R&D NOTE

An Analysis of the Use of Electrical Power Measurements for Process Control in Large-Scale Stirred Vessels

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The mechanical power that is transferred to a liquid via the shaft of an agitator is obtained from a measurement of the electrical power flowing into the electric motor within an accuracy of less than 5%. The accuracy obtained is limited by the calibration procedure. As the implementation of an electric power measurement is both simple and comparatively inexpensive, the technique is suitable for a continuous monitoring of the power used by agitators in the process industries.

La puissance mécanique qui est transmise à un liquide par l'intermédiaire de l'axe d'un agitateur est obtenue à partir d'une mesure de la puissance électrique consommée dans le moteur électrique avec une erreur inférieure à 5%. La précision obtenue est limitée par la procédure de calibration. Considérant que la mesure de la puissance électrique est une opération simple et relativement peu coûteuse, cette technique convient pour assurer une surveillance continue de la puissance utilisée par les agitateurs dans les industries de procédés.

Keywords: electrical power measurement, bioreactor, mechanical agitation

In process industries a continuous and accurate control of the power used by the agitator is often of interest. For instance, the power draw of the agitator is sensitive to changes in liquid viscosity, to the presence of gas in the liquid, to liquid level, etc. Power measurements can therefore be used to give information on the advancement of the process, information that in many instances can be hard to obtain otherwise. The techniques available for directly measuring the power transmitted via the agitator shaft are expensive and often difficult to apply in the industrial environment. For these reasons people often attempt to infer the transmitted power from a measurement of the electrical power that is needed to operate the agitator motor. But for many reasons most of these attempts often give results which are terribly inaccurate.

In connection with the European Commission project "Bio Process Scale-up Strategy" (Enfors et al., 1998) the present authors were given the task of providing continuous and accurate power measurements during experiments involving the 30 m^2 bioreactor at Biosentrum, Stavanger, Norway and the 9 m^3 bioreactor at Pharmacia and Upjohn, Strängnäs, Sweden. Both tanks are standard dished bottom tanks with aspect ratios of 4.78 and 2.35, respectively. In both cases the air is introduced via a sparge ring at the bottom of the reactor.

The most accurate method, that to the authors' knowledge, is available to measure and average the fluctuating torque that is transmitted via the agitator shaft, is to attach strain gauges to the shaft. The electrical connection to the non-rotating laboratory frame is then arranged via slip-rings or by telemetry. But with available techniques it is both difficult and hazardous to glue strain gauges to a system that needs to be sterilized. The next alternative is then to utilize commercially available mechanical torque sensors or to manufacture a suitable device ourselves, but all these systems require a substantial modification of the existing equipment or work that is difficult to do on site. This was judged to be both expensive, impractical and not in our case acceptable because the modifications had to be done to equipment that was not our own.

At this point it was judged to be possible to infer, with an acceptable accuracy, the mechanical power transmitted to the process fluid from the electrical power used to operate the motor. Normally this is not a simple task because part of the electrical power disappears as losses in the motor and gear box. Estimates of these losses are provided by the motor and gear box manufacturers but in biochemical reactors the three phase asynchronous motors are generally operated via a speed control system. This means that both the line frequency, the voltage wave form, the rpm and the torque of the motor are different from what the motor manufacturer bases his figures on. However, under the operation conditions of interest here, the mechanical power put into the process liquid had been measured under a variety of experimental conditions (torque and rpm) by measuring the increase in temperature as a function of time. These experiments were performed by Noorman (1993), for the Stavenger fermentor and by Wernersson and Trägårdh (1995) for the Strängnäs fermentor. The impellers were $D = T/3$ Rushton turbines and the measurements were performed at three (Stavanger, 1993) and five (Strängnäs, 1995) different rotational speeds and at varying liquid levels such that one, two, three or four turbines were immersed in the liquid. The mechanical power imparted to the liquid was then obtained in each case from the rate of temperature rise

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and the heat capacity of the liquid and the tank. The latter was determined by measuring the temperature change when 300 L of water with a temperature of 95°C was added to the water in the reactor. The heat losses to the environment were estimated from the temperature obtained when the agitator had been operated for a long time with a low speed. In Stavanger (1993) all data could be described within the estimated experimental error of 5% with the formula:

$$P_M = Po N_t N^3 D^5 \tag{1}$$

with the power number Po being 5.8. At Strängnäs the power number dropped from 6.4 at 80 rpm down to 3.5 at the maximum available shaft speed of 150 rpm. This drop was probably due to surface aeration. It should be possible to make use of these measurements to calibrate the method and to investigate the usefulness of the approach.

