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Laser-based flow measurement in performance assessment of FCC atomizer

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Abstract

Design and construction of a new two-phase atomizer of fluid catalytic cracking (FCC) process has been studied for atomizing the heavy oil feed by steam in low pressure. This atomizer has been tested quantitatively in air-water cold system using particle dynamic analyzer (PDA). The Taguchi method of experimental design has been used to optimize the two-phase atomizer's design parameters based on the proper average droplet size and distribution. The effects of spray flow pattern (upward and downward sprays) and different distances from feed injection on droplet size and velocity distribution have been studied for optimized atomizer.

Keywords: Atomizer; Fluid catalytic cracking (FCC); Taguchi analysis; Sauter mean diameter (SDM); Particle size and velocity distribution; Upward and downward spray

1. Introduction

Fluid catalytic cracking is a process used to change the oil heavy like vacuum gas-oil into light and more valuable products (petrol). This process is performed in the riser that the powder catalyst pours from the regenerator on the atomized feed. To achieve an impact surface of catalyst, one should atomize the feed using a two-phase atomizer. This process causes efficiency, selectivity and properties of FCC products to increase. In addition, the uniform feed atomization causes the increase of the initial catalytic cracking reaction of catalyst-hydrocarbon and the decrease of the decomposition of catalyst-products [1,2]. The uniform distribution of feed in FCC riser is followed by the increase of desirable products (petrol) and decrease of undesirable products (coke and dry gas) [3–5]. For designing such atomizer, the proper distribution of droplet size in low pressure is of much importance [6]. One can optimize the different parts of atomizer by means of experimental designing method (Taguchi) based on the mean droplets size produced [7]. As the catalyst in FCC process encounters with the feed in different distances of the feed injection in riser reactor, the effect of distance on size and velocity distribution of spray droplets is important on designing the efficient atomizers. Also, as the atomizers in FCC process are always in upward position, and most of the studies on sprays size and distribution focus on downward spray, studying the effect of upward and downward spray on its size and velocity has a major task to be done.

2. Atomizer design and construction

The two-phase atomizer is designed as three following sections (Fig. 1):

(a) Primary atomization.

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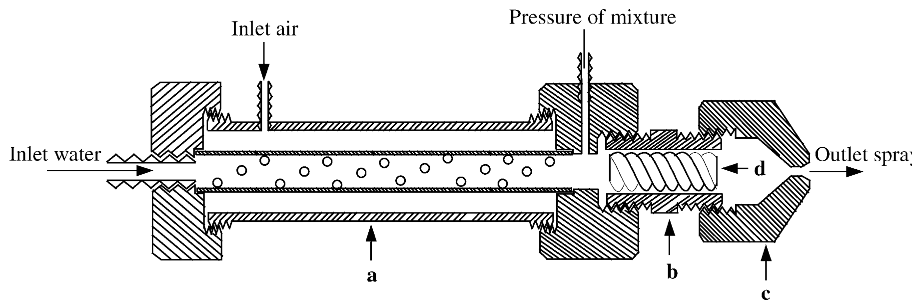

Fig. 1. Sketch of designed nozzle.

(b) Hard mixing.
(c) Final atomization.

The primary atomization section is consisted of two concentric tubes; along the internal tube there are some holes to mix liquid feed and atomizer gas. The liquid feed (water or vacuum gas-oil) and the atomizer gas (air or steam) enter into internal tube and annular space, respectively and mix together through the holes existing on the internal tube. Then the two-phase mixture enters to the hard mixing section, which is consisted of a cylindrical spiral (d) surrounded by a connecting tube. This spiral will produce a homogeneous mixture by the circulatory movement and hard mixing at the opening of the orifice [8–10].

Finally, the homogeneous mixture will be atomized to a solid conical spray after passing the circular orifice.

