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Microdrop Size Measurement in a Mixing Unit Using Laser Technique

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Abstract: One of the troublesome duties in chemical industrial units is determining the instantaneous drop size distribution, which is created between two immiscible liquids within such units. In this work a complete system for measuring instantaneous droplet size is constructed. It consists of laser detection system (1mW He-Ne laser), drop generation system (turbine mixer unit), and microphotography system. Two immiscible liquids, water and kerosene were mixed together with different low volume fractions (0.0025, 0.02) of kerosene (as a dispersed phase) in water (as a continuous phase). The experiments were carried out at different rotational speed (1180- 2090 r.p.m) of the turbine mixer. The Sauter mean diameter of the drops was determined by laser light according to the scattering (attenuation) of the laser beam during passing through the emulsion. The same droplet which where examined by the laser beam, where tested also under microphotography system. The result showed that the laser detection technique gives drop diameter smaller than that obtained by photographing.

Introduction

In chemical industries, much equipment with different shapes can be observed. Each of this equipment represents a chemical unit, where the chemical changes or physical changes are occurred. Some of these units are spray absorbers, dries and combustors, bubble columns, pipe line reactors, filters, spray cooling systems [1].

Most of these units include processes combines two different immiscible liquids of materials. In each process a range of drop sizes provided ranging from a few centimeters to several microns of diameters. This range is referred to as drop size distribution. Treatment with such units requires knowing the drop size distribution during the operation [1].

If the measurement of drop size can be done directly with the use of a suitable technique, it contributes to better understanding of heat and mass transfer and their applications. Consequently, an accurate control system on the results can be obtained. According to that, different methods are developed (conventional and new techniques) for covering this requirement [2]. For example sedimentation, coulter counter, photography, holography, and laser light scattering techniques. Most of these techniques give information about drop diameter with limitations, so they are not preferred to use in industry except the laser technique which provides fast and accurate results. Hence, the single beam of laser light scattering technique is considered in the present work.

Many investigators employed laser technique in their study a bout the drop size in different units. Rebelein and Blass [3] have used single beam light scattering for investigating the separating problem of the liquid-liquid dispersion. Tjaberinga et al. [4] were used a modified Fraunhofer technique for the (continuous) measurement of the dispersion droplet size. With the use of this technique, they studied the two-phase (liquid-liquid) flow, including dispersed phase droplet break up and coalescence. Boyaval and Dumouchel [5] have studied the relation between drop size produced

by sprays and the applied pressure. They mentioned that, the laser Doppler velocimetery (LDV) is never satisfactory technique for that study. So they employed the light obscuration (single beam scattering) to have droplet size data.

Theory

When a parallel beam of light is passed through an emulsion, part of light is scattered by particles of dispersed phase. The angular distributions, with intensity of the forward scattered and transmitted light are dependent on the aerosol size, which causes attenuation [6]. The scattered intensity is inversely proportional to droplet size. Theoretical treatment depends on the Mie scattering theory [7]. Fig. 1 shows how the light can be scattered when it passes trough a single drop.

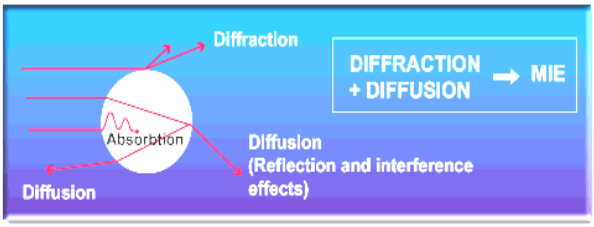


Fig. 1
The scattering of light caused by a single drop

Now consider that there are N identical drops per unit volume of space, Fig. 2. As the radiation incidence on the drops it will be scattered in all directions. The influence of the drops depends upon their individual properties like refractive index and size, which combined in the Mie parameter [8, 9].