Basic Considerations

Very often people try to infer the mechanical power from a measurement of the current that flows into the electric motor. But this is basically a very inaccurate method because in three phase asynchronous motors the electrical power, which is needed to infer the mechanical power, is the time average of the instantaneous product of voltage and current in the three phases namely:

$$P_E = \sum_{i=1}^{3} (1/T_t) \int_0^{T_t} V_i(t) I_i(t) dt \tag{2}$$

Normally an asynchronous three phase motor is a symmetrical system, i.e., the three phases all supply the same amount of power and we can write:

$$P_E = 3(1/T_t) \int_0^{T_t} V(t) I(t) dt \tag{3}$$

Commercially available Wattmeters with a magnetic AC current probe can measure this quantity within an error of a few percent even if voltage and current are being far from sinusoidal. In the present electrical power measurements it was decided to employ a Fluke 41B Power Harmonics Analyser. Figure 1 shows the voltage signal delivered by a Danfoss VLT100-150 speed control unit as it is observed by the Fluke 41B instrument. For a more detailed discussion of the power flow in three phase AC-circuits the readers are referred to standard text books on electric power measurements, ("The Dranetz Field Handbook for Power Quality Analysis", 1976; Dugan et al., 1976).

The Relationship Between Electrical and Mechanical Power

As three phase asynchronous motors are expected to show a complete symmetry among the three phases, they were chosen for their ability to sufficiently measure the electrical power in one phase. However, as a precaution, the electrical power flowing into each one of the three phases was consecutively measured when the agitator was running under stable conditions. As the power input to an agitator motor fluctuates with time due to the turbulent liquid motion, each measurement

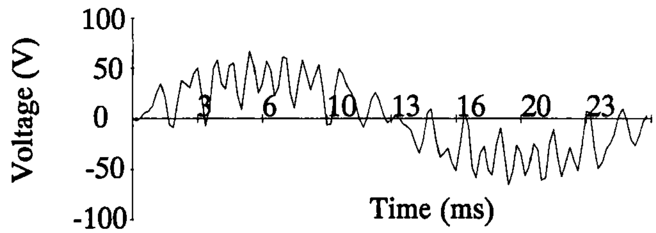

Figure 1. Typical voltage signal produced by a Danfoss VLT100-150 speed control unit.

represents an average of 100 short measurements during a 1000 s long measurement time. For these symmetry checks the largest deviations among the three phases were found to be 11% in Stavanger and 6% at Strängnäs. As the present measurements only attempt to relate the electrical power to a previous measurement of the mechanical power, any error in the electrical measurement that varies smoothly with power and is independent of time, disappears in the calibration procedure. For this reason the three phase systems at hand were considered sufficiently symmetrical for the present purpose.

Tables 1 and 2 show rpm values, number of engaged turbines, the power inferred from previous measurements

Table 1. Summary of the Power Calibration Measurements in Stavanger.

rpm	No. of turb.	El. power (kW)	Mech. power
97.6	1	8.66 ± 0.4	4.07
115.1	1	12.85±0.64	6.69
132.4	1	14.97 ± 0.70	10.2
97.6	2	13.02 ± 0.39	8.14
115.1	2	18.98 ± 0.80	13.38
132.2	2	25.38 ± 0.36	20.4
65.8	3	8.19 ± 0.76	3.75
97.6	3	16.70 ± 0.50	12.21
115.1	3	25.71 ± 0.60	20.37
132.4	3	35.36 ± 1.0	30.6
65.8	4	9.54 ± 0.58	5.0
97.6	4	21.29 ± 0.59	16.28
115.1	4	32.97 ± 0.74	26.76
132.4	4	47.03 ± 0.94	40.8

