Chem. Pharm. Bull. 22(11)2607—2613(1974)

UDC 915.011.4.014

Agitation Torque and Energy Efficiency on Liquid-Liquid Dispersion[1)]

SHUN'ICHI TSUKIYAMA and AKIRA TAKAMURA

College of Meiji Pharmacy[2)]

(Received May 7, 1974)

In this paper, it is purpose to measure the agitation torque for the breakup of droplet and to require the energy efficiency of agitation in the wide range of particle size from 1 μ to 100 μ.

The values of torque are measured by rotary torque meter adapted to the middle of rotary shaft of agitator. The photographs of drop are taken by a microscopic method. Then, each mean surface volume diameter is calculated and still more energy efficiency of agitation is required.

So, the following results are obtained.

1) Agitation torque is proportional to 2.038 power of revolution number.

2) Agitation torque is proportional to 5.188 power of impeller diameter.

3) A relationship of specific interfacial area to agitation torque is shown as next experimental equation.

$$\log S = 0.3994 \log P + 0.37575$$

When emulsifiers having an optical particle size are widely desired on mechanical agitation, it will be very useful for a scale-up of the emulsifying experimental equipment that the value of agitation energy or agitation torque on liquid-liquid dispersion is calculated. On chemical engineering fields, it has already studied by Rushton[3,4)] and Nagata,[5,6)] as the relationship of agitation torque to Reynolds Number, and then many valuable dimensional analyses have been obtained.

We have investigated the liquid-liquid dispersion on mechanical agitation from different two points of view of surface chemistry and chemical engineering. And then, we have mentioned a few results about the relation of particle size to agitation time and angle of impeller in our first report,[7)] and still more the experimental equation concerned with particle size and impeller diameter have been discussed in our seventh report.[8)]

In this paper, it is purpose to measure the agitation torque for the breakup of droplet and to require the agitation energy efficiency in the wide range of particle size from 1 μ to 100 μ. And we discuss experimentally to pay attention to following three points of view.

(1) Relationship of agitation torque to revolution number or impeller diameter

(2) Relationship of agitation power to specific interfacial area

(3) Relationship of energy efficiency to particle size or agitation time

Theory

Agitation Torque and Agitation Energy

When a liquid-liquid dispersion is carried out in agitation tank, input power of agitation is generally given in Eq. (1).[9)]

1) S. Tsukiyama and A. Takamura, *Chem. Pharm. Bull.* (Tokyo), **22**, 2565 (1974).
2) Location: *Yatocho, Tanashi-shi, Tokyo.*
3) J.H. Rushton, E.W. Costich, and H.J. Everett, *Chem. Eng. Progress*, **46**, 395, 467 (1950).
4) J.H. Rushton and J.Y. Oldshe, *Chem. Eng. Progress*, **49**, 161, 267 (1953).
5) S. Nagata, *Chem. Eng.*, **18**, 228 (1954).
6) S. Nagata, "Kakuhanki no Syoyōdōryoku," Nikkan Kōgyō, 1961.
7) S. Tsukiyama, H. Takahashi, I. Takashima, and S. Hatano, *Yakugaku Zasshi*, **91**, 305 (1971).
8) S. Tsukiyama, A. Takamura, and N. Nakura, *Yakugaku Zasshi*, **94**, 490 (1974).
9) J.H. Rushton, D.E. Mack, and H.J. Everett, *Trans. Am. Inst. Chem. Engrs*, **42**, 441 (1946).

$$P = N_p \rho_c N^3 D^5 \quad (1)$$

Here, N_p is named to power number and it is the function of type of impeller and Reynolds Number. If physical properties such as viscosity and gravity of dispersed phase are constant, input power of agitation is found to be proportional to the product of third power of revolution number and fifth power of impeller diameter from Eq. (1). And then the relation of rotary torque given by impeller to input power of agitation is shown in Eq. (2).

$$P = \omega T \quad (2)$$

Here,

$$\omega = 2\pi N \quad (3)$$

Accordingly, rotary torque is indicated as follows.

$$T = k'(\rho_c N^2 D^5) \quad (4)$$

Therefore, rotary torque is proportional to the product of second power of revolution number and fifth power of impeller diameter.

