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Power consumption measurements in a liquid vessel that is mixed using a vibratory agitator

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Abstract

The power consumption measurements are reported for a reciprocating plate agitator for different Newtonian liquids mixed in a tubular vessel. The maximum power consumption is calculated by multiplying the maximum force acting on the shaft and the maximum velocity of the reciprocating plate. Lounes and Thibault (see reference 7) reports a general form of the results of this investigation. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Power consumption; Mixing vessel; Reciprocating plate agitator; Power consumption

1. Introduction

This work is an extension of previous studies [1] carried out on the same reciprocating plate agitator, in which additional information may be found; a single correlation covering the whole range of Reynolds numbers was proposed for the generalization of the maximum power consumption for that case. The present study investigates the effect of a wide range of values of the process parameters on the mixing power in an experimental system; all variables may be independently measured and their effect incorporated in an overall dimensionless correlation. The general equation is well suited for computer calculations as well as for the engineering design of the correct dimensions of the reciprocating plate agitator drive. Moreover, it should be noted that reciprocating plate agitators have enjoyed worldwide acceptance for a number of years as modern equipment in the chemical, food and pharmaceutical industries. However, only a few papers [2–7] dealing with the measurement of the transient behaviour of the power requirement for pulse or reciprocating plate columns are available.

Some of the first workers to carry out theoretical and experimental studies with the model proposed by Jealous and Johnson [8] were Baird and coworkers [2,3,5,7]. The objects of their investigation were a reciprocating baffle-plated column [2,5,7] and a tube [3] with a series of wall baffles. As shown by these workers the measurements of the power and energy dissipation for oscillatory flow agree with the quasi-stated flow model. Moreover, Baird and Stonestreet [3] proposed an alternative new acoustic model based on the acoustic principle and the concept of eddy viscosity. These models give good agreement with experimental data at high Reynolds numbers for fluids of very low viscosity. Recently, Hafez and Prochazka [6] have proposed equations based on the theoretical analysis of the momentum and energy balances for the instantaneous acting force on a set of plates and the instantaneous pressure on the bottom of both pulsed and reciprocating plate columns. Hafez and Baird [5] determined the power consumption in the Karr column using two different methods. They found that the simple quasi-state method fitted the experimental data reasonably well at low frequency and high amplitude. Tojo et al. [4] studied power dissipation in a reciprocating plate column with no perforation, and proposed an empirical correlation for estimating the power dissipation. They confirmed that the power dissipation in the column is mainly controlled by the maximum drag force exerted in the reciprocating plate at the maximum velocity of the plate vibration. Lounes and Thibault [7] studied the hydrodynamics and power consumption of a reciprocating plate gas liquid column. The power consumption was calculated using the instantaneous pressure drop obtained from the energy conservation law. They proposed relationships for the calculation of the maximum and average power consumption given to the fluid mixture and obtained an expression for the average orifice coefficient for the laminar flow regime.

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From the above review, it can be seen that there are no data available describing the power consumption in a mixing vessel with a low-frequency reciprocating plate agitator covering a wide range of liquid properties and process parameters.

2. Experimental details

The measurements of power consumption were made using the apparatus shown in Fig. 1. All the experimental work was performed using a vertical tubular cylindrical vessel of 0.248 m in diameter and 0.678 m in height which was resistant to corrosive liquids. The mixing was carried out with a single perforated plate [9] and without perforation oriented horizontally where reciprocating in a vertical direction. The dimensions of the vessel are shown in Fig. 1. The agitator was always placed at half of the liquid height in the vessel. An electric a.c. motor coupled through a variable gear and a V-belt transmission turned a flywheel. A vertical oscillating shaft with a perforated plate and a hardened steel ring through a sufficiently long crankshaft were articulated eccentrically to the flywheel. An inductive transducer (Vistronic AE1, Poland) mounted inside the ring and a tape recorder (Motokompensator MKT1, Germany) were used to measure and record the inductive voltage directly proportional to the elastic strain of the ring. The magnitude of the total force straining the shaft carrying the plate cannot be measured directly, but can be evaluated from the vertical oscillation of the voltage. The calibration of the ring was carried out by means of a tensile and compression testing machine. A typical example of the instantaneous total force curve is given in Fig. 2. Similar diagrams were recorded for other fluids, as well as for various operating parameters changed over a wide range. Beet molasses, aqueous solution of molasses, heavy oil, machine oil, used oil, glycerol, water and transformer oil were used in the experiments. The viscosity data of the liquids were obtained with a Viscotester VT02 (HAAKE Mess-Technik GmbH u., Germany). By changing the transmission ratio, we were able to control the frequency. The amplitude of the reciprocating plate was adjusted on the scale. The temperatures were measured with copper-constantan thermocouples. One thermocouple was located in the vicinity of the vessel bottom and another was fixed near the liquid surface. During mixing of the reciprocating plate agitator, a small amount of heat was generated. The heat was removed by a continuous flow of water through the cooling jacket of the mixer and the temperature of the liquid was stabilized.

