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Mixing system for highly concentrated fine-grained suspensions

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The mixing equipment for highly concentrated fine-grained suspensions must be designed differently from the equipment in which a suspension with a low concentration of the solid phase or bigger particles is mixed. It is due to the different rheological properties of the suspensions. In this work we are trying to find a suitable mixing system for a highly concentrated fine-grained suspension. The aim was to determine an effect of particular geometrical parameters of the tested mixing systems on a suspension process, especially from the energetic viewpoint. The energetic costs of all the used mixing systems were compared on the basis of the power consumption which was necessary for reaching the state of sufficient suspension movement in the whole mixed bulk. As a result, it was confirmed that multistage impellers can be used even in standard vessels (with a liquid level height equal to a vessel diameter) with a profit. During experiments, the state of sufficient movement was determined by a visual observation of the suspension at the vessel bottom, at the wall and also at the suspension level.

Keywords: Mixing, suspension, high concentration, fine particles, rheology.

INTRODUCTION

Mixing of the suspension is a frequent operation which occurs in many industries, such as in chemical, food or ceramic industry. In many applications, especially in ceramics, highly concentrated fine-grained suspensions have to be mixed. These suspensions behave differently in comparison with the low-concentrated suspensions or the suspensions with bigger particles, as it can be seen from Fig. 1, where the tested aqueous suspensions of chalk with different amounts of solid phase are compared[1].

Most of the fine-grained and highly concentrated suspensions behave like viscoplastic fluids and their rheology can be described using the Bingham model. In our case, it has been proved that the Bingham model can be used in the ranges of low and high values of shear rate only, but the transition region between these ranges has to be described using some other model. To be able to describe the rheological behavior of the tested suspensions in the whole range of shear rate, a combined Bingham model has been proposed by Rieger and Moravec[2]. The mathematical description of the combined Bingham model is

$$\tau = \frac{\tau_{01} + \mu_{p1}\dot{\gamma}}{\left[1 + \left(\dfrac{\tau_{01} + \mu_{p1}\dot{\gamma}}{\tau_{02} + \mu_{p2}\dot{\gamma}}\right)^{b}\right]^{\frac{1}{b}}} \tag{1}$$

where the parameters with indexes 1 stand for the low shear rate values, the parameters with indexes 2 hold for the high shear rate values and the parameter b characterizes the transition range. The parameters of all the tested suspensions were determined before the suspension measurements started. Their values were presented in[1].

Regarding the difference in the flow properties, the mixing equipment for the highly concentrated fine-grained suspensions must be designed differently from the equipment with the low concentration of the solid phase or with bigger particles in the suspension. This work aims to find a suitable mixing system for the mixing of such highly concentrated fine-grained suspensions.

