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Study on Characteristics of Different Types of Nozzles for Coal-Water Slurry Atomization

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Three types of nozzles: a low-pressure multistage nozzle, an effervescent nozzle and a newly developed internal-mixing air-blast nozzle, for atomization of Coal-Water Slurry (CWS) were investigated. Influence of CWS properties including surface tension and apparent viscosity on atomization was studied. Comparisons among the nozzles were carried out in terms of spray droplet mean diameter and fuel output. Versatility of each nozzle was investigated and atomization mechanism of each nozzle was analyzed as well. The results showed that the newly developed internal-mixing air-blast nozzle has high fuel output and small mean droplet size in the spray, but the multistage nozzle has high versatility for handling of low quality CWS.

Keywords: CWS, coal-water slurry, atomization, nozzle.

Introduction

CWS appeared as an alternative to fuel oil since the 1970s. During the past two decades, CWS technology developed quickly in terms of preparation, transportation, atomization and combustion. CWS technology, characterized with high efficiency and low pollutant emission, has reached such a stage of technical refinement[1] that its application covered more fields than originally intended, such as handling of coal sludge[2]. Its application to disposal of black liquor in pulp & paper industry is currently in the research phase[3].

For liquid fuels including CWS, atomization plays a key role in the determination of flame speeds, flame stability, and ignition limits[4]. Design of nozzles for CWS encounters challenge due to its high apparent viscosity, non-Newtonian rheological property and high-density particle-liquid constitution. Most conventional nozzles were of the "prefilming" type, in which the fuel was first spread out into a thin, continuous sheet and then subjected to the shearing force of air stream[5]. But for CWS, small slots not only decrease nozzle output, but greatly increase possibility of blockage, which is detrimental to CWS industrial application. Improvement on coal beneficiation level may to some extent solve the problem[6], but consequently increases economic investment.

The main purpose of the study is to develop a kind of nozzle with high output and high droplet fineness for atomization of CWS. Three kinds of nozzles, with the same orifice diameter of 5mm, were investigated: a low-pressure multistage nozzle, an effervescent nozzle and a newly developed internal-mixing air-blast nozzle (Fig.1). The low-pressure multistage nozzle has been employed in several fields[7], demonstrating such advantages as low CWS pressure, low erosion rate and no blockage. The effervescent nozzle, referred to in a number of recent publications[8], has been receiving attention for its good atomization performance insensitive to variations in liquid viscosity[9]. Unfortunately, previous research on effervescent nozzle has focused almost entirely on atomization of uniform phase liquid fuel, the result of which is not quite applicable to atomization of CWS. The newly developed internal-mixing air-blast nozzle for atomization of CWS, though similar to effervescent nozzle in geometric structure except that far less number

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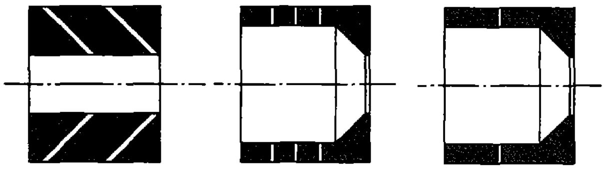
	Nomenclature	r_i	Capillary inner radius, (m)
AFR	Air-to-fuel mass flow ratio	SMD	Sauter mean diameter, (μm)
D_{32}	Sauter mean diameter, (μm)	$\Delta P_{\max}$	Pressure discrepancy between inside and outside bubble, (Pa)
G	Gravitational constant, (m/s^2)		
H	Height of CWS above the capillary orifice, (m)	σ	Surface tension, (N/m)
M_{CWS}	CWS mass flow rate, (kg/h)	ρ	CWS density, (kg/m^3)
P_a	Atomizing air pressure, (MPa)	θ	Surface expansion rate, (s^{-1})
P_{CWS}	CWS tank pressure, (Mpa)	μ	CWS apparent viscosity, (mPa. s)
Q	Volume flow rate of air through the capillary, (m^3/s)	γ	Shear rate, (s^{-1})
r_c	Capillary outer radius, (m)		

of air slots are applied, works under different operating conditions and by air-blast mechanism.

Atomization performance of each nozzle in terms of droplet Sauter Mean Diameter (SMD) at given spatial measurement position in the spray (150 mm downstream from the nozzle orifice) and fuel output were measured as a function of operation condition and CWS properties. Comparison among the three nozzles was carried out. Some experimental results were presented and factors contributing to the differences were discussed.



