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Minimum Power Requirements for Complete Suspension of Solid Particles in an Agitator

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ABSTRACT

The suspension of solids in a liquid is an operation common to many applications of mixing in process engineering. A new concept is suggested for calculating the minimum theoretical power requirement to suspend a given amount of solids in a stirred vessel. A material balance equation, based on the effective adsorption of gold cyanide onto activated carbon and ion-exchange resin in a stirred vessel, was used to estimate mass-transfer parameters which were used to derive an optimum impeller speed. It will be demonstrated that the minimum theoretical power derived here is in agreement with other concepts proposed in the literature, and in some cases even suggest smaller minimum values. Furthermore, it will be shown that inert fines in solution can enhance the effective mass transfer, thus minimizing the power input.

INTRODUCTION

The phenomena involved in the suspension of solids in a mixer as the power input is increased have been fully described by many writers (1–4). Two extreme conditions of suspension can be defined, namely: complete homogeneous suspension, in which the solids concentration is uniform throughout the vessel, and the other extreme is represented by all solids settling out on the base of the tank. The power input for a complete homogeneous suspension is usually high, and such a condition is seldom essential to the process. It has long been recognized that the impeller speed at which solids just become fully suspended is the most important speed. Therefore, the power requirements linked to this optimum condition are critical.

Zwietering (5) defined the condition of "just suspended" as when there are no particles at rest for more than about 1 second on the base of the tank. Kneule (6) investigated the rate of solution of crystals and stressed the importance of the point at which all particles are just in suspension. In many cases it is most efficient to design a mixer for this condition, because beyond this point the rate of mass transfer is affected only by increased power input. Oldshue (7) summarized nine different correlations to predict the speed and hence derive the power required to just suspend solids in mixers. However, these correlations are based on empirical measurements of mixer power and give no indication of the allocation of power between turbulence and suspension of solids.

Einenkel (8) studied the effect of stirring speed on mass transfer in a suspension of potassium chloride in water. Although he observed that the mass-transfer coefficient and the effective mass-transfer area increased rapidly with stirring speed, no critical stirring speed or optimum power input was related to this process. Due to the fact that abrasion of equipment and attrition of solids increase with power input, the shape of the solid particle will contribute to the optimization of the mixing operation. Van Vliet and Young (9) showed quantitatively that an increase in the surface roughness of solids enhances the effective mass transfer. Thus, the influence of the presence of fines in a liquid/solid mixing system, such as a typical slurry reactor, needs to be investigated more clearly.

It is the objective of this paper to calculate the minimum theoretical power input for a mixer using a material balance equation derived from the mass transfer of gold cyanide to activated carbon and ion-exchange resin. The influence of inert fines on the mass-transfer operation will also be investigated so as to shed more light on the optimization of the mixing process.

EXPERIMENTAL

Experiments were carried out in a tank of internal diameter 11 cm, height 15 cm, and three evenly spaced baffles of width 1 cm. Agitation was provided by a flat blade impeller of width 6 cm and height 5 cm, driven by a Heidolph variable speed motor, which enabled continuous adjustment of impeller speed from 80 to 2000 rpm. Since measurement of particle suspension was not the major interest of this study, only one reactor/impeller type was used. Figure 1 gives a schematic representation of the vessel and impeller dimensions.

A coconut shell carbon, Le Carbone G210 AS with an average diameter of 1.4 mm and an apparent density of 838 $kg \cdot m^{-3}$, and an ion-exchange resin (DU A161) with an average diameter of 0.8 mm and a wet-settled density of 700 $kg \cdot m^{-3}$, were used. Potassium aurocyanide was used as an adsorbate, and the concentration decay of the aurocyanide ion was

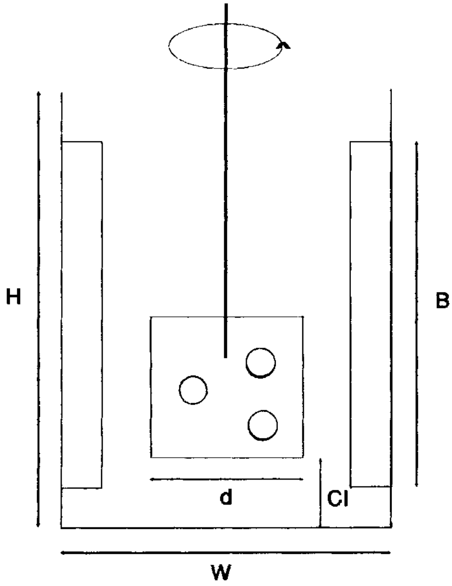

FIG. 1 Schematic representation of experimental apparatus. W = 110 mm; Cl = 15 mm; d = 60 mm; B = 100 mm; H = 150 mm.

monitored on a Varian Techtron AA-1275 atomic absorption spectrophotometer. All experiments were performed at room temperature, and distilled water was used throughout. In some experiments the carbon particles were pretreated in a suspension of silica sand so as to give insight into the sensitivity of mass transfer parameters. (90% of the silica particles were smaller than 15 μm.)