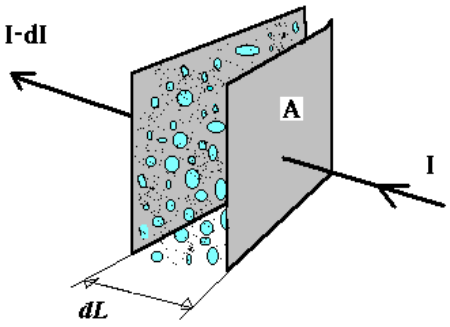


Fig. 2 Variables for loss of light by transmission through a scattering medium [7].

The mathematical equation which governs the forward transmitted (unscattered) portion of the laser light through the dispersion is the following [7, 10]:

$$\ln\left(\frac{I_0}{I}\right) = Q_s \cdot \frac{\pi}{4} d_{32}^2 \cdot N \cdot L \qquad (1)$$

$$Q_s = \frac{C_{sca.}}{A} = \frac{Power Scattered}{Power Incident} \qquad (2)$$

$$N = \frac{\varphi}{\frac{4}{3}\pi \cdot (\frac{d_{32}}{2})^3} = \frac{\varphi}{\frac{\pi}{6} d_{32}^3} \qquad (3)$$

where
I_o: Incident laser light intensity,
I: Transmitted (unscattered) laser light intensity,
d_{32}: Sauter mean diameter,
L: Dispersed phase thickness,
Q_s: Scattering efficiency,
$C_{sca.}$: The scattering cross-section,
A: The geometrical cross sectional area, and
φ: Volume fraction of the dispersed phase.

Experimental data and calculations by several investigators showed that the scattering efficiency Q_s is extremely sensitive to drop sizes near the wavelength of the incident light. The effect of drop diameters, however, decreases with increasing drop size. Calculations by a group of workers [11] showed that for the limiting conditions the scattering efficiency Q_s is essentially constant for drops larger than 50 μm, as it is referred by Virgil et al. [11]. So that, they assumed that the Q_s (which they named it as scattering factor $\alpha = Q_s/4$) is just function of relative specific refraction (M) or Lorenz-Lorentz coefficient, as shown in Fig. 3.

However, in most cases the scattering efficiency Qs for spheres of liquids are calculated from [7, 12]:

$$Qs = 2 - \frac{4}{\kappa}\sin\kappa + \frac{4}{\kappa^2}(1-\cos\kappa) \qquad (4)$$

where:

$$\kappa(radians) = 2x\left(\frac{n_d - n_c}{n_c}\right) \qquad (5)$$

and

$$x = \frac{\pi\, d\, n_c}{\lambda} \qquad (6)$$

is the size parameter, where n_d and n_c are the refractive index of drop phase and continuous

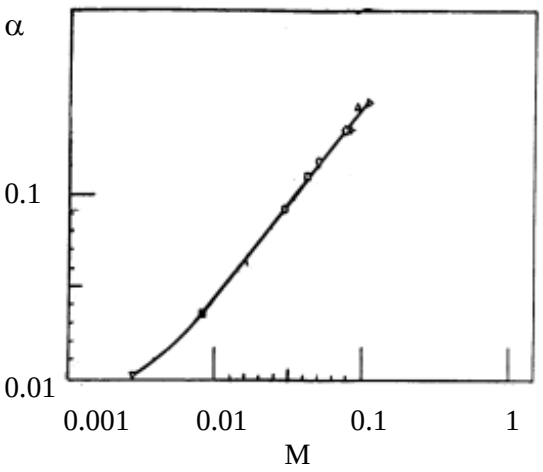


Fig. 3 Scattering factor α as a function of relative refractive index M [11].

phase respectively, while λ is the wavelength of the incident light (λ=0.6328 μm for He-Ne laser). The size parameter χ, which is called Mie parameter [9], is the important parameter, which relates the drop size to the incident wavelength and refractive index.

