Study on Suspension of Solid Particles in Reactors with Mechanical Mixing Systems

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In the frame of present work reviewed the principals results of researches realized for identification of vessel form influence about the suspending process of solid particles. To improve the suspending operation efficiency is suggested a new type of reactor, characterized through his spherical form, as well as through the presence of a cone located to the downside of the vessel. Through experimental determinations are demonstrated the superiority of spherical reactor, as compared to the cylindrical flat-bottomed type. At the same time, there are established calculus relations for impeller complete suspension speed, as well as for power number when using fully filled spherical vessels with radial baffles.

Keywords: mixing, suspending, impeller, flow rate, solid particle

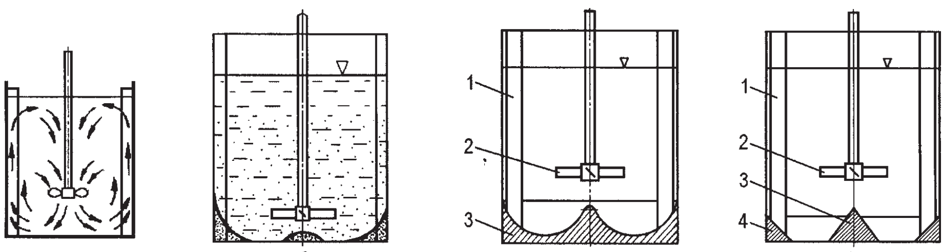
The realization of solid particles suspensions in vessels with mechanical mixing devices is a frequently achieved process in the equipment of process industries [1, 2]. Usually, the suspensions of solid particles are obtained in flat bottomed cylindrical reactors, with radial baffles (fig. 1.a). Although this geometry is simple and easyly obtained, it must be mentioned that its characteristics do not recommend it to be used in this domain.

Thus, the efficiency of this type of equipment is low, because motionless zones of unsuspended solid particles appear below the impeller, and at the tank bottom-to-wall junction, owing to induced recirculation loops (fig. 1.b). The loads of unsuspended particles are very persistent and require a considerable growth of impeller speed and, implicit, of power input, for their setting in suspension. In this situation, for the efficiency improvement of the process of mixing, that it is for the reduction of impeller working speed, is necessary the perfecting of the vessel form as well the perfecting of the impeller form.

The first solution for the improvement of suspending process efficiency consists in the modification of the geometry of the vessel, so that to be avoided the sudden two changes of the current of fluid direction. The ideal form of the vessel for the suspension of solid particles was proposed for first time [3] and then, developed in [4]. The solution consists in the use of so-named reactor with a "fully profiled bottom" (fig. 1.c), whose form corresponds to the flow pattern created by an impeller with axially descending discharge (fig. 1.a), which allows a very good entrainment of the solid particles. Unfortunately, this form is too complex to be easily manufactured and it would be unlikely for it to gain universal industrial acceptance.

Grasping this deficiency, Chudacek proposes an approximation of "fully profiled bottom", replacing the toroidal surfaces with conical surfaces. The conical surfaces are located in the critical zones of the vessel bottom, which are below impeller and at the tank bottom-to-wall junction. This simpler variant named "the cylindrical cone-and-fillet-bottom tank" has comparable performances with reactors with "fully profiled bottom" and can be easily realized. More than that, it can be adapted to the flat-bottomed reactors already in use (fig. 1.d).

With regard to the efficiency of suspending operation, it is show that for the touch the complete suspension to 6.1% solid particles concentration and 0.33·D distance from bottom of impeller, the vessels with the fully profiled bottom and with the cone-and-fillet-bottom need just 45%, respective 67% from the input power for the vessel with the flat bottom [4]. Also, it is noticed that if the solid particles have bigger sizes, the performances of vessel with the cone-and-fillet-bottom are closer to one of the vessel with the fully profiled bottom. Apart from the saving of energy, the decrease of suspension speed has also other favorable effects: smaller capital investments for the mixing device, due to smaller necessary power; a smaller impeller abrasive wear, because this is proportional with the impeller speed.



- a - - b - - c - - d –

Fig. 1. Types of cylindrical vessels for suspension of solid particles: a- flow pattern created by an impeller with axially descending discharge into a cylindrical vessel with flat bottom and radial baffles; b- location of the last loads of unsuspended particles in a cylindrical vessels with flat bottom, endowed with an impeller with axially descending discharge (six 45°- pitched blade turbine);
c- vessel with the "fully profiled bottom"; 1-baffles; 2- impeller; 3- fully profiled bottom; d- vessel with the "cone-and-fillet-bottom": 1-baffles; 2- impeller; 3- con; 4- fillet

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As for the used impellers in the processes for the solid particles suspending, all specialty literature emphasizes the superiority of impellers with axially descending discharge versus the one with axially upward discharge or with radial discharge.