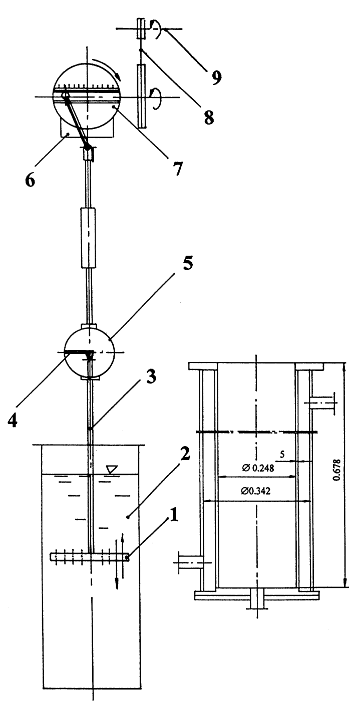

Fig. 1. Experimental set-up: 1, plate; 2, vessel; 3, shaft; 4, inductive transducer; 5, ring; 6, variable gear; 7, flywheel; 8, V-belt transmission; 9, a.c. electric motor.

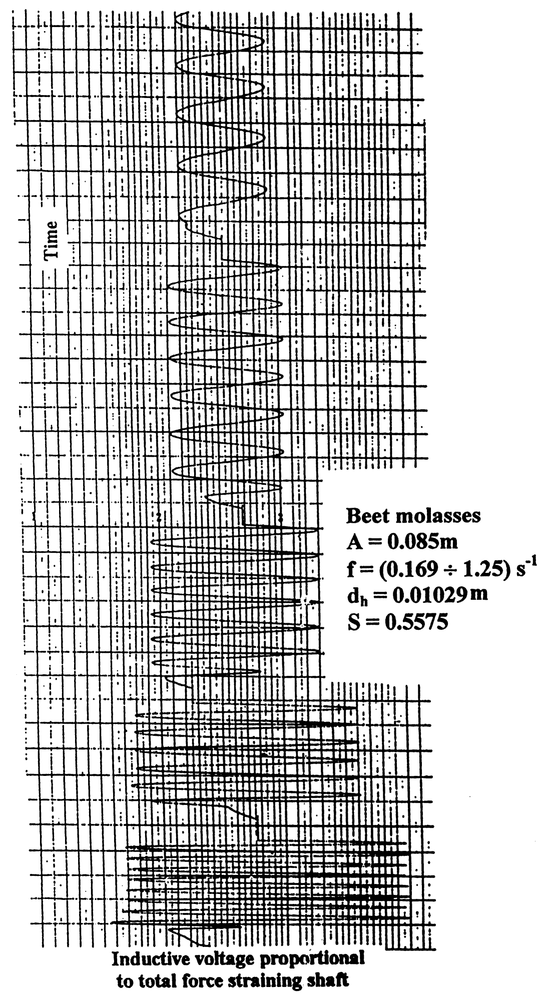

Fig. 2. Typical examples of instantaneous acting force curve.

3. Results and discussion

3.1. Power characteristic

In the present investigation, the power input to the mixed liquid is described by a well-known relationship between the power number, *Po*, and Reynolds number, *Re*. This relationship for a reciprocating plate agitator has the form

$$Po_v = f(Re_v) \tag{1}$$

In the case of a reciprocating plate agitator, the dimensionless group must be defined by introducing the instantaneous acting force, and the velocities of the reciprocating plate agitator and of the mixed liquid into the power number and the Reynolds number.

The major factor, due to the nature of the problem, is the need to assure a relatively simple form of the functional dependence useful for practical calculation. For this reason, the power number, Po_v, and the Reynolds number, Re_v were calculated using the peak velocity of the plate.

