Mechanical Power Requirements of Gas-Liquid Agitated Systems

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The power requirements for mechanical agitation of liquids have been investigated extensively, since this parameter is an important criterion for scaling-up stirred reactors, and it also relates to the overall mass transfer coefficient. There is only a limited number of useful correlations for its estimation such as those of Oyama and Endoh (1955), Michel and Miller (1962), Clark and Vermeulen (1963), Pharamond et al. (1975), and a recent contribution of Hassan and Robinson (1977). Oyama and Endoh (1955) introduced the correlation of the gassed-to-ungassed mechanical mixing power ratio with the aeration number. The new correlating procedure of Michel and Miller (1962) cannot be reliably applied to large scale equipment and also failed at extreme values of gas flow rate. It is also not applicable for prediction of the effect of surfactants on the mixing power input. The correlation by Pharamond et al. (1975) is restricted to correlating only their experimental data developed with six-blade turbine impellers. The correlations of Clark and Vermeulen (1963) and Hassan and Robinson (1977) appear to have the most merit, since they use the impeller Weber number and measured gas holdup. The correlation of Clark and Vermeulen (1963), however, was developed with unusual method of gas sparging, using a perforated plate covering the entire bottom of the vessel. The correlation of Hassan and Robinson (1977) may vary with different tank sizes and requires the measurement of the gas holdup which is somewhat inconvenient for applications involving fermentation broths. All aforementioned correlations are restricted to Newtonian fluids.

In order to improve the accuracy of estimating the mixing power input, an empirical correlation for predicting the gassed-to-ungassed power ratio is suggested as follows:

$$\frac{P_g}{P} = C\left[\frac{Q}{Nd^3}\right]^m\left[\frac{N^2d^3\rho_L}{\sigma}\right]^n \qquad (1)$$

EXPERIMENTAL RESULTS AND DISCUSSION

For the experimental work reported herein, a modified strain-gauge dynamometer (Aiba et al., 1973) was employed to measure the torque of a rotating impeller shaft. The air flow rate to the tank was measured by a rotameter. The fully baffled stirred tank contained one single-hole orifice sparger. The stirred-tank geometry and ranges of operating variables of the mixed system are given in Figure 1. The physicochemical properties of liquid solutions used in this study are given in Table 1.

Power Requirement in Nongassed System

It was confirmed here that the mechanical power input of turbulent Newtonian liquids in nonaerated, agitated, fully baffled tank varied with the cube of the impeller rotational speed. The power number N_p was found to be equal to 6.14 for a six-blade turbine. This agrees well with the work of Rushton et al. (1950). The experimental results in this study also indicated that the mechanical power input in nonaerated, agitated non-Newtonian liquids in a turbulent regime also varied with N^3 as indicated by Calderbank and Moo-Young (1959). It could thus be generalized that the power consumption for mixing in turbulent regime is proportional to N^3 for both Newtonian and non-Newtonian fluids.

Power Requirement in Gassed System

The experimental results indicated that the change in power ratio P_g/P was dependent, as expected, upon whether the mixing parameter was changed by altering the gas flow rate or the impeller rotational speed. The power ratio consistently decreased when the gas flow rate was increased at a constant rotational speed of impeller. Based upon these observations and the work of Oyama and Endoh (1955) as well as Hassan and Robinson (1977), a nonlinear correlation for the power ratio and the aeration number is suggested (Figure 2):

$$\frac{P_g}{P} \alpha \left[\frac{Q}{Nd^3}\right]^m \qquad (2)$$

The regression analysis of all experimental data obtained in this study resulted in correlation of the power ratio P_g/P and $Q^{-0.38}$. This result is consistent with the work of Cooney (1969) and Hassan and Robinson (1977).

It was also observed that when the gas flow rate was kept constant at different points of a fairly wide range and the N was varied, the mechanical power input re-

STIRRED TANK GEOMETRY

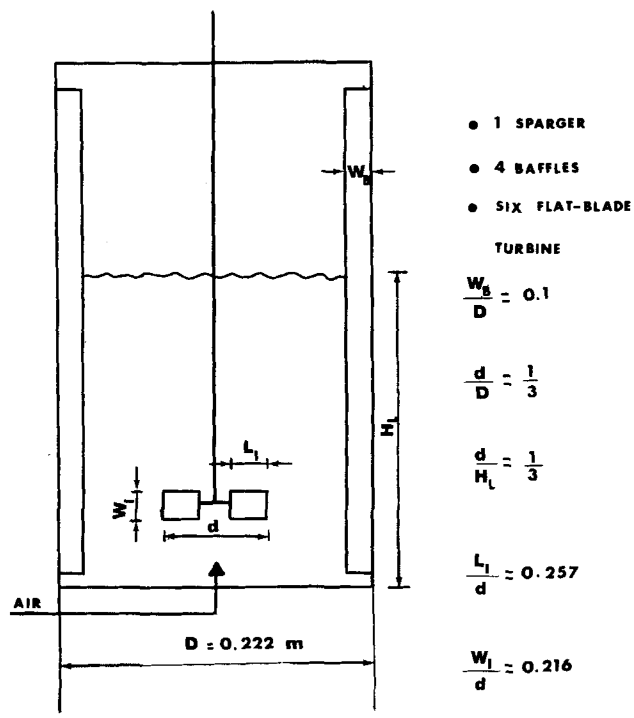

Figure 1.