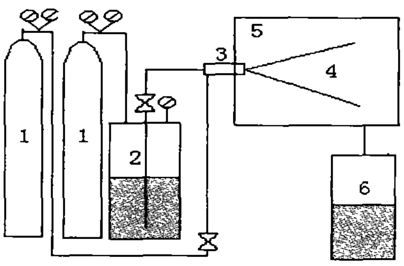
multistage nozzle effervescent nozzle internal-mixing nozzle

Fig.1 Schematic diagram of different nozzles

Experiments

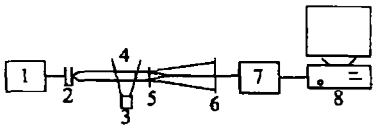
Fig.2 shows the overall atomization facility for the experiment. CWS atomizing characteristics was measured using Malvern 2600 Particle Sizer (Fig.3), which determined droplets size distribution by collecting laser beam diffracted by those passing through the beam. Collected laser energy distribution was processed by model independent analysis. In the test, 300 mm-focused lens was employed, corresponding to a droplet volume distribution ranging from 5.8 to 564 μm.

Four kinds of CWS were used in the study, labeled as No.1 through No.4. CWS No.1 and No.2, with coal content of 57.8% and 58.9% respectively, are commercial products with different dynamic surface tension and apparent viscosity. CWS No.3, with coal content of 57.8%, is coal sludge without any additive. CWS rheological characteristics were measured with typical rotation viscometer. CWS No.4, possessing the same constitution as CWS No.2 except that coal particles has to some extent coagulated, was applied only to determine nozzles' versatility for atomization of CWS with various quality of preparation. Dynamic surface tensions of CWS were measured by the maximum bubble pressure technique[10]. The test facility is shown schematically in Fig.4. A capillary with an outer radius of 0.5 mm was inserted vertically into the vessel holding



1 air tank 2 CWS tank 3 nozzle 4 spray
5 atomization chamber 6 CWS reservoir

Fig.2 CWS atomization system



1 laser 2 beam expander 3 nozzle 4 spray
5 lens 6 detector 7 electronics 8 computer

Fig.3 Diagram of Malvern sizer

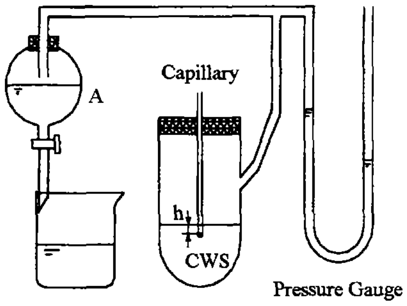


Fig. 4 Schematic illustration of the maximum bubble pressure technique

the CWS under test. During the test, water drained out from vessel A, causing the pressure inside the system to be lower than the ambient air pressure. Driven by the pressure difference, ambient air went through the capillary and formed bubbles at the capillary orifice. The pressure bias could be measured by U-shaped manometer. The bubble pressure varies due to the changes in bubble radius. The maximum pressure bias was reached as the bubble radius was at the minimum at the outer orifice. The dynamic surface tension could be calculated from measurements of the maximum bubble pressure[11]:

$$\sigma = (\Delta P_{\max} - \rho g h)\, r_c/2$$

the surface expansion rate $\theta = Q/\pi r_i^3$.

Results and Discussions

Influence of CWS property on atomization performance

Rheological behaviors of the tested three types of CWS, demonstrating pseudoplastic flow characteristics in terms of relation between apparent viscosity η and shear rate γ, are shown in Fig.5.

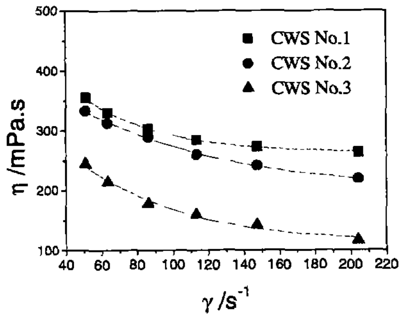


Fig.5 CWS rheology

Value of dynamic surface tension for CWS is much higher than the corresponding static surface tension because insufficient time exists for the migration of surfactant additives to the newly born interface from the bulk mixture. As shown in Fig.6, dynamic surface tension of CWS increases dramatically with the increase of surface expansion rate. Dynamic surface tension at high surface expansion rate, rather than the static surface tension, is the more appropriate parameter of CWS atomization, due to rapid increase of surface area in atomization process[12].

