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REPORTED DROPLET SIZE DISTRIBUTION DATA IN DISPERSED TWO-PHASE FLOW

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Introduction

The primary purpose of this manuscript is to present summary tables of reported work on droplet size and distribution in dispersed two-phase flow. The work is primarily intended for use by those engaged in design and analysis of two-phase, dispersed flow systems and by researchers in the field. The nature of the droplet size and distribution plays a major part in the behavior of the system, for example, with respect to heat transfer and pressure drop.

The results are presented primarily in tabular form. They represent the results from a literature search and indicate a summary of the reported work indicating, where possible, the influence of the primary variables on the droplet size.

TABLE I

Table I shows the reported experimental data. It is divided into three parts, (IA) constant flow across sections, (IB) nozzles orfices and sprays and (IC) liquid-liquid systems. Since there is not a consensus on the mechanism of droplet formation and break-up, the relationship between these systems is not known. Despite the substantial difference between the systems, there appears to be a good deal of similarity in the reported droplet size range and in the distributions.

These tables indicate a need for a standardization of measurement techniques (not necessarily for a single technique) and for a standarized system of data reduction and for the reporting of the reliability of the data. Further, it would be extremely helpful if there were a few standard representations of the data reported (such as the Sauter Mean Diameter) in order to provide quick and easy comparisons between one set of data and another. Finally, it would be useful if the distributions could be compared to several of the frequently reported distributions systems such as Mugele and Evans (1951), Rosin—Rammler (1933), and Nukiyama and Tanasawa (1938).

Another substantial need is to have reported experimental data in a form that would be useful to test hypotheses or predictive expressions or to indicate the influence of variables such as gas velocity, on the resultant droplet sizes and distributions.

Many of the reported works satisfy a great deal of the desired conditions listed above and are certainly helpful in understanding the nature of the droplet size and distributions to be expected in certain flow systems. The field, however, seems to be at a point where a greater uniformity of measurement and data presentation, together with systematic experimental planning could and should be followed in the future. Certainly, for achievement of the verification of predictive expressions to be used in the analysis and design of two-phase flow systems, substantially more and carefully planned experimental studies will be required.

In conclusion, much useful and carefully gathered data have been reported, however, there is great need for more work which should be reported in a uniform method. Secondly, experiments should be carefully planned to test proposed mechanisms and show the influence of the primary variables.

TABLE II

Table II presents a summary of predictive expressions for droplet size and distribution. The predictive expressions for sprays orifices and liquid-liquid systems were omitted. Also, the table was limited to expressions which would appear to be useful in design and analysis studies.

It may be seen that the expressions vary widely in form and that there is not a consensus regarding the identification of the primary variables, except for that of the continuous fluid velocity.

The authors also differ in the mechanism which they have proposed to produce the various droplet sizes and distributions. These mechanisms may be divided into two general classes:

1. Those which study formation of the droplet from waves or ligaments. These generally begin with the work of Kelvin-Helmholtz on wave growth.
2. Those which study the droplet already formed. The analysis predicts its size and conditions for break-up. This study usually follows a force balance of the pressure gradient opposed by the forces produced by the fluid properties.

TABLE III

Table III attempts to show the state of knowledge with respect to the primary variables as evidenced by the reported experimental data. This table is divided into several parts. The first shows the influence of gas velocity. The second, shows the influence of geometry and the third, the influence of the fluid properties.

These tables show some consensus but, as mentioned previously, there is a considerable need for more data, particularly from carefully planned experimental systems, to show the influence of the primary variables. The reported data could be said to show that the droplet size is generally proportional to the gas velocity to the minus one to the minus two power with the consensus, apparently, toward the minus one power. The influence of the other proposed variables is less clear.

SUMMARY AND CONCLUSIONS

In summary, the reported data on droplet size and distribution is substantial and certainly helpful to those working in the field. If, however, the objective is to obtain reliable predictions of droplet size behavior in various fluid systems with various flow conditions, then, substantial additional work is needed. Further, this work should be reported in a uniform and orderly manner and the experiments should be planned with careful consideration given to the work of current and previous investigators.