Table 2 Summary of the Power Calibration Measurements at Strängnäs.

rpm	No. turb	El. power (kW)	Mech. power (kW)
80	1	3.86	3.744
90	1	4.98	3.973
102	1	6.63	6.397
80	2	6.53	7.291
102	2	12.3	12.875
125	2	21.3	20.1
80	3	9.39	8.697
102	3	18.4	15.863
150	3	59.9	40.948

(Noorman, 1993) and (Wernersson and Trägårdh, 1995) and the electrical power measured by the Fluke 41B Power Harmonics Analyzer at the two installations. The relation between mechanical and electrical power is further shown in Figures 2 and 3. From the figures it appears that within the measurement errors the relationship is purely linear. A linear regression analysis gives the mechanical power in terms of the electrical power as:

$$P_M = A + BP_E, \tag{5}$$

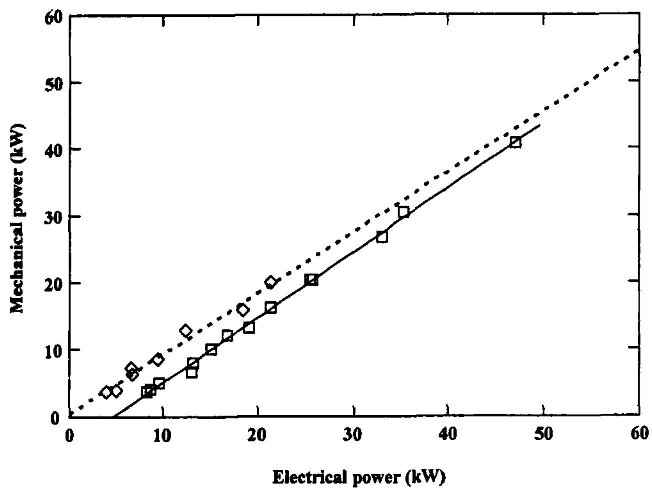

Figure 2. Mechanical power as a function of electrical power. The boxes are the data from the Stavanger bioreactor. The diamonds are the data from Strängnäs, The solid and dash lines are the fits to the Stavanger and Strängnäs data according to Equation (5) with the parameters given in the text.

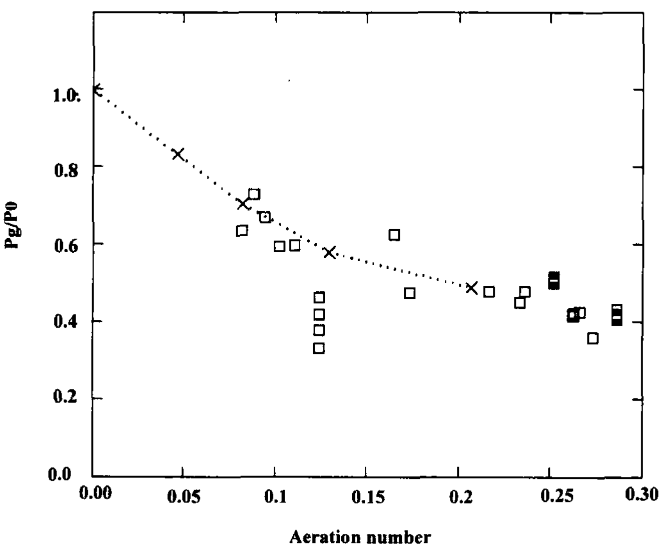

Figure 3. Ratio of aerated mechanical power to unaerated power as a function of the aeration number $Fl = Q/(ND^3)$ when using four Rushton turbines in the Stavanger bioreactor. The boxes are the results obtained during the fermentation process where both the gas flow and the rpm have been varied. Note that several boxes fall on top of each other. The crosses connected with the dotted line is the power obtained during the holdup measurements when the speed has been held constant at 115 rpm.

with $A = -4.459$, $B = 0.966$ (Stavanger) and $A = 0.43$, $B = 0.905$ (Strängnäs). The fact that the curves appear to be quite different (the constant A is very different) is believed to be due to the fact that the frequency inverter at Stängnäs is equipped with a filter which removes most of the higher frequency components.