Various impeller off-bottom clearances were tested to find the optimum clearance, so that a clearance of 0.25d (i.e., 15 mm) was taken as constant for all the experiments.

DETERMINATION OF MASS TRANSFER PARAMETERS

The simplest form of mass transfer from the free solution to the particle surface is based on the assumption that all resistance to mass transfer is in the external liquid film surrounding the particle. Weber (10) showed that the intensity of agitation influenced the extent to which the film transfer mechanism dominates the kinetics in a stirred tank.

For the adsorption of gold cyanide onto activated carbon and ion-exchange resin in a stirred tank, the mass balance for the liquid phase yields

$$\frac{dC}{dt} = \frac{6k_f M}{\rho d_p V}(C_s - C) \tag{1}$$

A linear concentration gradient from the bulk liquid to the particle surface is postulated in the early stages of the adsorption. Furthermore, it is assumed that the adsorbate (gold) concentration at the particle surface C_s is negligible in the early stages, compared to the bulk liquid concentration C. This means that Eq. (1) will simplify to

$$-\frac{dC}{dt} = \frac{6k_f M}{\rho d_p V} C \qquad \text{as } t \rightarrow 0 \tag{2}$$

Integrating Eq. (2) results in

$$\ln\left(\frac{C_0}{C}\right) = \frac{6k_f M}{\rho d_p V} t \qquad \text{as } t \rightarrow 0 \tag{3}$$

A plot of $\ln(C_0/C)$ versus time yields a straight line passing through the origin, and the film transfer coefficient (k_f) can be determined from the slope of this line. It should, however, be stressed that this method of estimating k_f is valid only in the early stages of adsorption. As all of these experiments were carried out at different stirring speeds (n), the value of k_f can thus be linked directly to n.

In a typical mixing system there is a correlation between the Power number (N_P) and the Reynolds number (N_RE), and this can generally be expressed as

$$N_\mathrm{P} = f(N_\mathrm{RE})^A \tag{4}$$

The theoretical power can be calculated as follows:

$$P = N_\mathrm{P} \rho n^3 d^5 \tag{5}$$

RESULTS AND DISCUSSION

Optimum Stirring Speed

In these tests, 1 g activated carbon or 1 mL wet-settled resin was subjected to a 20 ppm solution of gold cyanide. As mentioned earlier, only one type of reactor was used and it contained 1000 mL of solution. The value of k_f was estimated from a plot of $\ln(C_0/C)$ versus time for different stirring speeds. These results are illustrated in Fig. 2 which indicates that k_f levels off at higher values of the stirring speed. At a stirring speed of 60 rpm it was observed that a large fraction of the carbon and resin parti-

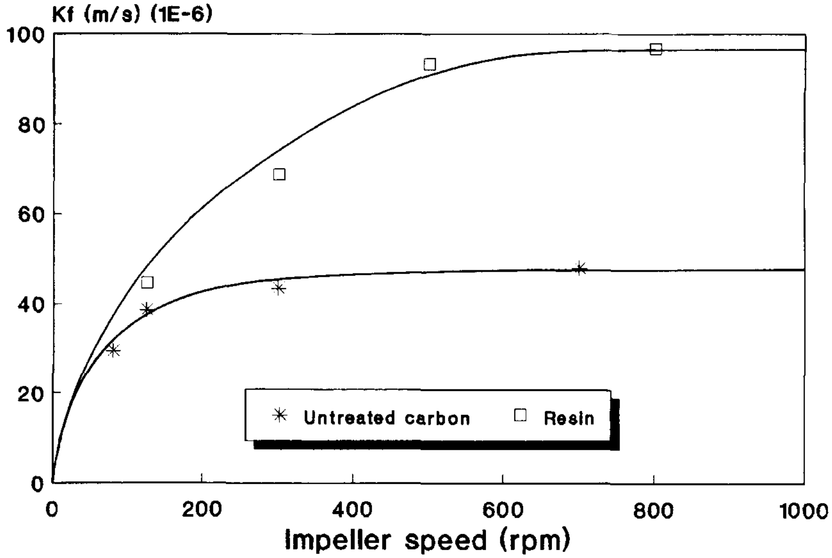

FIG. 2 The effect of impeller speed on k_f for resin and untreated carbon.

cles was lying at the bottom of the reactor. At 30 rpm no particles were in suspension. From Fig. 2 it is clear that different flow regimes can be recognized from the slope of the curve. In the lower part of the curve, when the particles are on the bottom of the tank, the film transfer coefficient k_f increases rapidly with an increase in stirring speed. As the speed is increased, so the particles are gradually suspended, and hence the local concentration of solids just above the bottom of the tank increases. However, if these particles are completely fluidized, an increase in stirring speed will have no significant effect on the adsorption kinetics. This is manifested in the change of slope in Fig. 2 at high stirring speeds. Furthermore, it was observed that from 600 rpm the value of the film transfer coefficient levels off for the resin, and the same at 280 rpm for carbon, and the rate of uptake of gold cyanide by either resin or carbon was independent of the stirring speed. This implies that the kinetics should no longer be dependent on k_f, and confirmed earlier results by Van Deventer (11). Thus, Fig. 2 suggests an optimum stirring speed for effective mass transfer, and hence a minimum power input for complete suspension.