Agitation energy given to a liquid-liquid dispersion is shown as the product of input power and agitation time.

$$E_A = P\theta \quad (5)$$

As a rotary torque is measured on this experiment, agitation energy is obtained by substituting Eq. (2) and Eq. (3) to Eq. (5).

$$E_A = 2\pi N T\theta \quad (6)$$

Specific Interfacial Area and Energy Efficiency

Mean surface-volume diameter of droplet is represented as next.

$$d_{32} = \frac{\sum d_i^3}{\sum d_i^2} = \frac{\sum d_i^3/n}{\sum d_i^2/n} = \frac{d_3^3}{d_2^2} \quad (7)$$

Specific interfacial area per 1 g of dispersed phase is given by

$$S = 6/(\rho_d \cdot d_{32}) \quad (8)$$

And specific interfacial energy is written by

$$E_s = \gamma \cdot S = 6\gamma/(\rho_d \cdot d_{32}) \quad (9)$$

Furthermore, energy efficiency is defined as Eq. (10),

$$\eta = E_s/E_A = \gamma \cdot S/P \cdot \theta \quad (10)$$

So, we will investigate how the effect of agitation energy contributes to the increasing of specific interfacial energy. If agitation energy is calculated by using Eq. (10), it will be a valuable guide for the research of the physical and mechanical optimum condition in order to make a good emulsion.

Experimental

Measure Method of Agitation Torque——Agitation tank and agitation impeller are used as the same as these dealt with previous report.[10] Rotary torque meter is Yamazaki SS-IR type (Yamazaki Seiki Laboratories). Torque meters used by this experiment are the kinds of four ones such as 100 g-cm, 500 g-cm, 2 kg-cm and 10 kg-cm, respectively. Storoboscope is Sugawara PS-240 type (Sugawara Laboratory). A sketch for the measurement apparatus of agitation torque is shown in Fig. 1. Firstly, torque meter is tightly adapted to the middle of rotary shaft of agitator not to cause a precessional motion. A liquid-liquid dispersion is practically done, the values of torque meter are directly read with a beam of stroboscope to be

10) S. Tsukiyama, A. Takamura, and N. Nakura, *Yakugaku Zasshi*, **94**, 490 (1974).

exactly adjusted to the revolution number of impeller. Then, the values for each diameter of agitation impeller and each revolution number are given in Table I.

Measurement Method of Particle Size——Distilled water, in which Tween-20[11] is dissolved, is used as continuous phase. And a mixture of n-C_7H_{16} and CCl_4, of which density is adjusted to 1.000 (g/cm^3), is used as dispersed phase. Emulsifying concentrations are 0.01, 0.1 and 1.0%, respectively. Experiment is carried out under the next three conditions.

(1) Impeller diameter are altered for 50.30, 65.20, 80.30, 90,10 and 99.20 mm under the revolution number to be constant.

(2) Revolution number are exchanged for 330, 400, 530, 660 and 812 rpm under the impeller diameter to be constant.

(3) Sampling times are selected to logarithmic ten points from 0.5 min to 120 min at 330 rpm.

Then, every particle size is measured by a microscopic photograph method, and the values of mean surface diameter and mean volume diameter are calculated.[12]

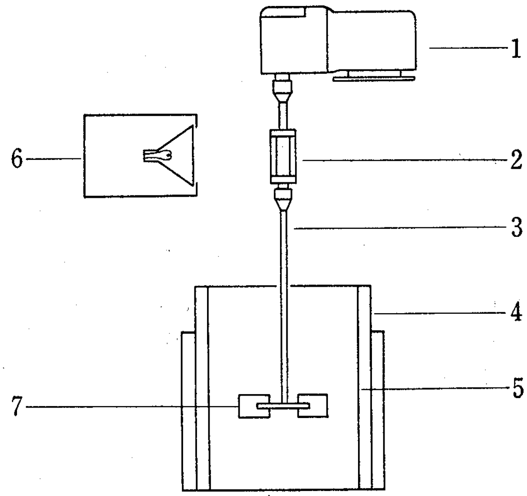

Fig. 1. Apparatus

1: motor
2: toruqe meter
3: shaft
4: tank
5: baffle
6: storobo scope
7: impeller

Table I. Impeller Diameter and Revolution Number

	Impeller diameter (mm)	Revolution number (rpm)					
Impeller I	50.30	203	335	404	539	666	821
II	65.20	203	335	401	539	661	816
III	80.30	202	334	401	531	659	792
IV	90.10	202	334	401	530	648	750
V	99.20	202	334	401	530	626	

Results and Discussion

Relation of Agitation Torque to Revolution Number or Impeller Diameter

Agitation torque is measured in the case of each impeller size and each revolution number.

