CORRELATING DROP SIZES IN ANNULAR GAS / LIQUID FLOWS IN VERTICAL AND HORIZONTAL PIPES

Ayse Sarimeseli[1], Barry Azzopardi[2]

1 Inonu University, Department of Chemical Engineering, Malatya 44280, TURKEY.
2 School of Chemical Environmental and Mining Engineering, University of Nottingham, Nottingham NG7 2RD, UK.

ABSTRACT

Annular gas/liquid flow in pipes is an unusual area of atomisation and sprays. It is characterisedby a film on the channel walls on which there are large structures called disturbance waves from which the drops are atomised. The drops are carried by the gas and eventually redeposit onto the film. The fraction of liquid carried as drops is important foor processes such as heat transfer, erosion, corroision etc. This paper collects together available data on drop sizes and used the data base created to test the predictive capability of published equations as well as newly developed ones. The equations giving the best predictions are identified together with conditions for which equations do less well.

INTRODUCTION

Because of the flexible nature of the gas/liquid interface, there is an infinity of ways in which the phases can arrange themselves in pipes. However, it is possible to classify most of cases into a small number of configurations termed flow patterns. Annular flow is the term used to describe the most important of these flow patterns which can occur for all orientations of pipes from vertically upwards flow, through horizontal flow to vertical downflow. It occurs at higher gas volume fractions and is characterised by part of the liquid flowing as a film on the channel walls whilst the rest is carried as drops by the gas in the centre of the pipe. Moreover, there is constant interchange between the film and the drops with there being atomisation of part of the liquid film (a process usually called enterainment) and redeposition of drops onto the liquid film. The flow pattern is also known as annular-mist or mist flow. Annular flow is of considerable industrial importance as it occurs in a wide variety of industrial equipment such as reboilers, condensers, fired heater, oil/gas wells and pipelines and conventional and nuclear boilers. Knowledge of this flow pattern is required to calculate the pressure drop as it flows through pipes, to determine the conditions of dryout and hence critical heat flux and the consequent deterioration of heat transfer. Parameters of importance are entrained fraction, rates of entrainment and deposition and drop size.

Publications on drops, size, creation (as in entrainment) and disappearance (deposition) have been reviewed by Azzopardi [1] whilst maximum drop size has been the subject of another review by Azzopardi and Hewitt [2]. These reviews show that though there have been a number of papers on drop size, there is still a great deal to be learned in the area. This paper considers available data and correlations to describe the mean drop sizes. Both existing correlations and new, hitherto unpublished ones sre examined.

DATA USED IN DEVELOPING AND TESTING CORRELATIONS

In this section the data that is used in the development and testing of correlations are considered. They are grouped according to the orientation of the pipe. There is most data for vertical up flow, slightly less for horizontal flow and only one set for downflow. A thorough review up to 1997 is given by Azzopardi [1]. From the assessment made in that paper, certain data sets have been ignored. These were promarily earier data obtained using photography but which had not measured enough drops to mave the results meaningful.

Vertical up flow

A summary of the sources and parameter ranges for the available data for vertical upflow, horizontal flow and vertical downflow are listed in Table 1. Two of the papers [3, 4] report data taken using photography but with large enough samples to be staticxtically significant. Okada et al. captured the drop on oil-covered slides. The rest used laser diffraction as their basis of measurement. Amongst these two used the latest equipment (Malvern Spraytec) which has in built correction for the effects of multiple diffraction. Earlier instruments had been shown to be accurate by Azzopardi [5. 6] whilst the effectiveness of the Spraytec was reported by Starkey [7] and Treballier *et al.* [8].

Table 1: Sources of data for drop size in annular flow

	Source	Pipe Diameter (m)	Press (bar)	Superficial Velocity (m/s)	
				Gas	Liquid
VD	Andreussi *et al.* [3]	0.024	1	26 - 65	0.036 - 0.29
VU	Azzopardi *et al.* [9]	0.032	1.5	23 - 42	0.016 - 0.16
VU	Azzopardi *et al.* [10]	0.125	1	30 - 43	0.008 - 0.026
VU	Jepson *et al.* [11]	0.01	1.5	22 - 67	0.04 - 0.1
VU	Jepson *et al.* [11](Helium)	0.01	1.5	44 - 76	0.04 - 0.15
VU	Jepson *et al.* [12](CF_4)	0.01	1.5	8 - 24	0.03 - 0.122
VU	Azzopardi *et al.* [13]	0.02	1.5	30 - 59	0.041 - 0.124
VU	Jepson [14]	0.01	1.5	28 - 42	0.04 - 0.14
VU	Hay *et al.* [4]	0.042	~1	36	0.022 - 0.123
H	Ribeiro *et al* [15]	0.032	~1.35	25 - 42	0.03 - 0.11
H	Azzopardi *et al.* [16]	0.065	1	19-25	0.11-0.16
H	Simmons & Hanratty [17]	0.095	~1	30-50	0.016-0.09
H	Al-Sakhri & Hanratty [18]	0.025	~1	30-50	0.04-0.125
VU/H	Zaidi *et al.* [19]	0.038	1.5	15-30	0.02-0.16