NOTES

The means of representing droplet sizes and distributions follow, with notes on:

Effective Droplet Diameters
Volume - Mass Diameters
Expressions for Droplet Distributions

EFFECTIVE DROPLET DIAMETERS

There are general methods of representing effective droplet diameters. These diameters are designed to effectively represent the droplets distribution for specific studies such as size comparisons, heat and mass transfer, etc. The particular effective diameter is designated by subscripts and defined in the following expression:

$$d_{q\,p}^{(q-p)} = \frac{\displaystyle\int_{d_{min}}^{d_{max}} d^{q}\left(\frac{dn}{dd}\right) dd}{\displaystyle\int_{d_{min}}^{d_{max}} d^{p}\left(\frac{dn}{dd}\right) dd}$$

The subscripts and exponents, p and q, are assigned integer values to produce the effective diameter required. (dn/dd) is the derivative of the droplet distribution curve.

Thus the system of (p q) allows the determination of effective droplet diameters to suit a geometry description and a specific application as shown below

EFFECTIVE DIAMETERS

p	q	Geometry	Application (Examples)
0	1	Linear	Comparison,
0	2	Surface Area	Surface heat transfer, Absorbtion
0	3	Volume	Hydrology

1	2	Surface-diameter	Absorption
1	3	Volume-diameter	Molecular diffusion
2	3	Volume-surface mean (Sauter)	Mass transfer, reactions
3	4	DeBrakere	Combustion, equilibrium

Other droplet diameters frequently used are

d_{max} = maximum droplet diameter

d_{mean} = average droplet diameter

d_{median} = median droplet diameter

d_{prob} = most probable droplet diameter

VOLUME - MASS DIAMETERS

In addition to representations with respect to droplet size, effective diameters have been defined with respect to the volume or mass of the entire droplet population. Most common of these are diameters related to total droplet volume defined as:

$d_{m\,(\;)}$ or $d_{v\,(\;)}$ = droplets diameter such that the number in ( ) indicates the portion of the total volume of droplets with diameters greater than d.

also,

$d_{v\,(\text{mean})}$ = median volume diameter or diameter where an equal volume of droplets have diameters larger and smaller than d.

EXPRESSIONS FOR DROPLET DISTRIBUTIONS

Several investigators have proposed expressions which will represent droplet size distributions. It is difficult to assess the agreement between these distributions and the reported data because, for example, some allow setting empirical constants or variables to fit any data group. Further, not all investigators have attempted to fit their data to the proposed expressions. Following are four of the often-used expressions.

It is not possible at this present state-of-the-art to determine whether or not the droplet distributions are a strong function of the flow system and the flow conditions.

CUMO et al (1974)

$$\frac{\Delta n/N}{\Delta d} = \frac{d}{d_{prob}} \; e^{-(d/d_{prob})}$$

MUGELE and EVANS (1951)

(Upper Limit, Log Normal Distribution)

$$dv/dy = \frac{\delta}{\sqrt{\pi}} \, e^{-\delta^2 y^2}$$

where

$$y = \ln \, {}^{ad}\!\Big/_{d_{max} - d}$$

a = constant

dv = volume diameter

δ = distribution parameter

NUKIYAMA-TANASAWA (1938)

$$\frac{\Delta n_{T/N}}{dd} = Bd^2 \, e^{-bx^{\delta}}$$

B = constant

b = size parameter

δ = distribution parameter

Δn_T = number of droplets having a diameter greater than d

ROSIN-RAMMLER (1933)

$$1 - v = e^{-(d/\bar{d}_R)^{\delta}}$$

$1 - v$ = volume fraction of total droplet population occuring diameter greater than d

$\bar{d}_R$ = size parameter

δ = distribution parameter

TABLE I (IA)

