JUL 16 1990

DOE/PC/88912--T6

DE91 004212

QUARTERLY REPORT

ROLES OF ADDITIVES AND SURFACE CONTROL IN SLURRY ATOMIZATION

by

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July 10, 1990

Work performed under Grant No. DOE-FG-22- 88PC88912

for

U.S. Department of Energy
Office of Fossil Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania 15236

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AIRBLAST ATOMIZATION OF MICRONIZED COAL WATER SLURRIES
USING TWIN-FLUID JET ATOMIZER

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ABSTRACT

Airblast atomization of micronized coal water slurry is carried out using twin-fluid jet atomizers of various distributor designs. Drop size and size distribution are measured using the laser diffraction technique. We found that the atomized drop sizes of micronized coal water slurries substantially decrease as the atomizing air pressure exceeds a threshold value. We also found that the atomized drop size, represented by the mass median diameter (MMD) can be described by the wave mechanism-based models in terms of three non-dimensional groups, namely, slurry-to-air mass ratio ($\dot{M}_S/\dot{M}_A$), the Weber number (We), and the Ohnesorge number (Z):

$$MMD/D = (1 + \dot{M}_S/\dot{M}_A) \{ x_2 \cdot We^{-x_1} + x_3 \cdot Z^j \cdot x_1 \}$$

where $j = 1$ and 2 , and Z is based on the high shear slurry viscosity. The exponents and coefficients (x_i , $i = 1$ to 3) are determined by the best least square fit of the equation to the experimental results using the iterative generalized inverse method. Coefficients of correlation of 0.97 to 0.98 have been obtained. Presence of coal particles causes a looser drop size distribution curve as compared to pure viscous liquids. Nevertheless, the effects of coal volume fraction on slurry atomization can be fully accounted for by its effects on slurry rheology. Likewise, the composition and the viscosity of the

suspending liquid affect drop size through their effects on slurry rheology. The effects of distributor design on airblast atomization are caused by its effects on the Weber number and the air mass flow rate.

INTRODUCTION

Micronized coal water slurry has the potential to replace oil in utility and industrial boilers with little burner retrofitting because the residual ash in the deeply cleaned micronized coal can be transported out of boilers in the gas stream. Twin-fluid atomizers, when used in slurry combustion^{1,2}, have a number of advantages over pressure atomizers including lower slurry pressure, finer spray, and thus, higher combustion efficiency. The twin-fluid jet atomizer used in this study is designed to minimize erosion of the nozzle tip. Specifically, the slurry passes axially through the center of the distributor. The atomizing air passes through the 15°-angled slits drilled in the 45° taper of the distributor and, thus, swirls around the slurry jet. The nozzle has a single discharge port of diameter larger than the diameter of the distributor for slurry passage.

This paper examines the effects of slurry rheology on slurry atomization and determines whether or not the wave mechanism-based models established for airblast atomization of viscous liquids^{3,4} can be used for micronized coal water slurries. It also compares the drop size distributions of micronized coal water slurries and viscous Newtonian liquids such as glycerol and its aqueous solutions.

EXPERIMENTAL SETUP

Atomization of micronized coal water slurries is carried out using one nozzle tip of 0.249 cm in diameter and three distributors whose dimensions are given in Table 1. The nozzle tip is positioned 0.254 cm downstream from the distributor tip. Distributors #1 and #2 have no internal chambers. Distributor #3, used in slurry combustion^{5,6}, has an enlarged internal chamber 0.40 cm in diameter and 0.16 cm in length where air and slurry meet prior to discharging to atmosphere. Distributor #1 is used in the atomization of slurries a), d), and e); distributor #2 in slurries c) and d); and distributor #3 in slurries b) and e). While detailed descriptions of the experimental setup, drop size measurement, and data analysis are given elsewhere^{3,4}, the slurry composition and rheology are given in Table 2, and a brief description follows.

SLURRY CHARACTERIZATION

As given in Table 2, the coal water slurries are composed of 0.40-0.47 volume fraction of micronized Upper Freeport coal (3-5 μm with both volume mean and mass median diameters of 4.4 μm) and Illinois #6 coal (3-25 μm with 60% within 3 μm to 4 μm , volume mean diameter of 7.8 μm and mass median diameter of 3.7 μm) in aqueous solutions of 20-40% glycerol or 42% ethylene glycol. The Upper Freeport coal is high volatile bituminous A, and has been cleaned by microbubble flotation to an ash content of 5.4% on dry basis. Other coal analyses are: 82.8% carbon, 5.1% hydrogen, 0.7% nitrogen, 1.2% sulfur, and 4.8% oxygen. The Illinois #6 coal is high volatile bituminous C, and has also been

cleaned by microbubble flotation. Its analyses are: 75.2% carbon, 5.2% hydrogen, 2.5% sulfur, 1.4% nitrogen, 4.2% ash and 11.5% oxygen on dry basis.