Experimental Verifications

The experimental design is shown in Fig. 4. It consists of a mixing unit which implements agitation vessel (dia.= 14.5 cm, height = 25 cm) supported with four baffles. The liquids were agitated with mixing motor (type Heidoph RZR 50) for the range of (1180- 2090) r.p.m. The impeller of the mixer was six flat blades. The generated drops in the mixing tank are withdrawn to a disc shape cavity covered with two circular windows of the visible light. This cavity is called flow cell. The geometry of the flow cell is given in Fig. 5. There was also a washing tank for cleaning the components after each test. Isopropanol was added to the washing liquid for degreasing the organic materials.

A He-Ne laser (output power = 1 mW, λ=0.6328 μm) was directed to the prepared dispersion in the flow cell. A beam expander was used for expanding the laser beam to 15mm diameter. The intensity distribution of the laser beam has top hat profile as shown in the Fig. 6, as it is the best profile recommended for light scattering experiment [13]. A large area detector (RS 652.027) of silicon type was used for detecting the unscattered laser light. The signals observed by an oscilloscope (200 MHz) for recording the transmitted light. Several optical elements (lenses, holders, mirrors, and pinholes) were used for alignment purposes. An optical arrangement consists of a lens and pinhole was placed in front of the detector for excluding the stray light from the unscattered light. In addition, the detector was positioned far from the scattering medium for enhancing the separation of the unscattered laser light from the scattered one. The microphotography device which is used for photographing the droplets is consists of a camera (ZENIT TTL. USSR) constructed on a microscope (Biovision NTX-3C) of magnification 40X.

