Power Consumption in a Mixer

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Power consumption is a basic integral quantity in a mixing operation that, in part, determines other process quantities. Blend time, holdup, and mass transfer coefficients such as k_La in gas-liquid contacting, drop size in liquid-liquid processing, reaction times for fast chemical reactions, and heat transfer coefficients are all related to power consumption. The effect of shear and elongation on biological systems in a mixing tank depends as well on power consumption. Utility costs in mixing are also important in plant operations from the viewpoint of operating costs.

The distribution of the power usage in mixing operations is of interest, and power actually delivered to the mixing is very important in judging the mixing performance being received from the agitator. Ironically, power consumption in industrial mixing operations is most often left unverified.

A mixing unit consumes power in its three basic subunits: the motor, the gearbox, and the tank in which the mixing takes place. Of these, power usage in mixing in the tank has the reputation of being very difficult to measure. Typically, specialized equipment is usually necessary to perform such measurements, and calibration of the measuring equipment is difficult. Such measurements are not performed on-site in a chemical plant and the end result is that power input to mixing is not documented in actual plant operations. The accepted power consumption in mixing for actual plant operation is that obtained from correlations used in design of the unit.

Differences occur between the power input calculated from design correlations and the actual power consumed in the mixing operation. Internal geometries in industrial tanks are not typically those used in the development of the power number correlations. Design changes frequently occur after the unit is in place. Furthermore, certain power data reported in the accepted engineering design literature are not accurate. Nagata and Yokoyama (1955), Bates et al. (1963), and Novak et al. (1982) have discussed the known inaccuracies for turbulent mixing. In laminar mixing, power measurements and correlations are still developing due to the complexities of the impeller/tank geometries, non-Newtonian flow behavior, and viscosity characterization. Chavan and Ulbrecht (1973a, b, 1974), Kappel (1979), and Chavan (1983) discuss inaccuracies in laminar power correlations. As a result of these factors, there is uncertainty concerning power consumed in actual mixing and the distribution of power usage in plant mixing operations generally.

In this study, a power meter is used to measure power usage in a 2 hp agitator unit. Power consumption data are obtained for the motor, gearbox, and in mixing. Power-number curves are generated for a pitched-blade turbine and a flat-blade open impeller from the power meter data and are compared with standard correlations and published data. Power-number data are also obtained for the gearbox. This work shows how power consumption in mixing can be measured on-site in a chemical plant using a simple power meter. Further, this work shows the distribution of power usage for a typical industrial agitator.

It should also be noted at this point that there are no published studies concerning power distribution in the various subunits of an agitator in the literature on mixing. Brown (1977) appears to be the only published article in the industrial-related mixing literature that discusses how power measurements can be performed on-site in a plant.

Background

In studying the power distribution and consumption in a mixing unit, the following additive relationship for power usage can be written

$$P_{total} = P_{motor} + P_{gearbox} + P_{mixing} \tag{1}$$

The power consumed in the motor, P_{motor}, can be considered independent of the other two terms in the expression (Dawes, 1952). The different mechanisms by which power is consumed in performing mixing are also known and are certainly independent of the conditions of the gearbox and motor. Hence, P_{mixing} is independent of P_{motor} and $P_{gearbox}$. Power consumed in the gearbox, $P_{gearbox}$, can be divided into two components: power consumed in mixing the oil lubricant and power consumed in overcoming frictional losses. Power consumed in mixing the lubricant in the gearbox is independent of load, that is, P_{mixing}. Power consumed in overcoming friction in bearings, seals, and gears may be dependent upon load or P_{mixing} to some degree, but the dependency is considered unimportant in this work. As a result, the terms in Eq. 1 can be considered independent of each other.

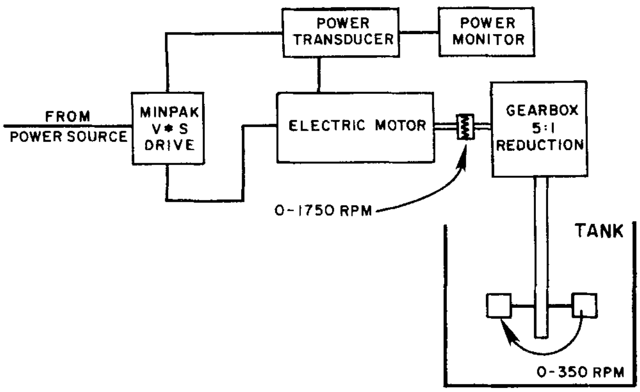

Figure 1. General equipment arrangement.

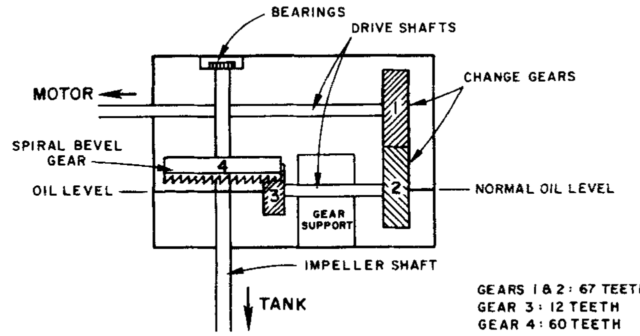

Figure 2. Internal arrangement of gears in gearbox.

