms and adequate mediums.

Adequate oxygen level can be achieved by both proper air volume input and its best possible dispersion i.e. the least oxygen bubbles and their most even distribution. To achieve this, adequate agitation power, air volume and an agitation system is necessary which is suitable for effective dispersion of air, for creation of intensive circulation and for even distribution of bubbles.

The level of dissolved oxygen (DO) can be measured during fermentation and can be adjusted by the regulation of power input and/or air volume – if there are adequate quantities.

Considering the sometimes high values e.g. in case of penicillin fermentation the efficiency of the process is a significant factor and it is affected by the structure of the agitation system besides the power input and adequate air volume. The problem is that however, we can calculate – at least approximately - the diameter and power requirement of the agitators and the air volume by the available procedures and relations, these data provide very little information on optimum design

Similarly to the added nutrients oxygen transfer occurs on the interfaces of air bubbles and medium particles and through the walls of microorganisms' cells. According to the double layer theory thinning of the laminar layers on the interfaces by creating turbulent liquid flow and shear stress due to this turbulence is necessary for the acceleration of mass transfer.

It is well known that vortexes are arisen during real liquid flow due to their viscosity and because of the collision of these vortexes turbulence proportional to the velocity of flow occurs. Shear stresses proportional to the velocity of flow occur between turbulent liquid layers which have important role in oxygen (DO) and mass transfer: these stresses thin the laminar layers of transferring interfaces, micromix the components of broths, disperse oil particles and air bubbles facilitating and accelerating mass transfer processes, disintegrate clots and in some cases cause morphological changes in the structure of microorganisms as in the case of penicillin fermentation.

The magnitude of hydrodynamic forces created by agitation can be seen from the fact that according to the calculations of Van't Riet and Smith the centrifugal acceleration behind the vortexes created by impellers can be seven-hundredfold of the gravity (5).

Shear powers may, however, damage microorganisms which are especially sensitive, contribute to the creation of stable liquefied foams which generally decrease oxygen transfer, and aeration of carbon-dioxide and other gases partially on direct way and partially due to antifoaming oils.

Microorganisms on the interface of vortexes can be disrupted while those in the centre of the vortex may abrade each other.

Consequently the intensity of agitation should remain within a narrow range for keeping damaging effect at a minimum level while maintaining maximum advantages and this is the purpose of optimization.

The characteristics of fermentation processes may vary due to the differences in viscosity, foaming properties, density, etc. A typical feature is that while foaming generally decreases the oxygen transfer, in certain cases the increased persistence of bubble may raise the rate of oxygen transfer in liquefied foams, and antifoaming agents may decrease it.

Some microorganisms such as oxytetracycline producers do not need agitation, and their fermentation can be made in slim vessels without agitator which are much cheaper.

Air inflated into the broths dispersed, distributed and circulated in the medium of the fermentor by the agitation system proportionally to power input. Due to this procedure the volume of the medium is increasing and oxygen will be dissolved in the medium depending on the intensity of agitation, characteristics of medium and surface gas velocity v_s. The degree of oxygen transfer is depending on the viscosity of the medium the characteristics of air, medium and microorganism system, and coalescing properties of air bubbles. The entrapment of air and this way oxygen fusion can decrease greatly due to increased viscosity and bubble coalescence (Van't Riet, Smith 5., and Buchholz et al. 6.)

Besides the mentioned air entrapment broths volume can also be increased by the often very intensive foam formation depending on broths characteristics. Stable so called liquefied foams are formed on more viscous mediums such as in penicillin fermentation. Contrary to the air entrapment mentioned above this foam formation is detrimental since it limits oxygen transfer partially directly and partially through antifoaming agents, however rarely the opposite situation may occur.

Consequently maintaining the air input and power within a narrow range based on continuous instrumental measurement of fermentation parameters is an important requirement for dissolving oxygen and nutrients and also their transfer to microorganisms with adequate rate.

Considering economical importance of mass transfer problems arising from increasing size of fermentor vessels more efficient complex agitation systems were developed with lower power requirement, better dispersion and including far better circulation levels. In their paper published in 1987 B.C. Buckland et al. had revealed that application of Lightnin and Prochem propeller agitators providing better "top to bottom" blending of viscous broths is cost effective due to saving power input and/or by the application of these agitators the production can be increased because of the higher cell concentration due to better agitation (Buckland et al. 7). Papers on complex agitation systems have been published more often since the beginning of 1990s (Chemineer, 8).