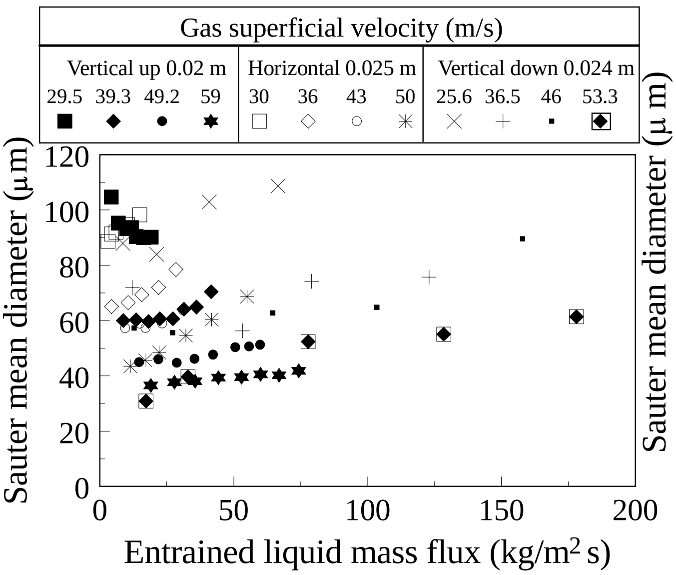


Fig. 1 Effect of gas and liquid flow rates and orientation on Sauter mean diameter

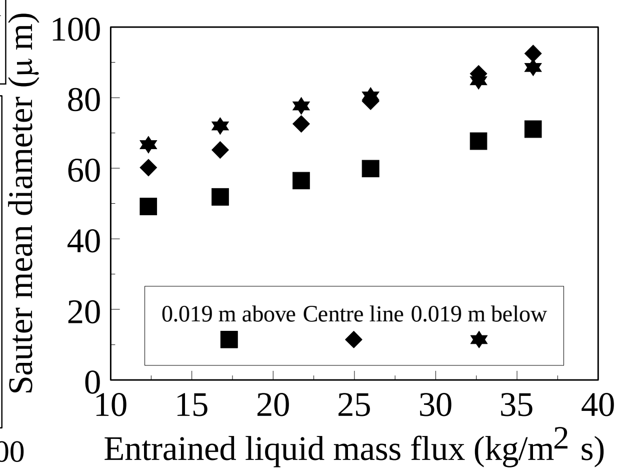
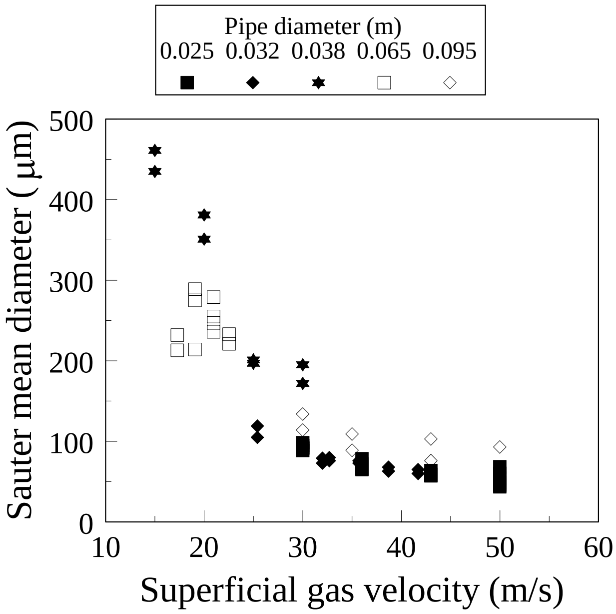


Fig. 2 Varition of Sauter mean diameter with vertical postion in horizontal flow.