SUMMARY OF REPORTED DROPLET SIZE - DISTRIBUTION

EXPERIMENTAL DATA

IA - CONST. FLOW CROSS SECTION - GAS-LIQUID SYSTEMS

Description of Study	Flow Condtions	Droplet Data	Misc. Data
Investigators - Date System Fluids	Flow Cross Section Quality (x) Gas Velocity (u_g)	Representative Size Range Distribution	Measurement Method Application Remarks
Azzopardi, Freeman & Whalley (1978) Vertical Upward Air - Water	ID = 32 mm x = .31 - .83 u_g = 23-42 m/s	d_{32} = 69-170 μm Rosin-Rammler distribution function fit	Diffraction (Laser) Basic Study
Cousins & Hewitt (1968) Vertical Tube Upward Flow Air - Water	ID = 0.375 " .95 cm x = 0.15 - 0.67 u_g = 93-163 f/s 28-50 m/s	d = 70-360 μm	Photography Basic Study For entrained droplets $u_d/u_g \approx 0.9$
Cumo et al (1974) Vertical Rectangular Upward Flow Freon	0.3 x 0.5 cm x = 0.96 - 1.46 Based on enthalpic balance - superheated vapor.	d_{prob} = 12-25.9 μm $d_{prob} = \frac{d_{mean}}{2}$ Fitted to proposed distribution function. See section on distribution functions.	Photography Basic Study Increased pressure reduced range of droplet size.
Forslund & Rohsenow (1968) Vertical Tube Upward Flow Nitrogen	D = 0.228" = 0.58 cm = 0.323" = 0.82 cm = 0.462" = 1.2 cm x = 0.3 - 0.8 u_g = 50-150 f/s = 15-45 m/s	100-1000 μm	Photography Boiling Burnout Study d = f (q/A)

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TABLE I (IA) (con't)

Lindsted, Evans, Gass & Smith (1978) Vertical Tube Upward Flow Air-Water	$D = 1.25''$ $= 3.2$ cm $x = 0.2 - 0.9$ $u_g = 30\text{-}70$ f/s $= 9\text{-}21$ m/s	$d = 250\text{-}2500$ µm	Photography Basic Study
Mayinger & Langner (1976) Vertical Tube Upward Flow R - 12		$d = 20 - 850$ µm	Photography In-tube boiling
Namie & Ueda (1972) Rectangular channel Horizontal Air-Water Air-Water + surface active agent	$D = 1.25''$ $= 3.2$ cm $u_g = 26$ m/s	$d = 40 - 450$ µm	Photography Examination of entrainment from single wave
Pogson, Roberts & Waibler (1970) Vertical Tube Upward Flow Steam - Water	$x = 0.5 - 0.8$	$d_{prob} = 30$ µm $d_{mean} = 41$ µm $\frac{\Delta n}{\Delta d} = 0.0003d^2\ e^{-0.08d}$	Photography Basic Study Heat Transfer

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TABLE I (IA) (con't)

Tatterson, Dallman & Hanratty (1977) Horizontal-Rectangular Air - Water	1 x 12" 2.5 x 30 cm	d_{vm} = 460-720 μm (volume mean diameter) $\frac{d_{max}}{d_{vm}} = 2.9$ $\frac{d_{30}}{d_{vm}} = 0.34$ $\frac{d_{10}}{d_{vm}} = 0.15$ Fitted to Mugele-Evans distribution function	High Voltage Probe Basic Study Also Anal. Data Woodmanese & Hanratty (1969) Cousins & Hewitt (1968) Wicks & Dukler (1966) Pogson et al (1970) Namie & Ueda (1972)
Wicks & Dukler (1966) Vertical Rectangular Air - Water	0.75 x 6" 1.9 x 15 cm x = 0.19 - 0.82 u_g = 77-253 f/s 23-77 m/s	d_{max} = 600-2000 μm	Electrical Conductance Needle Points Basic Study MacVean & Wallis (1969) discuss measurement method & data reduction
Whalley, Azzopardi, Pshyk & Hewitt Vertical tank Upward tube	0.01m x 0.06m x = 0.16 - 0.71 u_g = 34-63 m/s	d_{mean} = 23-41 μm	Oil capture/microscope Basic Study

TABLE I (IB)

