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The effects of pulsation and retraction on non-Newtonian flows in three-stream injector atomization systems

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HIGHLIGHTS

- Self-generating pulsatile industrial scale three-stream coaxial airblast injector.
- Effects of geometry, numerics, gas flow rate, and superimposed flow modulation.
- Pressure drop found to be proportional to retraction; new correlations introduced.
- Universal axial droplet size function.
- Computational time savings achieved by reduced order models.

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ABSTRACT

The effects of geometry, numerics, gas flow rate, and superimposed flow modulation on the self-generating pulsatile spray produced by an industrial scale three-stream coaxial airblast reactor injector have been studied for a non-Newtonian slurry and high-pressure gas (SH) system. A fully retracted design showed the most inner gas pulsation, and the spray character changed significantly between a flushed and retracted design; the flushed design showing more radially synchronized and focused pulsations. Pressure drop was found to be linearly proportional to retraction, and new correlations were introduced. Higher inner gas flows typically widened sprays for the base geometry only and lowered the droplet length scales, indicating that the lower droplet size limit was not set by viscosity limitations. Modulation of the inner gas at its dominant tone did not strongly affect many metrics, except that the inner gas pulsations substantially increased. Slurry video analyses provided spray angle directional trends so that a subset of the domain could be simulated to save computational time.

Relative to prior air-water (AW) studies, SH flow patterns and acoustics typically differed significantly, with the exception of the base geometry spray profiles at the higher inner gas flows, along with the droplet length scale. In general, SH simulations showed lower pressure drop, astoundingly lower pressure temporal variability, higher dominant tones, and less periodicity (more diffused spectra). Furthermore, the relationship between 3D SH droplet size and distance was of the form constant/distance; the constant was the same for both feed materials. It appears that acoustics cannot be linked between the two feed materials, but there is some connection in mean droplet size.

1. Introduction

The breakup of non-Newtonian (NN) fluids is germane to various processes and industries, such as food processing, energy production, and waste management. Many have studied atomization of NN liquids and slurries; see for example [1–13]. Among these studies, the effect of viscosity and/or surface tension on Sauter mean diameter (SMD) has been explored by Aliseda et al. [7] and Senecal et al. [5]. In relation to non-Newtonian fluids, Senecal et al. [5] considered high speed viscous sheets in quiescent air, such as those found in pressure-swirl atomizers of an internal combustion engine. Predicted primary droplet diameter as a function of liquid phase Ohnesorge number was given. A critical gas phase Weber number of about 1.7 was used as a demarcation between two regimes. Above 1.7, short waves became the dominant player in the primary breakup process, making liquid viscosity very important. They also showed that in higher Weber number

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Nomenclature

AS	axisymmetric
AW	air-water feed stocks
AWE	air-water equivalent (conjugate pair for a slurry-high pressure gas cases)
COV	coefficient of variation = standard deviation/mean * 100%
D_{32}	Sauter mean droplet length scale
D_I	nozzle innermost diameter normalized by nozzle outer diameter
D_M	nozzle intermediate diameter normalized by nozzle outer diameter
D_O	nozzle outermost diameter normalized by the maximum outer diameter
FFT	fast Fourier Transform
H	cycle time scale
IG	inner gas stream
La	Laplace number = Re^2/We = Suratman number
L_{AG}	outer annular gap normalized by nozzle outer diameter
L_C	some characteristic length scale
L_{RI}	inner retraction length normalized by nozzle outer diameter
L_S	shoulder length, or spray lift-off, measure normalized by outer diameter
M	gas/liquid momentum ratio = $(\rho U^2)_G/(\rho U^2)_L$
Ma	Mach number
Mag.	FFT magnitude, or spectral focus
OG	outer gas stream
Oh	Ohnesorge number = $\sqrt{We}/Re = 1/\sqrt{La}$
P	pressure; tabulated pressure drops are normalized by outlet pressure
Pr	liquid phase Prandtl number
Q	viscous capillary length
Re	Reynolds number = $\rho UD/\mu$
S	velocity ratio, U_G/U_L