In the experiments analysed in this paper, in all cases, the total instantaneous force acting is a simple periodic function of time. From the above, it is clear that the maximum total acting force exerted on the reciprocating plate agitator can be expressed by double the amplitude of the instantaneous force curve. Then, the maximum force at the maximum velocity of the reciprocating plate agitator gives the maximum power consumption. It is evident that the maximum power given to the mixed liquid is a decisive factor in the selection of the drive motor and transmission assembly.

The power number is defined on the basis of Eq. (2) in [3]

$$Po_v = \frac{P_v S^2}{\rho D^2 (2\pi A f)^3 (1-S^2)} \tag{2}$$

The Reynolds number is defined in terms of the maximum displacement velocity and hydraulic diameter

$$Re_v = \frac{2\pi A f d_h \rho}{\eta} \tag{3}$$

The fraction of open area of the reciprocating plate S and the hydraulic diameter d_h are calculated from the following relationship

$$S = \frac{\left(D^2 - d^2 + n d_{oh}^2\right)}{D^2} \tag{4a}$$

$$d_h = \frac{D^2 - d^2 + n d_{oh}^2}{D + d + n d_{oh}} \tag{4b}$$

Hence, the relationship (Eq. (1)) may be written in the following form

$$\frac{2\pi A f F}{D^2 (1 - S^2/S^2) \rho (2\pi A f)^3} = f\left(\frac{2\pi A f d_h \rho}{\eta}\right) \tag{5}$$

where F is the total maximum force exerted on the reciprocating plate agitator. Physical properties in the dimensionless groups are evaluated at the mean temperature of the liquids.

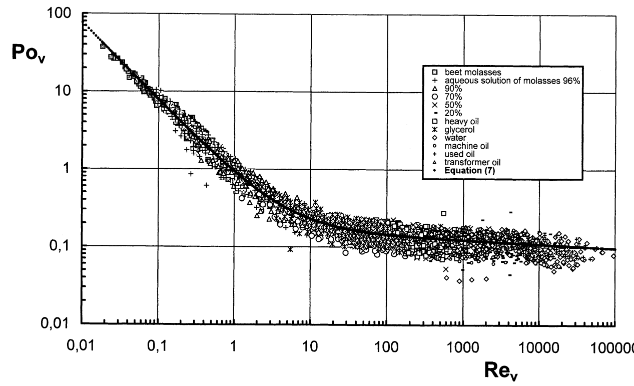

Fig. 3. Effect of Reynolds number on power number.

In order to establish the effect of the Reynolds number on the power consumption, over a wide ranges, data obtained in this work are graphically illustrated in a log versus log system in Fig. 3. Fig. 3 shows the final plot of a single correlation for all fluids and for different geometrical parameters of the agitators. This simplification is supported by the greater scatter among the plotted experimental data represented by points. Initially, the results indicate a great reduction in the power number with an increase in the Reynolds number. Within this laminar region of the flow, the curve defined by the experimental points is not significantly different from a straight line with slope of -1. From the above, it is clear that relationship (Eq. (5)) can be approached in well-known dimensionless form, which is used for rotational agitators. Beyond the laminar flow region, the power has a tendency to curve downward in contrast with the power curve for turbine systems.

The characteristics of the Po_v versus Re_v curve are rather more analogous to the *Po* versus *Re* curve for helical [10,11] and helical-screw [12,13] agitators rather than the linear *Po* versus *Re* relationship for turbine or propeller agitators. Fig. 3 indicates that the power number gradually decreases as the Reynolds number increases. Both the liquid viscosity and intensity of vibration determine the Reynolds number. It is clear that the viscosity has a greater influence on the Reynolds number than the intensity of vibration of the low-frequency reciprocating plate agitator. The form of the curve in Fig. 3 shows that, beyond the central region of this graph, when the viscosity of the liquids is greatly reduced, the curve is approaching asymptotically limiting values. This indicates that the turbulent region is reached. The experimental results shown in Fig. 3 suggest that the Po_v versus Re_v dimensionless relationship can be analytically described by a unique monotonic function. This results in an equation for the whole range of the Reynolds number of the form

$$Po_v = C_1 Re_v^a \left[1 + C_2 Re_v^b\right] \tag{6}$$

in which it is necessary to use different values of the exponents a and b for different regimes of flow. The constants and exponents a and b are computed employing the principle of least squares. Then Eq. (6) can be rewritten in the form

$$Po_{\mathrm{v}} = 0.767\, Re_{\mathrm{v}}^{-1}\left[1 + 0.225\, Re_{\mathrm{v}}^{0.95}\right] \tag{7}$$

