A New Two-Impinging-Streams Emulsifier

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In the present work, the idea of impinging streams, which has been applied by Elperin and Tamir to some processes in chemical engineering (Elperin and Tamir, 1982; Tamir et al. 1984; Tamir and Luzzatto, 1985 Tamir and Hershkowitz, 1985), is further developed as a new kind of emulsifier. A comparison of its performance with other emulsification apparatus proved its superiority in many respects.

The purpose of an emulsification equipment is to break up or disperse one phase in the other. Among the common emulsification devices (Becher, 1965; Kirk-Othmer, 1978) the following may be mentioned: agitated vessels (employing aeration, propeller, or turbine agitation), colloid mills, and homogenizers. In the latter two cases, emulsification is achieved by forcing the liquid at high pressures through small clearances under extremely high shearing action. The high frequency or ultrasonic emulsifier is another batch emulsifier, best suited for low viscosity liquids.

The device developed in this work is based on two streams of an emulsion droplet spray flowing one toward the other in countercurrent flow in a cell. The streams impinge at the impingement zone, as well as on the walls of the cell, and finally are discharged in a form of continuous liquid emulsion. The droplets are formed while an immiscible liquid mixture is forced by an air stream through a spray nozzle. The materialization of the emulsification device is achieved by using two common spray guns for creation of the spray. This spray consists of a mixture of kerosene in water, the o/w (oil in water) emulsion. In order to evaluate the performance of the new emulsifier, it was compared with a homogenizer and with a device employing one stream impinging on a wall. To the best of the authors' knowledge, the latter device also has not been encountered in practical applications.

EXPERIMENTAL

The experimental program was directed toward exploration of the following properties of the new two-impinging-streams emulsifier: stability of the emulsion, mean drop size of kerosene droplets in water as well as their size distribution, energy consumption, and operating characteristics. The experiments were performed in three distinct devices: the new two-impinging-streams and a one-impinging-stream continuous emulsifiers, and a batch homogenizer. The latter two systems were chosen especially to compare the new device with their performances.

Two-Impinging-Streams Continuous Emulsifier

This experimental system, shown in Figure 1a, consisted of the following components: (*1*) two spray guns, (*2*) Perspex emulsification cell (0.3 m × 0.25 m × 0.25 m), (*3*) impingement zone of the sprays, (*4*) air vent, (*5*) emulsion discharge, (*6*) air rotameter, (*7*) water-emulsifying agent vessels, (*8*) kerosene vessel, and (*9*) pressure gauges.

Each spray gun, operates as follows (Figure 1b): Compressed air enters at point *1* and creates a vacuum at point *2*. Consequently, a mixture of water and kerosene is sucked at point *3*, undergoing a shear action in the vicinity of the exit zone *4* of the gun. In the emulsifier, the streams leave the two spray guns in the form of a conical spray and impinge at zone 3 of Figure 1a, as well as on the walls of the emulsification cell. A single stream is finally formed, an emulsion of kerosene droplets in water, which leaves the emulsification cell through discharge 5 of Figure 1a.

One-Impinging-Stream Continuous Emulsifier

This device is similar to the above system, but only one spray gun is operating. The conical spray formed impinges on the walls of the cell, where it undergoes coalescence and leaves the system at point 5 of Figure 1a.

Batch Homogenizer

This device, manufactured by Halstead of Essex, England, is a batch unit with a power of 375 W. The rotating part revolves at about 10,000 rpm. The homogenizer, an impeller with a close-fitting casing, pumps the immiscible mixture through narrow clearances, in which shearing forces acting on the mixture induce the formation of an emulsion of oil droplets in water.

Experimental Procedure and Parameters Tested

In order to test the new device, the formation of an emulsion of kerosene droplets in water was minutely investigated. The volume percent of kerosene in the solution varied in the range of 2.5 to 10%.

The emulsifier used was a blend of Span 80 and Tween 80 (both of which are stearates), manufactured by Atlas Europe 21020 Ternate, Italy. Detailed information about emulsifiers and their use can be found in Becher (1965, Ch. 6). The formation of an emulsion is controlled by the choice of the emulsifier, which is based on its concentration, chemical type and HLB (hydrophilic-liophilic balance). The latter is an expression of the relative simultaneous attraction of an emulsifier for water and for oil. For Span 80, HLB = 4.3, and for Tween 80, HLB = 15; for a stable kerosene in water emulsion, HLB = 8 to 18 (Becher, 1965, p. 233). Preliminary experiments with kerosene-water mixtures, carried out in test tubes, revealed that for optimum stability of the emulsion the optimal HLB = 8 to 10.