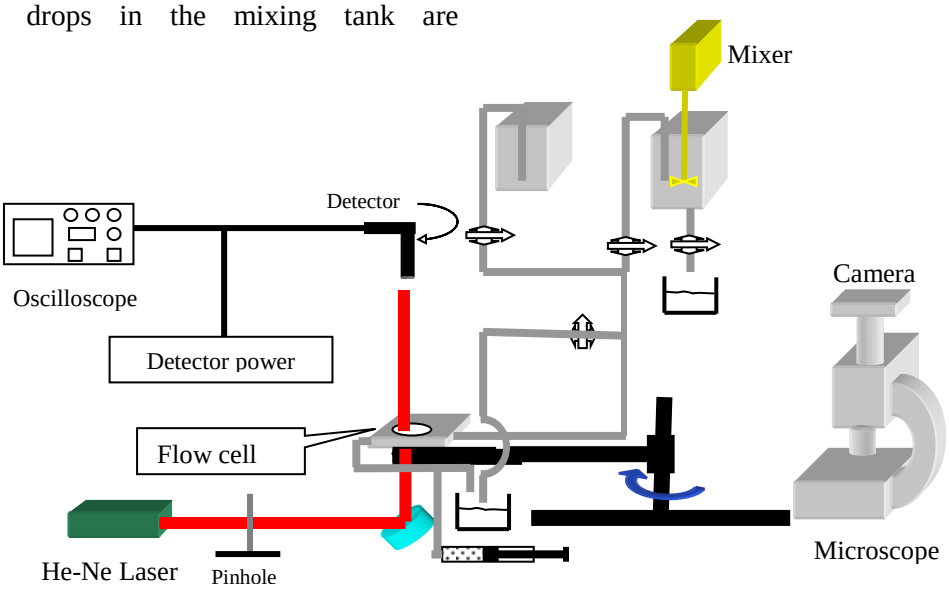


Fig. 4 The experimental setup

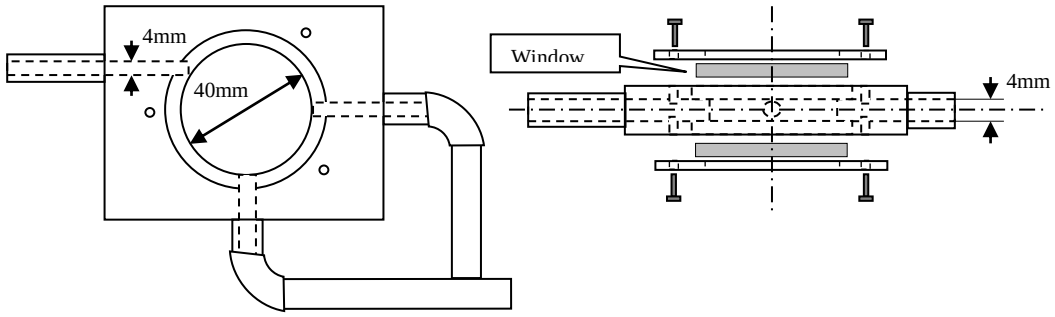


Fig. 5 Schematic diagram of the flow cell

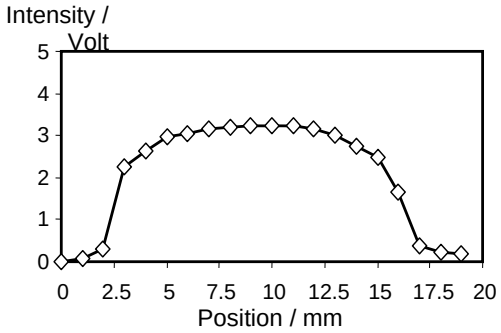


Fig. 6 Intensity profile of He-Ne laser beam

Procedure

Two immiscible liquids, water and kerosene were mixed together with different low volume fractions (0.0025, 0.005, 0.0075, 0.01, and 0.02) of kerosene (as a dispersed phase) in water (as a continuous phase). When the liquids were added in the agitation tank they were mixed together at different rotational speeds of the mechanical turbine mixer (1180-2090) RPM, and at constant room temperature (25 ºC) for a period of time more than 20 minutes [12]. When a good dispersion was obtained in the mixing tank, a sample of dispersion was taken from the tank by a sampling tube. The dispersion sample is then withdrawn through a 1cm-diameter tube by evacuation creation in the flow cell. Accordingly, the flow cell will fill with dispersion; herein the droplets were prepared for testing. It is not significant to homogenize the inner surface areas of the tubes with dispersion phase, as it is observed by Rebelein and Blaβ [14] too. This is because of low volume fraction of dispersed phase. As soon as the dispersion (droplets) is prepared in the cavity of the flow cell, they were tested by laser system and microphotography device. The detector sense is recorded then the Sauter mean diameter (d_{32}) was found and compared with that obtained by photographs. A sample of droplets photograph is shown in Fig. 7.

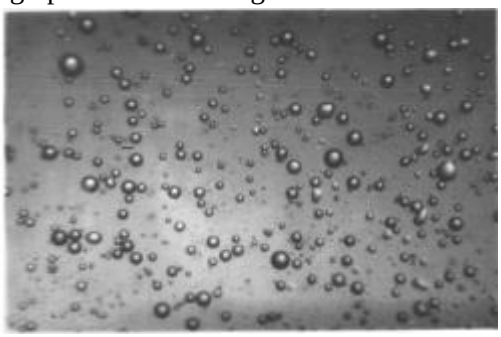


Fig. 7 Images of the droplets at conditions, φ=0.005, RPM=2000, d_{32}=58.8 μm

Results and Discussion

There are various ways to represent the average drop size of a spectrum of drop diameter [12]. In our calculations the Sauter mean diameter (d_{32}) was employed to represent the mean diameter of the droplets as it is appropriate diameter for heat or mass transfer calculations. The Sauter mean diameter is calculated from:

$$d_{32} = \frac{\sum_{i=1}^{n} n_i d_i^3}{\sum_{i=1}^{n} n_i d_i^2} \qquad (7)$$

where

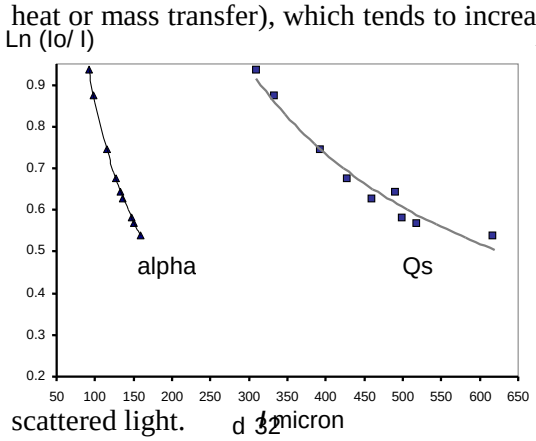
d_i : is the diameter of the i-th group of drops,

n_i: is the number of the drops of i-th group.