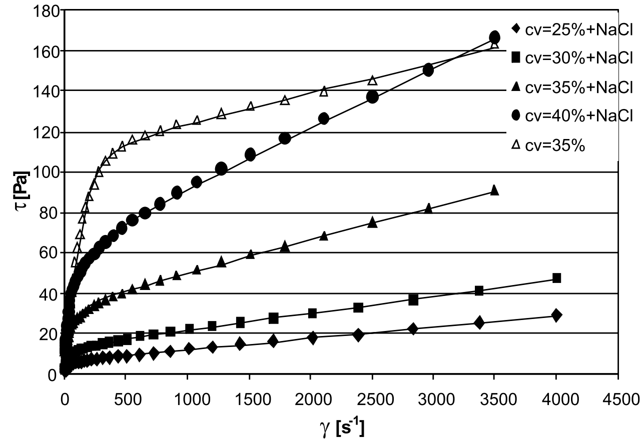
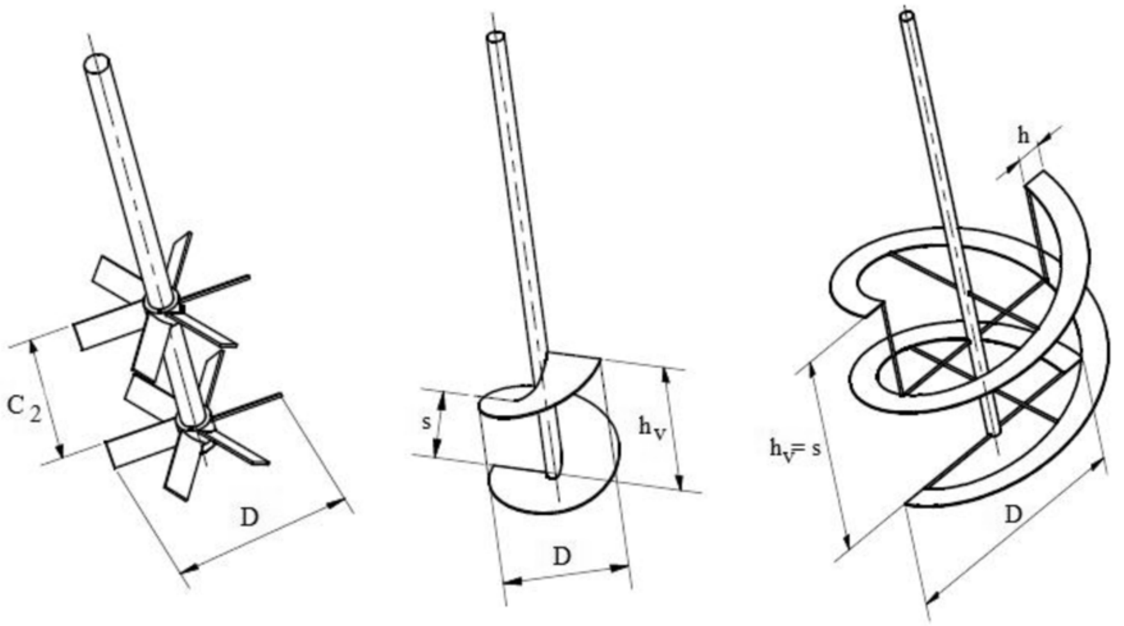


Figure 1. Dependences of shear stress τ on shear rate γ of tested suspensions

EXPERIMENTAL

Mixing system

Several mixing systems consisting of different types and sizes of impellers were used. A down pumping pitched six-blade turbine with pitch angle 45° of two diameters $D = 100$ mm and $D = 66.7$ mm were used as the first two mixing systems (1x6SL100-C_1, 1x6SL67-C_1). The clearance of the turbines above the vessel bottom varied in the range $C_1 = (0.25 - 1.25)D$. Two such impellers of the same diameter were then used for another mixing system – the multistage impeller (2x6SL100-C_1-C_2, 2x6SL67-C_1-C_2 – Fig. 2a). The distance between both turbines was changed in the range $C_2 = (0.5 - 1.75)D$. Also some agitators were tested during the experiments. It was an eccentrically placed screw agitator (SE) of a diameter $D = 75$ mm (Fig. 2b), the same screw agitator with a draft tube (SUV – Fig. 3) and a helical ribbon (PAS) of a diameter $D = 190$ mm and a ribbon width $h = 20$ mm (Fig. 2c).



a) multistage impeller b) screw agitator c) helical ribbon

Figure 2. Different impellers used in the experiments

Other equipment

All experiments were carried out in a transparent cylindrical vessel with a dished bottom. The vessel diameter was equal to T = 200 mm and the liquid level was $H = T$ (Fig. 4). Four or two radial baffles of a width $b = 0.1T$ were used in configurations, where turbines were used for mixing. The number of baffles didn't influence the results. At both configurations of the screw agitator and also during the measurements with the helical ribbon, the baffles were not used.

Suspension

The suspensions were created from water with 5% b.w. of NaCl and the chalk. The mean volumetric concentration of the chalk varied from 25 to 40% and the mean volumetric diameter of the particles was d_p = 4.6 mm. The particle size distribution of the chalk can be seen in Fig. 5.