With these values of A and B it appears that the agitator at Strängnäs becomes a perpetual motion for $P_E < 4.5$ kW. It was therefore decided to force A to zero for this instance in which case B became 0.95. But this is larger than the expected efficiency for this drive train, given by the manufacturer as 90%. However, the people who measured the mechanical power from the heating up of the Strängnäs reactor with stirring (Wernersson and Trägårdh, 1995) do not claim a higher accuracy than 10%. For these reasons it was decided to use $A = 0$ and $B = 0.9$ for this case.

In the Strängnäs reactor no significant difference could be found between power measurements at different rpm. In Stavanger the basic power measurements were somewhat more accurate, i.e., 5% instead of 10%, and a small such dependence could be observed. However, including the appropriate modification of Equation (4) to take this into account, did not noticeably reduce the error in the fit. For this reason it is only possible to claim that the rpm dependency of the efficiency of the drive train is less than 5% of the converted power. As the average error between measured and fitted mechanical power is 0.54 kW, it is concluded that the accuracy of the electrical power measurement is limited by the accuracy of the calibration to about 5% of the converted power.

Examples of Measurement Results

The technique has been applied during fermentation studies and measurements of holdup, thickness of foam layer, mixing times, and liquid velocities in the two installations (Enfors et al., 1998). Figures 3 and 4 show how the power imparted to the liquid varies with the aeration number $Fl = Q/ND^3$ during fermentation, using Rushton turbines in the two installations.

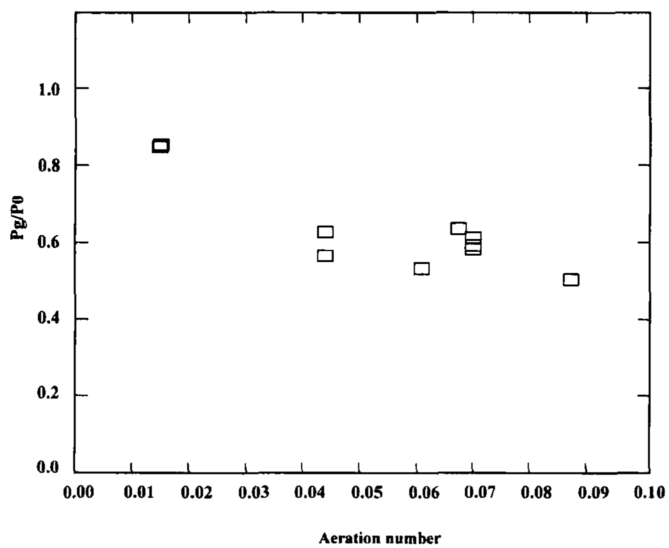

Figure 4. Ratio of aerated to unaerated power as a function of the aeration number when using three Rushton turbines in the Strängnäs bioreactor. The data are from a fermentation operation where both air flow and agitator speed have been varied.