SUMMARY OF REPORTED DROPLET SIZE - DISTRIBUTION

EXPERIMENTAL DATA

IB - NOZZLES, ORIFICES, SPRAYS

DESCRIPTION OF STUDY	FLOW CONDITIONS	DROPLET DATA	MISCELLANEIOUS DATA
Investigators - Date System Fluids	Geometry Relative Gas Velocity	Representative Size Range Distribution	Measurement Method Application Remarks
Boll, Flais, Maurer & Thompson (1974) Venturi Air - Water	D_{throat} = 14" 35 cm $u_{g_{throat}}$ = 100-300 f/s m/s	d_{32} = 50-400 µm	Light transmissometer (interferometer)
De Corso (1960) Nozzle Air - Water	Nozzle	d_{32} = 40.7-108.4 µm	Photography Fuel Nozzle Explored influence of ρ_g (air) Minimum in d_{32} vs p
Dombrowski & Munday (1968) (Book Chapter) Sprays Air-Liquid			Summarize reported work of 11 investigators on: Drop Size Relations for Impact Jet Atomizers

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TABLE I (IB) (con't)

Frazer, Dombrowski, and Routley (1963) Twin fluid Atomiser Rotating Cup Air - Oils	D_{cup} = 4" Rotation speeds 1500-6000 rpm x = 0.15-0.19 u_g = 29-198 m/s	d_{32} = 23-230 μm d_{max} = 210-630 μm Data fitted by Rosin Rammler	Photography Absorption Basic Study
Gooderum & Bus-nell (1969) Superheated Waterjets Air - Water	Superheated water stream into air $D_{orifice}$=0.01&0.02 in. =0.025&0.05 cm.	d_{32} = 10-150 μm	Optical light scattering Basic Study $d_{32}/D_{orifice}$ Correlates with liquid jet temperature
Ingebo & Foster (1957) Spray Air - Iso Octane - JP 5 - Benzene - Carbon tetrachloride - Water	$D_{orifice}$ = 0.010 in. = 0.025 cm. = 0.020 in. = 0.050 cm. = 0.030 in. = 0.075 cm. = 0.040 in. = 0.10 cm.	d_{30} = 42-103 μm d_{max}= 75-375 μm $\frac{d_{max}}{d_{30}} \simeq 3$ (for Water)	Photography Fuel Nozzle
Mugele & Evans (1951) Sprays Anal. data of: Lee (1932) - Houghton (1950) Kolupaev (1941) Johnstone & Kleinschmidt (1938) Air-fuel Cooper (1937) Harkins & Beeman (1929) Oil into Emulsion	Sprays into continuous phase.	Lee (1932) d_{32} = 69 μm Houghton (1950) d_{32} = 19 μm Kolupaev (1941) d_{32} = 239 μm Fitted data to proposed distribution function	

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TABLE I (IB) (con't)

Nukiyama & Tanasawa (1939) Orifices-Nozzles Air - Water -Alcohol-Water - Glycerene-Water	Sharp Edged Orifices Cylindrical Nozzles	$d_{mean} = \frac{1.83}{(u_g - u_\ell)}\sqrt{\frac{\sigma}{\rho}}$	Encapsulation in oil then microscopic measurement Basic Study
Simmons (1977) Spray Air-JP 4	21 Nozzles 16 Different Designs	$d = 10\text{-}500\ \mu m$ $d_{32}\ \alpha\ d_{\substack{mass\\median}}$	Optical-TV camera and wax droplet capture. Both methods produce same results Fuel Nozzle
Vorontsov (1976) Nozzle Steam - Water	Nozzle	$d = 10\text{-}80\ \mu m$	Electrical conuction needle points Basic Study Larger droplets at nozzle center line than at edge or cone.
Wang & Tien (1972) Nozzles N_2 - Carbopol (non-newtonian) - Water - Glycerene	Nozzle Grooved core	Square Root Normal Distribution $f(d) = \frac{1}{s\sqrt{2\pi}}\, e^{\frac{-\left(d^{1/2} - d^{1/2}_{mean}\right)^2}{2s^2}}$ s = standard deviation	Droplet freezing and sieving Basic Study Same relationships hold for Newtonian and non-Newtonian

