TESCE, Vol. 32, No. 3, pp 1-13

Effects of Impeller Geometry on Mixing of Carrot Concentrate

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ABSTRACT

Mixing of carrot concentrate to be homogenized was investigated using flat – bladed impeller. The rheological properties of Carrot concentrate were studied over the range 10-70°C, solid concentration 66 wt% of Carrot concentrate, and speed of spindle 50-250 rpm. Shear stress-Shear rate data indicate that the concentrate behaves as non-Newtonian Bingham plastic fluid with yield stress. Geometry was studied by varying the impeller to column diameter. An impeller mixer was connected with Ammeter in order to predict the power of the mixer. The relation between Power number, Blend number, Pumping number and Reynolds number were calculated at different D/T. Scale-up of the mixing process from the laboratory to the production plant scale was carried out utilizing the aforementioned correlations.

KEYWORDS: Mixing of non-Newtonian fluids, Rheology of carrot concentrate, Power consumption, Scale-up of agitation system.

1 INTRODUCTION

Liquid agitation is a common unit operation in the chemical engineering and food processing industries and its practical use is widely published [1]. However, most of the literature on liquid agitation addresses Newtonian fluids, while only limited design information is available on the agitation of non-Newtonian fluids. Chemical engineers and food processors often deal with complex fluids in laminar regime which are, usually, highly viscous and shear thinning. It is clear that both vessel and impeller diameters have to be adapted to take these properties into account for distributive as well as dispersive mixing [2,3].

Kamiensky, [4] examined the influence of vessel diameter to mixer diameter ratio on power consumption. The results were presented in the form of graphical characteristics of power consumption and mathematically in the form of dimensionless equation. Later, the discharge flowrate number was correlated as a function of the paddle dimensions by an experimental investigation set up by Yuji and Hiromoto [5].

The impeller diameter to tank diameter ratio, D/T, affected the oxygen mass transfer coefficients and the overall heat transfer coefficients in a pilot scale fermentor of xanathan gum.. These data taken from practical fermentation were useful for the design and scale up of fermenter for economic production of xanathan gum [6] .

Experimental measurements of the influence of geometry of the pendulum agitators with clapping blades and of the physical parameters of mixed fluid on the homogenization time, the power consumption and the energy of mixing were analyzed and original formulas were proposed for the determination of the above mentioned mixing variables by Masiuk and Kawecka, [7].

There are several important dimensionless numbers that are required to design mixers [8, 9]. All must be determined experimentally for a given impeller configuration. These numbers can be used to quantify the performance characteristics of an impeller. Dimensionless numbers are affected by geometric factors, such as the ratio of impeller to tank diameter, D/T, and the ratio of clearance from the tank bottom to tank diameter, C/T.

The impeller power number, N_P, is used to predict impeller power, P, directly and torque, t, indirectly:

$$N_P = P / \rho n^3 D^5 \quad (1)$$

Where, N_P is the power number, P is the power of the mixer, watt, D is the diameter of the impeller, m, n is revolutions per second, and ρ is the density of the concentrate, kg/m^3.

The impeller blend number, N_B, is used to predict the blend time, θ, in a mixed system. Blend number, N_B, attempts to predict the effect of impeller D/T on the results:

$$N_B = n\theta (D/T)^{2.3} \quad (2)$$

where, N_B is the blend number, n is revolutions per second, D is the diameter of the impeller, m, T is tank diameter, m, and θ is time in second.

The impeller pumping number, N_Q, is used to predict the impeller pumping rate, q, directly and bulk fluid velocity, v_{bf}, indirectly:

$$N_Q = q / nD^3 \qquad (3)$$

and,

$$v_{bf} = 4q / \pi T^2 \qquad (4)$$

where, q is volumetric flowrate of fluid leaving the impeller blades, m^3, n is revolutions per second of impeller, D is impeller diameter , v_{bf} is bulk fluid velocity,m/s and T is tank diameter, m.

Finally, Reynolds number, Re, for non-Newtonian fluids measures the ratio of inertial to viscous forces within the mixing environment The generalized Reynolds number is calculated from the following equation for non-Newtonian fluids [6]

$$Re = \rho n D^2 / \mu \qquad (5)$$

Where, ρ is the density of the concentrate, n is revolution per sec, D is the diameter of the impeller, m, μ is apparent viscosity, Pa.sec.