NaCl dissolved in the water had a positive effect on the flow properties of the suspensions as it could be seen from the comparison of the behavior of the suspensions with 35% of the solid phase with and without NaCl (see Fig. 1). NaCl in suspension modified the particle surface charge density. There took place a change in the interparticle interaction forces in the suspension, which

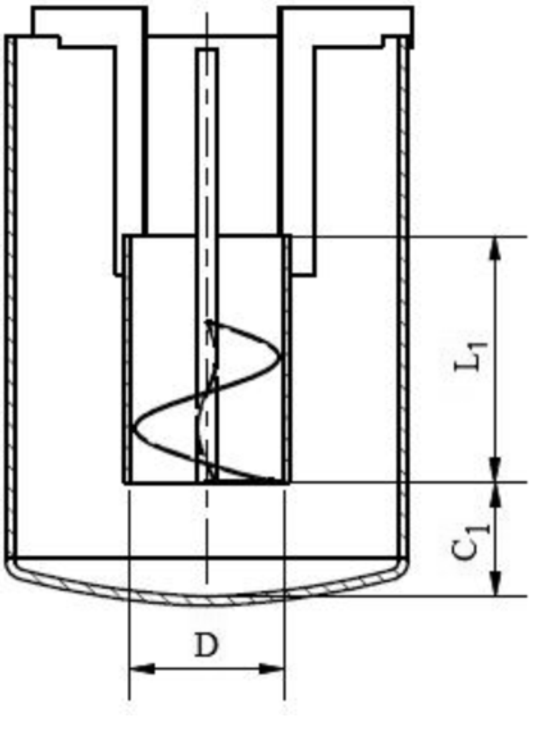


Figure 3. Screw agitator with a draft tube

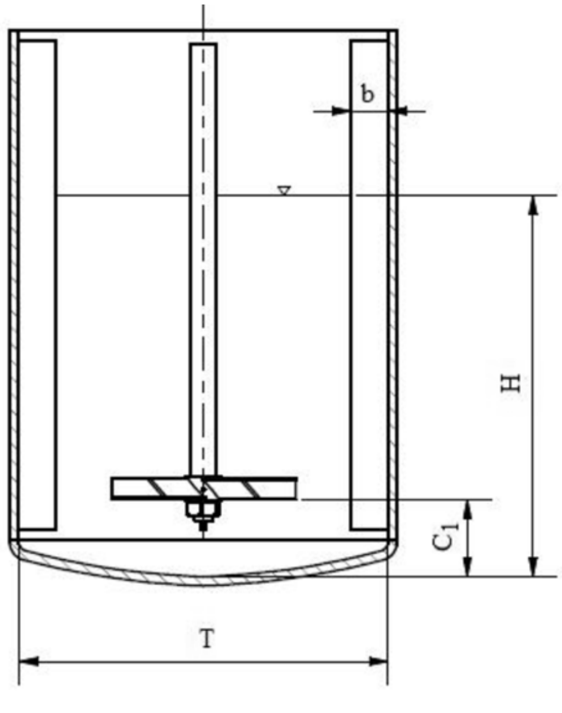


Figure 4. Experimental layout

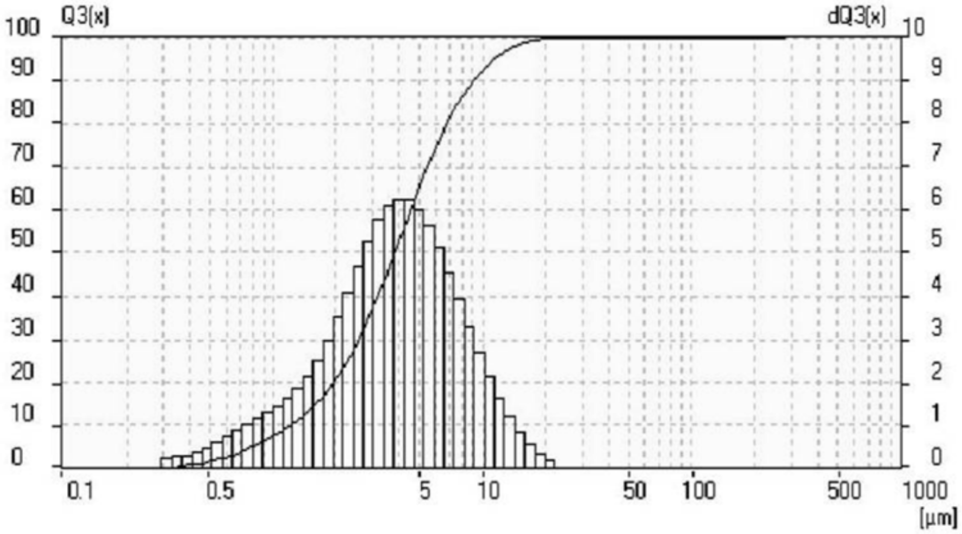


Figure 5. Particle size distribution of the used solid phase

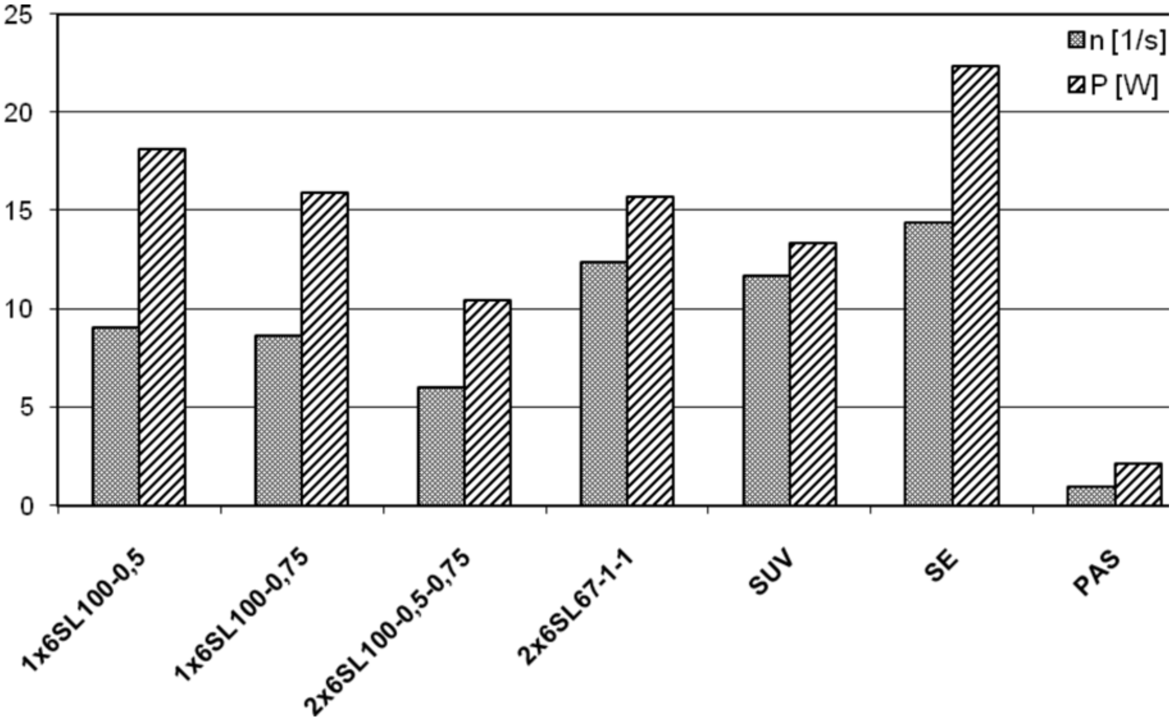


Figure 6. Impeller speeds and power consumptions of the most suitable mixing systems

led to the increase of kinetic energy and the aggregate stability of the system. As a result the suspension had much better flow properties.

RESULTS

At the first step the most suitable mixing systems were chosen during the experiments in suspension with 35% of the solid phase (with NaCl) according to a power consumption that was necessary for reaching the sufficient movement in the whole volume of the suspension. The movement of the particles was observed visually at the vessel bottom, at the vessel wall, and also at the suspension level. The sufficiency of the movement was defined as a state, in which the flow of the particles was observable during a short time period (approximately 2s) at all the above mentioned places.