The effect of the following parameters on the mean surface-area diameter of the droplets and their size distribution was explored in the two-impinging-streams device: L, the distance between the two impinging streams (Figure 1a), was varied from 0.02 to 0.17 m; H, the distance between the air exit in the spray nozzle and the spray outlet (Figure 1b), varied from 0.0065 to 0.0155 m; ΔP, the pressure drop on a spray gun, varied from 200 to 650 kN/m^2 (consequently air flow rates Q varied

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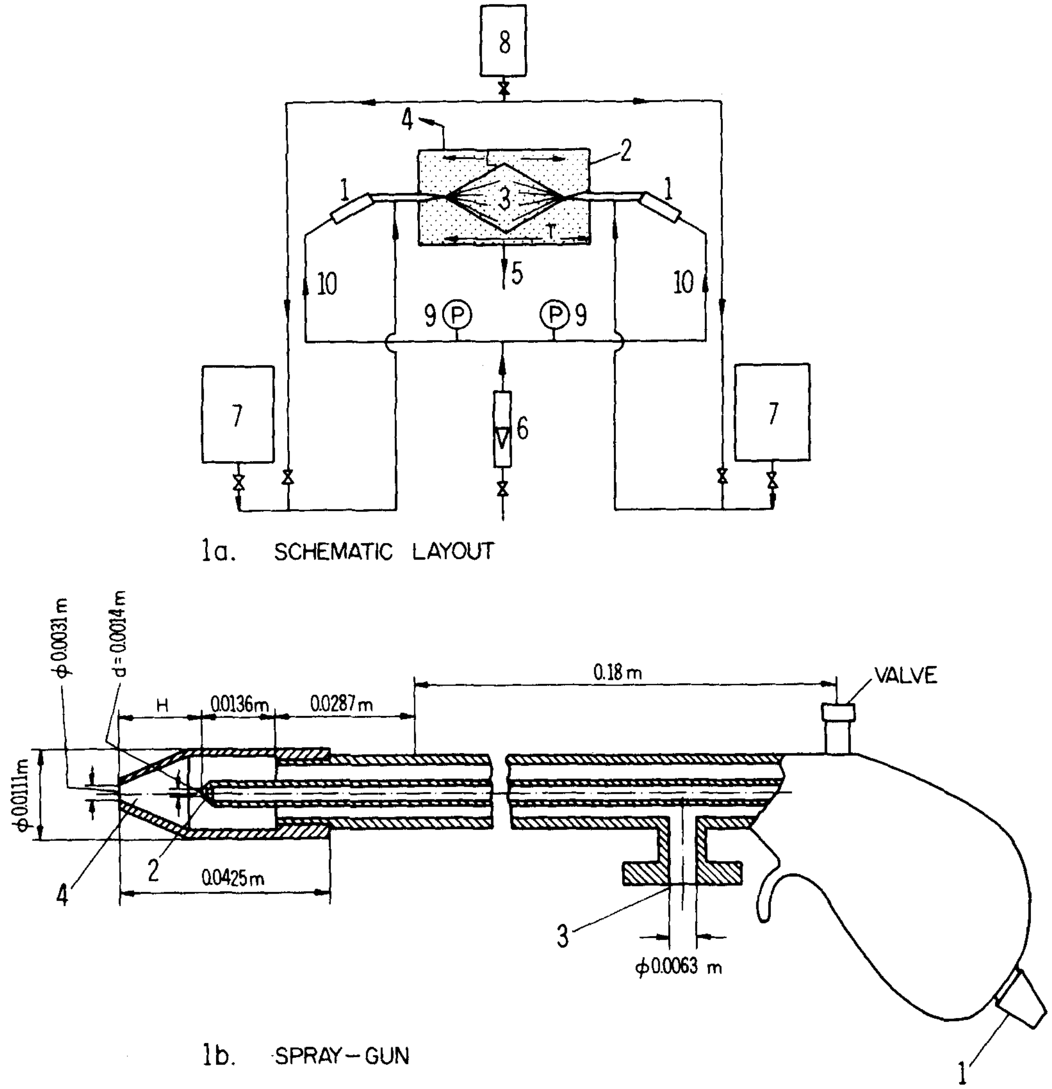

Figure 1. Experimental setup of two-impinging-streams emulsifier.

between 1.25 × 10^{-3} and 2.5 × 10^{-3} m^3/s); and the emulsifier concentration.