All of the dimensionless numbers just discussed are correlated with Re. These correlations depict the trends observed for the applied impeller system for different values of D/T. Thus a scale up procedure can be applied on a laboratory –size or pilot-unit size agitation system to design a full-scale unit.

The objectives of this paper are, firstly, to develop the effect of impeller to tank diameter ratio, D/T on the plot of the dimensionless groups, power number, N_P, blend number, N_B, flow number, N_Q, versus Reynold's number, Re. Secondly, to use the obtained relationships to scale up the fluid mixing process in non-Newtonian fluids. Since fluid rheology strongly impacts the design of an agitation system, a flow behavior investigation of the fluid (carrot juice concentrate) is carried out to serve for the objectives of the paper.

2 EXPERIMENTAL PROCEDURES

2.1 Samples Preparation

A sample of carrot concentrate with solid concentrations 66 wt. % was taken during the process of concentration. Carrot concentrate was obtained from fresh carrot; then the carrot were thoroughly washed, then transferred for pressing to extract the juice, whereas carrot were cut by a group of cylindrical knives. The half part of each fruit was pressed by a rose head shape to extract the juice which is cleared and refined from fine fibers by passing through a sieve 100 mesh equipped with Nylon brush. The extracted clear juice was collected in a stainless steel (316) tank to be pumped to the evaporator.

The concentrate was entered the chiller to decrease the temperature from 70 to 10°C and then pumped to the tank in which the temperature was maintained at 10 °C. The concentrate at 10°C was pumped to the filler.

2.2 Rheological Properties

Flow properties (shear rate, shear stress and apparent viscosity) of carrot concentrate were measured directly with Brookfield Digital Rheometer, model HA DVIII ultra (Brookfield Engineering Laboratories INC) The concentrate was placed in a small sample adapter, the SC4-21 spindle was selected for the sample measurement. A thermostatic water bath provided with the instrument was used to regulate the sample temperature. The rheological parameters for carrot concentrate were studied at four temperatures (10, 30, 50 & 70°C), speed of spindle 50-250 rpm, with increment of 50, at concentration (66%) for plotting shear stress- shear rate data.

2.3 Power Calculation

For calculating the power of the mixer, an impeller was connected with Ammeter to measure the current at different revolutions per minute of the mixer, then use the following equation:

$$P = IV \tag{6}$$

Where P is the power of the mixer, watt, I is the current, Ampere, and V is the voltage, volt.

The density of Carrot concentrate at temperature 10°C, 66% concentration is 1312 kg /m^3.

3 RESULTS AND DISCUSSION

3.1 Shear stress – Shear rate Relation

Shear rate –Shear stress relations are plotted in Fig.1 for 66% solid concentration of carrot concentrate at different temperatures 10, 30, 50, 70°C.

The results show that the four samples exhibit non-Newtonian Bingham plastic fluid behavior at all the studied temperatures. The stress –strain data obtained fitted well to the constitutive equation :

$$\tau = k\,\gamma + \tau_0 \tag{7}$$

Where, τ is the shear stress, Pa, k is the consistency index, Pa.sec, γ is the shear rate, sec^{-1}, and τ_0 is the yield stress, Pa .

The values of yield stress (τ_0) and consistency index (k) are shown in Table 1. at different temperatures.