3. Experimental set-up

Flow diagram of the experimental system is shown in Fig. 2. Water is pumped by pump P_1 from tank T_1. In order to eliminate the pump vibrations a knock out drum is used. Flow rate and pressure of the entering water is read by FI_1 and PI_1 and is controlled by valve V_1. The entering air to the system after passing the regulator PIC and valve V_2 is measured by FI_2 and PI_2. To prevent the recycle in air and water lines we used check valves CV_1 and CV_2 after PI_1 and PI_2, respectively. The pressure of air and water mixture in primary atomization section is measured by PI_3 before entering to the hard mixing section. For measuring the size and velocity of droplets, the particle dynamical analyzer (PDA, Dantec dynamics, Denmark) was used, which can measure the diameter and velocity of the spherical particles simultaneously in gas

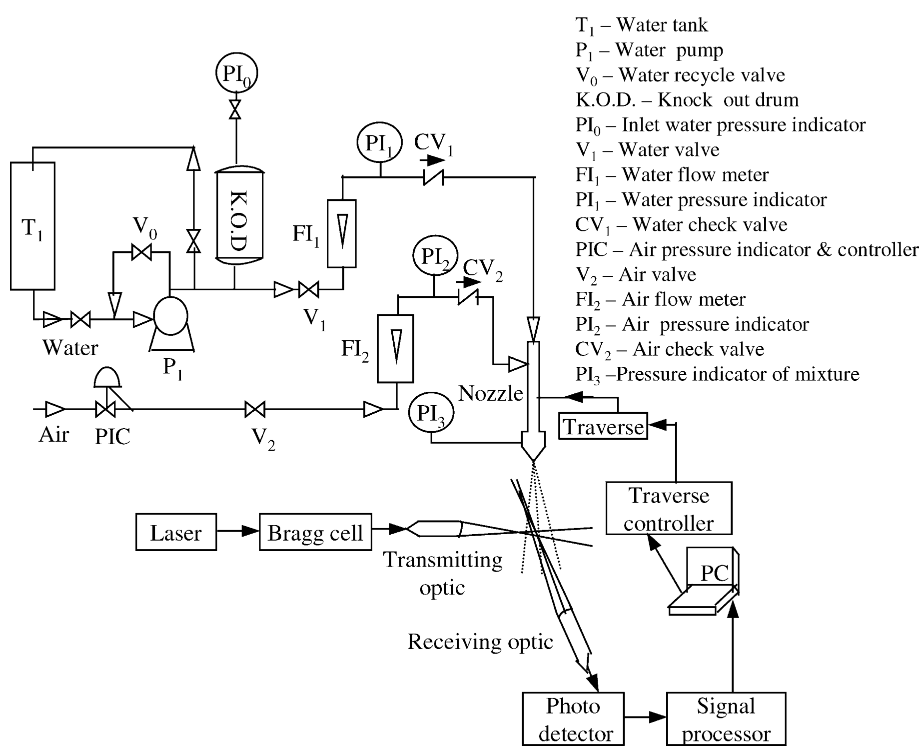

Fig. 2. Schematic view of experimental apparatus.

and liquid media [11]. This system can measure the diameter of spherical particles in the range of 0.5 μm to few millimeters. Also the maximum velocity of the particles measured is 500 m/s. The simultaneous measurement of diameter and velocity of the particles makes it possible to interrelate these quantities.

This system is based on Phase Doppler Anemometry, which is the developed model of Laser Doppler Anemometry [12]. In this system after producing laser beam, it divides into two beams by equal intensities through a Bragg cell. These two beams after passing through transmitting optics pass each other in the transmitter lens focal length. The receiving optic receives the lights reflected by the contacting droplets and sends them to photo detector and signal processor, respectively. Then the processed data is transmitted to the computer and will be analyzed by “BSA FLOW” software. This apparatus makes the simultaneous measurement of the velocity and diameter of the particles possible in any surface of spray. The measurement of the particles’ velocity is based on the change of frequency between “source light” and “received light”, while the measurement of the particles’ diameter is based on the phase differences of the reflected lights received by two detectors. This phase difference has a direct relation with particles’ diameters. A traverse is planned to interchange the atomizer in cylindrical, spherical and Cartesian coordinates in three X, Y and Z directions with an accuracy of one-tenth millimeter.

4. Experiments

The designed atomizer consists of 9 segments (factors). Each factor has 2 different types (levels of factors–Table 1). To achieve the best configuration of atomizer based on minimum produced droplet diameter, an L_{12} array was designed according to the Taguchi analytical methodology [13]. Therefore, the samples could be organized into only 12 groups and still yield results with the same confidence as if they were to be considered separately [14]. Table 2 shows the arrangement of samples into 12 groups according to Taguchi. The numbers indicate the various experimental layouts or levels of the different factors.

