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Research Article

POWER NUMBER CORRELATION AGITATED IMMISCIBLE LIQUID SYSTEMS

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ABSTRACT

The dispersion of immiscible liquids in agitated vessels has been studied for range of liquids and geometries under both batch and continuous conditions. Preliminary experiments were first carried out in a small scale single-stage mixer-settler unit operating with a 20% v/v TBP/OK, 5% M nitric acid, uranyl nitrate system. This was followed by measurements of power consumption and particle size distribution in above said systems in 6 and 9 inches baffled a side 20 cm square tank using six-flat bladed turbine type impellers. The particles were measured by a novel design photographical method. The various liquid systems used were MIBK, cyclohexane/water and 20% TBP/OK/0.05 nitric acid. Various fractions were studied 105, 15% and 20%. Impeller speeds varied from 300 rpm to 500 rpm. The power input measurements showed no difference for both batch and continuous flow systems. A constant power number of 4.63 over a large range of Reynolds Number > 10^4 for the baffled baffled systems, and of 3.74 for the un-baffled vessel of square cross section was obtained. It has been found that mean particles sizes in continuous flow were slightly bigger than that of in batch operations. Power number is measured by the Weber Number defined by $We = N^2 D_I^3 \rho_m / \sigma$

INTRODUCTION

Scope and Content

The dispersion of immiscible liquids in agitated vessel has been studied for a range of liquids and geometries under both batch and continuous conditions. Preliminary experiments were carried out first in a small-scale single mixer - settler unit operating with the 20% TBP/OK, 0.05M nitric acid, uranyl-nitrate system. This was followed by measurements of power consumption and drop size distribution in agitated liquid-liquid systems in 6 and 9 inches baffled, and a 20 cm side square tank using six-flat bladed turbine type impellers. The drop size measurement technique employed a rigid fiber optic probe, knit-mesh coalesce aid pad and photography.

Introduction

The need to determine the power requirements in liquid - liquid dispersed systems in numerous industrial and engineering applications became fundamentally important for the design of mixer-settlers of various scales. Buckingham (1) first time put forward pi (л) his theory in use. Buckingham's Theory was taken up by Rushton (2) and *et al.* further developed. In almost all related studies Rushton's studies were essentially based on in their works. Further, in industrial chemical, pharmaceutical, mining, petroleum and food industries, the mixing of two immiscible liquids in both turbulent and laminar flows are of common operations. All power that input into vessels of agitated by mechanically in two-phase flow liquids. The arrangement for power measurements for both systems is shown in Figure. 1 and Figure.2 respectively. In two of the three liquid-liquid systems, distilled water was used as major phase, at different volumetric holdup fractions. The third system was %20 TBP/OK, and 5% M nitric acid. The impeller speeds were 300 rpm to 700 rpm. In all cases the mean values of density and viscosities were calculated by using equation 3 and 4 and for the power consumptions equation 1.1 employed. The power numbers were calculated by the use of equation 1.2. The power results obtained from the experiments were correlated in terms of power number versus Reynolds Number separately for batch and continuous systems in agitated vessels of different geometries. The power correlation for batch system is shown by Fig.9 and Fig.10 and for the continuous operations in Figure 5. All the power data is given in the attachment.

Objectives and Background to the Study

This study is concerned with dispersions systems of immiscible liquids. The main purpose of such dispersions is to increase the interfacial area by power input so that mass

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transfers with or without chemical reactions takes place. The chemical reaction rates are directly related with the interfacial area therefore, droplet size that is created in reactions is a primary function of power dissipated into the system. The equipment used is mixer-settler specially designed and built by Perspex material due to its transparent status. The design of these devices at present is rather empirical due mainly to insufficient studies on dispersion behavior under varying conditions. For instance, although the design of large scale mixer-settlers for uranium purification is usually carried out by simply scaling-up the existing dimensions of a smaller unit. The basis for design is still not understood in spite of many years of operating experiences. The main problem often lies in design of the settler and in order that this may be optimized it is necessary to establish the relationship between settling capacity and the main flow sheet conditions, and the design parameters. One of the important parameter is power requirement related with power number.