During the visual measurements, the power consumption of the impeller in the suspension was determined from the torsion moment (torque) and the rotations of the impeller. The torque was measured using a rotary table on which the vessel was placed. The torque of the impeller was transmitted through the suspension to the vessel respectively to a rotary table according to the principle of action and reaction. The rotation of the table was blocked using a rod, which was strained in flexion thanks to the design of the equipment. The flexion strain respectively the corresponding voltage was measured using strain gauges connected to a bridge. The data were recorded using the A/D converter to the PC and recalculated using the calibration function to the torque values. The comparison of the obtained power consumptions and also the impeller speeds at the mentioned state is shown in Fig. 6. Only the most suitable systems are presented in the figure. The helical ribbon may seem to be the best choice for mixing, but it is not so because the suspensions just rotated in the vessel. It was not mixed in axial direction at the shaft. This could be seen thanks to the visual observation of the

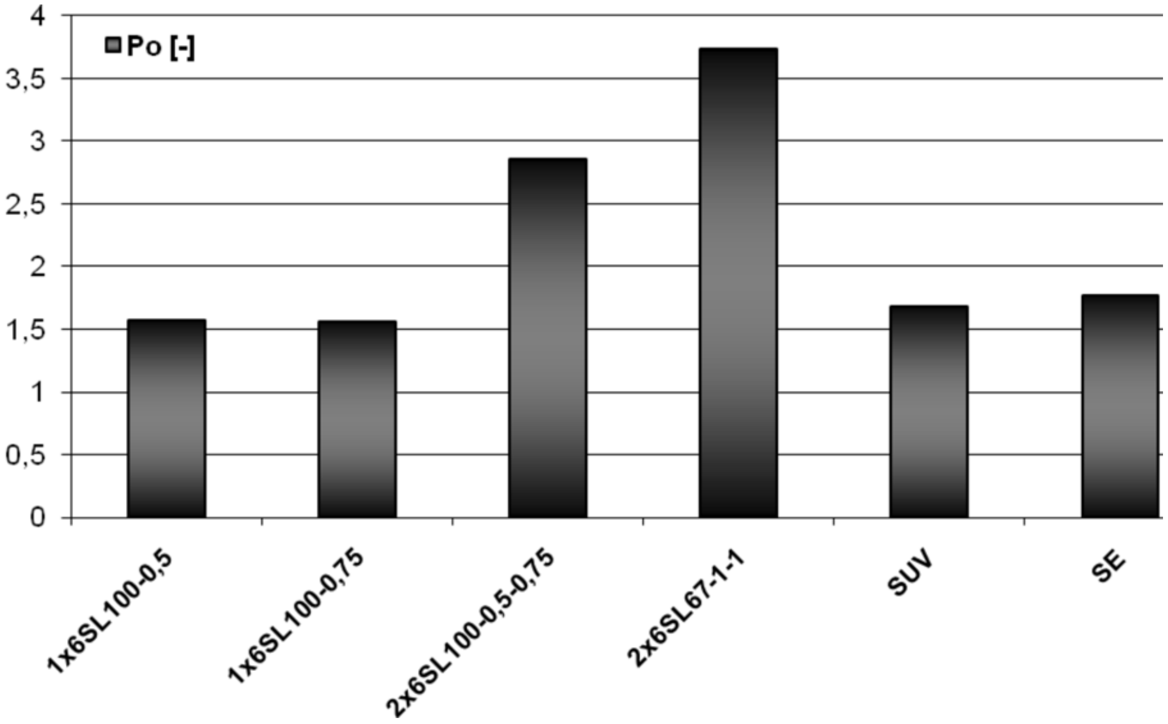


Figure 7. Power numbers of the most suitable mixing systems

suspension flow at the vessel bottom and also at the liquid level. With respect to this information, the most suitable mixing system for the tested suspension was created by the multistage impeller, which consisted of two pitched six-blade turbines of diameter D = T/2. The lower turbine was placed in the height C_1 = 0.5D above the vessel bottom and the distance between the turbines was C_2 = 0.75D (2x6SL100-0.5-0.75). Good results were also obtained when the screw agitator in a draft tube was used (SUV). The power consumption of the multistage impeller consisting of smaller turbines (T/D = 3 – 2x6SL67-1-1) was practically the same as the power consumption of a single turbine of bigger diameter (1x6SL100-0.75). The difference is only in the required impeller speed. The eccentrically placed screw agitator belongs then to the worse group of impellers.