The drop size measurement is correlated to the laser beam intensity by two ways. First by Equs. 1 to 3. The second way is by using the solution of Equs. 1, 3, 4, 5 and 6. A computer program of Matlab software was developed for the solution of the collection of these equations, to have the drop size. For simplicity, the results of the drop size obtained by the first way of the laser detection method are designated as (alpha), and the second one by (Q_s). While the data obtained by MS represents microphotography method.

The effect of drop diameter on the unscattered light intensity is presented in Figs. 8 to 12. Clear observation to these figures illustrates an inverse relation between d_{32} and the total amount of the scattered light intensity (i.e. direct proportion to the unscattered light) for specific volume fraction. This is surely by taking in consideration that the amount of the absorbed light is ignored, where the continuous phase (pure H_2O) has negligible amount of absorption of light at the visible region of the electromagnetic spectrum over several cm [6].

The proportional relationship between Sauter mean diameter and the intensity of the transmitted light is due to the following reasons. Consider a constant volume fraction, if the drop diameter decreased the number of the droplets will be increased, which means increasing the number of the scatterers and thereby this will increase the scattered light. In addition by decreasing the drop diameter the scattering efficiency will be increased. This is because of the scattering efficiency is a function of geometric cross-section of the droplets [7]. In other words, by decreasing the drop diameter the total surface area of the droplets per unit volume will be increased (this is favorite for efficient heat or mass transfer), which tends to increasing the scattered light.