Table 1
Main designing factors used in Taguchi method

Factors	Level 1	Level 2
Length of distribution tube (A)	14 cm	20 cm
Number of holes of distribution tube (B)	10	15
Holes diameter of distribution tube (C)	0.75 mm	1 mm
Length of connecting tube (D)	4 cm	8 cm
Length of spiral (E)	Whole of connecting tube	Half of connecting tube
Orifice shape (F)	Without cone	With cone
Orifice hole diameter (G)	0.75 mm	1 mm
Orifice hole depth (H)	5 mm	8 mm
Pressure of mixture (I)	30 psig	40 psig

Table 2
Standard orthogonal arrays of 12 different groups following Taguchi’s suggestion

Sampling no.\factor	A	B	C	D	E	F	G	H	I	Result ($\bar{D}$, μm)
1	1	1	1	1	1	1	1	1	1	29.98
2	1	1	1	1	1	2	2	2	2	52.68
3	1	1	2	2	2	1	1	1	2	30.71
4	1	2	1	2	2	1	2	2	1	27.75
5	1	2	2	1	2	2	1	2	1	33.64
6	1	2	2	2	1	2	2	1	2	23.78
7	2	1	2	2	1	1	2	2	1	45.42
8	2	1	2	1	2	2	2	1	1	26.16
9	2	1	1	2	2	2	1	2	2	54.54
10	2	2	2	1	1	1	1	2	2	78.42
11	2	2	1	2	1	2	1	1	1	22.01
12	2	2	1	1	2	1	2	1	2	30.88

The measurements were done at a cross-section 14 cm from the atomizer exit. To study the distribution of particles’ diameter in this surface, 131 points were chosen with $\Delta\theta = 30^\circ$ and $\Delta r = 2$ mm where $\Delta\theta$ is the angular distance and Δr is the radial distance between measuring points (Fig. 3). For measuring the particles’ diameter and velocity in each point by PDA, atomizer was moved by the traverse with 0.1 mm step size.

By S/N analysis of Taguchi method on the obtained experimental data (Table 2), the mean diameter of all data points (131 points) for the best atomizer has to be to 16.628 μm. This determined the effective main factors on atomizer design by ANOVA method. Based on these factors, an optimized atomizer was made and experimentally the mean diameter of the spray was measured as 18.21 μm. It had 9.5% difference with the calculated value based on the Taguchi method. The reason of this difference may be the error in designing or possibly the interactions between different factors, which have not been considered in design of the experiments and analysis.

The results obtained by ANOVA method indicate that hole’s diameter of distributor tube is the only non-effective factor in designing while the depth of orifice hole and the pressure of mixture are the most effective factors.

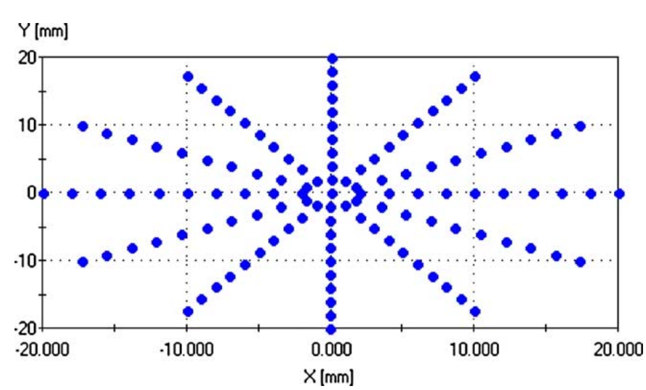

Fig. 3. Typical spray cross-section arrangement.

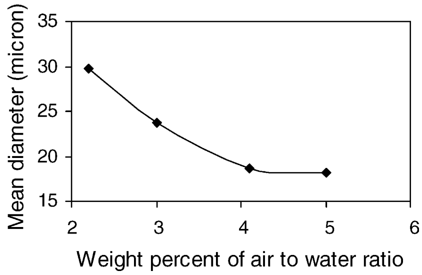

Fig. 4. Droplets mean diameter profile for different ratios of air to water flow rates.

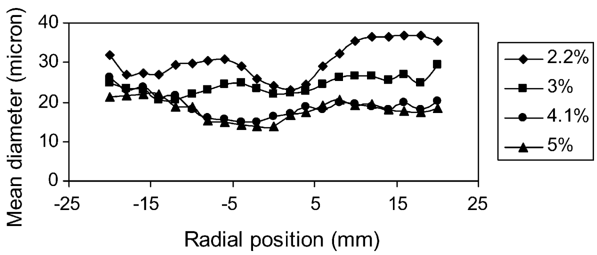

Fig. 5. Mean diameter distribution of droplets in a radial direction of spray and with different weight percents of air to water. Surface of measurement lies 14 cm from the atomizer exit.