These coal water slurries are pseudoplastic because the interparticular van der Waals attraction predominates over the interparticular electrostatic repulsion⁷. As shown in Table 2, slurry e) is the least pseudoplastic with a flow behavior index of 0.82. Slurries a) through d) have flow behavior indices ranging from 0.50 to 0.58. As shown in Fig. 1, slurries c) and d) are considerably less viscous than slurries a) and b) throughout the entire shear rate range from 20 to 7000 s^{-1} . Slurry e) is less viscous than slurries c) and d) at shear rates less than 200 s^{-1} , but more viscous than slurries a) and b) at shear rates above 2000 s^{-1} . Within the shear rate range of 400 s^{-1} to 2000 s^{-1} , slurry e) is more viscous than slurries c) and d), but less viscous than slurries a) and b). While slurries a) and b) have similar viscosities (40-12 P) at shear rates between 50 and 1000 s^{-1} , their viscosities at high shear rates ($>2000 \text{ s}^{-1}$) are significantly different ($<9 \text{ P}$ and $<8 \text{ P}$ for slurry a) and slurry b), respectively). In contrast, the viscosities of slurries c) and d) at shear rates above 400 s^{-1} are similar.

RESULTS AND DISCUSSIONS

Both regression analysis of drop mass median diameters (MMDs) and examination of drop size distributions indicate that the effects of atomizer design and slurry rheology, including the effects of coal fraction and liquid viscosity, on slurry atomization can be accounted for in terms of three nondimensional

groups, namely, the slurry-to-air mass ratio ($\dot{M}_S/\dot{M}_A$), the Weber number (We), and the Ohnesorge number (Z). The wave mechanism-based models³ established for airblast atomization of viscous Newtonian liquids are found to fit the slurry atomization data excellently, with coefficients of correlation of 0.97 - 0.98. As in glycerol atomization³, a threshold atomizing air pressure exists in the airblast atomization of micronized coal water slurries. Atomization is significantly better when the inlet atomizing air pressures exceed this threshold value which varies with the slurry-to-air mass ratio (see Table 3 and Fig. 2). The coefficient of correlation deteriorates to 0.87 if all of the experimental data are grouped together with no consideration of this threshold pressure. Detailed discussion of these models and effects now follows.

Wave Mechanism-based Models

The following wave mechanism-based semi-empirical models³ which have been established for airblast atomization of viscous Newtonian liquids are also used in this study:

$$MMD/L_C = (1 + \dot{M}_S/\dot{M}_A) \{x_2 \cdot We^{-x_1} + x_3 \cdot Z^{x_1}\} \quad (1a)$$

$$MMD/L_C = (1 + \dot{M}_S/\dot{M}_A) \{x_2 \cdot We^{-x_1} + x_3 \cdot Z^2 \cdot x_1\} \quad (1b)$$

$$MMD/L_C = (1 + \dot{M}_S/\dot{M}_A) \{x_2 (Z/We)^{x_1} + x_3\} \quad (1c)$$

$$MMD/L_C = (1 + \dot{M}_S/\dot{M}_A) \{x_2 (Z^2/We)^{x_1} + x_3\} \quad (1d)$$

where the linear scale factor L_C is equal to 0.152 cm, one of the distributor diameters, the Weber number (We) equals $\rho_A V_A^2 D / \sigma_L$, representing the ratio of aerodynamic force to surface tension, and the Ohnesorge number (Z) equals $\eta_S / (\rho_S \sigma_L D)^{1/2}$. D in We and Z denotes the diameter of the distributor for slurry flow during

atomization. Therefore, the Weber number for the same aerodynamic pressure and surface tension is greater in distributor #3 than in distributor #1 because of its larger diameter for slurry flow. The reverse is true for the Ohnesorge number.