Some qualitative results are noted in batch system and effect of impeller size. The effects of turbine type of impeller size on power consumption were examined in agitated vessels operating with air-liquid interface. The different ratios of D_I/D_T namely impeller size and tank size respectively were studied in order to assess the power characteristics of the various two-phase liquid systems. The dispersions of immiscible liquids were at various dispersed phase holdups. The dispersion of methyl-iso-butyl-ketone in water, cyclohexanol in water, and 20/80 by volume tri-butyl-phosphate/odorless kerosene in 0.05M nitric acid dispersions were produced in 6-9 inches in diameter fully baffled cylindrical and 20 cm a side square vessels. The application of direct photography by means of fiber optic probe was used. This is a novel technique which makes it possible to measure drop size distribution without seriously affecting the hydro dynamic conditions which had been established.

LITERATURE REVIEW

Large number of investigators reported impeller power characteristics in terms of two main dimensionless group ,the Power Number,Np, and the impeller Reynolds Number, Re .White and Brenner (1) were first to point out the possibility of correlating impeller power by dimensionless analysis. Hixon and Luedecc (2) and Johnstone and Thring (3) also made extensive studies for the development of a generalized form of a power equation. A general relationship including all variables of a system, in liquid -liquid mixing systems may be expressed as

$$F(D, T, H, C, S, L, W, J, \rho, \mu, g, N, P) = 0 \qquad \ldots\ldots\ldots.1$$

Development of a power equation in its full form based upon Buckingham's Pi (5) Theory, was well established by Rushton, Costich and Everett (4) from a classical dimensional analysis. In fact much of the published work has been developed from this work. Considering a flat-bottom cylindrical tank with an impeller centered on a vertical axis, they related the power delivered by the impeller into liquid system to the physical variables. Taking the impeller size as the reference length they obtained the power equation

$$N_p = K(N_{Re})^m (N_{Fr})^n (T/D_I)^t (H/D_I)^h (C/D_I)^c (S/D_I)^s (L/D_I)^t (W/D_I)^w (J/D_I)^j (B/N_o)^b (R/N_o)^r \qquad \ldots\ldots. 2$$

or,

$$Pg_c / \rho N_3 D_I^{\,5} = K(NRe)m\ (N_{Fr})^n (T/D_I)^t (H/D_I)^h (C/D_I)^c (S/D_I)^s (L/D_I)^t (W/D_I)^w (J/D_I)^j (B/No)^b (R/No)^r \quad \ldots..3$$

Although this equation appears to be in a complete form, it does not cater for off-centered impellers or multiple impellers etc. It contains three main dimensionless groups. Bates *et al.* (6) also pointed out that above equation 3 should be expanded to include baffle number and width, spacing between impellers, and off-center impeller location

1. Dependent variables as claimed by White and Brenner (1), called by the Power Number, Np.
2. Independent dimensionless terms, the Reynolds Number, N_{Re} and Froude Number, N_{Fr} respectively.
3. The remaining next seven terms defining the effects of tank geometrical factors and impeller measurements.

The last two terms are required to account for the modification of the impeller blades and baffling with reference to standard design configurations. In equation 3, N_{Re} indicating the Laminar flow charateristics whereas Froude Number,N_{Fr} during the mixing operations it indicates if vortex creation in the tank. If votex formation in swirling systems can be eliminated, the above equation can further be simplified as $N_p = Pg_c / PN^3D_i^5 = KN^m_{Re}$

If mixing operation is carried out ina baffled tank in the turbulent region for a given geometry of configuration proposed by (McCabe &Smith) as

$$Np = P/ rN^3D^5 = \text{constant} \qquad \ldots\ldots.. 4$$

This dimensionless power number, Np, represent an important parameter which enables the designer to predict the impeller power requirement for a given condition. The power consumption in liquid- liquid systems in a stirred vessel is a function of impeller type, speed of stirring, physical properties of liquids being mixed and the geometric measurements of impeller and the system. The power input is related with the equation for given input of power ,P, to the impeller creates a flow rate Q and a head ,h, for a low-viscosity liquid is thought to be in terms of the turbulence is generated.