5. Effect of liquid and gas flow rate on the performance of atomizer

In the designed experiments the effects of water and air flow rates and their ratio were not considered as two separate factors, because with change of the atomizer system in each experiment (based on L_{12} array), it was not possible to achieve the predefined levels of water and air flow rates. To overcome this difficulty, the pressure of mixture has been considered as a factor instead of the water and air flow rates. After characterizing the optimum atomizer in a fixed pressure of mixture, the water and air flow rates could be optimized. For this purpose the weight percent of air to water was considered as 2.2, 3, 4.1 and 5 and the mean diameter of spray at 14 cm from the atomizer exit were measured.

Figs. 4 and 5 show the variations of the spray mean diameter in different ratios of air to water flow rates for optimized atomizer.

The above results show that by adding 4.1 wt.% air to water one can reach to a homogeneous distribution of produced spray. In this condition the amount of water flow rate was 6.5 l/h and the pressure of mixture was 30 psig. The final characterization of optimized nozzle is shown in Table 3.

Table 3
Characterization of optimized nozzle

Factors	Optimum level
Length of distribution tube (A)	14 cm
Number of holes of distribution tube (B)	15
Holes diameter of distribution tube (C)	0.75 mm
Length of connecting tube (D)	8 cm
Length of spiral (E)	8 cm
Orifice shape (F)	With cone
Orifice hole diameter (G)	1 mm
Orifice hole depth (H)	5 mm
Pressure of mixture (I)	30 psig
Water flow rate	6.5 l/h
Air flow rate	205.95 l/h

The Sauter mean diameter (SMD) of each point in the spray cross-section is calculated by the following equation:

$$(D_{32})_j = \frac{\sum_{i=1}^{N_j} D_i^3}{\sum_{i=1}^{N_j} D_i^2} \tag{1}$$

in which 'j' is the measured points in the spray's cross-section and 'D_i' the samples diameter in each point of surface and 'N_j' the total numbers of sampled droplets in point j. $\bar{D}_{32}$ of spray is calculated by arithmetic mean of D_{32} on the same surface. This amount for optimized nozzle in downward condition was 78.48 μm. Fig. 6 shows the histogram of mean diameter and Sauter mean diameter by downward optimized nozzle. As shown in figure, most of the droplets have a mean diameter between 15 and 20 μm and Sauter mean diameter about 65–95 μm.

Fig. 7 shows the velocity distribution of droplets in considered situation. A relative uniform velocity distribution of droplets in spray is observed.

6. Spray flow patterns

6.1. Spray in downward condition

To study the performance of optimized nozzle due to diameter and velocity of the droplets in the surface of spray,

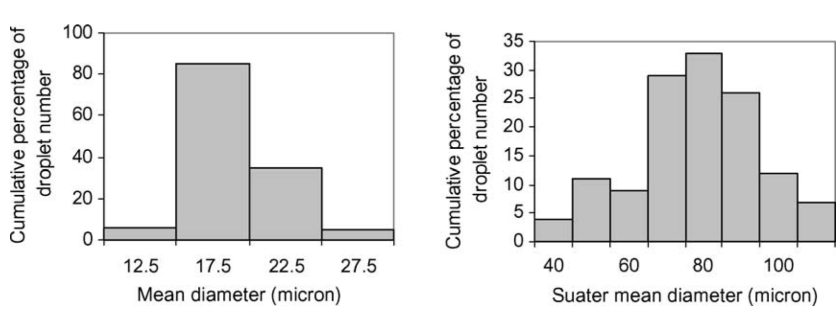

Fig. 6. Sauter and mean diameter histograms of droplets produced by optimized nozzle in downward condition at $Z = 14$ cm.

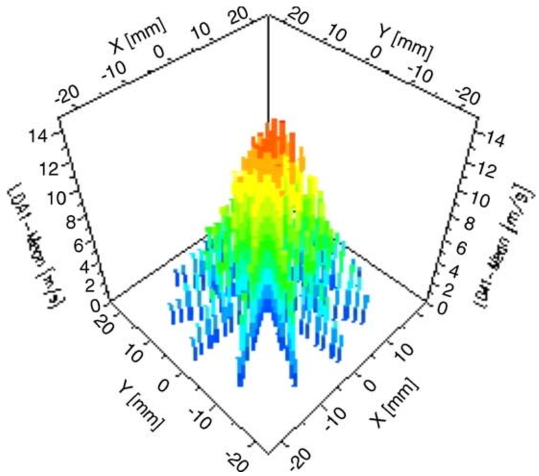

Fig. 7. Mean velocity distributions in downward condition at $Z = 14$ cm.

