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High Local Energy Dissipation Rates in Fine-Clearance Equipment

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ABSTRACT

From the specifications of various emulsifying and homogenizing machines, the local power dissipation in the fine-clearance volume is deduced. Values of the power dissipated per unit mass of liquid range from 4.5×10^5 to 4×10^8 W.kg^{-1}. Such high power dissipations can explain, on the basis of turbulence theory, the droplet sizes produced in dispersions of one liquid in another.

If the viscosity of the disperse phase is appreciable, the droplet sizes are higher than for low viscosity fluids. This is evaluated quantitatively, with applications to the homogenization of milk and the emulsification of bitumen.

INTRODUCTION

The well-known (Kolmogoroff, 1949; Hinze, 1955) derivation of the equation relating the maximum diameter of droplets (d_{max}) which can resist further dispersion in a turbulent flow field, is

$$\frac{4\,\sigma}{d_{max}} = \rho_c\,(v')^2 \qquad (1)$$

Here it is assumed that only the interfacial tension σ of a spherical drop resists the disruptive fluctuation pressure of the energy-containing turbulence eddies, which have fluctuation velocities v'. The density of the continuous phase is ρ_c, but the viscosity of the phases is not taken into account in eq.(1).

To obtain v', one uses for the energy-containing eddies the relation (see, for example, Davies (1972)):

$$v' = (P_M\, d_{max})^{1/3} \qquad (2)$$

where P_M is the local power dissipation per unit mass of liquid in the region of droplet break-up, and the relevant eddy length is taken to be d_{max}. Substitution from eq.(2) into eq.(1) gives

$$d_{max} = 2.3\,(\sigma/\rho_c)^{0.6}\,P_M^{-0.4} \qquad (3)$$

APPLICATIONS OF EQ.(3)

The practical question raised by this equation is how to subject the liquid-liquid dispersion to high enough values of P_M to produce values of d_{max} of a few micrometers. By studying closely the specifications of fine-clearance valve homogenizers, a liquid-whistle emulsifier and a "Hurrell" colloid-mill, Davies (1985) obtained the typical figures for P_M of 4×10^8 W.kg^{-1}, 1.3×10^7 W.kg^{-1}. and 4.5×10^5 W.kg^{-1}. respectively: these values are high because of the fine clearances between the working surfaces, and the high linear flow velocities, in equipment of these types. Hence one can calculate typical d_{max} values, though it appears from this and other studies (Davies, 1986) that the geometrical factor 2.3 in eq.(3) is an un-necessary complication, and one can use simply

$$\sigma/d_{max} = \rho_c (v')^2 \qquad (4)$$

and

$$d_{max} = (\sigma/\rho_c)^{0.6}\,P_M^{-0.4} \qquad (5)$$

Agreement between calculated (eq.(5)) and measured d_{max} values is reasonable. It must again be emphasised that this treatment applies only when μ_d, the viscosity of the disperse (i.e. droplet) phase is negligibly low, of the order 1mPa.s.

CALCULATED EFFECTS OF HIGHER μ_d

In his original paper, Hinze (1955) suggested that a term in μ_d should strictly be included in eq.(1). But Hinze's dimensionless group approach to this matter was criticized by Sleicher (1962) because Hinze's group did not involve a velocity; and Sleicher correlated his own data on break-up in pipe flow with the average overall flow-rate in the pipe. Davies (1985) pointed out that in general it is v', the turbulent velocity fluctuation that must be multiplied by μ_d, so that when v' is very high (as in valve homogenizers) the effect of an increase in μ_d will be more pronounced than when v' is lower (colloid mills or agitated tanks).

This approach permits a simple fundamental treatment, as in the eq.(2) of Davies (1985). Here the viscous resistance appropriate to rapid droplet break-up in the turbulent flow is obtained by adding to the interfacial resistance pressure the term μ_d/t_e, where t_e is the characteristic time of the eddies responsible, so that eq.(4) becomes

$$\frac{\sigma}{d_{max}} + \frac{\alpha\mu_d}{t_e} = \rho_c\,(v')^2 \qquad (6)$$

where α is an arithmetical factor, of the order unity.