$$P = rQgh \qquad \ldots\ldots\ 5$$

Rushton, Costich and Everett (4) studied the power characteristics of mixing impellers using five impeller types of diameters from 0.06 m to1.2 m. They used both baffled and un-baffled configurations, vessels of diameters from 0.2 to 2.5 m and fluids of viscosity from 0.001 kg/m-sec to 40 kg/m-sec. They developed their correlation of power:

$$Np = k\,(Re)^m \qquad \ldots\ldots\ldots\ 6$$

O'Connel and Mack (7) did some work on power relationship for flat –blade turbines by various blade numbers and impeller width-length ratios for laminar and turbulent flows under fully baffled conditions.

$$Pg_c/ \rho N^3D^5 = k\,(\mu/rND^2)\,(W/D)^b \qquad \ldots\ldots\ 7$$

In turbulent region Re > 10.000)

$$Pg_c/ \rho N^3D^5 = k\,(W/D)^b \qquad \ldots\ldots\ldots\ 8$$

Nagata *et al.*(8) obtained for fully baffled tanks

$$Np = A/R + B(H/T)^{(0.35+W/T)} \qquad \ldots\ldots\ldots\ 9$$

O'Kane (9) investigated the effect of blade width and number of blades on power consumption. Gray *et al.*(10) proposed a power correlation for DT's with six flat blades. He fixed a constant power number of 5.17 for data C/D > 1.1. For C/D < 1.1, Np varied with $(C/D)^{0.29}$. Caldebank (11)) did some study and find a power number of 1.63. Rao and Joshi (12) did some similar power works. Rewatkar *et al.*(13) conducted a series of experiments found power numbers 5.18 and 1.67 respectively. They derived a correlation:

$$Np = 0.653\ (D/T)^{0.11}\ (C/T)^{-0.23}\ (n_b)^{0.68}\ (A)^{1.82} \quad \ldots\ldots\ldots\ 10$$

For blade angled impeller. Chudacek (14) proposed that the effect of vessel bottom shapes should be included in the above analysis as the vessel bottom has direct influence in the circulation pattern and therefore influence the impeller power consumption. If $N_{Re} > 10^4$, power number N_p is not dependent on N_{Re} , and, therefore $N_p = K$. Here K is a constant and governed by geometric system parameters. Rushton and at al. (4) indicated that if, Reynold Number is less than 300, Froude number can be ignored. Figure.1. This is called power curve. These data can only be implemented for small scale single stage mixer-settlers successfully. Mehta and at al.(18) in a recent study they did a lot of aspects of power dissipation in liquid-liquid systems using flat-bladed turbine and propeller type creating radial and axial flow pattern. They found that unlike disk turbines, power requirements for the pitched -blade turbine decreased as the impeller off-bottom clearance decreased. In all cases disk turbine required more power than 45^{0} pitched -blade turbine. Armenante and *et al.* (19 & 20) measured power using multiple-disk turbines in agitated systems. They found powers numbers of single pitch-bladed türbine were found to be relatively constant in a wide range and to increase because of the throttling effect caused by the proximity of the impeller to the tank bottom.

Experimental Apparatus and Techniques used in the power study

Objective

The aim of the experimental apparatus as shown in Figure. 1 visually to investigate:

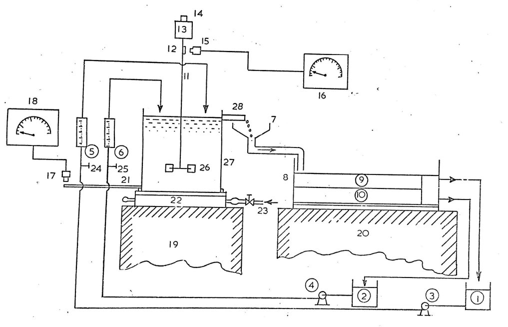


FIG 1 ARRANGEMENT FOR POWER INPUT MEASUREMENTS OF CONTINUOUS DESIGN

PARTS-LIST OVERLEAF →

1.Organic(Light Phase) Storage Tank	11.Impeller Shaft	20. Base
2.Aqueous(Heavy Phase) Storage Tank	12.A Piece of Ferrous Metal	21.Torque Arm
3.Organic Phase Pump	13.Motor	22.Air Bearing Disk
4. Aqueous Phase Pump	14.Variable Speed Gear	23.Compressed Air Supply
5.Organic Flow Rotameter	15.Magnetic Probe	24.Organic Flow Valve
6. Aqueous Flow Rotameter	16.Electronic Tacheometer	25. Aqueous Flow Valve
7. Collecting Pipe	17.Load Cell	26. Turbine Impeller
8.Settler	18.Display Transducer	27.Mixing Vessel
9.Light Phase Seperated	19.Base	28.Outlet For Emulsion
10.Heavy Phase Seperated		