This equation is valid for the following range of process parameters: $A = 0.02 - 0.17$ m; $f = 0.124 - 1.43\ \mathrm{s}^{-1}$; $2\pi Af = 0.0212 - 1.423\ \mathrm{m\ s}^{-1}$; $d = 0.08 - 0.24$ m; $d_{\mathrm{oh}} = 0.005 - 0.06$ m; $n = 0$ and $2 - 749$; $P_{\mathrm{v}} = 0.001 - 226$ W; $S = 0.25 - 0{,}916\ \mathrm{m}^2\ \mathrm{m}^{-2}$; $d_{\mathrm{h}} = 0.00552$–0.125 m; $\rho = 852 - 1485\ \mathrm{kg\ m}^{-3}$; $\eta = 0.001 - 17.722\ \mathrm{kg\ m}^{-1}\ \mathrm{s}^{-1}$; $Re_{\mathrm{v}} = 10^{-1} - 10^{7}$; $Po_{\mathrm{v}} = 0.0498 - 37.239$.

The ranges of values of Reynolds number for different fluids are as follows: beet molasses, $Re_{\mathrm{v}} = 0.126 - 6.532$; aqueous solution of molasses: 96%, $Re_{\mathrm{v}} = 0.0928 - 15.240$; 90%, $Re_{\mathrm{v}} = 0.116$–54.044; 70%, $Re_{\mathrm{v}} = 1.257 - 601.5742$; 50%, $Re_{\mathrm{v}} = 8.521 - 2158.948$; 20%, $Re_{\mathrm{v}} = 167.467 - 18300.750$; heavy oil, $Re_{\mathrm{v}} = 7.312 - 3776.448$; glycerol, $Re_{\mathrm{v}} = 167.467 - 18300.750$; water, $Re_{\mathrm{v}} = 430.399 - 95670.180$; machine oil, $Re_{\mathrm{v}} = 59.620 - 6438.092$; used oil, $Re_{\mathrm{v}} = 1976.733 - 57239.800$; transformer oil, $Re_{\mathrm{v}} = 274.317/10993.588$.

Eq. (7), which is presented in Fig. 3 as the full curve, correlates the data very well with a standard deviation $\sigma = 0.0284$. The average percentage error of all the data is + 0.0336%. The difference between the predicted and measured values is less than $\pm 15\%$ for approximately 80% of the data points. This agreement is satisfactory for engineering design purposes.

Eq. (7), which can be used in the generalization of the experimental results obtained in this work, has a somewhat different form from that commonly proposed to describe the power consumption for rotational agitators. Eq. (7) is much more attractive because it generalizes the experimental data obtained for all the important mixing process parameters in a relatively simple and uniform manner.

In a study of a reciprocating plate column, Tojo et al. [4] proposed a typical dimensionless correlation equation for values of the Reynolds number ranging from 200 to 50 000. From their work, it follows that the power number is almost independent of the Reynolds number. This finding may be explained by different type of experimental set and by the different methods used for measuring the force acting in their study. Additionally, they have generalized their experimental data using a somewhat different definition of the power number. Additional attention should be paid to Ref. [12]. In this work the experimental data were generalized using an equation in which the exponent on the Reynolds number was constant, but the exponents of the dimensionless ratios were a function of the Reynolds number. This equation was proposed for central unbaffled helical-screw systems.

3.2. Specific power

From a practical point of view, Eq. (7) should be transformed into a dimensional form in order to be more convenient for the calculation of maximum specific power

$$\left(\frac{P_{\mathrm{v}}}{V}\right)_{\max} = 0.977\, P^{*}\, Re_{\mathrm{v}}^{2}\left(1 + 0.225\, Re_{\mathrm{v}}^{0.95}\right) \qquad [\mathrm{Wm}^{-3}] \tag{8}$$

where:

$$P^{*} = \frac{(1-S^2)\eta^3}{S^2 d_{\mathrm{h}}^3 H_{\mathrm{L}} \rho^2} \qquad [\mathrm{Wm}^{-3}]$$

3.3. Comparison with literature data

The quasi-stated flow model proposed by Jealous and Johnson [8] was extended to the reciprocating baffle-plate column [2] and shell-and-tube heat exchanger [3]. Baird et al. [2] studied power dissipation in a reciprocating baffle-plate column and confirmed that this model appears to be best suited to full turbulent conditions. Additionally, the quasi-stated flow model was used by Baird and Stonestreet [3] to calculate the time-averaged power density for a baffled tube. It should be noted that the equations proposed