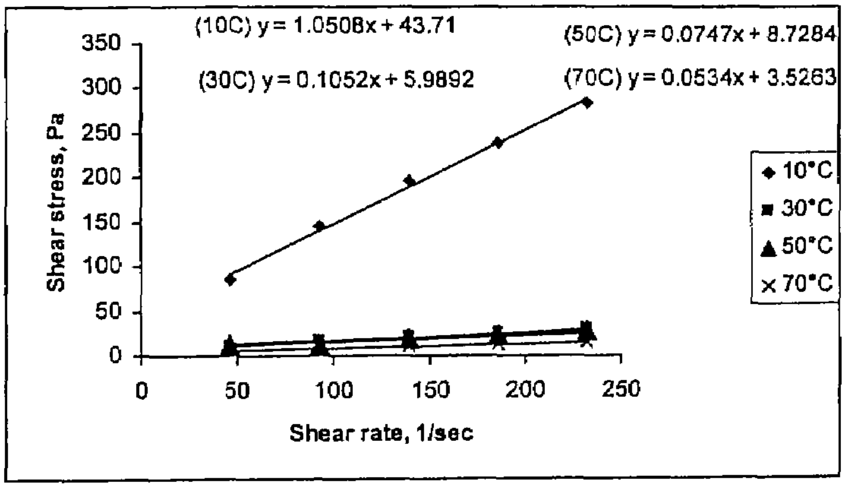

Fig.1 Relation between shear stress and shear rate at different temperatures of 66 wt% carrot concentrate.

Table 1. Relation between k and τ_0 with temperature

Temperature, °C	k	τ_0
10	1.0508	43.71
30	0.1052	5.9892
50	0.0747	8.7284
70	0.0534	3.5263

3.2 Effect of Impeller to Tank Diameter Ratio on Dimensionless Groups

3.2.1 Power Number – Reynolds Number Plot

The Power number is analogous to a friction factor. It is proportional to the ratio of the drag force acting on a unit area of the impeller and inertial stress, the inertial stress, intern, is related to the flow of momentum associated with the bulk motion of the fluid. [1]

The relation between Reynolds number and power number was fairly fitted to the following equation. [10]

$$\text{Log } N_P = \log A + B \log Re \qquad (8)$$

Where, P_0 is the power number, Re is Reynolds number, A and B are constants.

Figures (2-5), show the relation between power number and Reynolds number at different impeller to column diameter (D/T) ratios at temperature 10°C.