Parts List For Fig.1

1. Although the power requirement for single phase liquid mixing are well established for different systems properties in batch operations, the question remains, will the same amount of power input be required, and further will the existing power correlation be valid under continuous flow conditions. Single phase was out of this work. However, the power requirements are vary closely related with single phase system. The same question asked above are also even more valid, in two phase liquid systems uncertainties are mostly based on the determination of the mean values density and viscosities.
2. Therefore, the present work was initiated to investigate the quantitative effects of continuous flow on the power characteristics of the impeller employed in two phase liquid mixing process.

Procedure

The following procedure was considered to obtain experimental data for the power input in various two phases liquid systems under batch and continuous flow conditions in stir red vessels.

Batch process: the power input measurements were carried out at the experimental arrangement is shown

Figure. 2 the mixing vessel were open, flat-bottomed cylindrical tanks having diameters of 15 and 23 cm, and a square tank 20 cm a side. They were all made of persplex transparent material. In the torque Calculations Newton's third principle was based on.

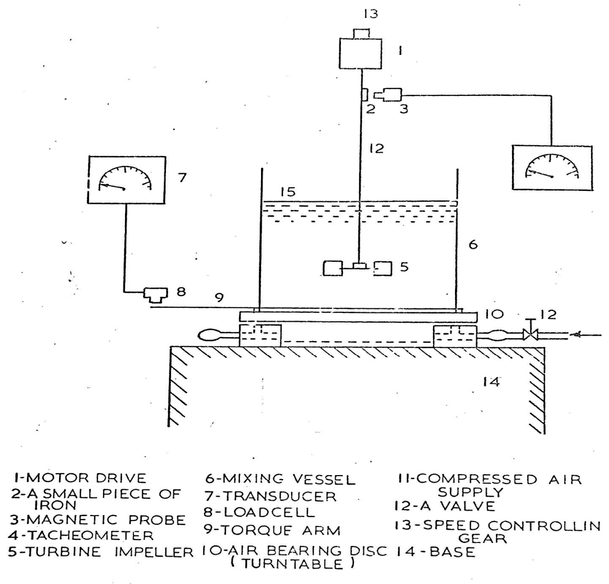


FIG 2 4ARRANGEMENT FOR POWER INPUT MEASUREMENTS FOR BATCH SYSTEM

The mixing vessel was placed on the air - bearing disc, the motor 1/10 HP, Heidolpy-50111ORZRO type variable speed controlled up to 2200 rpm and it was coupled with a electronic speed controller, Tachometer, Sapphire-701A with a precision of 98 % .It measures up to 30.000 rpm speed. All impellers Rushton type six-flat bladed stainless steel measurements are shown in Figure.3 The compressed air was placed on the air-bearing disc. When all ready experimental run started. The response of the torque arm was displayed on the transducer scale in conjunction with the experimental conditions.

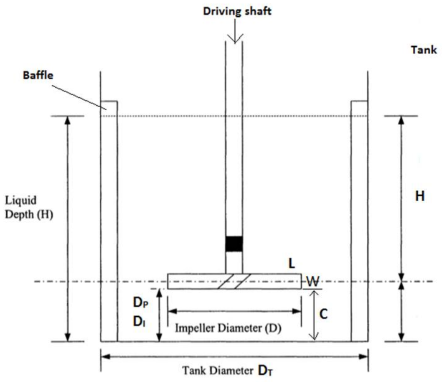


Figure 3 Tank Properties.

D_T:D_I=3.0	J:D_I=0.10
C:D_I=1.0	H:D_T=1.0
L:D_I=0.25	W:D_I=0.20
D_P:D_I=3:4	

Continuous process: The following procedure was followed to provide experimental data for the two-phase liquid system power requirements under continuous flow conditions. The arrangements are shown in Figure 1 and 2. To eliminate air entrainment very tight connections to the air-liquid interface made. The incoming flow was held at a distance equal to the vessel diameter so that the effect of flow jetting on the power consumption may be eliminated. This flow was introduced into the vessel very close to the air liquid interface for the elimination of air entrainments in the system which may cause some errors in the torque readings. Balance on the turn table was sustained. The mixing vessel was entirely isolated from its surroundings. This was important because even a slight touch made system faulty readings. To keep phase ratios corresponding to those the batch system conditions. The rest of the experimental procedures were basically the same as for the case of batch systems.