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Table 1. Physicochemical Properties of Aqueous Solutions (25°C)

Liquid/solution	Density, kg/m³	Viscosity, (N · s/m³) · 10³	Surface tension, (N/m) · 10³
Water	1 000	0.89	72.0
Ethylene glycol (8% by weight)	1 008	1.72	55.0
Methanol (10% by volume)	983	0.85	58.10
CMC (carboxy-methyl cellulose) (0.2% by weight)	1 000	—	59.2
CMC (0.4% by weight)	1 000	—	69.0
CMC (0.67% by weight)	1 000	—	71.5
Glycerol (40% by weight)	1 104	3.00	64.9

quired to agitate a gas-liquid dispersion was still proportional to the cube of the impeller rotational speed (Figure 3). This is consistent with the previous reports of Rushton et al. (1950), Moritz et al. (1974), Cooney (1969), and Hassan and Robinson (1977). Furthermore, a direct proportionality of P_g to N^3 could also be observed in the correlation of Michel and Miller (1962) and was implied in the correlation of Pharamond et al. (1975).

Since both P and P_g have been shown to vary with N^3, the power ratio P_g/P should be independent of N and constant at some specified gas flow rate. This was applicable for pseudoplastic non-Newtonian solutions (Figure 4) examined in this study.

From the above observations and Equation (2), it could be argued that the P_g/P power ratio should also be dependent upon another dimensionless term covering

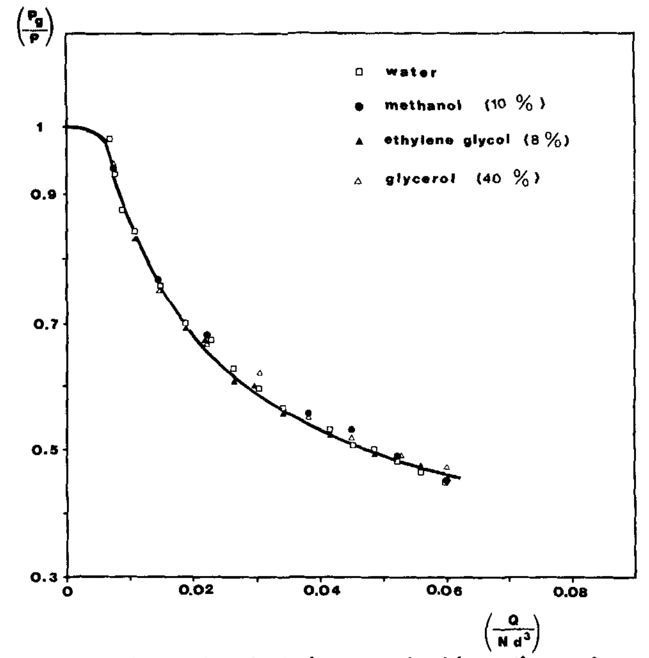

Figure 2. Variation of mechanical power ratio with aeration number.

the impeller rotational speed. The impeller Weber number including the rotational speed and physicochemical properties of two-phase media is eligible for correlation with the mixing power ratio as indicated by Clark and Vermeulen (1963) and Hassan and Robinson (1977). Equation (1) is suggested herein to correlate the mixing power consumption in gas-liquid dispersion. The regression analysis of the examined Newtonian fluids data resulted in the value for $n = -0.18$. The P_g/P ratio was appreciably different for non-Newtonian solutions. Analysis of the CMC solution experimental data resulted in $n = -0.194$. It is also important to note that the proportionality constant C resulting from the CMC solution data

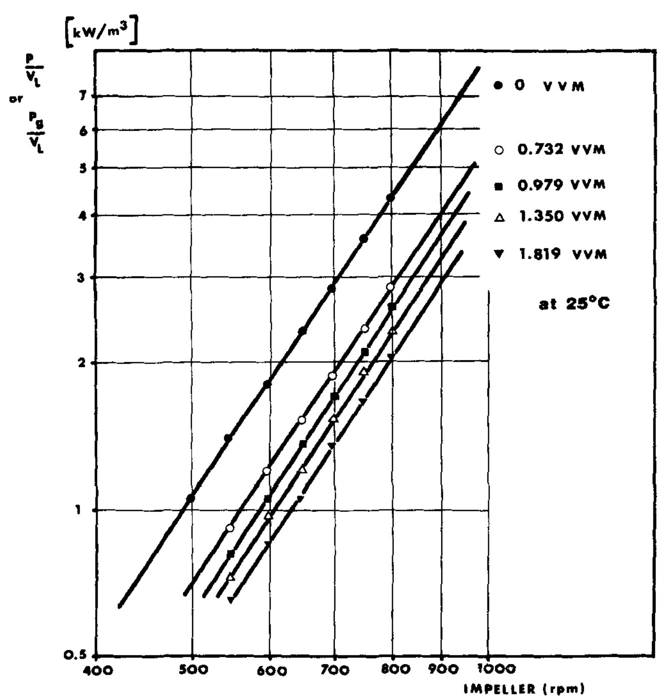

Figure 3. Variation of mechanical power input per unit volume with impeller rotational speed (Newtonian fluids).