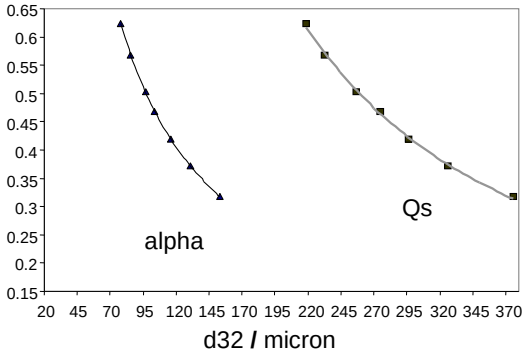


Fig. 8 A plot of d32 and ln (Io / I) at $\varphi = 0.02$

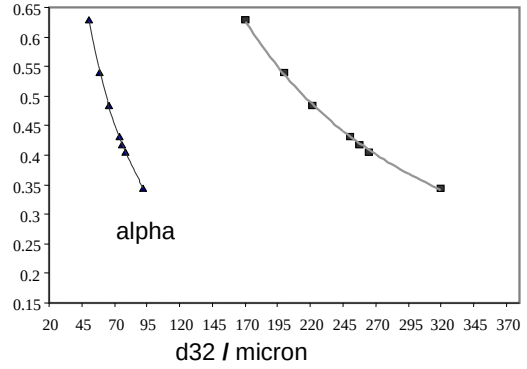


Fig. 9 A plot of d32 and ln (Io / I) at $\varphi = 0.01$

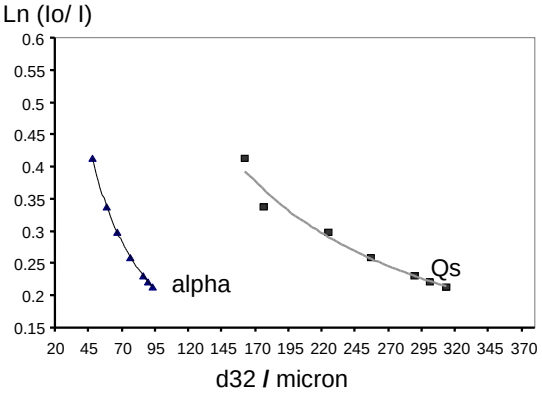


Fig. 10 A plot of d32 and ln (Io/I)at $\varphi = 0.0075$

Fig. 11 A plot of d32 and ln (Io/I) at $\varphi = 0.005$

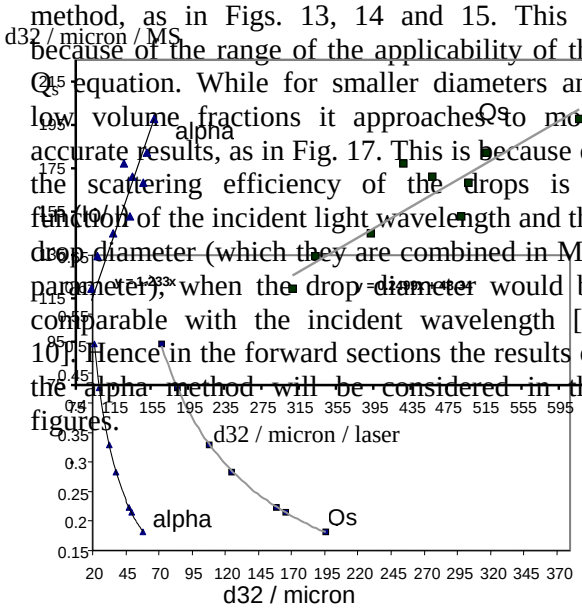


Fig. 12 A plot of d32 and ln (Io/I) at φ =0.0025

The comparison of the drop size measured by laser method and microphotography methods at the same operation conditions is presented in Figs. 13 to 17. These figures illustrate that the drop size obtained by the photography method does not coincide with that obtained by the laser method.

The data obtained show that micro-photography gives generally drop size greater than that predicted by the laser method (alpha), and smaller than (Q_s) method. This may be because of that not all the drops, which are exposed to laser beam, are examined by photography method. This is because of that the photographs detect the droplets that lay in the exaggerated region of the emulsion. But laser beam passes through all the drops and takes all of them in account of the determination.

Furthermore, Figs. 13 to 17 show that the Sauter mean diameter obtained by Q_s calculations give greater size than (alpha) method, as in Figs. 13, 14 and 15. This is because of the range of the applicability of the Q_s equation. While for smaller diameters and low volume fractions it approaches to more accurate results, as in Fig. 17. This is because of the scattering efficiency of the drops is a function of the incident light wavelength and the drop diameter (which they are combined in M.e parameter), when the drop diameter would be comparable with the incident wavelength [7, 10]. Hence in the forward sections the results of the alpha method will be considered in the figures.

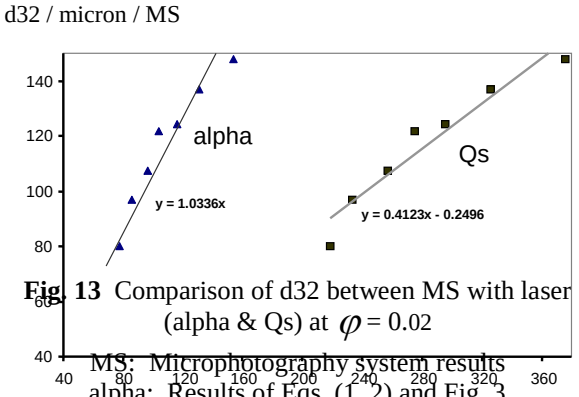
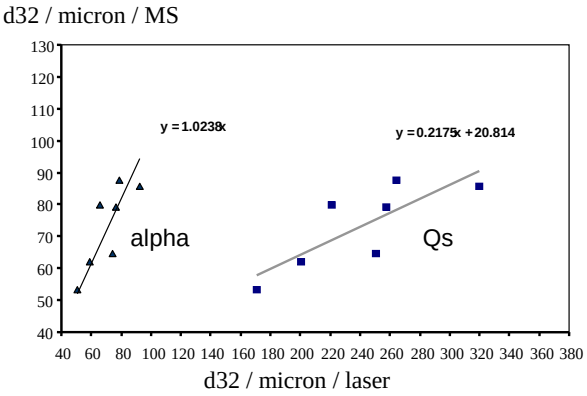