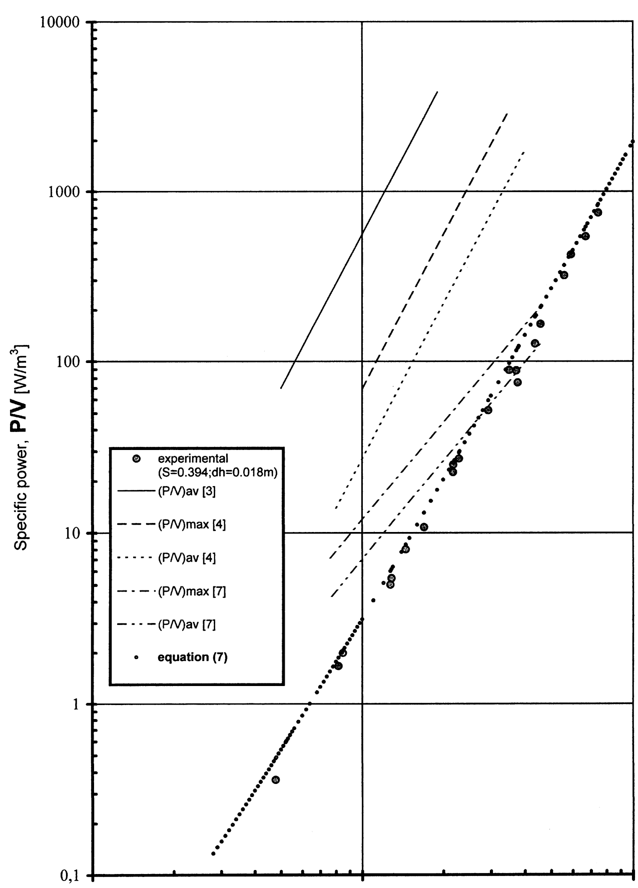

Fig. 4. Comparison of our results of specific power with those of other workers.

by these authors are independent of the liquid viscosity as observed in power consumption equations for turbine and propeller agitators working in a turbulent regime. The quasi-stated flow model is very useful because the power number in this case is only a function of the fraction of open area of the column and the orifice coefficient. Unfortunately, this model is not feasible for viscous liquids in a laminar flow regime.

A comparison of the results of our own investigations with the experimental findings reported in [3], [4] and [7] is presented in Fig. 4. This figure also compares the values of the maximum specific power calculated using Eq. (7). The marked points given in this figure are selected experimental data obtained for technical glycerol and for $S = 0.394$ and $d_h = 0.0183$ m. From Fig. 4, it can be seen that the time-averaged values of the specific power for a tube with 55 wall baffles reported in [3] and time-averaged and maximum specific power for a disc column with four stages reported in [4] and for a plate column with 18 perforated plates reported in [7] are greater than the maximum power density obtained in this work. The different results may be explained by the different geometrical configurations of the mixing systems and the different methods used for the measurement and evaluation of the power consumption.

4. Conclusions

1. The power consumption characteristic of the reciprocating plate agitator is described by a modified power number versus Reynolds number unique equation.
2. The effects of the reciprocating plate agitator geometry on power consumption are correlated by dimensionless Eq. (7).
3. The suitability of a selected reciprocating plate agitator geometry for practical application in chemical process engineering should be assessed in terms of the mixing energy. Hence mixing time experiments could prove useful to this end.
4. The quasi-stated flow model may be suited to calculate the time-averaged power dissipation in the full turbulent regime. The main drawback of the quasi-stated flow model is that it does not include the effect of liquid viscosity on the power density.

Appendix A. Nomenclature

A	amplitude (as one-half total distance (stroke) travelled by the plate) (m)
d	diameter of plate agitator (m)
d_{oh}	diameter of hole in the plate agitator (m)
d_h	hydraulic diameter defined by Eq. (4b) (m)
D	inner diameter of vessel (m)
f	frequency of reciprocating plate agitator (s^{-1})
F	maximum acting force (N)
H_L	height of the liquid in the vessel (m)
P_v	$P_v = 2\pi Af$ power consumption in mixing process (W)
Po_v	power number defined by Eq. (2)
Re_v	Reynolds number defined by Eq. (3)
S	fraction of open area of reciprocating plate defined by Eq. (4a)
V	volume of mixed liquid (m^3)

A.1. Greek letters

η	viscosity of liquid (kg m^{-1} s^{-1})
ρ	density of liquid (kg m^{-3})

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