During their developmental activities manufacturers besides the relations for calculation of main sizes and powers could mainly rely on experimental results which, however, provided merely informative results due to the above reasons. It should also be noticed that uniformization, development of systems which can be distributed widely and production of their own types and licensed products are the main interests of manufacturers. All these factors eventually lead to negligence of specific requirements of fermentations. Exerting themselves to protect their trade secrets, factories generally provide very little possibilities for carrying out profound studies fermentation process by the professionals of manufacturers.

According to the above characteristics and requirements of fermentation processes may differ very much. It follows from the above written that besides applied technologies and materials the success of fermentation processes also depends upon whether the agitation system used during fermentation is adequate for the specific requirements of fermentation. Consequently the characteristics, dispersion and circulation capabilities of agitation levels should be adjusted to the features and requirements of the fermentation which may, conversely, vary because of the differences between the experimental and industrial levels. In case of viscous liquids experimental levels do not provide data and indications of adequate accuracy for the adjustment. Although the analysis of experimental data has been improved very much since V. Charles through the application of computers, lesser changes may also be of significance due to the large volume of industrial fermentors and these changes cannot be designed with adequate accuracy.

It follows from the above that there is no adequate procedure available for actual optimization of industrial agitation systems and for establishment how much an agitation system can be considered optimal for a certain fermentation procedure.

The efficiency of an agitation system is depending on its structure and considering fermentation it is depending on how the agitation system's levels use power input for dispersion and circulation and how adequate this is for the requirements of a given fermentation process.

A solution for this problem may be if manufacturers provide special separated parts for the particular levels of the agitation system which could be fixed on the system by screw this was changing the characteristics of agitation. It would not be especially difficult to solve since power input is proportionally changed with the fifth degree of the diameter of the agitator and the characteristic of flows can be modified within a wide range merely with changing the shape and angle of blades of the impeller.

The application of this idea requires some change in viewpoint according to the following:

1. It cannot be expected that a manufacturer will provide an "optimal" agitation system, but it is expected to provide an agitation system of which perfusion properties can be modified within a wide range with auxiliary parts. It would be, of course, the obligation of the manufacturer to provide detailed user manuals and information sheet for the expectable effects of these auxiliary parts and provide professional assistance for testing on demand.
2. The obligation of the user would be the actual optimization of the agitation system according to provided directives and thorough analysis of the effects of the auxiliary parts. Inclusion of factory professionals in the selection of the most efficient system may solve the problems of scale-up sometime mentioned as dream by M. Charles (4) and may assist the establishment really optimal agitation systems.

Biogal

Pharmaceuticals established for the production of antibiotics together with research centers has endeavored to develop its devices since the beginning. According to the knowledge learned in the international symposium in Prague in 1964 where both European and US professionals attended, BIOGAL Pharmaceutical was the first pharmaceutical company applying two-turns driver engine which increased power utilization by 30-40%. At the beginning of 1970s the company changed the systems with Rushton agitators which had asymmetric structure, and 20% better power on the lowest level. This was due to the cognition of the fact that in the applied asymmetric systems the efficiency of the lower agitators compared to the upper ones was considerably decreased by the function of dispersion. Since the beginning of seventies the company had started to apply a complex system including propeller agitators and Rushton turbines and with this method narrow OTC fermentors without agitators could successfully be adapted for penicillin fermentation.

Based on these experiences also considering the construction of BIOGAL's newer complex agitation systems it can be concluded that there are more possibilities for the increase of efficiency and optimization of agitation systems through the application of modifiable impellers recommended above.

Conclusions

Conditions of optimization of the aeration-agitation systems of large-scale fermentors in case of viscous broths:

1. Providing flow modifying parts for the agitations system for variation of dispersion and circulation capabilities and adjustment for the requirements of a specific fermentation process.
2. Evaluation of the results of variation by fermentation professionals and choosing optimum variation.

Considering these on a long term basis may lead to gain profound knowledge about specific requirements of fermentation processes and industrial optimization may become unnecessary in the future.

NONATION

DO	dissolves oxygen
P/V	power/volume
k_La	volumetric oxygen transfer coefficient
v_s	gas velocity

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