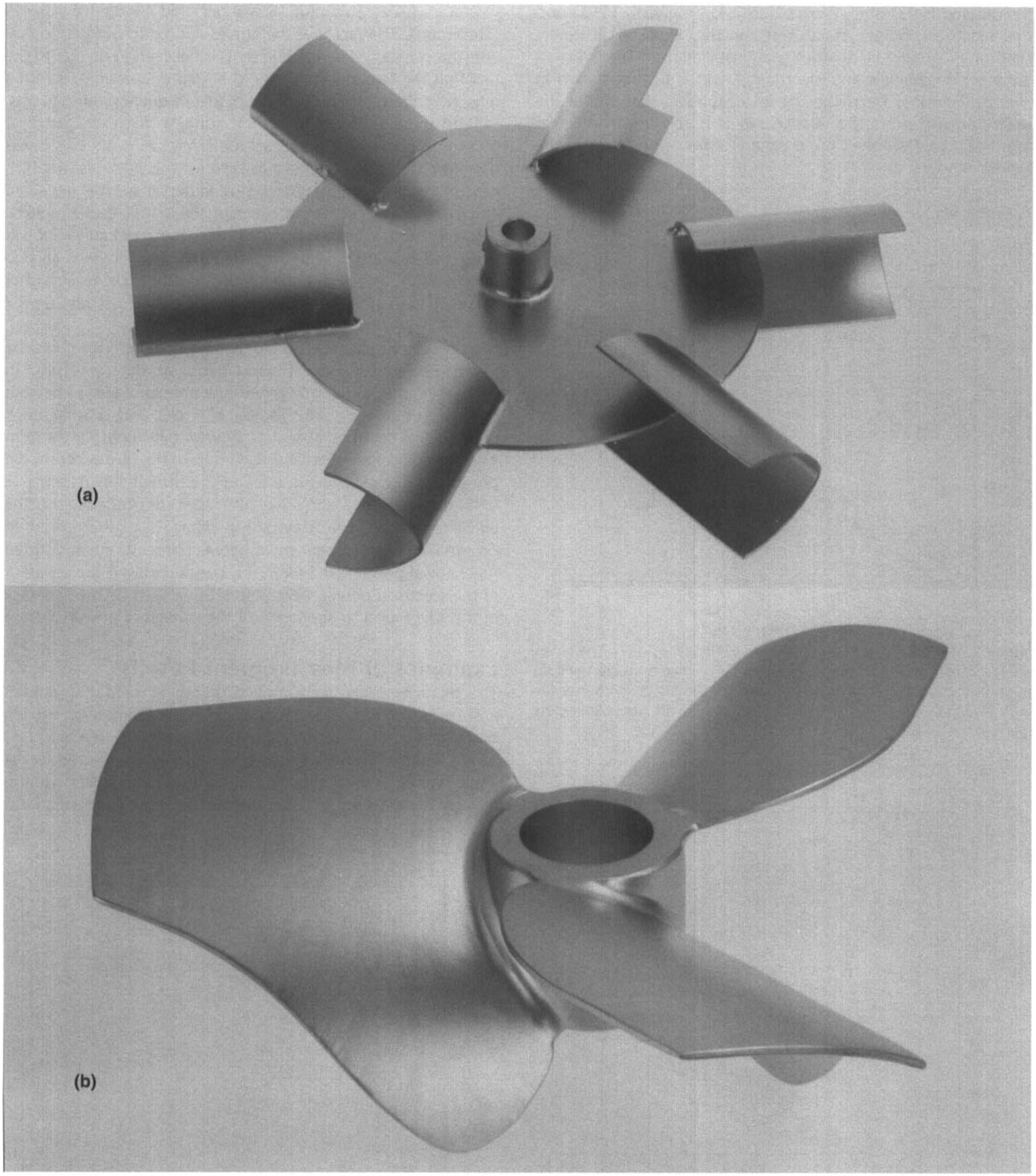

Figure 5. Models of the SCABA 6SRGT turbine (a) and the three blade SHP1 hydrofoil type impeller (b) employed at Strängnäs.

The large scatter in the data points is due to the fact that the power reduction depends on both air flow and agitator speed, while the figures only display the variation as a function of one variable, namely the aeration number. This is exemplified in Figure 3 where a curve with data obtained at 115 rpm is included.

In addition to the work using Rushton turbines an alternative stirrer configuration employing one SCABA 6SRGT turbine at the bottom, and with upward pumping, SCABA SHP hydrofoil type impellers on top were investigated. Figure 5 depicts these impellers. In Stavanger three four blade D = 1150 mm SHP impellers were placed on top of the D = 1050 mm turbine; at