The power consumption in the motor and gearbox can be combined to give total consumption in the drive portion of an agitator:

$$P_{drive} = P_{gearbox} + P_{mixing} \tag{2}$$

The difference between the total power consumption and the power consumption in the drive is the power consumed in fluid mixing, which is dependent upon the impeller type and whether the flow is laminar, transitional, or turbulent. For turbulent flow in a fully baffled tank, the equation for power consumption is:

$$P = K_1 \rho N^3 D^5 \tag{3}$$

and the equation for laminar flow is:

$$P = K_2 \mu N^2 D^3 \tag{4}$$

where constants K_1 and K_2 are dependent upon geometry. At a fixed diameter for turbulent flow, power is proportional to density and the cube of the impeller rotational speed; for laminar flow power is proportional to viscosity and the square of the impeller rotational speed. The transition between laminar and turbulent flow for an agitated tank occurs at an impeller Reynolds number between 10 and 1,000. Oil mixing in the gearbox follows Eqs. 3 and 4 as well depending upon flow condition.

Experimental Study

The agitation equipment used in this study is shown in Figure 1. A Reliance Electric Minpak V*S drive controller and a 2 hp DC Reliance Electric shunt motor were used for driving the agitator and produced rotational speeds up to 30 s^{-1}. A Chemineer 2 HTD-Z gearbox, shown in Figure 2, performed a 5-to-1 reduction in rotational speed to the impeller. A strobe light was used to measure the impeller rotational speeds involved in the study. Unfortunately, tank seals were not available for study.

A 900 mm ID flat-bottom Plexiglas tank, filled to 900 mm, was used as the mixing vessel for the experiments. Four baffles, 92 mm wide, were placed symmetrically on the wall inside the tank. The impellers were mounted 300 mm from the tank bottom along the centerline of the tank. Tap water was used as the process fluid. Two different impellers were studied: a four-bladed, 45° pitched-blade turbine, and a four-bladed, flat-blade open impeller. Each had a diameter of 304.8 mm. The diameters were accurately measured by centering on concentric circles.

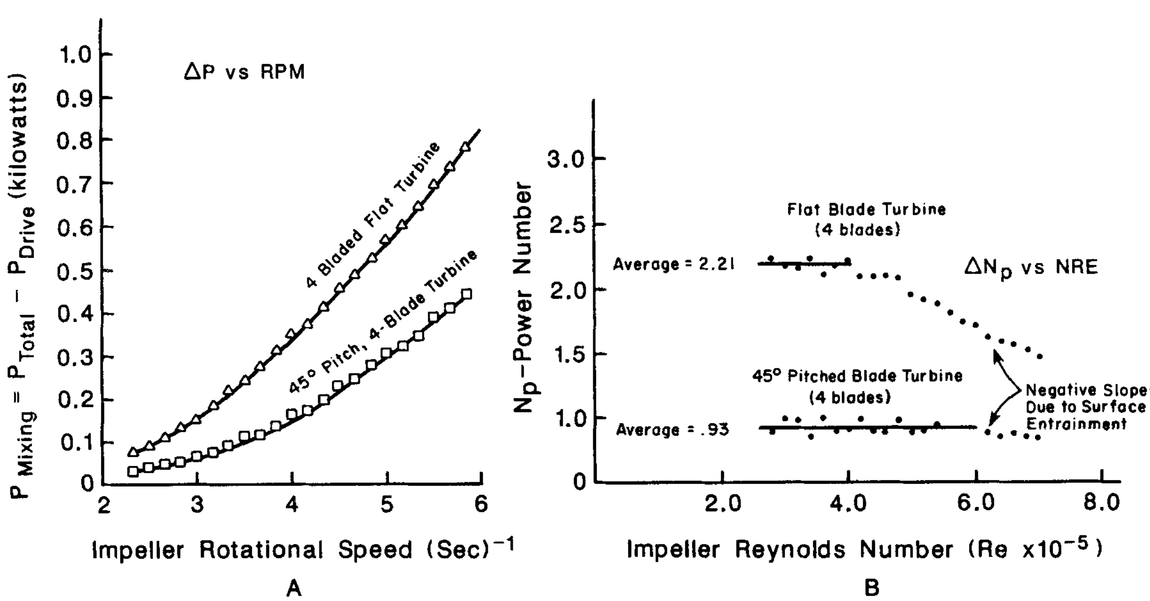

Figure 3. Power consumption and power number as functions of impeller rotational speed and Reynolds number.