TABLE I (IC)

REPORTED DROPLET SIZE - DISTRIBUTION

EXPERIMENTAL DATA

IC LIQUID-LIQUID SYSTEMS

Description or Study	Flow Conditions	Droplet Data	Miscellaneous Data
Investigators - Date System Fluids	Geometry Continuous Fluid Velocity	Representative Size Range Distribution	Measurement Method Application Remarks
Collins & Kundsen (1970) ——— Vertical Tube Downward Flow ——— Water - Shell Solv. - Light Oil - Iso Alcohol	D = 0.745 in. 1.9 cm. u = 14-20 f/s water = 4.3 - 6.1 m/s	d_{32} = 250-420 μm Light Oil d_{32} = 210-400 μm Shell Solv. d_{32} = 80-110 μm Iso Alcohol	Photographic ——— Basic Study (Reactors) ——— Light Oil & Shell Solv. show substantial d_{32} change up to 576 L/D downstream of injection.
Karabelas (1978) ——— Horizontal Tube ——— Water - Hydrocarbons	D = 5.04 cm u = 1-3 m/s water	d_{32} = 350-850 μm Distribution fits Rosin-Rammler (1933) & uppr. log. limit Mugele - Evans (1951) reasonably well ——— Does not agree with Collins-Kundsen (1967)	Encapsulation & Photographic ——— Basic Study ——— Encapsulation believed more accurate measurement method
Kubie & Gardner (1977) ——— Horizontal Tube Helical Tube Upward Flow ——— Water-Isoamyl Alcohol -nButyl Acetate	D_{horiz} = 1.72 cm D_{helix} = 2.54 cm 6° angle (to horiz) u = 1-3.4 m/s water	d = 100-700 μm	Photographic ——— Basic Study ——— Also analized data of Wicks-Dukler (1966) Cousins-Hewitt (1968)

TABLE II

SUMMARY OF PREDICTIVE EXPRESSIONS FOR DROPLET SIZE

(OMITTING SPRAYS, ORIFICES, LIQUID-LIQUID SYSTEMS)

Investigator(s)	Predictive Expression	Comparisons	Remarks
Cumo et al (1973)	$Re_{prob} = \frac{u_g \rho_g d_{prob}}{\mu_g}$ $= 123.1 \left(1 - p/pc\right)^{0.31}$ p_c = Fluid Critical Pressure	Own Data	Expression shows: ρ_g/ρ_ℓ a significant factor
Hinze (1949)	$We = \frac{\rho_g(u_g - u_\ell)^2 d_{max}}{\sigma}$ = Const. (13 to 22)	Isshiki (1959) Const = 6.5 Wicks & Dukler (1966) Agreement with range of Hinze const. if $\left(\frac{u_g - u_\ell}{2}\right)$ is used Forslund & Rohsenow (1966) Const. = 7.5	Forces on Formed Droplet Δp vs σ

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TABLE II (con't)

James (1976)	$d \alpha \frac{1}{u_g^2}$		Extends work of Bradley (1973) (Kelvin-Helmholtz) Droplet formation from waves (ligaments)
Rabin et al (1960)	$We = \frac{\rho_g \left(\frac{d_{max}}{2}\right) u_g^2}{\sigma}$ $Re = \frac{\left(\frac{d_{max}}{2}\right) u_g \rho_g}{\mu_g}$ Const. = $(We)(Re)^{1/2}$ Const. = 0.45-0.5 Non-burning Const. = 0.55-0.71 Burning	Own Data	Studied: Single, formed droplet subjected to shock wave
Tatterson et al (1977)	$\frac{d_{mass\ median}}{D} \left(\frac{\rho_g u_g^2 D fs}{\sigma}\right)^{1/2} = 0.016$ fs = smooth wall friction factor	Own Data Wicks & Dukler (1966) Cousins & Hewitt (1968) General Agreement ——— Namie & Ueda (1972) Pogson et al (1970) Some Agreement	Kelvin-Helmholtz droplet formation from waves (ligaments).