Since t_e is the eddy size divided by v', and if the eddy size can again be equated to d_{max}, then

$$\frac{(\sigma + \alpha\mu_d\, v')}{d_{max}} = \rho_c\,(v')^2$$

or, putting $v' = (P_M\, d_{max})^{1/3}$ on the right side, one can solve for d_{max}, obtaining

$$d_{max} = (\sigma + \alpha\,\mu_d\, v')^{0.6}\,\rho_c^{-0.6}\,P_M^{-0.4} \qquad (7)$$

If d_{max} is the maximum droplet size of the disperse phase when $\mu_d \to 0$, then it follows that

$$\left(\frac{d_{max}}{d_{omax}}\right)^{1.67} - 1 = \frac{\alpha\,\mu_d\, v'}{\sigma} \qquad (8)$$

This implies that the effect of μ_d, in different systems, can be represented by a single straight line if α is constant: for fine-clearance values, v' is typically high (e.g. 8 m.s.$^{-1}$), so the right side of eq.(8) can be important, even for moderate increases in μ_d, i.e. d_{max} is predicted to be considerably increased as μ_d is increased (other factors being constant in any given comparison).

APPLICATIONS OF EQS.(7) AND (8)

In the paper of 1985, Davies suggested that α was about 0.25. Since that paper was written, the more refined method (eq.(8)) of finding α has been developed, and the data of Walstra (1974) have been discovered, recalculated and substituted into eq.(8) to obtain a more reliable value of α. Though Walstra used 0.2% aqueous sodium lauryl sulphate to stabilize his emulsions, Davies (1985) has shown that for the very rapid break-up of droplets in fine-clearance equipment, the eddy forces act so quickly ($\sim$ 1μs) and so strongly that clean oil interfaces become exposed in the break-up process. Accordingly, σ is taken as 50 mN.m^{-1}. in our interpretation of Walstra's results for mixtures of paraffin oils with hexadecane. The value of α is found to be between 0.5 to 0.9, with a mean of 0.7 (Davies, 1986). In calculating the group μ_d v'/σ, the value of v' appropriate to each d_{max} at each value of μ_d, has been used.

That α = 0.7 (i.e. not far from unity) indicates that use of the shear viscosity μ_d of the dispersed phase in eq.(6) is realistic: the droplets are suddenly torn apart by very fast turbulent impulses, rather than slowly becoming highly elongated.

One application of eq.(7) is to the homogenization of milk in fine-clearance valve equipment. Droplets of mean diameter < 1 μm are required. With the appropriate viscosity correction in eq.(7), the turbulence mechanism can explain the observed findings: at 40^{o}C the fat drops in the milk are molten, with μ_d = 35 mPa.s. With v' = 12 m.s^{-1} (corresponding to an operating pressure of 140 bar), the term 0.7 μ_d v' is 295 x 10^{-3} Nm^{-1}. Since σ = 15 x 10^{-3} N.m^{-1}. for butter oil against water, (σ + 0.7 μ_d v')$^{0.6}$ is (310 x 10^{-3})$^{0.6}$, and with P_M = 4 x 10^{8} W.kg.$^{-1}$ in this system, eq.(7) gives d_{max} = 2.7 μm. The observed maximum value is a little lower at 1.8 μm, (mean diameter about 0.4 μm) but under practical operating conditions the temperature may well be above 40^{o}C, and so μ_d (and the calculated d_{max} would be reduced accordingly). Thus, with the necessary correction for μ_d, the turbulent mechanism does explain milk homogenization.

Another application is in bitumen emulsification in Hurrell colloid mills. The viscosity is first reduced below 200 mPa.s by mixing the bitumen with 3% of kerosene or diesel oil, followed by heating to about 135^{o}C. For a typical Hurrell colloid mill, v' is estimated to be 1.6 m.s^{-1} (Davies, 1985); and σ is about 6 mNm.$^{-1}$. The value of d_{max} calculated without the viscosity correction (i.e. by eq.(5)) is only 4 μm, compared with the experimental mean droplet size of about 5 μm (suggesting a d_{max} of perhaps 20 μm). Clearly, therefore, a viscosity correction is important with such a viscous oil, though eq.(7) with α = 0.7 leads to a rather high d_{max} value of 36 μm. Further studies would be of interest, to examine closely the viscosity of the oil (within the colloid mill) and the d_{max} actually observed at the exit of the mill.

NOMENCLATURE

d_{max} maximum drop diameter in dispersion, μm or m.

d_{omax} maximum drop diameter when μ_d is small, μm or m.

P_M local power dissipation per unit mass of liquid in region of dispersion, W.kg.$^{-1}$

t_e characteristic eddy time for energy-containing eddies, s or μs.

v' velocity fluctuation of energy-containing eddies, m.s^{-1}

Greek letters

α arithmetical factor in eq.(6)

μ shear viscosity of disperse phase, Pa.s or mPa.s.

ρ_c density of continuous phase, kg.m^{-3}.

σ interfacial tension, N.m.$^{-1}$ or mN.m^{-1}.

Subscripts

c continuous phase

d disperse phase

e eddy

max maximum

M per unit mass

o corresponding to $\mu_d \to 0$.

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