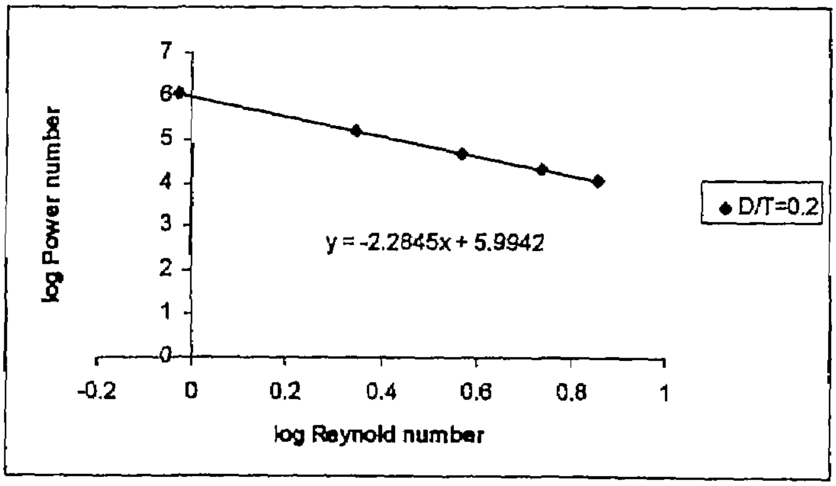

Fig. 2 Relation between log N_P and log Re of carrot concentrate at 10°C

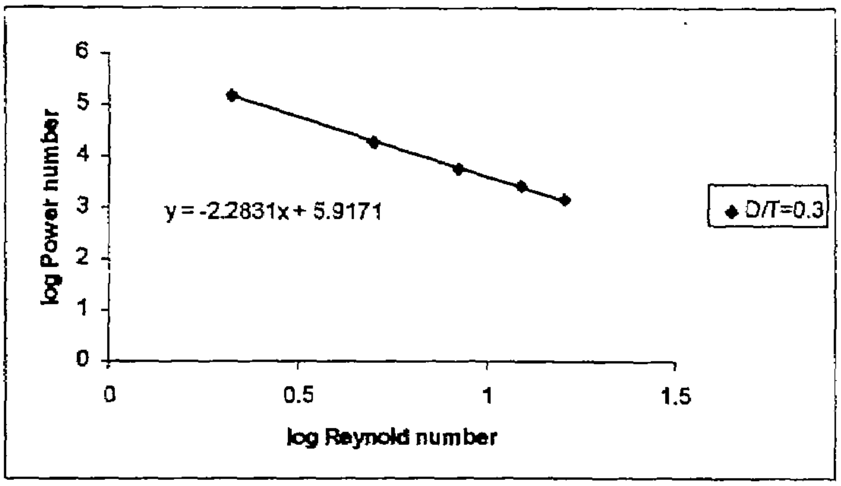

Fig. 3 Relation between log N_P and log Re of carrot concentrate at 10°C

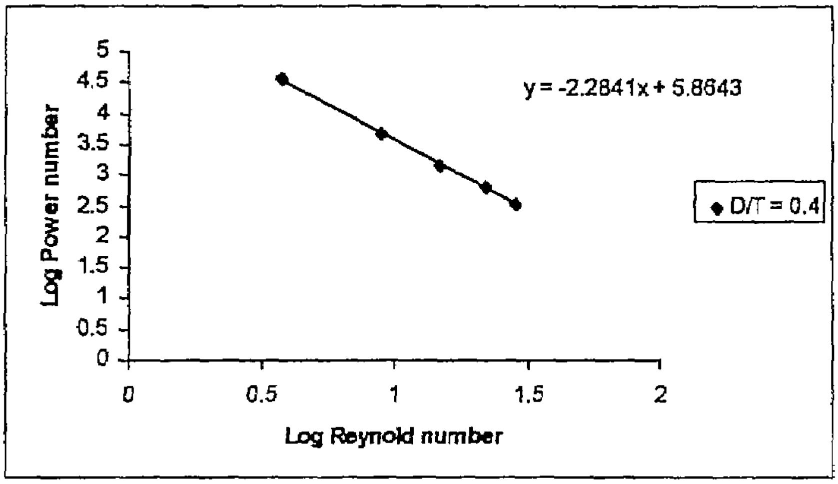

Fig. 4 Relation between log N_P and log Re of carrot concentrate at 10°C

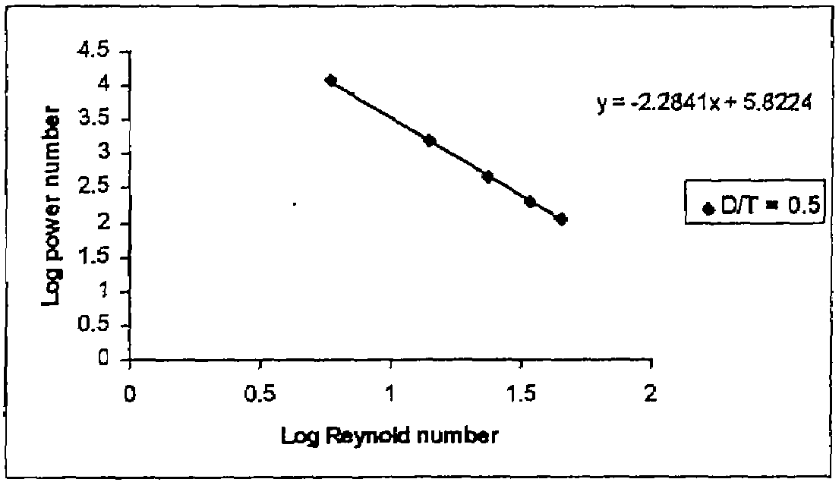

Fig. 5 Relation between log N_P and log Re of carrot concentrate at 10°C

3.2.2 Blend Number – Reynolds Number Plot

This correlation depicts the trends observed for axial flow impellers, such as flat-blade type, for different values of D/T. Figure 6 shows that as D/T increases, for the same blend number (i.e., same time of mixing), Reynolds number decreases (i.e., revolutions per second decreases) which is logically accepted.