TABLE III (IIIAa)

SUMMARY OF EXPERIMENTAL DROPLET SIZE DATA

WHICH SHOWS INFLUENCE OF:

IIIA CONTINUOUS PHASE (GAS) VELOCITY

IIIAa CONSTANT CROSS SECTION CONDUITS

AUTHOR SYSTEM GEOM. FLUIDS	DATA RANGE	APPARENT INFLUENCE
Azzopardi et al (1978) Vertical Upward 3.2 cm dia Air - Water	u_g = 35-66 m/s x ~ 0.25-0.9 d_{32} = 17-170μm	$d_{32} \alpha \frac{1}{u_g^{1.4}}$
Cumo et al (1973) Vert. Rectangular 0.5cm x 0.3 cm Freon	d_{prob} = 12-26 μm	$Re_{prob} = \frac{G \times d_{prob}}{\mu}$ Implies first power gas velocity
Forslund & Rohsenow (1968) Vertical Tube 0.23, 0.32, 0.46 in.D cm Nitrogen	u_g = 50-150 f/s 15-46 m/s x = 0.3 - 0.8 d = 100-1000 μm	We (d_{max}) = 7.5 Indirectly verified
Lindsted et al (1978) Vert. Upward 1 1/4" diameter Air - Water		Data available but reduction required

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TABLE III (IIIAa) con't

Tatterson et al (1977) ——— Horiz.-Rectangular 1" high, 1/2" wide ——— Air-Water	u_g = 7-15 f/s 2.1-4.6 m/s $x \simeq$ 0.1 - 0.9 $d_{v\mu}$ = 460-720 μm (volume mean dia)	$\frac{d_{50\%}}{\bar{h}} \propto u_g^{-(1)}$ $d \propto u_g^{-\left(\frac{1.8}{2}\right)}$
Wicks - Dukler (1966) ——— Vert. Downward (rect) 3/4" x 6" channel ——— Air - Water	u_g = 77-253 f/s 24-77 m/s d_{max} = 600-2000 μm	$We_{d_{max}} = \frac{1}{\frac{u_g}{2}^{\,2}}$

TABLE III (IIIAb)

SUMMARY OF EXPERIMENTAL DROPLET SIZE DATA
WHICH SHOWS INFLUENCE OF:
CONTINUOUS PHASE (GAS) VELOCITY

IIIAb; b = Nozzles, Orifice, Sprays

AUTHOR SYSTEM GEOM. FLUIDS	DATA RANGE	REMARKS
Banerjee et al (1969) Air Nozzle thru liquid entrains droplets Air - Water - Water Glycerine	$d_{32} = 400\text{-}800\ \mu m$	$d_{32} \alpha \frac{1}{u_g^{1.8}}$
Boll et al (1974) Venturi Scrubber Air-Water	u_g (throat) = 100-300 f/s = 30-91 m/s $\dot{m}_L/\dot{m}_g = \frac{5\text{-}20 \text{ gal}}{1000 \text{ f}^3}$ $d_{32} = 50\text{-}400 \mu m$	$d_{32} \alpha \frac{1}{u_g^{1.602}}$
Dombrowski & Monday (1968) Summary Jet Atomizers Swirl Nozzles Air-Water -Fuels		Atomizers $d = u_g^{-1/2}$ (2EQ) $= u_g^{-(1)}$ (1EQ) $= u_g^{-0.79}$ (1EQ)

Page 2
TABLE IIIAb (con't)
Nozzles, Orifice, Sprays

Ingebo & Foster (1957) Orifice - Spray Air - Isooctone - JP 5 - Benzine - Carbon tetrachloride - Water	u_g not given directly $d_{orifice} = 0.01\text{-}0.04$ in $d_{30} = 42\text{-}103$ µm $d_{max} = 75\text{-}375$ µm	$\frac{d_{30}}{d_{max}} \approx \alpha \left(\frac{We}{Re}\right)^{1/4}$ $\sim \alpha\, u_g^{1/4}$
Nukiyama & Tanasawa (1939) Sharp edged orifice Air - Water - Alcohol Water - Glycerene Water		For high quality $d_{32}\ \alpha\ \frac{1}{u_g}$
Wang & Tien (1972) Nozzle N_2 - Non-Newtonian Polymer - Carbopol		$\bar{d}\ \alpha\ \frac{1}{u_g^{0.8}}$