In this experiment, ratios of impeller diameter to tank diameter are 0.335, 0.435, 0.535, 0.601 and 0.661 respectively. And the flow in agitation tank belongs to turbulent flow so that Reynolds Number are high from 909 to 5705. And viscosity of continuous phase is low near 1 cp.

Firstly, relation of torque to revolution number is shown in Fig. 2. It has a similar slope on a paper of log-log coordinate with each impeller size. And the values of grades of plotted dots in Fig. 2 are calculated by a least squares method and given in Table II. From Fig. 2, it is found that agitation torque is proportional to second power of revolution number.

$$T \propto N^{2.038} \quad (11)$$

Secondly, relation of torque to impeller size is shown in Fig. 3. It has a similar slope on a paper of log-log coordinate in each revolution number, too. The values of grades of plotted dots in Fig. 3 are calculated by a least squares method and given in Table II. From data of Table II, it is thought that agitation torque is proportional to fifth power of impeller size.

11) S. Tsukiyama, A. Takamura, and Y. Moronuki, *Yakugaku Zasshi*, **94**, 401 (1974).
12) S. Tsukiyama, A. Takamura, Y. Wakamatsu, and I. Takashima, *Yakugaku Zasshi*, **93**, 191 (1973).

$$T \propto D^{5.188} \tag{12}$$

From Eq. (11) and Eq. (12), Eq. (13) may be established,

$$T \propto N^2 \cdot D^5 \tag{13}$$

Relation of agitation torque to a value of $\rho N^2 D^5$ is appeared in Fig. 4. It shows a straight line on log-log coordinate, the next experimental formular is found out from this result.

$$\log T = 1.059 \log N^2 D^5 - 6.458 \tag{14}$$

When revolution number and impeller diameter have already required, an optical torque will be able to be calculated from Eq. (14). The calculated values of torque by using Eq. (14) are given in Table III.

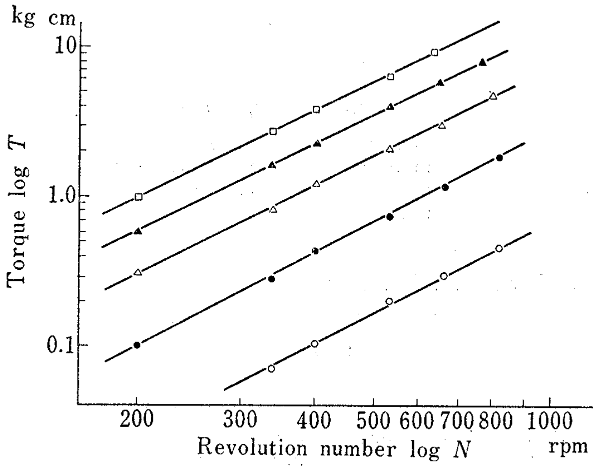

Fig. 2. Relation between Torque and Revolution Number

○: impeller I (50.30 mm), ▲: impeller IV (90.10 mm), ●: impeller II (65.20 mm), □: impeller V (99.20 mm), △: impeller III (80.30 mm)
emulsifying agent: Tween-20, concentration: 0.1%