For all impeller systems, the power number was computed at the impeller speed at the state of sufficient movement in the whole bulk. The following equation was used

$$Po = \frac{P}{\rho n^3 D^5} \tag{2}$$

The obtained results are shown in Fig. 7. If the values are compared with the power numbers of the impellers which were determined in pure liquid[3] it can be seen that the difference is very small and is caused just by an inaccuracy in the calculation of the power number according to the eq. (2). Here, the mean density of the suspension calculated from the equation

$$\rho = c_v \rho_s + (1 - c_v)\rho_l \tag{3}$$

was used. However, the density of the suspension is not the same in the whole bulk due to different amounts of particles in different zones of the mixed bulk. The off-bottom distance of the mean density zone changes with the size of the particles used in the suspension and also their concentration. This was presented for example by Rieger and Rzyski[4]. Therefore, the values of the power numbers differ in a close range, but their values are always near to the value of the power number obtained from pure liquid measurements (for example 1.81 for the pitched six-blade impeller of diameter D = T/3).

Five of the most suitable mixing systems obtained from the previous results (i.e. 1x6SL100-0.5, 1x6SL100-0.75, 2x6SL100-0.5-0.75, 2x6SL67-1-1, and SUV) were then tested in suspensions with a different amount of the solid phase. The impeller speeds and the power consumptions necessary for the sufficient movement in the whole bulk of the suspension were compared again. The results are presented in Fig. 8. It can be seen, how the power consumption and the impeller speed of different mixing configurations changes with the amount of the solid phase in the suspension. In the figure, the data for the SUV system at the concentration 40% are missing. This system was unusable at such highly concentrated suspension, because the air was sucked into the suspension from the space above the liquid level at the shaft before the suspension started to move at the whole bulk.

CONCLUSIONS

From the results, it is clearly seen that multistage impellers can be used even in standard vessels (with a liquid level equal to a vessel diameter) with a profit. With a growing amount of a solid phase in suspension the profitability increases, especially in the case when the diameters of the turbines, the distance between the turbines, and also the distance above a vessel bottom are chosen properly. In the presented figures, it can be seen that the most suitable impeller for the mixing of highly concentrated fine-grained suspensions (non-Newtonian behavior) is the multistage impeller with parameters T/D = 2, C_1 = 0.5D and C_2 = 0.75D, i.e. with the impellers of bigger diameters and uniformly allocated within the level height. The power consumption of these systems can be about 50 – 70% lower than in the case of the single pitched six-