Example results are shown in Fig. 1. This presents data for vertical upflow, horizontal flow and vertical downflow for pipes of approximately the same diameter. The physical properties are essentially the same for all three data sets. The strong effect of gas velociy is evident. In addition, there can be seen to be a dependence on liquid flow rate.

Earlier studies have argued that this should be a dependence on entrainmeted liquid flow rate rather than total liquid flow rate. This proposal bas based on numerous experiments and arises from the idea and increased concentration, probably through coalescence processes provides the variation in drop size. It is also noted that the horizontal data show steeper gradients. This set was taken with the latest Spraytec equipment with its more thorough treatment of multiple diffraction. The vertical upflow data was only taken when the incident boeam oscuration was <0.5, conditions which were considered to minimise multiple diffraction. The difference highlighted here indicate this might not be enough.



For the horizontal flow cases, another feature is the vertical position at which measurements were made. Fig. 2, data of Simmons and Hanratty [17], shows a distinct effect which was also observed by Azzopardi et al. [16]. In the experiements of Al-Sahkri and Hanratty [18], the measurment volume occupied the greater part of the pipe diameter. Ribeiro *et al.* [15]shone the laser beam from top to bottom insead of laterally.

In the horizontal case there is an indication that there might be a different dependence on gas velocity above and below 30 m/s, see Fig. 3. It is not yet clear why this is.

CORRELATIONS

From the analysis of the experimental data carried out by various investigators, a number of drop size correlations have been proposed. Azzopardi et al. [9] proposed the following equation, which was derived from turbulence break-up and coalescence analysis:

$$\frac{D_{32}}{D_t} = 1.91\frac{\mathrm{Re}_G^{0.1}}{We^{0.6}}\left(\frac{\rho_G}{\rho_L}\right)^{0.6} + 0.4\frac{m_{LE}}{\rho_L U_{SG}} \qquad (1)$$

Azzopardi [19] proposed a correlation as a modification of the equation presented by Azzopardi et al. (1980) as

$$\frac{D_{32}}{\lambda_T} = \frac{15.4}{We_{\lambda T}^{0.58}} + \frac{3.5 m_{LE}}{\rho_L U_{SG}} \qquad (2)$$

The author calculated $We_{\lambda T}$ and λ_T as

$$We_{\lambda T} = \frac{\rho_L U_{SG}^2 \lambda_T}{\sigma}$$

Ambrosini *et al.* [21] derived a correlation as

$$\frac{D_{32}}{\delta} = 22\left(\frac{\sigma}{\rho_G\ f_i\ U_{SG}^2\ \delta}\right)^{0.5}\left(\frac{\rho_G}{\rho_L}\right)^{0.83}\exp\left(0.6\ \frac{\dot{m}_{LE}}{\rho_L\ U_{SG}}\ \frac{D_t}{D_{32}} + \frac{99}{We}\right) \qquad (3)$$

where δ is the mean film thickness, f_i is the interfacial friction factor

Al-Sarkhi and Hanratty [18] have used their own data form a 0.025 m diameter pipe as well as that of Simmons and Hanratty [17] [0.095 m diameter pipe] to develop an equations similar to (4) and (5). They argued that the two sets of results indicated that the drop size showed a dependence on the pipe diameter to the power of 0.5. Their equation is:

$$\left(\frac{D_{32}U_{SG}^{2}\rho_G}{\sigma}\right)^{0.55}\left(\frac{D_{32}}{D_t}\right)^{0.55} = 29.5\frac{m_{LE}}{\rho_L U_{SG}} + 0.112 \tag{4}$$

A similar equation with lightly different constants was used to correlate the mass median diameter. Al-Sarkhi and Hanratty comment that though such an equation gave a good fit to data, it was not very useful to industrial designers, as the entrained liquid flow rate was not always known. Consequently, they developed a second, simpler equation which was independent of any type of liquid flow rate. For the Sauter mean diameter this is:

$$\left(\frac{D_{32}U_{SG}^{2}\rho_G}{\sigma}\right)^{0.55}\left(\frac{D_{32}}{D_t}\right)^{0.36} = 0.154 \tag{5}$$

Again different constants are inserted when the mass median diameter is being correlated.