$(1+\dot{M}_S/\dot{M}_A)$, with unit exponent, is included in these equations based on the assumption that the air, after transferring part of its kinetic energy to the slurry, and the resulting atomized drops travel at the same velocity V , and the momentum balance⁸:

$$\dot{M}_S V_S + \dot{M}_A V_A = (\dot{M}_S + \dot{M}_A) V \quad (2)$$

We further assume that the total surface energy of the atomized drops is proportional to the loss of kinetic energy:

$$\sum N_i D_i^2 \sigma_S \propto \dot{M}_S V_S^2 + \dot{M}_A V_A^2 - (\dot{M}_S + \dot{M}_A) V^2 \quad (3)$$

where N_i is the number of drops with a diameter D_i produced per unit time, and σ_S is the drop surface energy per unit area.

Substituting Eq. (2) and $\dot{M}_S = \rho_S \sum N_i D_i^3 / 8$ into Eq.(3) yields

$$SMD \propto (1+\dot{M}_S/\dot{M}_A)$$

where the Sauter mean diameter (SMD) equals $\sum N_i D_i^3 / \sum N_i D_i^2$.

Therefore, $(1+\dot{M}_S/\dot{M}_A)$ is used in these models. In fact, regression analysis using the exponent of $(1+\dot{M}_S/\dot{M}_A)$ as an additional parameter does not improve the coefficient of correlation and yields a solution close to unity. It should be noted that $(1+\dot{M}_L/\dot{M}_A)$ was used in the basic equation for prefilming atomizers⁹ although exponents ranging from 0.4 to 2 were reported for other atomizers¹⁰ in airblast atomization of low viscosity liquids.

Since the flow field in airblast atomization is unknown, the effects of slurry rheology on atomization of pseudoplastic coal water slurry is first examined in order to determine which viscosity should be used in the calculation of the Ohnesorge number. Table 3 shows that although the drop MMDs of slurries e) and a) obtained at atomizing air inlet pressures above the threshold value are similar, the MMDs of slurry e) atomized at inlet air pressures below the threshold value are significantly larger than those of slurry a) atomized under comparable conditions. It should be noted that the viscosity of slurry e) at shear rates above 2000 s^{-1} is greater than that of slurry a), but smaller at shear rates below 2000 s^{-1} . Likewise, Table 3 also shows that slurry e) is much more difficult to atomize (similar drop MMDs are obtained at lower slurry-to-mass ratio and larger Weber number) than slurry d) because slurry e) is much more viscous than slurry d) at shear rates above 1000 s^{-1} even though they have similar viscosities at shear rates between $100\text{--}300 \text{ s}^{-1}$ (see Fig. 1). Therefore, the high shear slurry viscosity based on the free stream slurry velocity at atomization conditions, equivalent to shear rates above 2000 s^{-1} , is chosen in the calculation of Z . The effects of slurry rheology will be discussed further later.

Iterative computation using the generalized inverse method¹¹ is carried out to determine the exponents and the coefficients of Eqs. (1) and (2) by the best least squares fit of these equations to 35 experimental data points. Wide ranges of the aforementioned dimensionless groups are covered:

$1+\dot{M}_S/\dot{M}_A$	We	Z
1.65-6.70	64-1065	0.80-2.72

Eqs. (1c) and (1d) consistently give poorer coefficients of correlation (as low as 0.92 for atomization at inlet air pressure above the threshold value) than Eqs. (1a) and (1b). Therefore, only Eqs. (1a) and (1b) with the best least squares solutions obtained from the iterative generalized inverse method are listed in Table 4. Fig. 3 demonstrates the excellent agreement (coefficients of correlation of 0.97 and 0.98) between the experimental data and the 3-parameter models (Eqs. (1a) and (1b)) with the listed best least squares solutions. Note that the coefficient of correlation in Table 4 is reduced by at least 1% when any one of these parameters exceeds the given range.

Effect of Distributor Design

As shown in Fig. 4, the atomization air mass flow rate using distributor #1 varies with the inlet pressure similarly for slurries a) and e). These atomizing air mass flow rates at constant inlet pressures are higher than those for atomization of slurry d), but substantially lower than those for atomization of glycerol using the same distributor and nozzle.

The mass flow rate of the atomizing air varies with the distributor design. Distributor #1 gives rise to the highest air mass flow rate at a constant inlet air pressure as a result of its largest cross section for air flow and much smaller diameter for slurry flow relative to the discharge port (0.152 cm vs 0.249 cm). Distributor #3 gives rise to the smallest air mass flow rate because its diameter for slurry flow is only slightly smaller than that of the discharge port (0.244 cm vs 0.249 cm).

At the same inlet air pressure, distributor #2 gives rise to a smaller air mass flow rate than distributor #1 due to its smaller cross section. However, it gives rise to a much higher velocity and, thus, a much higher Weber number as shown in Table 3.