It is also interesting to note from Fig. 2 that the values of k_f for the resin particles were higher than those for the carbon. This can be attributed to the fact that the particle size of the resin used in this study was smaller than for carbon. From Eq. (3) it is clear that particle size inversely affects

TABLE 1
Sensitivity of k_f Values for Untreated and Pretreated Carbon Particles at Different Stirring Speeds

Impeller speed N (rpm)	k_f (m/s)	
	Untreated carbon	Pretreated carbon
80	2.94	2.249
125	3.847	3.081
300	4.343	3.292
700	4.797	4.049

the rate of mass transfer across the external liquid film, thus influencing the value of k_f.

Experiments were then devised to investigate the effect of pretreatment of activated carbon with fine material, and hence the effect on the film transfer coefficient k_f. Carbon particles (1 g) were subjected to a solution containing 3 g silica/L distilled water and stirred for 3.5 hours. These carbon samples were then rinsed with water and contacted with a clear solution of gold cyanide. Table 1 clearly shows a decrease in the values of k_f for the pretreated carbon compared to the untreated carbon. The intrusion of fines into the pores of the activated carbon particle makes

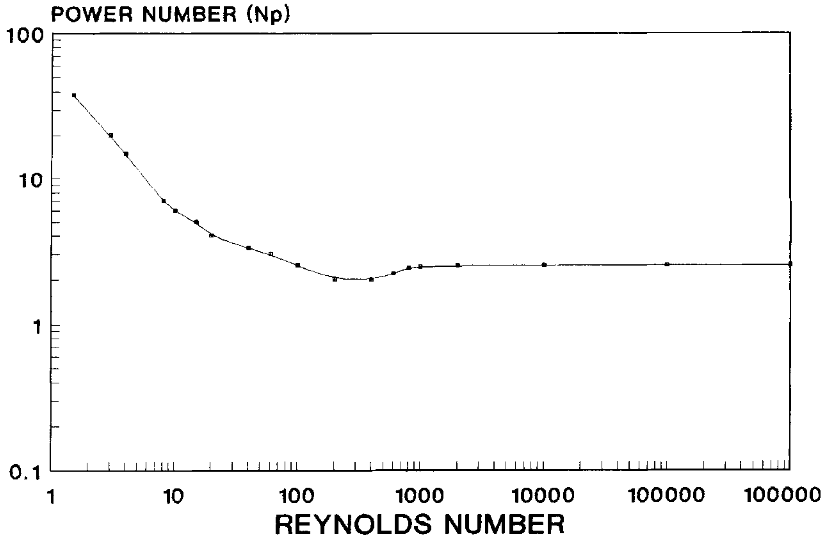

FIG. 3 Power number (N_p) versus Reynolds number (N_{RE}) for impeller/reactor configuration.

TABLE 2
Minimum Theoretical Power for Complete Suspension of Solids Obtained in the Literature Compared with That Obtained in the Present Study

Reference	Minimum power (W)
Cloete and Coetzee (2)	0.65
Koide et al. (12)	6.3
Present study	2.25

the edges more smooth, thus reducing the film transfer coefficient (9). Very little is known about the interaction between fines and coarse particles in a mixing system, which deserves a great deal more research.

Minimum Power Requirements for Complete Suspension

The minimum power input calculated here is based on the optimum stirring speed derived in the previous section. It is therefore assumed that particles are in complete suspension at this condition. Furthermore, an optimum Reynolds number (N_{RE}) can thus be calculated, and the Power number (N_{p}) can be estimated using Fig. 3, which was derived for the impeller/reactor configuration used in this study. Table 2 illustrates the theoretical power calculated using Eqs. (4) and (5), and compares it to values determined by other methods in the literature. From the values in Table 2, the minimum theoretical power calculated here compares favorably to values obtained in previous studies.

CONCLUSIONS

A new concept, based on the effective mass transfer of gold cyanide to activated carbon and ion-exchange resin, used for estimating an optimum impeller speed, was investigated. This impeller speed was then used to calculate the minimum theoretical power input for complete suspension of particles. The minimum power calculated by our concept compares favorably to those obtained in earlier studies. Furthermore, it was found that the presence of inert fine material in solution enhances the film transfer coefficient, thus reducing the optimum impeller speed.

NOMENCLATURE

A	exponential constant in Eq. (4)
B	height of baffle (m)

Cl	clearance (mm)
C	solution concentration ($\mathrm{mg \cdot L^{-1}}$)
d_p	particle diameter (m)
d	impeller diameter (m)
H	height of reactor vessel (m)
k_f	film transfer coefficient (m/s)
M	mass of carbon or resin (kg)
n	stirring speed (rps)
N_p	Power number
N_RE	Reynolds number
P	power (W)
t	time variable (s)
V	volume of reactor ($\mathrm{m^3}$)
W	width of reactor vessel (m)
ρ	density ($\mathrm{kg \cdot m^{-3}}$)

Subscript

s	surface of particle

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