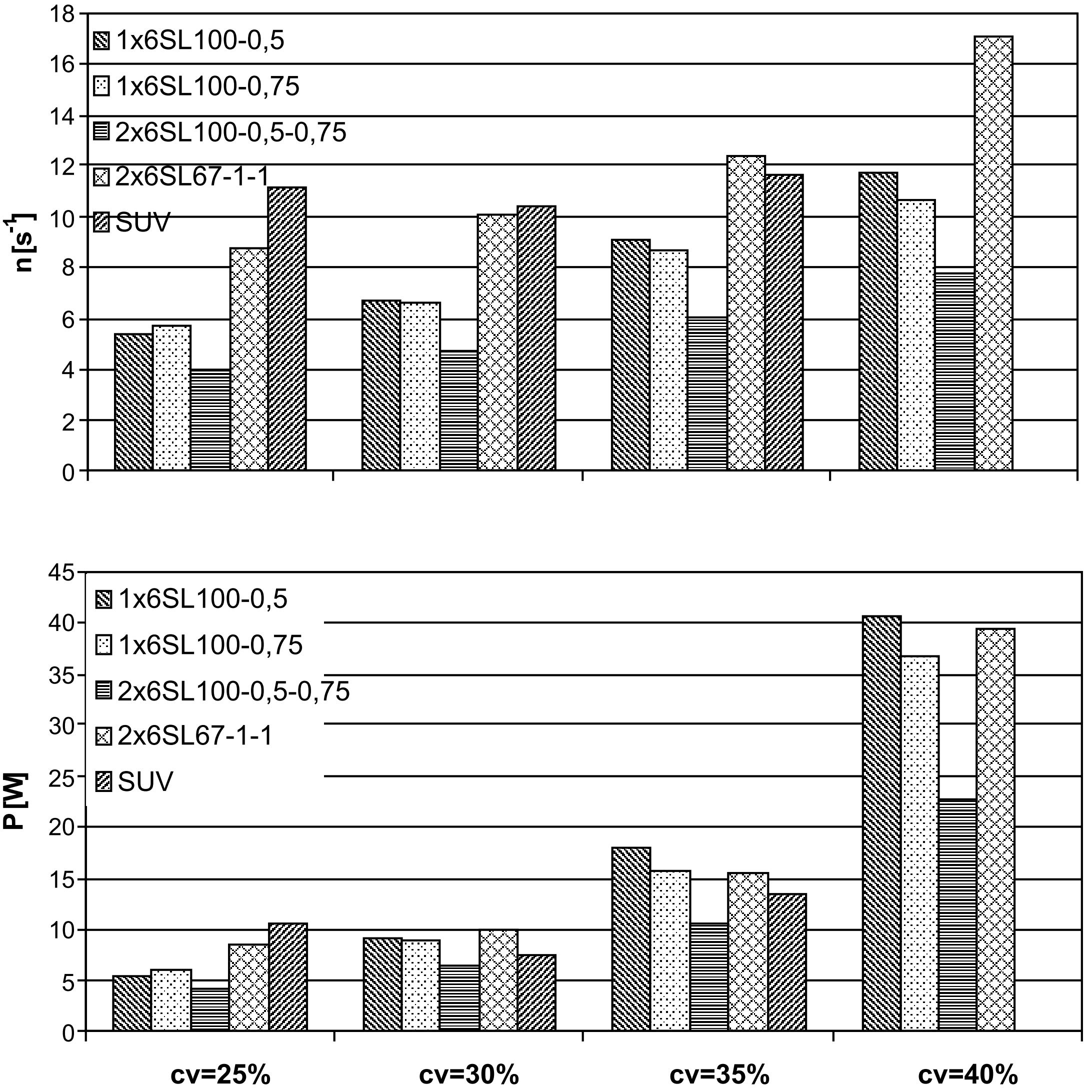


Figure 8. Comparison of the impeller speed and power consumption of the best systems at different concentrations

blade turbine, which is very often used in industry. If the single turbine is used, it is better to chose bigger diameter and the placement $C_1 = (0.5 - 0.75)D$ above a vessel bottom. The usage of the close-clearance agitators was not considered as a good choice in our case. The screw agitator gave indeed good results (better than the simple pitched six-blade turbine of a bigger diameter), but this impeller has a complicated shape from the viewpoint of a design and manufacture.

NOMENCLATURE

b	– parameter of the combined Bingham model (eq. 1) [-]
b	– baffle width [m]
c_v	– mean volumetric concentration of solid phase [-]
C_1	– impeller off-bottom clearance [m]
C_2	– distance between the impellers [m]
d_p	– mean volumetric particle diameter [m]
D	– impeller diameter [m]
h	– width of a bend or a blade [m]
h_v	– height of the agitator [m]
H	– height of a liquid level [m]
n	– impeller speed [s^{-1}]
P	– power consumption [W]
Po	– power number [-]
s	– pitch of screw or helical ribbon agitator [m]
T	– vessel diameter [m]
$\dot{\gamma}$	– shear rate [1/s]
μ_{p1}	– plastic viscosity at low shear rates [Pa·s]
μ_{p2}	– plastic viscosity at high shear rates [Pa·s]
ρ	– suspension density [$kg \cdot m^{-3}$]
ρ_l	– liquid density [$kg \cdot m^{-3}$]
ρ_s	– solids density [$kg \cdot m^{-3}$]
τ	– shear stress [Pa]
τ_{01}	– yield stress at low shear rates [Pa]
τ_{02}	– yield stress at high shear rates [Pa]

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