Atomization performances, in terms of SMD (d_{32}), of different nozzle with different CWS are shown in Fig.7. For air-blast nozzle, i.e. multistage nozzle and internal-mixing nozzle in the study, SMD in the spray varies monotonously with the apparent viscosity of CWS. Higher viscosity leads to worse atomization. In air-blast atomization, the droplet size to a considerable extent depends on the range of excitable wavelength on the interface, the shorter wavelength limit being due to viscous damping[5]. Influence of CWS surface tension on air-blast atomization performance, tending to impede atomization[13], cannot be determined definitely in the study.

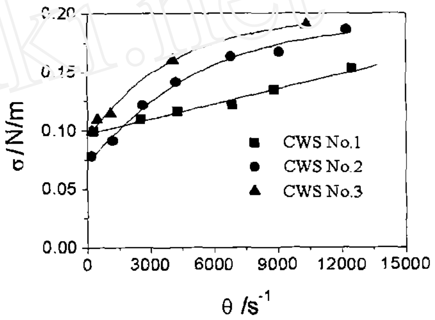


Fig.6 CWS surface tension

In the case of effervescent nozzle, CWS dynamic surface tension affects atomization performance within operation condition of low Air-to-Fuel mass Ratio (AFR) more dramatically than CWS viscosity. As shown in Fig.7(b), spray SMD varies monotonously with the CWS dynamic surface tension. The lower the dynamic surface tension, the smaller the SMD in the spray. In effervescent atomization, the key technique is to introduce air into the flowing CWS in the mixing chamber upstream of nozzle orifice to create a stable bubbly two-phase flow. Higher surface tension causes higher value of interface energy and thus weakens effervescing ability of CWS and stability of bubbly flow, deteriorating effervescent atomization performance. With increase of AFR, the working mechanism changes gradually toward air-blast atomization and the effect of CWS surface tension on SMD is diminished.

Evaluation of nozzle performance

Comparison of atomization performance among nozzles was carried out in terms of spray SMD and fuel output. Fig.8 shows the difference of spray SMD of different nozzles within similar operation range. Increase of AFR or CWS tank pressure reduces droplet mean diameter, reflecting an increase in the air blast momentum and energy available for slurry jet breakup. The test data plotted in Fig.8 also demonstrates that the effect of CWS pressure lessens as the pressure is increased.

Newly developed internal-mixing nozzle creates the smallest droplet mean diameter over the operation range in the test, which is similar to that in industrial

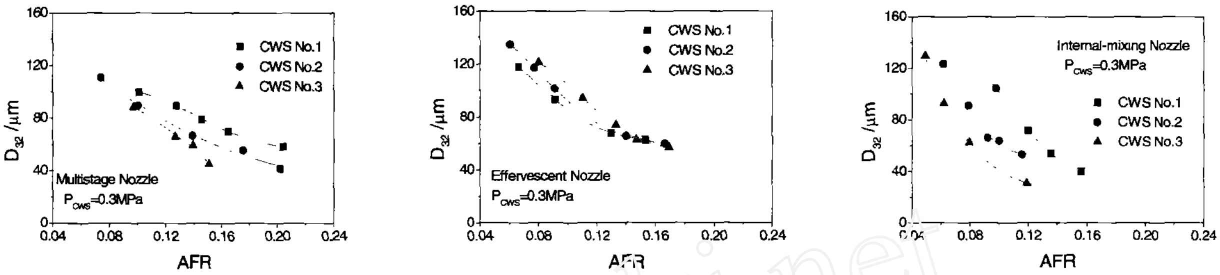
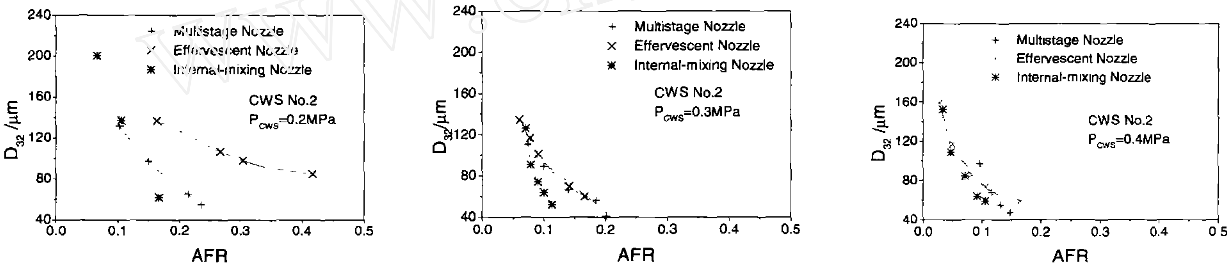
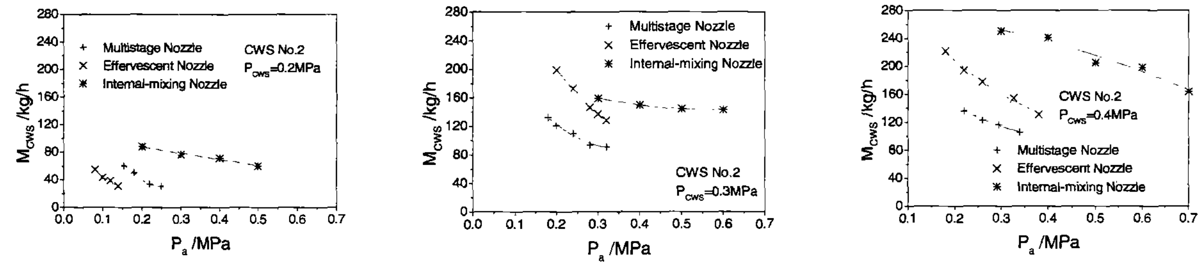