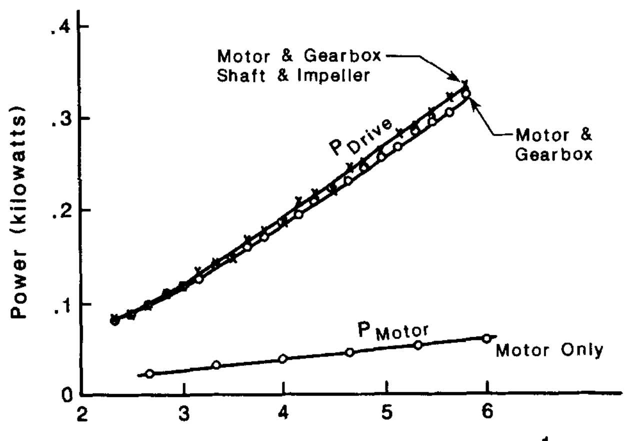

Figure 4. Power consumption in drive and motor.

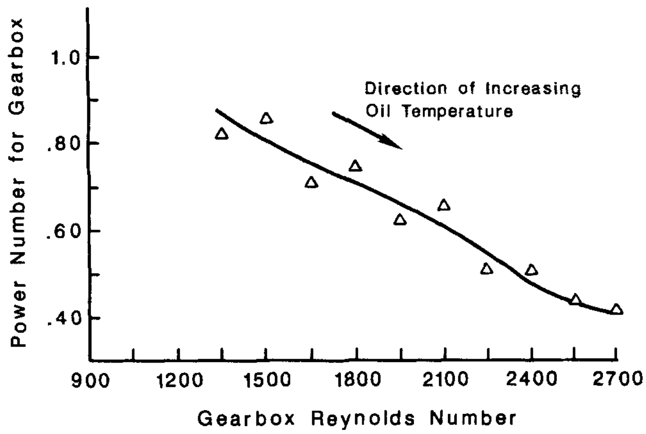

Figure 5. Gearbox power number as a function of gearbox Reynolds number.

The projected blade width to impeller diameter ratio for both impellers was 1/6.

A Valenite power meter was used to measure the power consumed by the equipment. The meter used a power transducer to monitor both current and voltage in order to determine power. An independent test of the power meter indicated that measurement errors of power were within the error specifications given by the manufacturer.

Results and Discussion

Data taken concerning power consumed in mixing in this study are shown in Figure 3. The power consumed in mixing, $P_{total} - P_{drive}$, is plotted in Figure 3a and as power numbers in Figure 3b. The negative slopes occurring at the end of the power-number curves were due to air entrainment from the surface. The power numbers in Figure 3b are different from those obtained from standard correlations (Bates et al., 1963): 0.93 as opposed to 1.27 for the pitched-blade turbine; 2.21 as opposed to 4.0 for the flat-blade open impeller. However, these particular power numbers in the literature were for six-bladed impellers with different blade widths than used in this study. Scaling upon blade number and width, the power numbers shown in Figure 3b are reasonable. For turbulent mixing, power consumption is roughly proportional to impeller blade number (Rushton et al., 1950; Nagata et al., 1955; Bates et al., 1963) and blade width (Bates et al., 1963). Based upon these scalings, the expected power numbers were 1.13 and 2.4, respectively, for the pitched-blade turbine and the flat-blade turbine used in this study.

Data on the power consumption in the drive train are plotted in Figure 4, showing two curves. The curve labeled P_{Motor} was generated using the power meter with the coupling disconnected between the motor and gearbox. The curve provides the power consumption in the motor. The second curve, P_{Drive}, is for the drive train and includes the power consumption in the gearbox and motor. The power consumption data for the drive train were obtained when the impeller was rotating in air since the power consumed in the mixing of air (i.e., a low-density, low-viscosity fluid) is negligible. In considering total power usage, the drive power can represent a significant portion of the power consumption occurring in a mixing operation, as can be observed in comparing Figures 3 and 4. Furthermore, given the agreement noted above between the published literature values and the power meter data taken in this study, the power consumption in the drive train can be considered independent of the impeller type, which can be expected given the independence of the various terms in Eq. 1, as stated above.

The difference between the curves, P_{Drive} and P_{Motor}, in Figure 4 is the power consumed in the gearbox. Initially, the gearbox was considered to be another turbulent agitated tank, the gears being essentially impellers. However, although not shown in Figure 4, the P_{Drive} data were found to decrease significantly with time. This power reduction was attributed to the decrease in oil viscosity, Eq. 4, as the oil heated up to its operating temperature. Figure 5 shows the power number for the gears plotted as a function of their gear Reynolds number. The correlation, however, is not a static relationship due to the dependency of viscosity on temperature and does include power consumption due to gear friction. Buckingham (1949) discusses gear friction and gear efficiencies in depth.

Conclusions

A power meter was successfully applied to the measurement of power distribution in a mixing operation. Furthermore, the equipment can be used on-site in a process setting. Data included power consumption in the motor, the gearbox, and in mixing. The power-number data obtained for the mixing were in reasonable agreement with other reported data and correlations. Power-number data were also reported for gears in the gearbox. An interesting situation was observed in which laminar mixing was occurring in the gearbox and turbulent mixing in the processing tank.

Notation

D = impeller diameter
K_1, K_2 = constants dependent upon geometry
N = impeller rotational speed
N_p = power number
P = power
Re = Reynolds number
μ = viscosity
ρ = density

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