As part of the present exercise, new correlations have been developed. Again they show a relatively complex dependence on gas and liquid flow rates. Therefore we suggest the following empirical equations for vertical flow:

$$D_{32} = \left[0.069U_{SG} + 0.0187\left(\frac{\rho_L U_{LS}}{\rho_G U_{SG}}\right)^{2}\right]\frac{\sigma}{\rho_G U_{SG}^{2}}\times 10^{6} \tag{6}$$

and for horizontal flow:

$$D_{32} = \left[0.37U_{SG}^{0.5} + 0.602\left(\frac{U_{LS}}{\rho_G U_{SG}}\right)^{0.5}\right]\frac{\sigma}{\rho_G U_{SG}^{2}}\times 10^{6} \tag{7}$$

RESULTS AND DISCUSSION

The predictions of the equations laid out in the previous section are compared with the experimental data from the sources listed in Table 1. Root mean square errors are given in Table 2. The comparison between calculated and measured Sauter mean diameters are given in fig. 4 for vertical upflow and fig. 5 for horizontal flow.

Table 2 Root mean square errors

Criterion	Azzopardi *et al.* [9]	Azzopardi [20]	Ambrosini *et al.* [21]	Al-Sarkhi and Hanratty [18]	Al-Sarkhi and Hanratty [18] **No entrainment**	Present work
Graphs	(a)	(b)	(c)	(d)	(e)	(f)
All vertical	31.8	34.6	27.4	47.0	60.0	(28.5)
All Horizontal	30.6	26.6		28.0	27.8	24.0
U_{gs}>30 m/s	28.2	20.6		20.3	22.2	19.0

Examination of Table 2 shows that the equation of Ambrosini *et al.* [21], equation (3), gives the best prediction for vertical up flow. This is not surprising as the constants of the equation were optimised on much of the data in the present data base. The simple equation developed in the present work is almost as good. However, it is noted that it does very badly for the helium/water data. The figure quoted in table 2 does not include that subset of data. That is why it is presented in parenthisis. It is noted that equations (4) and (5) [18] were developed on a horizontal data set with a single fluid pair (air/water) though for two widely different pipe diameters. It is probably unfair to compare them to the vertical data. Fig. 4 shows that most methods find it difficult to handle the data from te largest diameter pipe.

Given that equations (4) and (5) were developed on two of the larger horizontal data sets, it is not surprizing that they do so well. It is interesting that tother equations can do as well or better, particularly when data with gas superficial velocities below 30 m/s are omitted. Given the distinctly different slope visible in Fig. 3, it is not surprising that equations do better on the restricted data set.