The continuous flow power studies were made with system, 0.05M nitric acid used against 20% try-butyl-phosphate hereby referred as TBP, with odorless kerosene by volume in a cylindrical fully baffled 6-in. ID and a square 20 cm a side vessel. The rest of liquid system could not be studied due to the material form which the experimental rig was built up and also the physical properties of the liquid concerned. All liquids used were technical grade. They were mutually saturated before they were used for the purpose of drop size measurements studies. See Table: 1 for the physical properties of the liquids.

Table 1 Physical Properties of liquids used at 200C

Liquid	**ρ (g/cc)**	**$\mu(cp)$**	**σ(dyne/cm)**
		3.00	
20% TBP/OK	0.82	1.02	14
0.05M HNO_3	1.03	681	-
Cyclohexanol	0.96	1.00	4.500
Distilled water	1.00	0.57	-
MIBK[2]	0.800		10.50

(1)- Hand book of Chemistry,1976
(2)- Taken from I.C.T
*- Interfacial tension against aqueous phase (0.05M HNO_3)

Correlation of power consumption and determination

The procedure used to compute the power consumption obtained from the experiments carried out under batch and continuous flow conditions in all cases as follow. The power consumed by the impeller in all cases determined by means of

$$P = 2xNxM I \qquad \ldots\ldots \quad 11$$

Where:
P: power delivered into liquid system,
N: Impeller shaft speed, rpm,
M: weight placed on the weighing pan,
I: The length of torque arm.

The power input is therefore linearly proportional to the agitator shaft speed. Power data derived from the experiments carried out under both batch and continuous flow conditions were used to determine in the dimensionless power number.

$$N_p = Pg_c / N^3 D_I^5 \rho_m \qquad \ldots\ldots. \ 12$$

Where:

P : power dissipated in the system,
g_c : gravitational factor
D_I Impeller size,
ρ_m: mean density

In the computation of the main values of density and viscosity, the weighted -arithmetic mean, originally proposed by Miller and Mann (21) and recommended by Vermeulen (11) were used. The Reynolds Number for two phase liquid systems were determined by using existing equation, by taking the mean value of density and viscosities.

$$P_m = P_c\theta_c + (1-\theta c)\rho d \qquad \ldots\ldots 13$$

and the mean viscosity values for all cases used .this was recommended by Treybal and Laity (16)

$$\mu m = \mu_c / 1-\theta_d \quad (1+ 1.5x\theta_d x\mu_d / \mu_c + \mu_d) \qquad \ldots\ldots 14$$

The Reynolds Number for two phase liquid systems were determined by using existing equation, by taking the mean value of density and viscosities.

$$N_{Re} = ND_I^2 \rho_m / \mu_m \qquad \ldots.. \ 15$$

The power number was plotted against the Reynolds Number of the logarithmic graph paper is shown for continuous operation in Figure.5 and Figure.6 as straight line was obtained.

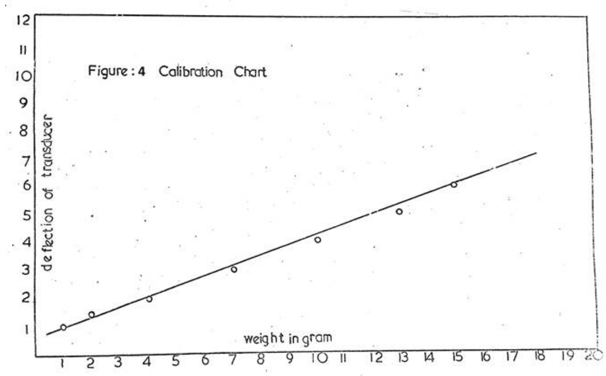
Calibration of Load cells

A linear relationship was obtained between the output from the load cell and (Type BKI-1 of Bofors) the display

Transducer. A calibration chart was established on a linear scale which is shown in Figure 4.