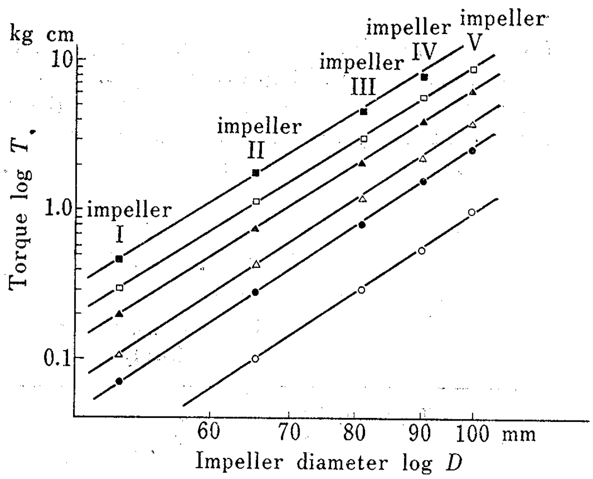

Fig. 3. Relation between Torque and Impeller Diameter

○: 200 rpm, ●: 330 rpm, △: 400 rpm, ▲: 530 rpm, □: 660 rpm, ■: 812 rpm
emulsifying agent: Tween-20, concentration: 0.1%

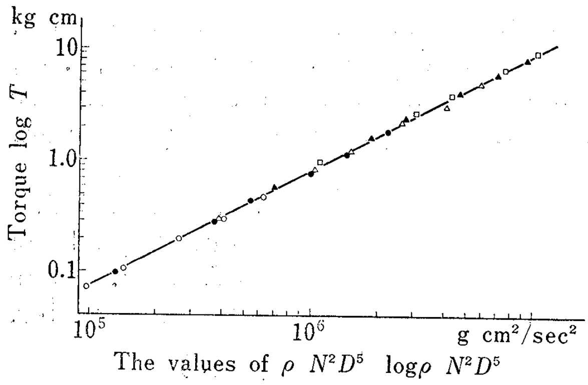

Fig. 4. Torque *v.s.* Values of ρ N^2D^5

○: impeller I ●: impeller II, △: impeller III, ▲: impeller IV, □: impeller V
emulsifying agent: Tween-20, concentration: 0.1%

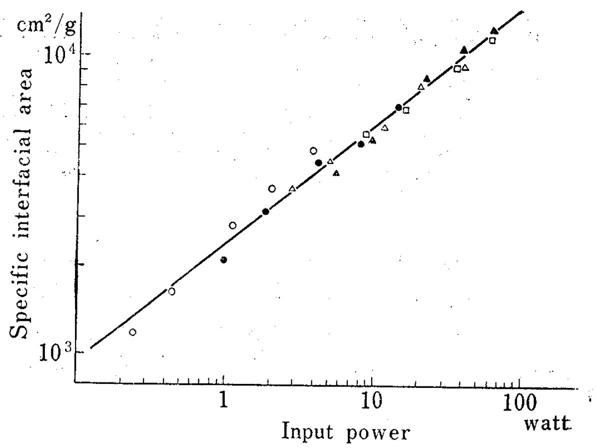

Fig. 5. Specific Interfacial Area *v.s.* Input Power

○: impeller I, ●: impeller II, △: impeller III, ▲: impeller IV, □: impeller V
emulsifying agent: Tween-20, concentration: 0.1%

Energy Efficiency on Mechanical Agitation

Nextly, we deal with effect of agitation to the increasing of liquid-liquid interfacial area.

TABLE II. Calculated Values on Each Experimental Condition

	Impeller I	II	III	IV	V	Average	Standard deviation
Calculated values from Fig. 2							
gradient	2.124	2.085	2.009	2.005	1.966	2.038	0.0578
interrelation coefficient	1.000	1.000	1.000	1.000	0.999		

	200 rpm	330	400	530	660	812	Average	Standard deviation
Calculated values from Fig. 3								
gradient	5.466	5.320	5.276	5.113	5.034	4.918	5.188	0.185
interrelation coefficient	1.001	1.001	1.001	1.001	1.000	1.000		

TABLE III. Calculated Torque from Eq. (14)