Among the impellers with axially descending discharge the best results are mentioned related to the propeller type impellers and the impellers Ekato-Isojet, but at the same time is underlined the difficulty of such impellers [5]. For this reason they did researches which had as the objective the substitution of these impellers with simpler impellers from constructive viewpoint, but with comparable results, as is for instance, the six 45°- pitched blade turbine.

Theoretical

During the solid particles suspension, with the increase of impeller speed, can be defined two main states of suspension: the complete suspension, in which all particles are in move, and the homogenous suspension, in which the concentration of particles is uniform in the whole vessel. It must be mentioned that until to reach complete suspension speed, the surface of solid particles is not efficiently used for the transfer of substance. On the other hand, above this speed, the rapidity of processes increases in insignificant way, while the consumption energy has a very big increase.

In the frame of this work the author proposed the settlement of calculus relations for the complete suspension speed in the case of spherical reactors and the verification of theoretical results through experimental researches.

The first expression for this speed is established considering avoiding sedimentation of a particles found out in suspension, to reach the equilibrium between force of entrainment the vertical, F, and force of gravitation, G:

$$F = G. \qquad (1)$$

The relation (1) can be also writen in the form [6]:

$$c \cdot \frac{v^2}{2} \cdot \rho \cdot \frac{\pi \cdot d_p^2}{4} = \frac{\pi \cdot d_p^3}{6} \cdot g \cdot \Delta\rho, \qquad (2)$$

where:

c is the entrainment coefficient of particle (for a spherical particle $c = 0{,}4$);

υ – upward liquid speed;

ρ - density of liquid phase;

$\Delta\rho$ - difference among the densities of liquid phases;

d_p - average size of solid particles;

g – gravitational acceleration.

In order that the particle remains suspended, the upward speed of fluid must be at least equal with the settling speed of solid particle:

$$\upsilon = w_s. \qquad (3)$$

The settling speed of a solid particle group, w_{ss}, can be expressed through the settling speed of a single solid particle, w_s, and the volumetric concentration of the solid phase φ_υ [7]:

$$w_{ss} = w_s \cdot (1 - \varphi_v)^{2,4}, \text{ pentru Ar} > 10^6, \qquad (4)$$

and the minimal specifical power for the avoiding of solid particles sedimentation has the form:

$$\varepsilon = \varphi_v \cdot w_{ss} \cdot g \cdot \frac{\Delta\rho}{\rho}. \qquad (5)$$

Further on, admitting the hypothesis that all the energy provided by the impeller is used to keep the solid particles suspended, it can be written :

$$\varepsilon = Ne \cdot \frac{n^3 \cdot d^5}{\pi \cdot D^3/6}, \qquad (6)$$

where:

N_e is the power number (the Newton criterion);

n – impeller speed;

d – impeller diameter;

D – vessel diameter.

Replacing the relations (2) ÷ (6) in the relation (1) is obtained:

$$n = \frac{0{,}985 \cdot D \cdot d_p^{0{,}166} \cdot (g \cdot \Delta\rho/\rho)^{0{,}5} \cdot \varphi_v^{0{,}33} \cdot (1-\varphi_v)^{0{,}8}}{N_p \cdot d^{1{,}66}}. \qquad (7)$$

With help of relation (7) it can be calculated the minimum complete suspension speed of solid particles existing in a vessel, being applicable only for conditions Re $\in (10^3; 10^5)$ or Ar $> 10^6$, where Ar is the Arhimede's number. To use this relations for the spherical reactors, one must know the correlation $N_p = f(\mathrm{Re})$, for turbulent regime and for a given type of impeller [5].

The second expression for complete suspension speed of solid particles is established admitting the hypothesis that the suspension of solid particles from the bottom of vessel is produced thanks to local eddies, with a particular critical size. The eddies with the smaller sizes than the critical one have not the necessary energy to move the particles which are in rests, and the eddies with the elder sizes have a diminished probability to meet and suspend the particles.

In the isotropic turbulence case, the variable speed of critical eddies, u, can be expressed through proportionality relations [6]:

$$u \sim \sqrt[3]{\frac{\varepsilon \cdot d_p}{\rho}} \qquad (8)$$

where ε is the energy provided by the impeller on the unit of volume (6).