Nevertheless, the effects of distributor design on slurry atomization can be fully accounted for in terms of the aforementioned nondimensional groups. Regression analysis shows that drop MMD varies with the slurry-to-air mass ratio ($\dot{M}_S/\dot{M}_A$), the Weber number (We), and the Ohnesorge number (Z) in similar manners for all distributors. Furthermore, the atomized drop size distributions with similar MMDs are independent of distributor design. For example, as shown in Fig. 5, the drop size distribution of atomized slurry d) with $340\mu\text{m}$ MMD from distributor #1 is similar to that with $338\mu\text{m}$ MMD from distributor #2, and the drop size distribution with $51\mu\text{m}$ MMD from distributor #2 lies between those with $74\mu\text{m}$ MMD and $45\mu\text{m}$ MMD from distributor #1 (see Table 3 for the atomization conditions). Likewise, the drop size distribution of atomized slurry e) with $141\mu\text{m}$ MMD from distributor #3 lies between those with $246\mu\text{m}$ MMD and $118\mu\text{m}$ MMD from distributor #1.

Effects of Coal Volume Fraction and Liquid Viscosity

As shown in Table 2 and Fig. 1, although the flow behavior index increases only slightly, the slurry viscosity decreases considerably as the coal volume fraction decreases from 0.47 in slurry a) to 0.43 in slurry c). From Table 3, we see that the drop MMD obtained from atomization of slurry c) is significantly smaller than that from slurry a). This result can be attributed

to a higher We due to the use of distributor #2 and a lower Z due to a much lower viscosity of slurry c). A slightly more pronounced bimodal drop size distribution is seen in Fig. 5 for atomized slurry c) with respect to slurry a).

A comparison between Figs. 5 and 6 shows that the drop size distributions of atomized slurry d) (42% ethylene glycol suspension at 0.43 coal volume fraction) are very similar to those of slurry a) (40% glycerol suspension at 0.47 coal volume fraction). Because of its much lower viscosity, slurry d) can be atomized to similar MMDs at less severe atomization conditions than slurry a). Therefore, we conclude that the slurry rheology, rather than the liquid composition or the liquid viscosity, dictates the drop size and size distribution in airblast atomization of micronized coal water slurries.

Effects of Slurry Rheology

As mentioned earlier, the effects of slurry rheology on slurry atomization drop sizes can be described in terms of the Ohnesorge number based on the high shear slurry viscosity. This is further illustrated in Fig. 2 in which the dotted lines (slope of unity) represent the MMD's corrected for the effect of $(1 + \dot{M}_S / \dot{M}_A)$. When atomized at inlet air pressures below the threshold value, slurry e) gives rise to much larger MMDs than slurries a) and d) because of its much larger high shear viscosity (7-8 P for slurry e), 4 P for slurry a), and 2-3 P for slurry d)). Slurry d) gives rise to drop MMDs comparable to those from slurry a) but at smaller Weber numbers because of its lower viscosity.

Likewise, when atomized at inlet air pressures above the

threshold value slurry d) gives rise to drop MMDs comparable to those from slurries a) and e) but at much smaller Weber numbers. Slurries c) and d) give rise to similar drop sizes at comparable atomization conditions because their high shear viscosities are similar. Note that the high shear viscosities at these atomization conditions for slurries e), a), c), and d) are 7-8 P, 6-7 P, 2-3 P and 2-3 P, respectively.

Comparison with Viscous Newtonian Liquid Atomization

The drop MMDs of atomized glycerol (9.8 P, open circles and open triangles), and its aqueous solution containing 92% glycerol (3.8 P, open inverse triangles) are also given in Fig. 2 for comparison. Open circles and open triangles in this figure designate glycerol atomized at Weber numbers ranging from 265 to 280, and from 415 to 460, respectively. The numbers next to the clusters of solid points in this figure are the Weber numbers for atomization of coal water slurries. From Fig. 2 we see that it is more difficult to atomize pseudoplastic slurry e) with high shear viscosities of 7 to 8 P than to atomize glycerol, which is Newtonian with a viscosity of 9.8 P. The atomization behavior of pseudoplastic slurry a) with high shear viscosities of 4 to 7 P is similar to that of glycerol (9.8 P). Pseudoplastic slurry d), which has high shear viscosities of 2 to 3 P, atomizes more readily than glycerol, but less readily than aqueous glycerol with a viscosity of 3.8 P. Thus, although the high shear viscosity dictates the atomized drop sizes, the slurry pseudoplasticity plays a significant role in slurry atomization.