Correlation of Power input

Rushton and co-workers (4) claimed that for the Reynolds Numbers less than 300, it is possible that to correlate results for any given geometrically similar systems without involving the Froude number. The conventional plot of lop N_p against log N_{Re} is the best way topresent data on power characteristics of an impeller used for mixing liquid systems. This relation is known as the Power Curve.



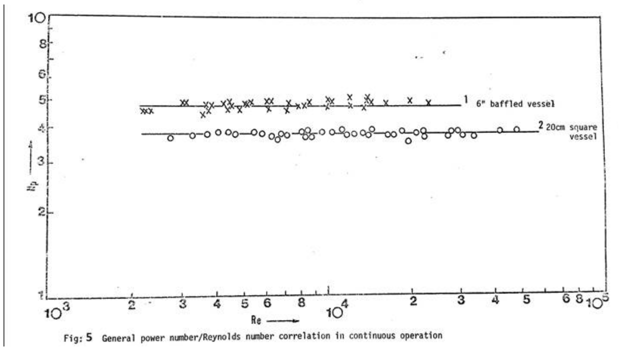


Fig: 5 General power number/Reynolds number correlation in continuous operation

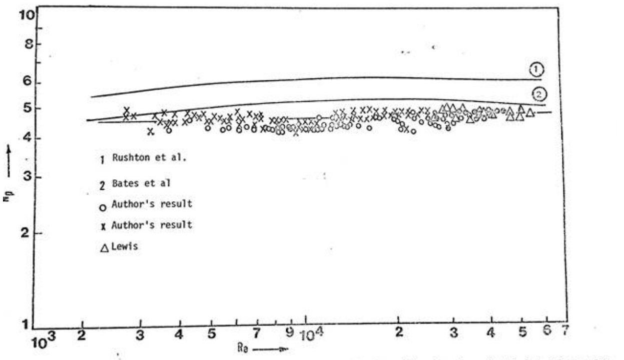


Fig: 6 General correlation of power number/Reynolds number in cylindrical baffled system

Each geometrical configurations has its own power curve and since the plot involves dimensionless groups, it is independent of tank size (17) provided that the tank systems have the same geometrical configuration.

Figure.7 shows the power curve for the standard tank configuration,

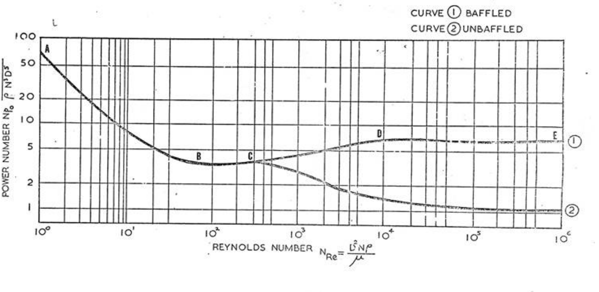


FIG 7 POWER NUMBER/REYNOLDS NUMBER CORRELATION FOR STANDARD TANK DESIGN.

The Power Curve has three distinctive regions:

I-Reynolds Number less than 10,it is a linear in the laminar flow region AB with a slop of -1.The mixing is dominated by viscous forces in this region and the power is given by

$\rho = \mu K N^2 D_I^3$ …… 16

where K = 71 .0 for the standard tank configurations (17)

Thus for laminar flow, power is directly proportional to dynamic viscosity for a fixed agitator speed. It can be seen above that the power dissipated into the liquid system is also proportional to the square of impeller speed and the cube of impeller size.

For the region BCD which is known as the transition zone, which extends up to N_{Re} = 10000, the parameter K in the above equation 16 vary continuously.