SH	slurry-high pressure gas feed stocks
St	Strouhal number
SMD	Sauter mean diameter (“D_{32}”)
Tone	dominant frequency from FFT analysis
t	time
t_{LI}	thickness of inner lip
t_{LO}	thickness of outer lip
t_{SLAN}	thickness of slurry annulus
UDF	user-defined function
y^+	$\rho u_t y/\mu$
We	Weber number = $\rho U^2 L_C/\sigma$
Z	density ratio, ρ_G/ρ_L

Greek

ϕ	liquid volume fraction
ε	turbulence dissipation rate
Ω	modulation ratio
σ	surface tension
γ	outer gas/liquid annular approach angle normalized by maximum value
Λ	ratio of the pressure tone to shoulder tone
Γ	ratio of pressure mag. to shoulder mag.
ϑ	ratio of pressure tone to droplet length scale tone
Ξ	ratio of pressure mag. to droplet length scale mag.
ψ	ratio of pressure tone to spray spreading metric tone
Σ	ratio of pressure mag. to spray spreading metric mag.

Subscripts and Superscripts

G	gas
I	inner gas
L	liquid
O	outer gas

systems, like those in the present work, the effects of liquid viscosity can be paramount. Aliseda et al. [7] found for coaxial (also known as air-assisted) primary atomization that instability wavelength was substantially affected by higher viscosities. As expected, higher viscosities hindered the growth of instabilities resulting in larger droplets, but only when viscosity was well above ten times that of water. In fact, there was an extremely pronounced coupling effect of surface tension and viscosity. They [7] proposed that the lower surface tension of the non-Newtonian solutions (about one third that of water) prevented their SMD values from being orders of magnitude larger than that of water, instead of just two to three times its value. Since NN materials normally have a high viscosity, the liquid feed condition is typically laminar such that the primary disintegration instability mechanism is determined by gas phase turbulent structures and the gas phase boundary layer development [14,15].

Most atomization studies in the literature deal with two-stream systems, and often these do not involve pulsating sprays. Some might consider all coaxial atomization to be pulsatile in that, from a fixed reference frame watching the passing spray, temporal oscillations in liquid volume fraction and spray droplet number density exist. Various breakup regimes ranging from Rayleigh-type to “superpulsating” were described by Farago and Chigier [16]. Herein, we define “pulsations” to imply those which are driven by, or effectively drive, pure feed stream oscillations.

A unique video analysis technique offered by Osta et al. [17] involved data collection from X-ray imaging. They injected a turbulent round jet of water into quiescent air at atmospheric and sub-atmospheric conditions, and distinguished bubbles, droplets, and ligaments using the video images. They studied a range of water feed passage length:diameter ratios, proposing that this ratio dictates combustion quality. A surface breakup efficiency factor was defined as the total ligament area in an image to the total area. They found that ligament sizes correlated with their separation distances. Li et al. [18] used LabVIEW in order to characterize specific flow regimes using a neural network. Additionally, a fractal approach to study liquid atomization (natural fractal process) was discussed by Grout et al. [19]. They discovered aerodynamic forces were negligible when the local fractal dimension was at a maximum and where droplet production was the most effective, indicative of the final SMD. They also presented a new dimensionless group relating the near-orifice textural dimension to surface tension.

The basis for the current work is the experimental and computational three-stream studies of Strasser [20], and Strasser and Battaglia [21–23]. Therein, self-generating and self-sustaining pulsatile flow for air-water systems were considered, and this produced a “Christmas tree” type of spray as noted by Zhao et al. [24]. The violently bulk pulsatile behavior creates a vigorous atomization process that would not otherwise be present in a non-pulsing system, essentially, improving atomization without additional energy input. Inner nozzle retraction and flow modulation, along with the associated references for similar work in the literature, were addressed in detail for air-water systems [20–22]. Special attention was given to developing correlations which related retraction to important metrics. Additionally, video analysis methods were developed for air-water systems [20], where the radially expanding