A comparison between the drop size distributions of the

atomized slurries (Fig. 5 for slurries d) and e) and Fig. 6 for slurry a)) and the atomized glycerol and its aqueous solution (Fig. 7) reveals that drop sizes with peak intensity at $350\text{ }\mu\text{m}$ appear in the slurry atomization as well as in the atomization of glycerol and its aqueous solution. Neither the chemical composition of the liquid mixture (glycerol vs ethylene glycol) nor the presence of coal particles has any significant effect on these primary drop sizes. In contrast, considerable differences between the atomized slurries and the atomized glycerol are seen with respect to distributions of smaller sizes. A very high percentage of drop sizes smaller than $30\text{ }\mu\text{m}$ is produced when either glycerol or aqueous glycerol is atomized at inlet air pressures above the threshold value. The percentage of $<30\text{ }\mu\text{m}$ drops is negligible in slurry atomization at all atomizing air pressures. Both slurries and aqueous glycerol solutions yield high percentages of $45\text{--}50\text{ }\mu\text{m}$ drops. In fact, except for the $<30\text{ }\mu\text{m}$ sizes, the slurry drop size distributions are quite similar to those of the aqueous solution containing 92% glycerol. The looser structure of the slurry drop size distribution curve with respect to the atomized glycerol (9.8 P) may be attributed to disruption of the continuous phase by impurities such as water and coal particles.

CONCLUSIONS

This study clearly demonstrates that while the pseudoplastic behavior has a significant effect on airblast atomization of a micronized coal water slurry, the high shear slurry viscosity dictates the atomized drop size and size distribution. Coal

volume fraction, liquid composition, and liquid viscosity affect slurry atomization via their effects on slurry rheology. Like water, coal particles cause disruption in the continuous phase of the medium to be atomized and, thus, yield a looser drop size distribution curve. Nevertheless, the wave mechanism-based semi-empirical models are shown to fully account for the effects of slurry rheology, as well as atomizer design, on drop mass median diameters in terms of three nondimensional groups, $1 + \dot{M}_S / \dot{M}_A$, the Weber number, and the Ohnesorge number.

ACKNOWLEDGMENTS

Support of this work by a grant from the Department of Energy under the University Coal Research Program (DE-FG22-88PC88912) is gratefully acknowledged.

NOMENCLATURE

D	Diameter of liquid jet or atomizer distributor diameter
D_i	Diameter of atomized drop
L_C	Characteristic length
MMD	Mass median diameter of drops
M	Mass flow rate
N_i	Number of drops with diameter D_i produced per unit time
P	Pressure or Poise
V	Velocity or average velocity
VMD	Volume mean diameter
SMD	Sauter mean diameter
We	Weber number $\rho_A V_A^2 D / \sigma_L$
Z	Ohnesorge number, $\eta_S / (\rho_S \sigma_L D)^{1/2}$

ρ	Density
η	Viscosity
σ	Surface tension or surface energy per unit area

Subscripts

A	Atomizing Air
L	Liquid
S	Slurry or particle

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TABLE 1

ATOMIZER DIMENSIONS

Nozzle tip No.	Discharge Diameter cm	Cross Section cm ²
1	0.249	4.866x10 ⁻²

Distributor No.	dia. cm*	Slit Design No.-cm x cm	Cross Section, Liquid	cm ² Air
1	0.152	4-0.24 x 0.076	1.815x10 ⁻²	7.354x10 ⁻²
2	0.152	6-0.076x 0.086	1.815x10 ⁻²	3.950x10 ⁻²
#3	0.244	6-0.086x 0.114	4.676x10 ⁻²	5.925x10 ⁻²

*Diameter of the central opening for slurry flow

#Variflo atomizer by Delavan corp., South Carolina

TABLE 2

PROPERTIES OF COAL SLURRIES AND SUSPENDING LIQUIDS

Slurry	Flow index	Consist index	Coal Vol. Fraction	Suspending liquid Conc. wt%	Visco. cP	S. Tension* dyne/cm
a)	0.54	290	0.47 UpF	40% glycerl	3.6	71
b)	0.50	308	0.47 UpF	20% glycerl	1.7	72.2
c)	0.58	145	0.43 UpF	40% glycerl	3.6	71
d)	0.52	175	0.43 UpF	42% glycol	3.0	65.5
e)	0.82	35	0.40 Ill	40% glycerl	3.6	71

*Surface tension is measured using the Fisher Surface Tensiometer Model 20, and the results are comparable with those obtained from the CRC Handbook of Chemistry and Physics.