TABLE III (IIIAc)

SUMMARY OF EXPERIMENTAL DROPLET SIZE DATA
WHICH SHOWS INFLUENCE OF:
CONTINUOUS PHASE (GAS) VELOCITY
IIIAc LIQUID-LIQUID SYSTEMS

AUTHOR SYSTEMS FLUIDS	DATA RANGE	REMARKS
Collins & Kundsen (1970) Downward - vert 0.745 inches Water-Shell Solv. -Light Oil -Iso Alcchol	u_{cont} = 14-20 f/s = 4.3-6.1 m/s Conc (vol) = 0.6-10 d_{32} = 80-420 μm	Complex expression roughly $d \alpha \frac{1}{u_{cont}^{0.8}}$
Karabelas (1978) Horiz 5.04 cm D Water-Hydrocarbons	u_{cont} = 1-3 m/s d_{32} = 350-850 μm	$d_{95} \alpha \frac{1}{u_{cont}^{1.1}}$
Kubie & Gardner (1977) Horiz. Tube Helical Tube Water-Isoaml Alcohol -nbutyl Acetate	u_{cont} = 1-3.4 m/s d = 100-700 μm	d same for helical & horiz. $d \alpha \frac{1}{u_{cont}^{(1.1)}}$

TABLE IIIB

SUMMARY OF EXPERIMENTAL DROP SIZE DATA

WHICH SHOWS INFLUENCE OF:

CONDUIT SIZE (DIAMETER OR HYDRAULIC DIAMETER)

AUTHOR SYSTEM FLUIDS	DATA RANGE	REMARKS
Karabelas (1978) Horiz. 5 cm D Liquid - Liquid Water-Hydrocarbons	D_t = 5 cm d_{32} = 350-850 µm u cont. phase = 1-3 m/s	$d_{95}\ \alpha\ D$
Kubie et al (1977) Horiz Tube 17.2 mm dia. Helical 25.4 mmD Liquid-Liquid Water - Iso-Alcohol -nButl Acetate	D_t = 17.2 mm horiz D_z = 25.4 mm helical d = 100-700 µm u cont = 1-3.4 m/s	Wicks-Dukler Air-Water Cousins-Hewitt Incl. date W-D C1966 C-H L1968 $d_m\ \alpha\ D^{3/4}$
Tatterson et al (1977)	D = 1" x 12" Horiz	$d\ \alpha\ D^{1/2}$
Horiz-Rectangular 1in. x 12 in.		
Plus Wicks-Dukler (1966)	3/4" x 6" Vert Down	
Pogson et al (1970)	3.4 cm Vert Up	
Cousins-Hewitt(1968)	3/8" & 1 1/4" Vert Up	
Air-Water Steam-Water (Pogson)	u_g = 7-253 f/s 2- 77 m/s d = 6-2000 µm	

TABLE IIIC

SUMMARY OF EXPERIMENTAL DROPLET SIZE DATA

WHICH SHOWS INFLUENCE OF:

FLUID PROPERTIES, (σ,μ) Droplet, ρ_g (Continuum)