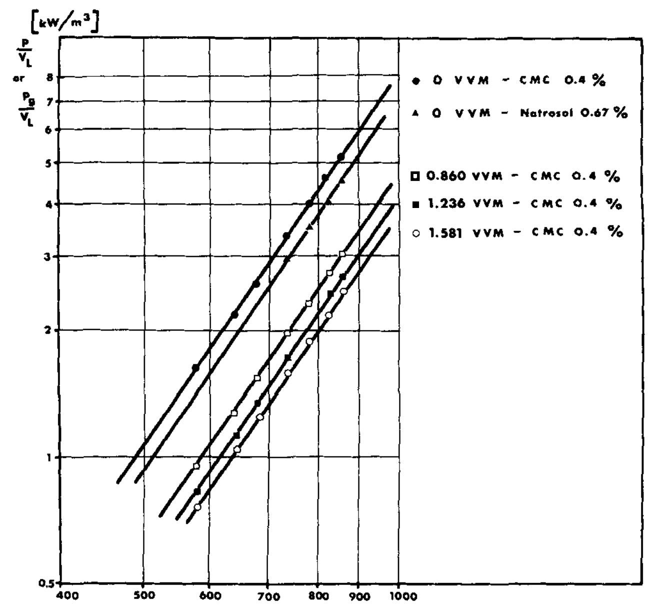

Figure 4. Variation of mechanical power input per unit volume with impeller rotational speed (non-Newtonian fluids).

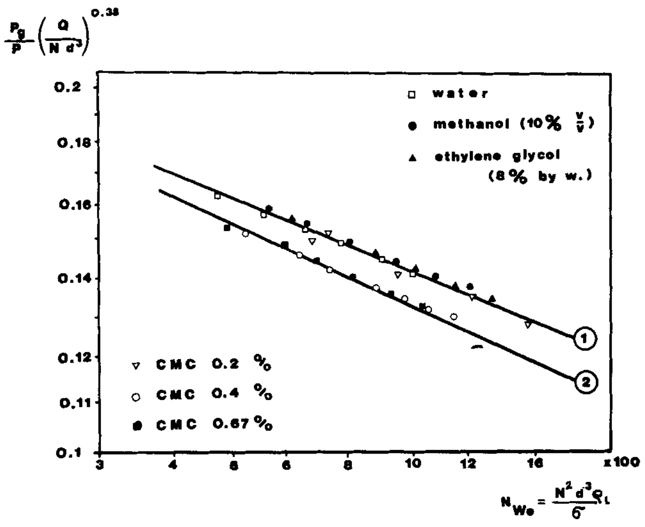

Figure 5. Variation of power function with impeller Weber number.

$$1)\ \frac{P_g}{P} = 0.497 \left(\frac{Q}{N d^3}\right)^{-0.38} \left(\frac{N^2 d^3 \rho_L}{\sigma}\right)^{-0.18}$$

Correlation coefficient = 0.985

$$2)\ \frac{P_g}{P} = 0.514 \left(\frac{Q}{N d^3}\right)^{-0.38} \left(\frac{N^2 d^3 \rho_L}{\sigma}\right)^{-0.194}$$

Correlation coefficient = 0.989

is slightly different from that for Newtonian solutions (Figure 5). In effect, the exponent n and the constant C in Equation (1) do not merely reflect geometric system parameters but also depend on the characteristics of fluids. The CMC solution (0.2%) data, however, resulted in the P_g/P ratio quite similar to the one for Newtonian solutions at the same operating conditions. This can be explained by still rather Newtonian character of the weak CMC solution.

This work is aware that the effect of isothermal expansion of gas pumped into the gas-liquid dispersion was neglected in evaluating the mixing power input data. According to Hassan and Robinson (1977), this is allowable for many practical applications.

NOTATION

C = proportionality constant in Equation (1)
d = impeller diameter
N = impeller rotational speed
N_p = power number, $P/\rho_L N^3 d^5$
P = mechanical agitation power in ungassed liquid
P_g = mechanical agitation power in gassed liquid
Q = volumetric gas sparging rate
ρ_L = mass density of liquid
σ = air-liquid surface tension

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The Effect of the Array of Disks on Mass Transfer Rates to the Tube Walls

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In a recent publication (Koncar-Djurdjevic and Dudukovic, 1977), we have discussed the effect of single stationary objects placed in the fluid stream on mass transfer rates to the walls of a coaxial cylindrical tube. The results obtained indicated very complex interactions

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