TABLE 3

EFFECTS OF DISTRIBUTOR DESIGN AND SLURRY RHEOLOGY
ON SLURRY ATOMIZATION

Slurry	Distr No.	$1+\dot{M}_S/\dot{M}_A$	We	Z	P_A kPa	*	P_S kPa	MMD μm
<hr/>								
d)	1	5.24	67	0.73	149	<	245	340
	2	6.70	285	0.60	156	<	280	338
	2	2.86	547	0.83	197	<	252	139
	2	2.98	647	0.78	190	<	252	125
	1	2.49	252	0.83	190	>	254	74
	2	2.77	1060	0.69	238	>	280	51
	1	2.26	288	0.85	212	>	254	45
	1	2.12	410	0.80	236	>	280	36
	<hr/>							
	2	4.97	749	0.76	183	<	252	224
c)	2	3.80	978	0.79	245	<	276	132
	2	3.26	1065	0.83	266	>	276	73
	2	3.30	1015	0.85	245	>	252	65
	<hr/>							
b)	3	4.54	279	1.41	218	>	262	149
	3	3.57	295	1.62	218	>	252	115
	3	3.92	295	1.54	210	>	259	110
a)	1	4.42	204	1.98	183	<	333	271
	1	3.10	269	2.26	190	<	324	128
	1	2.05	252	3.08	170	>	349	74
	1	1.79	305	3.21	204	>	245	50
	1	1.76	447	2.91	244	>	280	36
	<hr/>							
e)	1	3.93	159	2.00	156	<	276	336
	1	2.88	217	2.09	167	<	252	246
	1	2.91	265	2.03	183	<>	276	118
	1	2.39	265	2.14	190	>	252	62
	1	1.93	442	2.16	235	>	276	34
	3	5.00	426	1.88	190	>	254	141
	3	3.99	519	1.91	225	>	254	87
	3	3.40	655	1.93	250	>	254	57
	<hr/>							
	9.8 P glycerl	3.20	173	2.81	156	<	249	159
		2.81	502	2.81	204	>	314	74
		1.84	527	2.81	225	>	245	36
	<hr/>							
	3.8 P glycerl- water	3.64	189	1.10	163	<	221	109
		4.43	224	1.10	218	>	266	54
		2.83	288	1.10	238	>	266	41

* below or above the threshold atomizing inlet air pressure

TABLE 4

SEMI-EMPIRICAL MODEL FOR AIRBLAST ATOMIZATION
OF GLYCEROL AND ITS AQUEOUS SOLUTIONS#

$$\text{MMD}/L_C = (1 + \dot{M}_S/\dot{M}_A) \{x_2 \cdot \text{We}^{-x_1} + x_3 \cdot Z^{x_1}\} 10^{-2} \quad (1a)$$

$$\text{MMD}/L_C = (1 + \dot{M}_S/\dot{M}_A) \{x_2 \cdot \text{We}^{-x_1} + x_3 \cdot Z^2 \cdot x_1\} 10^{-2} \quad (1b)$$

	x1	x2	x3	x4	c.o.c.*	Equation
(a)	0.33 ±0.03	11.68 ±1.0	1.41 ±0.05	---	0.98	(1a)
(b)	0.31 ±0.03	9.67 ±1.0	0.22 ±0.05	---	0.98	(1a)
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** (a)	0.47 ±0.05	8.5 ±1.0	1.40 ±0.05	---	0.93	(1a)
** (b)	0.60 ±0.05	12.0 ±2.0	1.10 ±0.05	---	0.93	(1a)
<hr/>						
(a)	0.30 ±0.03	10.44 ±1.0	1.22 ±0.05	---	0.98	(1b)
(b)	0.31 ±0.03	9.66 ±1.00	0.23 ±0.05	---	0.98	(1b)
<hr/>						
** (a)	0.30 ±0.04	5.3 ±0.7	0.98 ±0.07	---	0.93	(1b)
** (b)	0.38 ±0.03	6.0 ±0.5	0.81 ±0.05	---	0.93	(1b)

The units of MMD and D are μm and cm, respectively

* Coefficient of correlation

** Glycerol atomization

(a) Atomizing air pressure below the threshold value

(b) Atomizing air pressure above the threshold value, MMD is replaced by VMD in the case of glycerol atomization

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Fig 1

Fig. 3

Fig. 4

Fig. 7

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