Fig. 13 Comparison of d32 between MS with laser (alpha & Qs) at φ = 0.02

MS: Microphotography system results
alpha: Results of Eqs. (1, 2) and Fig. 3
Qs: Results of Eqs. (1, 3 - 6)



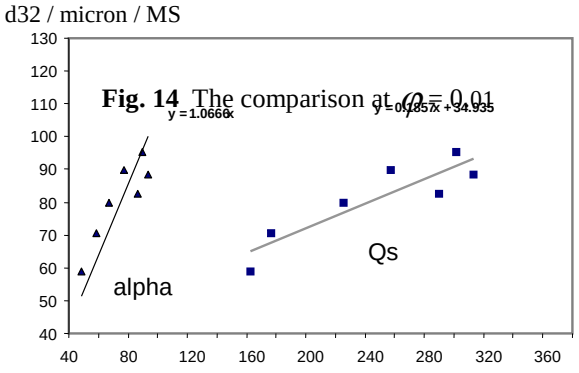


Fig. 14 The comparison at φ = 0.01

Fig. 15 The comparison at φ = 0.0075

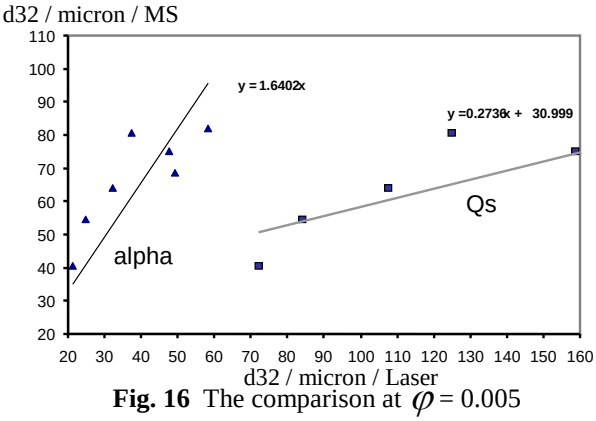


Fig. 16 The comparison at φ = 0.005

Fig. 17 The comparison at $\varphi = 0.0025$

Usually the drops appeared to be perfect spheres except in some cases; they were deformed, as in Fig. 18. Perhaps this phenomena can causes further error in reading.

In addition, some of air bubbles occasionally are observed in the dispersion medium, as in Fig. 19, that also contributes with other factors causing incompatibility between the both methods.

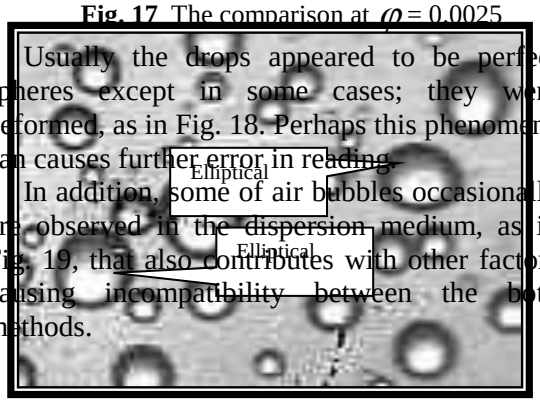


Fig. 18 Example of the elongated drop in the dispersion medium.