AUTHOR SYSTEM FLUIDS	DATA RANGE	REMARKS
Collins & Knudsen (1970) Downward Vert 0.745" diameter Liquid-Liquid Water-Shell Solv. -Light Oil -Iso Alcohol	dyne/cm cp Lbm/f^3 σ μ ρ Shell Solv 40 1 48 Light Oil 17.6 15 53 Iso Alcohol 13 8.5 53 Water 72 Measured at Sta. Downstream of injection L/D = 27.3-576	Station Downstream (L/D) 27.3 576 d_{32} = 420 250 = 400 210 = 110 80 Expression for $d_{(\ )}$ complex. Cannot easily separate property effect. Initial droplet size may indicate effect of σ (certainly not linear). Breakup pattern over length may indicate a strong time (rate) factor for some property combinations.
Cumo et al (1974) Vert. Rectangular 5 mm x 3 mm Freon	d_{prob} = 12-26 μm	$d_{prob} = f\left(\rho_\ell/\rho_g\right)$
Ingebo & Foster Orifices Air - Iso Octane - JP 5 - Benzine - Carbon Tetrachloride - Water		$D\ \alpha \left(\frac{We}{Re}\right)^{1/4}$

Page 2
TABLE IIIC (con't)

Nukiyama & Tanaswama (1939) Sharp Edged Orifices Air - Water - Alcohol-Water - Glycerene-Water		For high quality $d_{32} \alpha \left(\frac{\sigma}{\rho_\ell}\right)^{1/2}$
Wang & Tien (1972) Nozzle N_2 - Carbopol - Water-Glycerere		$\bar{d} \alpha \mu^{0.24} \rho^{-0.12} \sigma^{0.312}$

TABLE III D

SUMMARY OF EXPERIMENTAL DROPLET DATA

WHICH SHOWS INFLUENCE OF:

QUALITY OR FILM THICKNESS

AUTHOR SYSTEMS FLUIDS	DATA RANGE	REMARKS
Azzopardi et al (1978) Upward flow - 32 mm diameter Air - Water	u_g = 35-66 m/s x = 0.25-0.9 d_{32} = 17-162μm	For behavior with quality: 1) Predictions of James(1976) & Hinze (1949) for d_{32} shows moderate increase with decreased quality. 2) Correlations of Boll et al (1974) and Nukiyama & Tanasawa (1938) show no change in d_{32} with quality. 3) Experimental data of authors show a minimum for d_{32} at 25-30% quality. 4) Measured size below all predictions.
Boll et al (1974) Venturi Air - Water	$\frac{L}{G} = \frac{\text{5-100 gal}}{1000\ f^3}$ u_g = 100-300 f/s = 30-90 m/s d_{32} = 50-400 μm	2 Term Expression $d_{32} \overset{\alpha}{\simeq} \left(\dot{m}_\ell / \dot{m}_g\right)^{1.9}$
Nukiyama & Tanaswa (1939) Orifce Air - Water - Alcohol Water - Glycerene Water		For Q_A/Q_L Small $d_{32} \alpha \frac{\dot{m}_\ell}{\dot{m}_g}$

Page 2
TABLE III D (con't)

Tatterson et al (1977) ——— Horiz-Rectangular 1" high, 12" wide ——— Air - Water	$x = 0.1-0.9$ u_g = 7-15 f/s = 2-4.6 m/s $d_{50\%}$ = 460-720 μm	$\frac{d_{50\%}}{\bar{h}} = f\left(\frac{\sigma}{\rho g \; u_g^2 \; \bar{h}}\right)^{1/2}$ $\bar{h}$ is a function of quality

Nomenclature

d	drop diameter
D	conduit diameter (or equivalent diameter)
f_s	smooth surface friction factor
$\overline{h}$	mean liquid film thickness
m	mass rate of flow
n	specific number of droplet population
N	total number of droplets
q	heat transfer rate
R_e	Reynolds number, $\frac{ud\rho}{\mu}$
u	fluid velocity
W_e	Weber number, $\frac{\rho_g u_g^2 d}{\sigma}$
x	quality
μ	viscosity
σ	surface tension
ρ	density

Subscripts

cont	continuum fluid
g	gas
ℓ	liquid

For special subscripts of (d) see the section on Effective Droplet Diameter.

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Summary tables of reported work on droplet size and distribution in dispersed two phase flow are presented. Results for tests with constant flow across sections, flow from nozzles, orifices and sprays and flow in liquid - liquid systems is reported. A summary table of predictive expressions for droplet size and distribution is given, and the apparent influence of gas velocity, geometry and fluid properties is reported.

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