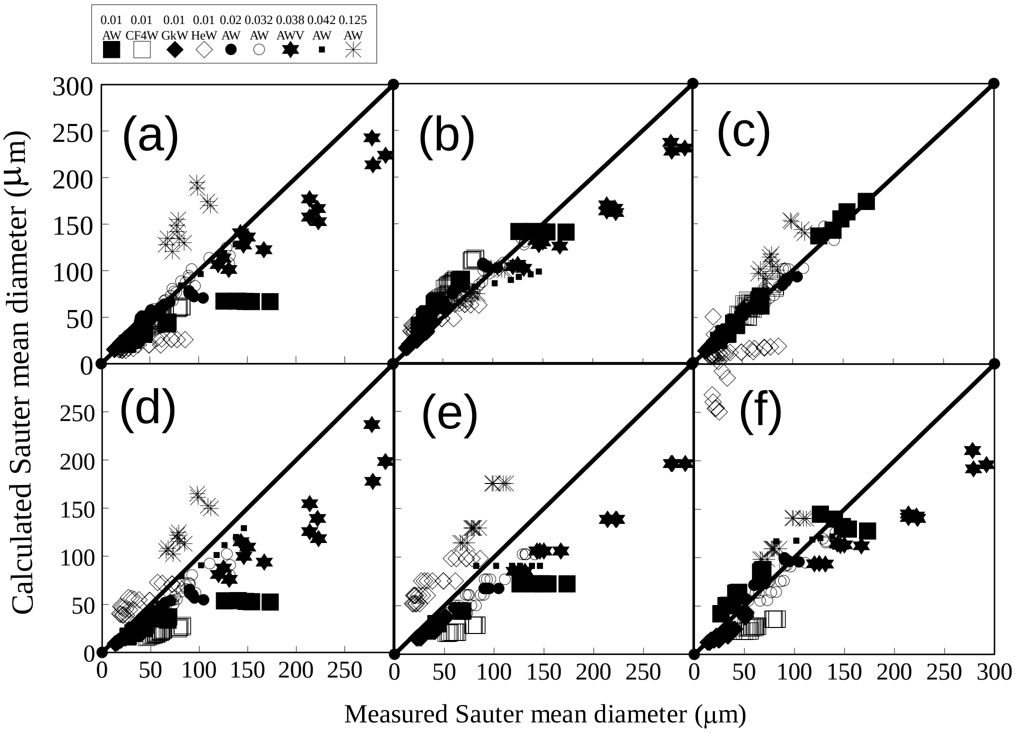


Fig. 4 **C**omparison between calculated and measured sauter mean diameters for vertical up flow flow. (a) Azzopardi *et al.* [9]; (b) Azzopardi [20]; (c) Ambrosini *et al.* [21]; (d) Al-Sarkhi and Hanratty [18]; (e) Al-Sarkhi and Hanratty [18] – no entrainment; (f) present work.

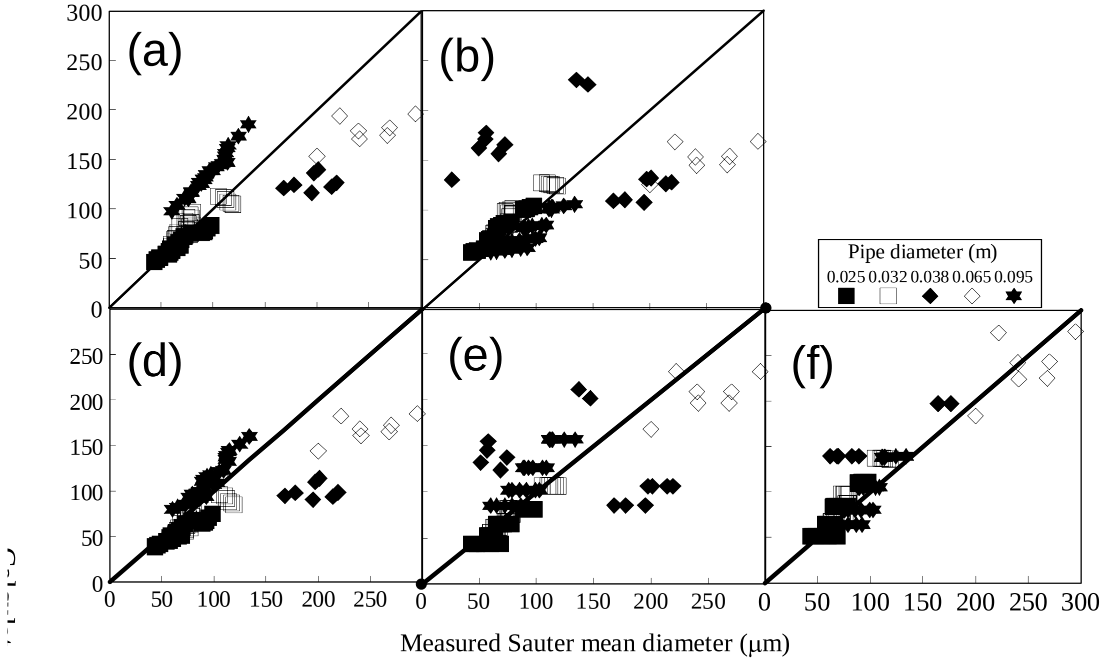


Fig. 5 **C**omparison between calculated and measured sauter mean diameters for horizontal flow. (a) Azzopardi *et al.* [9]; (b) Azzopardi [20]; (d) Al-Sarkhi and Hanratty [18]; (e) Al-Sarkhi and Hanratty [18] – no entrainment; (f) present work.

CONCLUSIONS

From the above it can be concluded that:

- The equation proposed by Ambrosini *et al.* [21] gives best predictions for verticcal upflow.
- The empirical equation proposed in the present work, equation (7), gives best results for horizontal flows.
- There is a need for data from larger pipe diameters.

- There is a need for non-air/water data in horizontal flow.

NOMENCLATURE

D_{32}	Sauter mean diameter (m)	D_t	Pipe diameter (m)
f_i	Interfacial friction factor (-)	m_{LE}	Entrained liquid mass flux (kg/m^{2}s)
U_{GS}	Gas superficial velocity (m/s)	U_{LS}	Liquid superficial velocity (m/s)
Re	Reynolds number	We	Weber number
$We_{\lambda T}$	Weber number based on Talyor length scale (m)	λ_T	Taylor length scale (m)
ρ_G	Gas density (kg/m^3)	ρ_L	Liquid density (kg/m^3)
σ	Surface tension (N/m)		

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