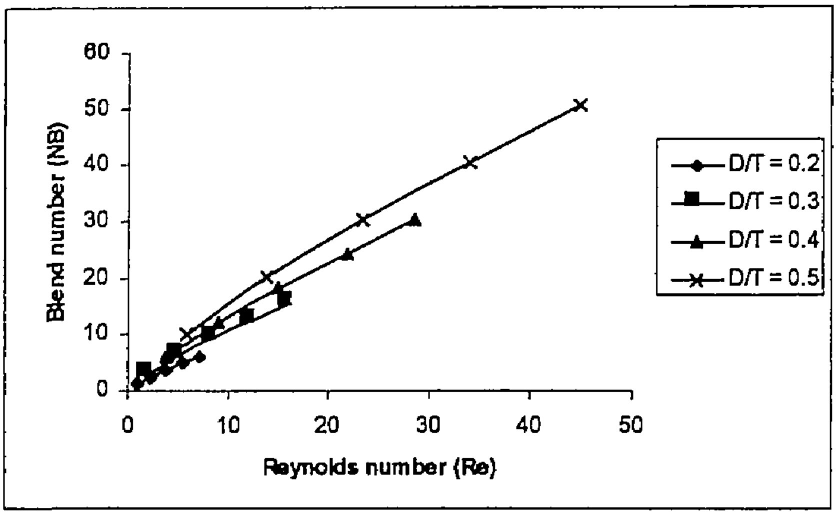

Fig. 6 Blend number (N_B) as function of Re at different D/T ratios

3.2.3 Pumping Number – Reynolds Number Plot

Figure 7 presents the effect of D/T ratio on pumping number. It is clear that the increase in D/T ratio causes decrease in pumping number at the same Reynolds number. This may be explained due to the fact that constant volumetric flowrate of fluid leaving impeller, q, requires the decrease of pumping number with increase in impeller diameter. (Eq. 3).

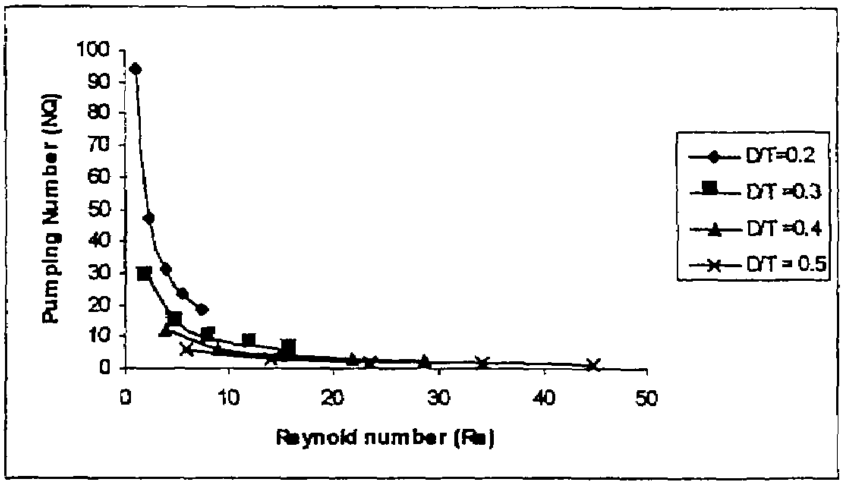

Fig. 7 Pumping number (N_Q) as function of Re at different D/T ratios

3.3 Mixer Scale-up

The scale-up procedure applied in this paper is based on the assumption that lab-scale and plant-scale are geometrically similar and holding power per volume , P/V, fixed that is probably the most commonly used criterion in mixing scale-up because it is easily understandable and practical. Also, fixed P/V correlates well with mass transfer characteristics in the mixer, and it is conservative enough to provide adequate performance in production scale equipment.

To calculate P/V, rearrange Eq. 1 to solve for P and V is calculated by:

$$V' = \pi T^2 Z / 4 \qquad (8)$$

where, V' is tank volume, m^3, T is tank diameter, m, Z is tank height, m.

Table 2 contains the scale-up calculation summary for the $0.117m^3$ plant-scale mixer. It is noticed that the successive increase in revolutions per second, n, results in higher value of motor power, P_M. Although the values of motor power, P_M, range between 0.836 - 1 hp for the investigated rotational speeds 34 – 172 rpm respectively. It is recommended to apply the 68.82 rpm scale-up value because in food processing it is undesirable to exceed 100 rpm. as the microstructure of the fluid would be affected [2].

The scale-up rule (based on fixed P/V) that must be applied to determine the plant-scale mixer speed n_{ps} to be used to duplicate the lab-scale results using n_{ls} is:

$$n_{ls} D_{ls}^{2/3} = n_{ps} D_{ps}^{2/3} \quad (9)$$

where, n_{ls} and n_{ps} are revolutions per second in lab and plant scale respectively, D_{ls} and D_{ps} are impeller diameter in lab and plant scale respectively.