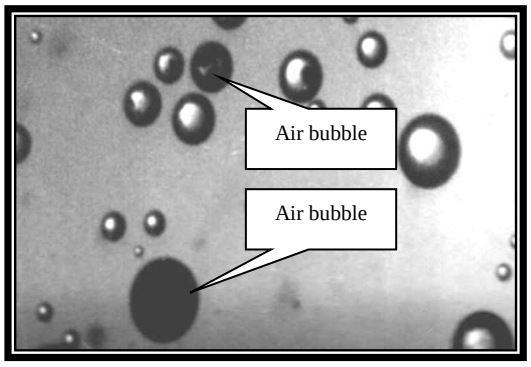


Fig. 19 A photograph illustrating the air bubbles

Conclusions

1. The use of laser technique based on laser light scattering provides a rapid (simultaneous) and accurate method for the determination of drop size in a chemical units during the process.
2. The results of drop size obtained by (alpha) method gives are accurate than that obtained by the Q_s method. This is because of the range of the applicability of the relevant equations. Hence, it is recommended to employ the Q_s method for the smallest drops, which are comparable with the incident light wavelength.

References

1. R. N. Sherev and J. A. Brink, "Chemical Process Industries", McGraw Hill, Kogakusha (1977).
2. L. Silverman and C. E. Billings, "Particle Size Analysis in Industrial Hygiene", Academic Press, N.Y. (1971).
3. F. Rebelein, E. Blass, "Separation of micro dispersions in fiber-beds", Filtration and Separation, Sept./ Oct., 360 (1990).
4. W. J. Tjaberinga, A. Boon and A. K. Chesters, *Model experiments and numerical simulations on emulsification under turbulent conditions*, Chem. Eng. Sci. **48**, 285 (1993).
5. S. Boyaval and C. Dumouchel, *Investi-gation on the drop size distribution of sprays produced by a high-pressure swirl injector. Measurements and application of the maximum entropy formalism*, Sys. Charact. **18**, 33 (2001).
6. C. F. Bohren and D. R. Huffman, "Absorption and Scattering of Light by Small Particles", Wiley - Interscience (1983).
7. L. P. Bayvel and A. R. Jones, "Electromagnetic Scattering and its Applications", Applied Science Pub., London (1981).
8. A. Deepak and M. A. Box, *Forward scattering correction for optical extinction measurements in aerosol media: Part 1, Monodispersion*, Appl. Opt. **17**, 2900 (1978).
9. A. Deepak and M. A. Box, *Forward scattering correction for optical extinction measurements in aerosol media: Part 2,*

Monodispersion, Appl. Opt. **17**, 3169 (1978).
10. M. Kerker, "The Scattering of Light and other Electromagnetic Radiation", Academic Press, N. Y. (1969).
11. G. T. Virgil and A. R. Walton, *Light transmittance as a measure of interfacial area in liquid- liquid dispersions*, AIChE Journal **2**, 205 (1956).
12. P. Sherman, "Emulsion Science", Academic Press, N. Y. (1968).
13. D. Allano, *Droplet sizing using top-hat laser beam technique*, J. Phys. D: Appl. Phys. **17**, 43 (1984).
14. F. Rebelein and E. Blaβ, *A measuring technique for drop diameters in the μm-range in liquid- liquid dispersion*, International Solvent Extraction Conf. (ISEC), part III, p. 387 (1986).

قياس أبعاد القطرات المايكروية في وحدة مزج بأستخدام تقانة الليزر

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الخلاصة

في هذا البحث تم بناء منظومة متكاملة لقياس أبعاد القطرات المايكروية بصورة انية . تتكون المنظومة من أجزاء هي منظومة كشف ليزر الهيليوم نيون ، ووحدة مزج ، و منظومة التصوير الفوتوغرافي الدقيق . تم مزج الماء مع تراكيز واطئة من الكيروسين وبسرع تدوير مختلفة وجرى تعيين معدل أقطار Sauter **أعتماداً على عملية استطارة حزمة الليزر من المزيج . أظهرت النتائج أن أبعاد القطرة المقاسة بأستخدام تقانة الكشف بالليزر تقل عن تلك المعينة بالتصوير الفوتوغرافي .**