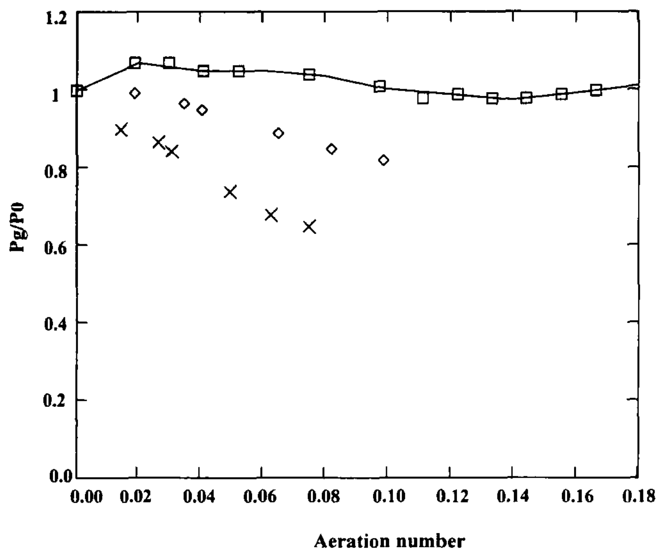

Figure 6. Values of Pg/PO. The boxes correspond to the values obtained by Saito et al. (1992) for the SRGT turbine. The soild curve is the spline of interpolation of these data whioch is used when deriving the data for the secondary SHP impellers. The diamonds are the data as observed for the entire stirrer in Stavanger. The crossess are the data derived, as described in the text, for the secondary SHP impellers.

Strängnäs two three blade D = 1050 mm SHP impellers were placed above the D = 950 mm turbine.

The power utilized by this impeller configuration was measured in Stavanger at 100 rpm and at four different liquid levels. According to this measurement the power number of the 6SRGT turbine is 1.65 and the power numbers of the three SHP impellers in order of distance from tank bottom were 0.51, 0.44 and 0.41. For the 6SRGT turbine this number agrees with the value reported by Boon (2000) but is 10% smaller than the value obtained in SCABA's laboratory for a single impeller system with $H = T$ and $D = T/3$. For the SHP impellers the values found are ≈30% lower than the values obtained in laboratory tests with single impeller systems with $H = T$ and with $D = T/3$. The reasons for these differences are believed to be that the D/T ratios are larger than 0.5 in Stavanger and that the inter-impeller clearance is relatively small. Similar observations have been made by other researchers (Hudcova et al. 1989).

The diamonds in Figure 6 show the ratio of aerated power to unaerated during a fermentation using the alternative stirrer configuration. In comparison with Figures 3 and 4 the power reduction due to aeration is much lower. This is due to the excellent gas handling ability of the SCABA SRGT turbine. The boxes in Figure 6 show the data as obtained by Saito et al. (1992), for how the aerated power relative to the non-aerated power varies with the aeration number for this turbine. Assuming that the small deviation from unity in this curve is independent of the Reynolds and Froudes numbers, of the presence of other impellers in the tank, and of the detailed geometry, it is possible to infer the behaviour of the upward pumping SHP impellers on aeration. This is done by simply subtracting the estimated power draw of the turbine from the total power input. The result is shown in by the crosses in Figure 6. At the maximum aeration number of 0.1 the ratio of gassed to ungassed power is 0.65. This is similar to the results of Boon (2000) for two upward-pumping SHP impellers placed on top of a 6SRGT turbine.

Conclusions

The present study shows that it is possible to obtain estimates within 5% accuracy of the power that is imparted to the liquid via the agitator shaft by measuring the electrical power used by the motor. It is especially possible to make very detailed investigations of the behaviour of the agitator in this way. The advantages of the method are two, namely: i) ease of implementation it only takes a few minutes to install a Wattmeter with a magnetic AC current probe; and ii) costs. The price of the Wattmeter used here is only about one tenth of the cost of any other power measurement device that can be fitted to a full sized industrial agitator.

The big drawback of the method is that for maximum accuracy it needs to be calibrated and this can be a cumbersome and tricky procedure. The easiest way is probably to try out the drive train at the manufacturer's laboratory but this is possible only with new installations. If the speed control unit produces a voltage that is close to being sinusoidal, a reasonable accuracy (≈10%) can probably be obtained over a large range of torque and rpm values by simply using the manufacturer's estimate of the efficiency.

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Nomenclature

D	impeller diameter, (m)
$I(t)$	instantaneous electric current, (A)
N	impeller speed, (s^{-1})
N_t	number of engaged turbines
P_E	electrical power, (W)
P_M	mechanical power, (W)
Po	impeller power number
PO	unaerated power, (W)
Pg	aerated power, (W)
Q	air flow, (m^3/s)
T	tank diameter, (m)
T_t	time integration limit, (s)
t	time, (s)
$V(t)$	instantaneous electric voltage, (V)

Greek Symbols

ρ	liquid density, (kg/m^3)

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