On the other hand, from the equation of equilibrium of the forces for an element of volume, it was shown that [8]:

$$u^4 = \frac{3 \cdot c \cdot d_p \cdot w_s \cdot g \cdot \Delta\rho}{\rho} \cdot \varphi_v \cdot (1-\varphi_v)^{2,4}. \qquad (9)$$

Knowing that the sedimentation speed of a solid particles is [9]:

$$w_s = 1{,}74\sqrt{\frac{d_p \cdot g \cdot \Delta\rho}{\rho}}, \text{ for Re} \in \left[10^3; 10^5\right], \qquad (10)$$

from the equations(8) ÷ (10) results:

$$n = k \cdot \frac{D \cdot d_p^{0{,}167} \cdot \varphi_v^{0{,}25} \cdot (1-\varphi_v)^{0{,}6}}{Ne^{0{,}33} \cdot d^{1{,}666}} \cdot \sqrt{\frac{g \cdot \Delta\rho}{\rho}}. \qquad (11)$$

Relation (11) is a semi-theoretical relation, because to define it shall be necessary experimental researches to establish the coefficient k. It can be applied for the calculus of complete suspension speed in the case of spherical vessels and is valid for Re $\in [10^3; 10^5]$.

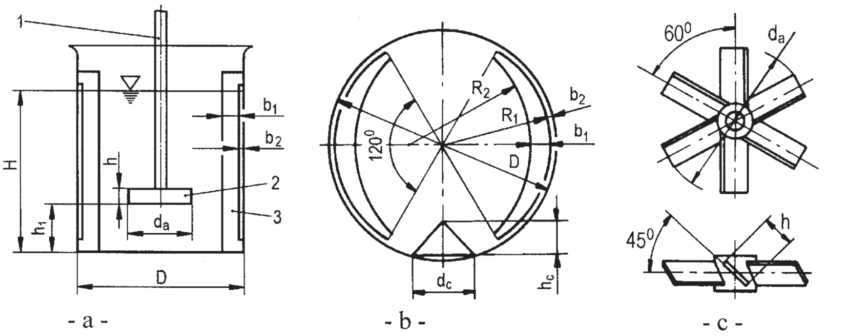

Fig. 2. Geometric parameters of vessels and impellers used for the experimental determinations: a- cylindrical vessels: 1- shaft of impeller; 2- impeller; 3- baffles; D = 0.250 m; d_a = 0.075 m; h = 0.015 m; $h_1 = d_a$; H = D; b_1 = 0.1D; b_2 = 0.02D; b- spherical vessel: D = 0.250 m; R_1 = 0.48D; R_2=0.55D; b_1 = 0.1D; b_2 = 0.02D; d_c=0.25D; h_c=0.15D; c- the six 45°- pitched blade turbine: d_a = 0.075 m; h = 0.015 m

Experimental part

The experimental researches aims to the determination of vessel form influence to the complete suspension speed, using "the 1s criterion" [10]. In accordance with this criterion the suspension is considered complete when the solid particles do not remain motionless at the bottom of vessel more of a second.

There are used a cylindrical vessel and a spherical vessel, with the geometry presented in the figures 2.a and 2.b. The two vessels had equal diameters (*D* = 0.25 m) and they were equipped with three radial baffles; downside of spherical vessel were located a cone to manage the current of liquid.

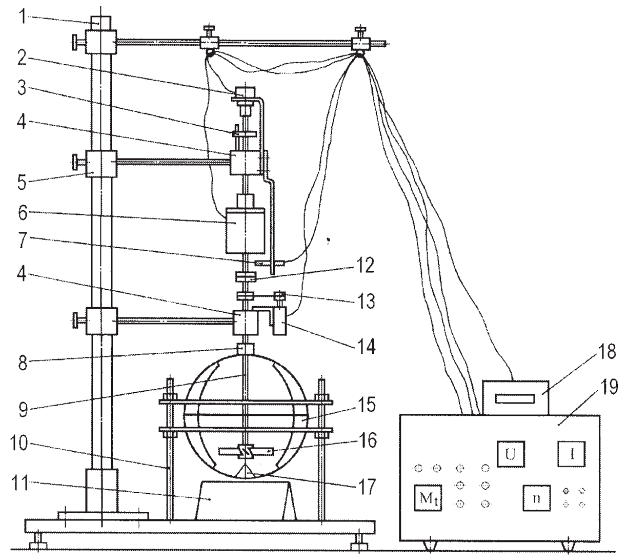

Fig. 3. Experimental set-up: 1- column; 2- resistance transducer; 3- dynamometer with spiral spring; 4- bearings; 5- link; 6- engine; 7- photoelectrical sensor; 8- hydraulic shut-off; 9- shaft; 10- support; 11- mirror; 12- coupling; 13- driving belt;14- tacho-generator; 15- baffles; 16- impeller; 17- cone; 18- electronic speed measuring device; 19- control panel