Fig.7 Performance of nozzles atomizing different type of CWS



(a) (b) (c)

Fig.8 Comparison of spray SMD



(a) (b) (c)

Fig.9 Comparison of nozzle output

application. Whereas effervescent nozzle for CWS atomization shows some disadvantages, major one of which is that too many air slots decrease pressure drop between air-side and CWS-side, and thus increase the possibility of CWS blockage in air slots. The reason for effervescent atomization behavior of CWS not so good as that of uniform phase liquid fuel[14] may possibly be the existence of coal particles that cause either instability of bubbly flow or high value of thickness of CWS film between bubbles.

Fig.9 shows comparison of fuel output among different nozzles. The internal-mixing nozzle gives the highest value of CWS mass flow rate over the operation range the test covered. Nozzle output depends on its operation condition including air pressure, CWS pressure, AFR etc., number of air slots, velocity of air jet from the slots, interaction angle between air jet and CWS flow. Test data plotted in Fig.9 also shows that increasing CWS tank pressure or lessening air pressure increases nozzle output.

In nozzle design, atomization efficiency and nozzle output play opposite roles. Sheer increase in nozzle size to increase nozzle output, increases mean drop size[5], due to decrease of wetted perimeter in comparison with fuel mass flow rate. On the other hand, in the same nozzle, more vigorous interaction between air and CWS will inevitably increase CWS flow resistance. In internal-mixing atomization, combination of high efficiency and high output is due to the disintegration of CWS in a more efficient way. Sufficient momentum exchange between air and CWS is performed in mixing chamber and CWS column is primarily shattered. In convergent section upstream of discharge orifice, air-droplet mixture is so accelerated that velocity difference between air and droplet causes secondary breakup soon after discharged from the orifice.

Versatility of nozzles for atomization of low-quality CWS

In industrial application, some poorly prepared low-quality CWS with coal particle clots is occasionally met. To test the versatility of nozzles, CWS No.4 was applied to simulate such conditions. Variation of SMD with AFR is shown in Fig.10. With increase of AFR, spray SMD decreases monotonously. There is no dramatic difference between multistage atomization of CWS No.4 with that of other CWS tested. But in the case of internal-mixing nozzle, spray mean droplet diameter is insensitive to variation of AFR, significantly different from atomization of other CWS. This is because limited number of air slots in internal-mixing nozzle inhibits overall shear action exerted directly by air jet, whereas the disturbance alone caused by air jet in mixing chamber is not sufficient for disintegration of coal clots. In multistage nozzle, peripherally arranged high-speed air jets act on CWS column directly, breaking up coal clots effectively.

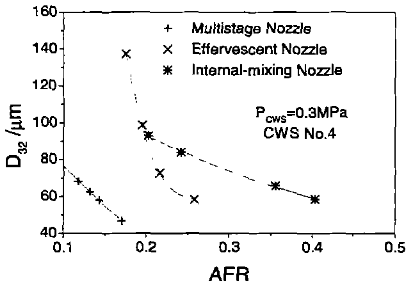


Fig.10 Atomization of low quality CWS

Conclusions

In the study, three kinds of nozzles for atomization of CWS were investigated. Conclusions can be drawn as:

1. In CWS air-blast atomization, apparent viscosity rather than dynamic surface tension plays the key role affecting nozzle performance. In CWS effervescent atomization, dynamic surface tension is more important than viscosity.
2. Effervescent nozzle is not suitable for atomization of CWS due to its special properties and tendency to air slots blockage.
3. Internal-mixing nozzle creates finer spray droplets and demonstrates higher fuel output than multistage nozzle does, but is not so versatile as multistage nozzle in handling of low quality CWS.

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