Impeller diameter (cm)	Revolution number (rpm) 200	300	400	500	600	700	800	900	1000
3.0	1.50 $\times 10^{-3}$	3.56 $\times 10^{-3}$	6.53 $\times 10^{-3}$	1.06 $\times 10^{-2}$	1.55 $\times 10^{-2}$	2.14 $\times 10^{-2}$	2.84 $\times 10^{-2}$	3.65 $\times 10^{-2}$	4.56 $\times 10^{-2}$
4.0	6.91 $\times 10^{-3}$	1.64 $\times 10^{-2}$	3.00 $\times 10^{-2}$	4.82 $\times 10^{-2}$	7.09 $\times 10^{-2}$	9.80 $\times 10^{-2}$	1.30 $\times 10^{-1}$	1.67 $\times 10^{-1}$	2.09 $\times 10^{-1}$
5.0	2.25 $\times 10^{-2}$	5.33 $\times 10^{-2}$	9.78 $\times 10^{-2}$	1.57 $\times 10^{-1}$	2.32 $\times 10^{-1}$	3.21 $\times 10^{-1}$	4.26 $\times 10^{-1}$	5.46 $\times 10^{-1}$	6.82 $\times 10^{-1}$
6.0	5.92 $\times 10^{-2}$	1.40 $\times 10^{-1}$	2.58 $\times 10^{-1}$	4.13 $\times 10^{-1}$	6.08 $\times 10^{-1}$	8.41 $\times 10^{-1}$	1.12	1.44	1.79
7.0	1.34 $\times 10^{-1}$	3.16 $\times 10^{-1}$	5.82 $\times 10^{-1}$	9.27 $\times 10^{-1}$	1.37	1.91	2.54	3.09	4.06
8.0	2.72 $\times 10^{-1}$	5.11 $\times 10^{-1}$	1.18	1.90	2.79	3.86	5.14	6.59	8.25
9.0	5.08 10^{-1}	1.20	2.20	3.54	5.20	7.21	9.57	12.3	15.4
10.0	8.85 10^{-1}	2.09	3.84	6.17	9.09	12.6	16.7	21.5	26.9

unit: kg-cm

The relation of interfacial area per 1 g to agitation power is shown in Fig. 5. It is found that interfacial area is proportional to agitation power from Fig. 5. And then, an experimental equation is obtained by a least squares method as follows.

$$\log S = 0.3994 \log P + 0.37575 \qquad (15)$$

When emulsified products having an optical interfacial area are intended to be made, needed agitation power will be possible to be calculated by using Eq. (15). If a value of revolution number or impeller size is not same but a value of agitation power is same, emulsion will become a state having a same specific interfacial area.

Specific interfacial area is obtained by substituting mean surface-volume diameter into Eq. (9), and agitation energy is required by substituting agitation torque into Eq. (6), and then these calculated values are given in Table IV. Moreover, energy efficiency is demanded by substituting both values of interfacial energy and agitation energy into Eq. (10).

A relation of energy efficiency to mean surface-volume diameter is shown in Fig. 6. A value of energy efficiency becomes in the range of 10^{-6} and 10^{-8} at 1 hr's agitation time. As an energy required for moving a viscous liquid is sufficiently larger than an energy for making

TABLE IV. Experimental Calculated Values

		Mean surface volume diameter (μ)	Specific interfacial area (cm^2/g)	Interfacial energy (joul)	Agitation energy (joul)
I	330	51.01	1176	9.526×10^{-4}	8.64×10^2
	400	36.65	1637	13.260	15.66
	530	21.40	2804	22.712	39.96
	660	16.24	3695	29.930	73.44
	812	12.24	4902	39.706	139.32
II	330	28.31	2119	17.164	34.60
	400	19.00	3158	25.580	65.16
	530	13.17	4556	36.904	151.20
	660	11.41	5259	42.598	292.68
	812	8.56	7009	56.773	547.20
III	330	18.68	3212	26.017	98.64
	400	13.24	4532	36.709	180.36
	530	10.09	5946	48.163	410.40
	660	7.32	8197	66.396	752.40
	812	6.30	9524	77.144	1402.92
IV	330	14.48	4144	33.566	197.28
	400	11.25	5333	43.197	340.20
	530	6.84	8772	71.053	781.20
	660	5.55	10811	87.569	1434.60
	812	4.75	12632	102.319	2241.72
V	330	10.90	5505	44.591	320.40
	400	8.82	6803	55.104	576.00
	530	6.35	9449	76.537	1270.80
	660	5.05	11881	96.236	2148.12