The following experimental procedure was adopted:

1. The kerosene and water flow rates were adjusted so as to obtain the desired concentration of kerosene.
2. The emulsifier was added to the water vessels (element 7 in Figure 1b) in which it is dissolved.
3. Air was introduced into the system and hence sucking of kerosene-water mixtures into the spray guns occurred.

As soon as a steady state was reached, the pressure drop was recorded, the emulsion flow rate measured, and samples were taken for photomicroscopic studies of droplet diameters and size distribution, together with surface tension and density determinations. This procedure was also adopted in the case of one impinging stream. The parameters tested in this case were the pressure drop on one spray gun and the distance T between the spray gun exit and the cell's wall (Figure 1a).

The batch experiments in the homogenizer were performed in the following manner: A solution of water-emulsifier was introduced into a vessel in which the homogenizer was immersed and kept rotating at the same speed. At a certain time, a known amount of kerosene was added, which formed a prescribed mixture. Samples of the emulsion were taken at certain time intervals so as to keep track of the change in the mean droplet diameter, up to its ultimate value. The current and voltage were also measured for energy consumption determinations.

Photomicroscopic Studies of Mean-Surface-Area-Drop Diameter and Size Distribution

A sample of the emulsion was poured on a microscope grooved slide on which a glass coverslip was placed. The slide was placed under a microscope equipped with a camera. Frames were taken and photographs were prepared (0.18 m × 0.23 m) so that the total magnification was about 350. In this way the droplet diameter could be determined quite accurately by means of a caliber. The number of droplets corresponding to a certain diameter was also counted, and the mean-surface-area-droplet diameter $\bar{D}$, gathered from one photograph, was calculated from

$$\bar{D} = \sqrt{\frac{\Sigma n_i D_i^2}{n}} \tag{1}$$

with the variance given by

$$\sigma = \sqrt{\frac{\Sigma n_i (D_i - \bar{D})^2}{n}} \tag{2}$$

n_i is the number of droplets corresponding to a certain drop diameter D_i where the total number of droplets $n = \Sigma n_i$. It should be noted that the mean-surface-area-droplet diameter was chosen as a representative value, because it is a useful quantity in determining the minimal energy needed for the creation of a new surface.

RESULTS

The major quantity determined was the mean surface-area droplet diameter. From this quantity conclusions were drawn regarding the stability of the emulsion, the effect of operating parameters (ΔP, Q, L, T, and H), the minimal energy for creating new surface (drops) as compared to the actual energy consumption, and the size distribution, which indicated the degree of the size uniformity of the emulsion.

The major results for two impinging streams, which were obtained from about 300 photographs, can be summarized as follows; the entire information is given elsewhere (Shibli, 1984):

1. The effect of the emulsion storage time on $\bar{D}$ of 2.5% kerosene in water (volume fraction) and 0.7% (kg emulsifier/kg water) emulsifier HLB = 8 for $L = 0.045$ m (Figure 1a), $\Delta P = 600$ kN/m^2, and $Q = 2.25 \times 10^{-3}$ m^3/s yielded that for storage time of 720 h $D = 5.34 \pm 0.84$ μm, where after 555 h $D = 5.04 \pm 0.44$ μm. The deviation from the means is σ, which was calculated from Eq. 2. A typical behavior is as follows:

t (h)	0	23	215	310	430	550	720
$\bar{D}$ (μm)	6.5	4.2	5.3	6.0	4.5	6.2	4.7

2. The effect of the stabilizer concentration (0.7 to 5% kg emulsifier/kg water, HLB = 8 to 12) on $\bar{D}$, for $L = 0.045$ m, $\Delta P = 600$ kN/m^2, $Q = 2.25 \times 10^{-3}$ m^3/s) was negligible, and $D = 5.56 \pm 0.24$ μm.
3. The effect of L (0.02 to 0.17 m, Figure 1a) on D (2.5 to 10% kerosene in water, emulsifier concentration of 0.7 to 5%, and HLB = 8 to 12) was negligible, and $D = 5.58 \pm 0.56$ μm.
4. The effect of H (0.0065 to 0.0155 m, Figure 1b) on D (2.5 to 10% kerosene in water, emulsifier concentration of 1.25% HLB = 8, $L \doteq 0.1$ m, $\Delta P = 600$ kN/m^2) was negligible, and $D = 5.20 \pm 0.18$ μm.
5. An effect of ΔP on D was observed. For example, for 2.5% kerosene in water, emulsifier concentration of 1.25% HLB = 8, and $L = 0.17$ m, the following variations were observed:

$\Delta P \times 10^{-2}$ (kN/m^2)	2.5	3.8	5.0	6.5
$\bar{D}$ (μm)	8.7	8.3	6.9	5.0

An important conclusion to be drawn from points 3 and 4 is that the processes taking place inside the spray guns probably govern the formation of the droplets, within experimental accuracy. As discussed later, this is probably different from the case in the one-impinging-stream emulsifier, where the walls of the emulsifier cell affect the drop diameter due to the coalescence phenomena. It is also possible (Enyakin and Dvoretskii, 1968) that secondary atomization occurs in the two impinging streams process, namely, droplet breakup in the impingement zone. However, this was not verified in the present work.

CORRELATIONS OF TWO-IMPINGING-STREAM DATA

A physical model for predicting the behavior of the new emulsifier is very complicated. Thus an attempt has been made to develop a plausible correlation by applying the Buckingham Pi method (Perry and Chilton, 1973, pp. 2–81). The following homogeneous function contains the possible influencing parameters (see also Figure 1) of the new emulsifier:

$$F(\Delta P, Q, \rho, \mu, \gamma, L, D, d, H) = 0 \qquad (3)$$

Use of the mass, time, and length as basic units indicates six independent groups that can be grouped as follows by the Buckingham Pi method:

$$\tilde{f}\left(\frac{\Delta P L^4}{Q^2\rho}, \frac{Q^2\rho}{\gamma L^3}, \frac{Q\rho}{\mu L}, \frac{D}{L}, \frac{d}{L}, \frac{H}{L}\right) = 0 \qquad (4)$$

Recalling that the effects of L and H on D are negligible, and multiplying the first two groups on the lefthand side by d/L, and the third group by L/D, resulted in the fact that the two-impinging-streams emulsifier can be described by the following dimensionless groups:

$$f\left(\frac{Q\rho}{\mu D}, \frac{\Delta P d}{\gamma}\right) = 0 \qquad (5)$$

$Q\rho/\mu D$ may be looked upon as the ratio between inertia forces to the viscosity forces and $\Delta P d/\gamma$ is the ratio between pressure forces to surface tension forces. A reasonable relation between the groups that correlated the entire kerosene-water emulsions data with a correlation coefficient of 0.86 reads

$$\frac{Q\rho}{\mu D} = 3.14 \times 10^5 \left(\frac{\Delta P d}{\gamma}\right)^{0.71} \qquad (6)$$

where ΔP(kN/m^2) is related to Q(m^3/s) by $\Delta P = -724.4 + 5.46 \times 10^5\, Q$ (7)

The limits of the quantities appearing in Eq. 6 are $250 < \Delta P(\text{kN/m}^2) < 650$, $5 < D\,(\mu\text{m}) < 10$, $1.75 < Q \times 10^3\,(\text{m}^3/\text{s}) < 2.5$, $1 \times 10^4 < \Delta P d/\gamma < 3 \times 10^4$, $2 \times 10^8 < Q\rho/\mu D < 5 \times 10^8$, $0.0065 < H(\text{m}) < 0.0155$, $0.02 < L(\text{m}) < 0.17$, and $d = 0.0014$ m. The relatively low concentration of kerosene in water (~2.5% in volume units), as well as that of the emulsifier (~1.25% kg emulsifier/kg water, HLB $\cong$ 8), did not change significantly the physical properties of the emulsion, which remain those of water. At 20°C the measured quantities were $\gamma = 31 \times 10^{-3}$ N/m, $\rho = 1{,}000$ kg/m^3, and $\mu = 0.001$ N·s/m^2. The significance of Eq. 6 is that it contains relevant design parameters and thus makes it possible to perform scale-up as well as to predict the mean surface area droplet diameter.

COMPARISON AMONG EMULSIFIERS AND CONCLUSIONS

Table 1 compares, under similar operating conditions, the major parameters of the new two-impinging-streams emulsifier with the one-impinging-stream and the homogenizer devices. In Figure 2, histograms of the drop size distribution of the various devices are given.