As Reynolds Number exceeds 10.000 the flow condition changes and becomes turbulent. In the region DE the curve becomes horizontal and the power function is independent of the Reynold Number. Hence the power is give by

$N_p = K_1$ ……. 17

Where the value of K_1 reported by Rushton and co. workers (4) as 6.3 and by Bates and his associates (6) as 5.0. rearranging the equation 16 which leads to

$P = K N^3 D_I^{\,5}$ ……. 18

In the fully turbulent region the power is proportional to the cube of impeller speed and the fifth power of impeller size. For a given system. At point C the power curves for the standard tank configuration given in Figure. 3. Sufficient amount of energy is being transmitted into the liquid system for vortexing to start. However, the baffles in the tank prevent this .If baffles were not fixed in the vessel then the vortexing would progress to an undesirable stage. This is indicated in Figure 7 curve number 2

The power curve for baffled system is identical with power curve for the unbaffled system up to point C, where Re=300.As the Reynolds Number increases beyond the point C in the unbaffled vessel the power falls sharply under vortexing conditions. Therefore, the power is governed by

$N_p = K (N_{Re})^m \ (N_{Fr})^n$ ………. 19

Where N_{Fr} is involved to account for the effect of vortexing on power consumption.

DISCUSSION OF POWER MEASUREMENTS

All power data were derived from two-phase liquid systems both from batch and continuous operations Fig.2 and 3 respectively (23). Various volumetric hold fractions were used. Power number correlations were done power number versus Reynold Number separately for batch and contious systems agitated in various geometries. They are shown in Fig.6 and Fig.8 for batch systems and for contious systems they were shown in Fig.5 .The effects of tuebine types and impeller size on power consumption examined. Three different ratios of impeller size to tank size were used. A substantial increase in power for four baffles of 12 % was reported by Bissel (23). Mack and Kroll (24) found a limiting ratio that the power did not increase. Nagata and his associates (25) agreed with Mack and Kroll for the maximum power consumption for two- bladed turbines. In this work effect of mixer speed investigated and the findings were shown in Fig.9, Fig.10, and experiments were carried out over a range of mixer speed from 300 to 700 rpm in agitated vessels. In addition, effect of liquid depth, effect of impeller height were also studied in deep scale as shown in Fig. 11, Fig.12 respectively.

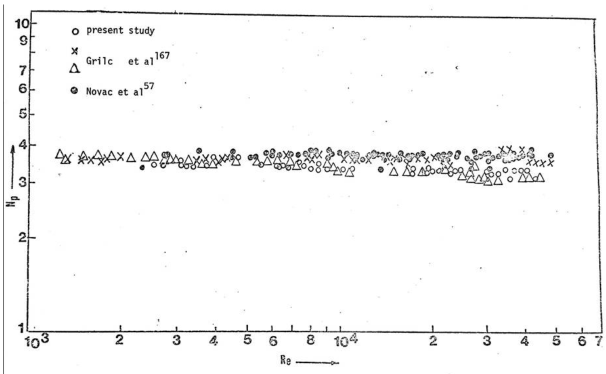


Fig: 8 Correlation of power number/Reynolds number in Turbine agitated square vessel

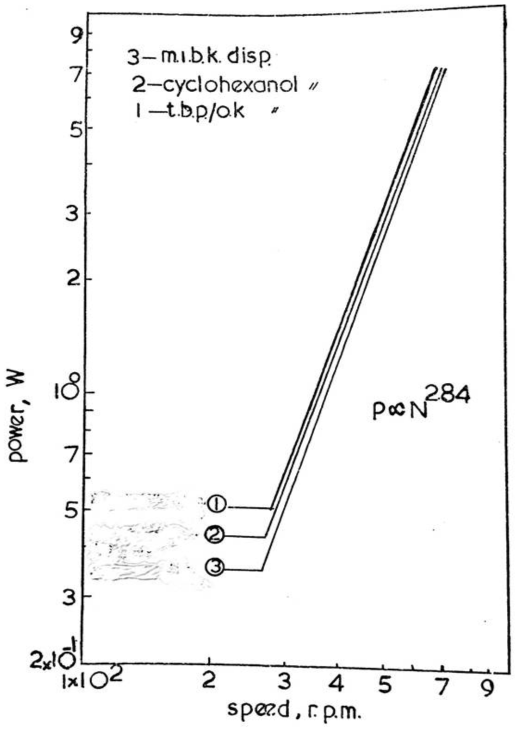


Fig: 9 Power input against impeller speed in square vessel (BATCH)