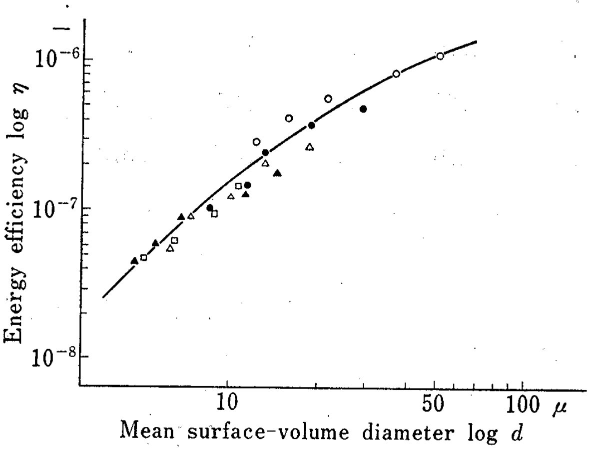

Fig. 6. Energy Efficiency *v.s.* Mean Surface-Volume Diameter

○: Impeller I, ▲: Impeller IV, ●: Impeller II, □: Impeller V, △: Impeller III
emulsifying agent: Tween-20, concentration: 0.1%

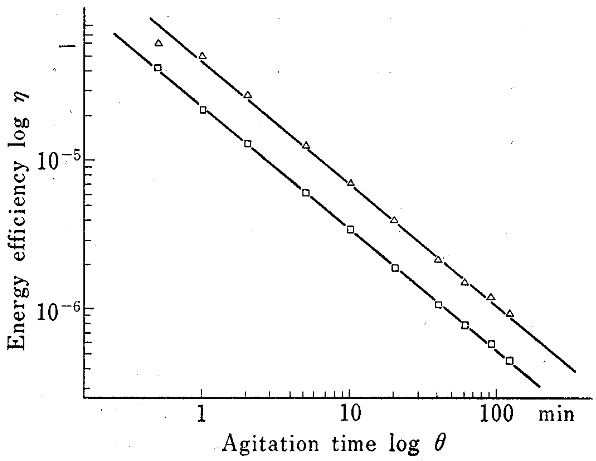

Fig. 7. Energy Efficiency *v.s.* Agitation Time

△: 0.01%, □: 1.00%
emulsifying agent: Tween-20
impeller diameter: 49.0 mm
revolution number: 330 rpm

a new interfacial area of drop, it may be that energy efficiency becomes a small value. And as a value of average diameter decreases, energy efficiency becomes further small value. It may be caused by the fact that the probability for breakup of drop decreases according as particle size becomes small.

A relation of energy efficiency to agitation time is shown in Fig. 7. Change of energy efficiency in the course of agitation time decreases gradually.

Conclusion

In view of the results of this investigation, the following conclusion are obtained.

(1) Agitation torque is proportional to 2.038 power of revolution number.

(2) ·Agitation torque is proportional to 5.188 power of impeller diameter.

(3) A relationship of specific interfacial area to agitation torque is shown as next experimental equation.

$$\log S = 0.3994 \log P + 0.37575$$

(4) As a value of average diameter decreases, energy efficiency of agitation becomes smaller.

(5) As an agitation time is longer, energy efficiency has a small value.

Nomenclature

D : impeller diameter (mm)
d_2 : mean surface diameter (μ)
d_3 : mean volume diameter (μ)
d_{32} : mean surface-volume diameter (μ)
E_A : agitation energy (erg/g)
E_s : specific interfacial energy (erg/g)
k' : constant, Eq. (4)
N : revolution number (rpm)
N_p : power number (—)
P : agitation power (watt)
S : specific interfacial area (cm^2/g)
T : agitation torque (kg-cm)
u : impeller velocity (cm/sec)
γ : interfacial tension (dyn/cm)
η : energy efficiency of agitation (—)
θ : agitation time (min)
μ_c : viscosity of continuous phase (poise)
ρ_c : specific gravity of dispersed phase (g/cm^3)
ρ_d : specific gravity of dispersed phase (g/cm^3)
ε : angular velocity (angle/sec)

Acknowledgement We gratefully acknowledge to Dr. M. Koishi, associate professor of Science University of Tokyo and Mr. H. Hidaka, lecturer of Meisei University for suggesting this problem and for stimulating interest in it.