D_{ls}= 0.12 m, $T_{ls} = Z_{ls}$ = 0.3 m

D_{ps}= 0.21 m, $T_{ps} = Z_{ps}$ = 0.53 m

$P_M = P / 0.85$

This design procedure requires successive calculations described in the Appendix at the end of the paper.

Table 2 Summary of scale-up analysis for D/T = 0.4

run	n, rpm	μ, Pa.s	Re	N_P	P, watt	P/V'	P_M, hp
1 lab.	n_{ls}= 50	1.856	8.45	5075.8	94.75	4469.3	0.148
Plant	n_{ps}=34	3.96	8.26	5336.2	533.4	4469.3	0.836
2 lab	n_{ls}= 100	1.568	20.09	702.2	106.1	5006.7	0.166
Plant	n_{ps}=69	3.35	19.83	723.5	585.0	5006.7	0.917
3 lab	n_{ls}= 150	1.408	33.55	217.6	111.0	5236.3	0.174
Plant	n_{ps}=103	3	33.11	224.2	612.6	5236.3	0.961
4 lab	n_{ls}= 200	1.284	48.99	91.59	110.5	5208.43	0.173
Plant	n_{ps}=138	2.74	48.42	94.08	609.4	5208.43	0.959
5 lab	n_{ls}= 250	1.222	64.42	49.0	115.8	5461.68	0.182
Plant	n_{ps}=172	2.6	63.57	50.5	639.0	5461.68	1

4 CONCLUSION

Carrot concentrate behaves as non-Newtonian Bingham fluid at temperatures (10. 30, 50 and 70°C) and solid concentration 66% wt.

An impeller mixer was used to predict the power number, blend number and pumping number as function of Reynolds number at different impeller to tank diameter ratios at 10°C and 66% concentration. The effect of D/T on N_P, N_B and N_Q was explainable.

The design logic described in this paper depends on having reliable values of N_P, N_B and N_Q over the laminar flow regime for the impeller system being analyzed. These data allow selection of the appropriate scale-up criterion, ultimately leading to economic scale-up of Bingham fluid mixing.

NOTATION

A and B	are constants in equation (8), dimensionless
D	impeller diameter, m.
I	current intensity, Ampere.
k	consistency index, Pa.sec
n	revolutions per second
N_P	power number
N_B	blend number
N_Q	pumping number
P	power of the mixer, watt
P_M	motor power, hp
q	volumetric flowrate of fluid leaving the impeller blades, m^3
Re	Reynolds number
T	tank diameter,m
V	voltage, volt
V'	volume, m^3
Z	liquid height in tank, m
γ	shear rate, sec^{-1}
μ	viscosity, Pa.sec
ρ	*density, kg/m³*
τ	shear stress, Pa
τ_o	yield stress, Pa

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APPENDIX

Scale-up Algorithm

The objective is to select conditions in plant-scale that will provide equivalent performance to that observed in lab-scale.

Step I. Define successful lab-scale conditions

- Measure fluid characteristics (shear rate and viscosity)
- Measure the system geometry of lab scale (D, T and Z) and calculate V' (Eq. 8)
- Define the impeller style used in lab scale (flat-bladed)
- Calculate Re for each n (rps of lab scale)
- Look up N_P for the calculated Re and selected D/T in lab scale (Fig. 4 & Eq.8)
- Calculate P (Eq. 1)
- Calculate P_M ($P_M = P / 0.85$)
- Calculate P/V'

Step II. Define plant – scale

- Calculate the system geometry of plant-scale from lab scale and geometric similarity

- Calculate n_{ps} (Eq. 9)
- Calculate Re for each n (rps of plant scale)
- Look up N_P for the calculated Re and selected D/T in plant scale
- Calculate P (Eq. 1)
- Calculate P_M ($P_M = P / 0.85$)
- Calculate P/V'

Repeat the calculations in StepI and Step II incrementing n_{ls} and updating N_P, P, P/V' and P_M in plant scale

Step III. Interpret the results in order to recommend the optimum n_{ps}, based on power consumption and maintaining the microstructure of the fluid unchanged, then the corresponding P_M for the plant-scale is proposed.