The major conclusions drawn from Table 1 and Figure 2 are:

1. The new two-impinging-streams device produces droplets having the minimal mean surface area diameter with a very

TABLE 1. COMPARISON AMONG EMULSIFIERS

Device	E^* Theor. Energy, kJ/kg	E Actual Energy, kJ/kg	D Mean Drop Dia., μm	% $D \cong 5$ (μm)
Two impinging streams	0.034	130	5.3	93
One impinging stream	0.038	175	7.5	38
Homogenizer	0.030	1	10.1	50

$E^* = \gamma A/W$, E (homogenizer) = Vit/W, E (one, two impinging streams) = $Q\Delta Pt/W$

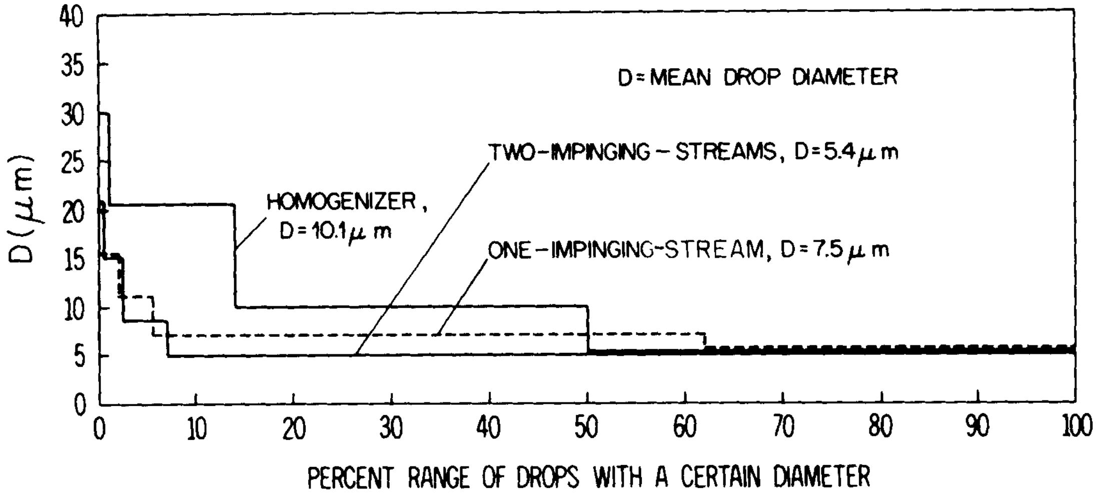

Figure 2. Comparison of drop size distribution among various emulsifiers.

narrow size distribution; 93% of the drops have a mean diameter of about 5 microns. It is possible that smaller drops are also produced in all cases but they could not be detected by the microscope.

2. Note that D (one impinging stream) > D (two impinging streams) might indicate that the wall effect is significant, namely, greater coalescence of drops occurs on the emulsifier cell walls in the case of one impinging stream. This makes the latter device inferior to the two impinging streams emulsifier.

3. The homogenizer is the least energy consuming device; however, it produces the largest droplets.

Other advantages of the new two impinging streams device over the other emulsifiers are:

1. It is a continuous device.

2. The formation of droplets creates high surface for heat and mass transfer. Hence the two impinging streams method is very efficient in cases where cooling must be employed when significant temperature rise occurs, due to tremendous shearing forces for the creation of the droplets.

3. The two impinging streams method has a geometrical advantage in that method the spatial double-cone body that is formed (Figure 1a) has less volume than the single cone formed in the one impinging stream device. This conclusion is based on the assumption that the distance between the two spray guns L is equal to the distance T from the exit of the one spray gun to the wall the spray impinges on (Figure 1a). For example, in the case of a spray gun with a spray opening angle of 60°, the volume ratio is 0.5.

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NOTATION

A = total area of droplets
d = spray gun nozzle diameter, Figure 1b
D_i = single drop diameter
$\bar{D}$ = mean-surface-area-droplet diameter calculated by Eq. 1, based on information gathered from one photo
D = mean value of all mean-surface-area-droplet diameters, based on several analyzed photographs,

$$D = \frac{\Sigma \bar{D}}{(\text{no. of photographs})}$$

H = distance between the air exit in the spray nozzle and the spray outlet—Figure 1b
HLB = hydrophilic-liophilic balance
i = current
L = distance between two spray guns, Figure 1a
n_i = number of droplets corresponding to a certain D_i
ΔP = pressure drop on a spray gun
Q = air flow rate at 740 mm Hg (98.4 kPa) and 20°C
t = collection time
T = distance betwen one spray gun and the wall, Figure 1a
V = voltage
W = weight of an emulsion sample
μ,γ,ρ = emulsion viscosity, surface tension, and density, respectively; in the present work they correspond to water
σ = standard deviation, Eq. 2

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