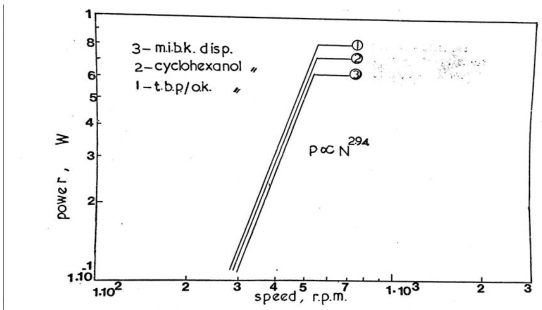


Fig: 10 Impeller speed against power input, 9-in. (BATCH)

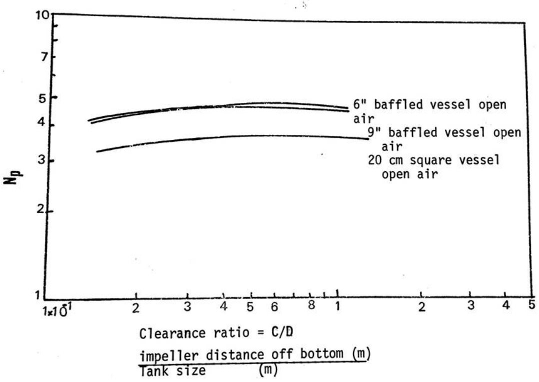


Fig: 11 Effect of impeller off bottom distance on power inputs

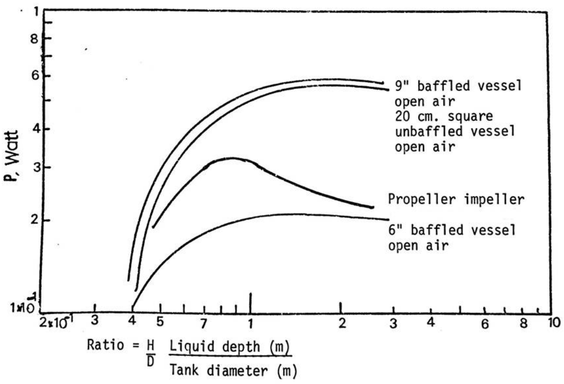


Fig: 12 Effect of liquid depth on power consumption

CONCLUSION RECOMMENDATIONS

The power input results showed that there are no detectable differences between batch and continuous operating conditions. The major fact which emerged from the power input studies indicate that the power against the Reynolds Number Correlation for two phase liquid-liquid systems confirmed that the correlation of power number against the Reynolds Number derived from single-phase liquid mixing can be safely used for two-phase liquid mixing systems under batch and continuous flow conditions provided that geometrical similarities existed.

It was also found that the power numbers obtained for the square and cylindrical vessels from the power study using the average values of the density and viscosities showed good agreement with the majority of previous works in publication.

Acknowledgement

I would like sincerely to acknowledge late Professor W.L. Wilkinson's guiding whom has shown me during this project under his supervision in Chemical Engineering Department as The Chairman School of Post- Graduate of Chemical Engineering Department at University of Bradford, England, The UK. I would like to acknowledge Turkish Ministry of Education for the financial support for this study to make possible.

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Nomenclature

л	*a constant,3,1416*
A	*Constant*
a	*radius of drop(mm)*
a	*acceleration*
$C_{1,}, C_{2}, C_{3}$	*constants*
D_{I}	*Impeller size (cm)*
D_{T}	*Tank size (cm)*
O/W	*oil to water*
W/O	*water to oil*
S/A	*solvent to aqueous*
L	*impeller blade width*
d	*drop size, mm*
d_{max}	*maximum drop size, mm*
d_{vs}	*volume-to-surface, mm*

d_{32}	*Sauter mean drop size, mm*
d_m	*drop size in a mono layer, mm*
M	*total drop number*
$N(n)$	*impeller speed rpm*
f_H	a sign of function
θ	*holdup percentage*
μ	*viscosity, cps*
σ	*interfacial tension dynes/cm*
ρ	*density, gr/cm^3*
$_I$	*Impeller size*
d	*dispersed phase*
d_i	*initial drop size*
c	*continuous phase*
T	*Tank size*
g	*gravitational force ,cm/sec^2*
d_0	*initial drop size*
H	*liquid level in tank, cm*
n_b	*number of baffle*
Y	*Normal probability density function*
M_i	*number of drops*
volume of tank	
s	*standard deviation*

Dimensionless Groups

NWe –WeberNumber - $N^2 D^3 \rho / \sigma$

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