Taking into account the recommendations from the specialty literature, for the experimental determinations an impeller with six pitched blade to 45° was used (fig. 2.c), with the diameter $d_a = D/3$, located to a distance against the bottom of the vessel $h_1 = 025 \cdot D$. The experimental set-up (fig. 3) allows a continuous variation of the impeller speed in the range of $0 \div 500$ min^{-1} [11]. At the same time, it can be measured the torque of impeller shaft, with a dynamometer with spiral spring.

The liquid phase was water ($\rho=10^3$ kg/m^3; $\mu = 10^{-3}$ Pa·s) and the solid phase was sand (ρ_s = 2600 kg/m^3) with a mean particle size d_p = 0.325 mm. The spherical vessel was fully filled with liquid and in the cylindrical vessel the liquid volume was equal to that from the spherical vessel.

Results and discussions

The results of experimental researches, presented in the figure 4, show that the complete suspension speed obtained through the use of spherical vessel is smaller than in the case of the use of cylindrical vessel with approximate 8%. Knowing that the mixing power depends on the cubic speed on can rely upon a substantial decrease in the energy consumption.

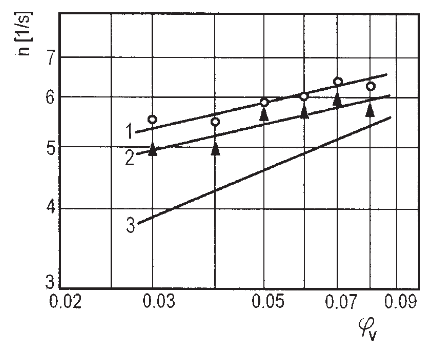

Fig. 4. Dependence between the complete suspension speed ("the criterion 1 s") and the solid phase concentration, for different types of reactors: 1- cylindrical reactor with the flat bottom; 2- spherical reactor with cone to manage the current of liquid; 3- results obtained by applying relation (7)

At the same time, it is obtained the final form of equation (11):

$$n = 0{,}94 \cdot \frac{D \cdot d_p^{0{,}167} \cdot \varphi_v^{0{,}25} \cdot (1-\varphi_v)^{0{,}6}}{Ne^{0{,}33} \cdot d^{1.666}} \cdot \sqrt{\frac{g \cdot \Delta\rho}{\rho}}. \qquad (12)$$

As it can be observed in the figure 4, the results obtained with theoretical relation (7) are lesser than the experimental results obtained for the spherical reactor, because of simplified hypotheses: all the energy provided by the impeller is used to keep the solid particles suspended; the solid particles are spherical; solid particles are fully wetted; the solid particle friction inside the reactor is small.

With regard to the expression of power input, $N_p = f(\mathrm{Re})$, in accordance to the existing results from the specialty literature related to the utilization of the six 45°- pitched blade turbine in cylindrical open vessels with radial baffles, the power number is expressed in turbulent regime through relation:

$$N_p = 2 = constant. \qquad (13)$$

In this work has been determined that the value of power number in turbulent regime when this impeller is used in a spherical fully filled vessel with baffles and the cone for manage of flow:

$$N_p = 4{,}3 \cdot Re^{-0{,}1}. \qquad (14)$$

So, in the case of fully filled spherical vessels, the impeller power number has a tendency of continuous decrease compared to the value given by the relation (13) for the open cylindrical vessels.

We have to specify that the previous observation contradicts the assertions of other researchers who support the idea that the impeller power number under turbulent regime of flow remains constant. However, this finding which at first sight seems surprising can be explained by the fact that the upper part of sphere, which plays the role of a lid, optimizes the flow pattern in the fully filled spherical vessel.

Conclusions

In the frame of present work there were reviewed the main results of researches realized for identification of vessel form influence on the suspending process of solid particles.

To improve the suspending operation efficiency is suggested a new type of reactor, characterized through its spherical form, as well as through the presence of a cone located to the downside of the vessel.

The improved efficiency of the spherical reactor is due to its constructive shape, having no contour discontinuities at the wall-bottom and wall-lid junctions, as would be the case for cylindrical vessel.

Through experimental determinations is demonstrated the superiority of spherical reactor, as compared to the cylindrical flat-bottomed type. At the same time, there are established calculus relations for impeller complete suspension speed, as well as for power number when using fully filled spherical vessels with radial baffles.

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