Table 4
Sauter and mean diameter of droplets in different distances from the top of optimized nozzle in upward and downward conditions

Mean diameter (μm)		Sauter mean diameter (μm)		Distance (cm)
Upward	Downward	Upward	Downward	
82.05	27.52	188.23	85.95	8
66.84	21.13	166.68	78.48	14
68.25	22.9	160.69	84.13	20

some experiments have been done in 8, 14 and 20 cm distance from the top of the nozzle (Z) in downward condition. Each of the experiments repeated twice and the diameters were calculated. The results based on mean diameter ($\bar{D}$) and Sauter mean diameter ($\bar{D}_{32}$) in each surface are shown in Table 4 and Figs. 8–10. The variations of mean velocity and

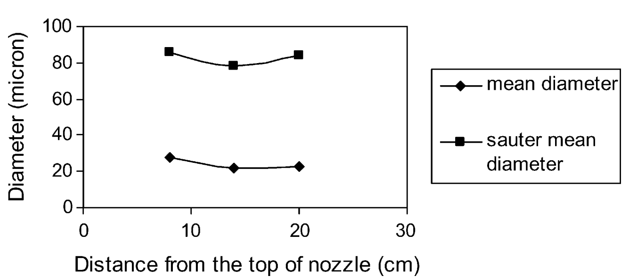

Fig. 8. Sauter and mean diameter variations with distance (Z) in downward condition.

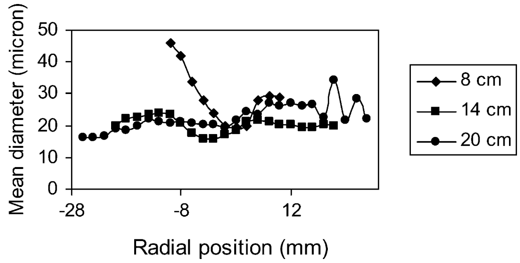

Fig. 9. Mean diameter distributions at different distances in downward condition.

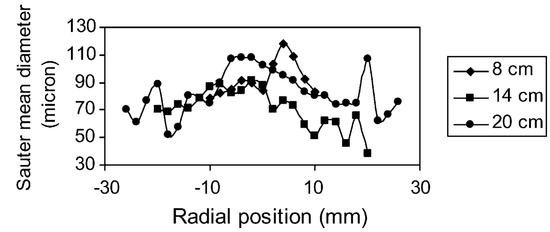

Fig. 10. Sauter mean diameter distributions at different distances in downward condition.

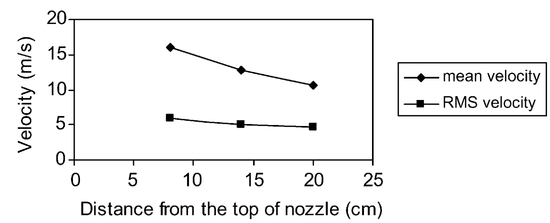

Fig. 11. Root mean square (RMS) and mean velocity variations with distance Z in downward condition.

RMS velocity to the distance of the nozzle (Z) are shown in Fig. 11.

6.2. Spray in upward condition

To accomplish the experiments of the upward atomizer we used a fiberglass chamber, to prevent back flow of water droplets meanwhile this chamber was built so that the returning droplets on the wall do not interfere with the measuring system.

To study optimized nozzle in upward condition the same experiments as downward spray were done in three 8, 14 and 20 cm distances from the top of the nozzle. The results are shown in Table 4. Fig. 12 shows the relation between the mean diameters ($\bar{D}$ and $\bar{D}_{32}$) and the surface distance for optimized nozzle in upward condition. Also the mean diameter and velocity profiles at 14 cm distance are shown in Figs. 13 and 14, respectively.

The comparison of mean diameter profiles between upward and downward spray for optimized nozzle is shown in Fig. 15. As it can be seen, the patterns are the same in both curves by this difference that the nozzle in upward condition produces larger droplets because of the gravity force. Figs. 16 and 17 show the drop velocity and diameter pro-

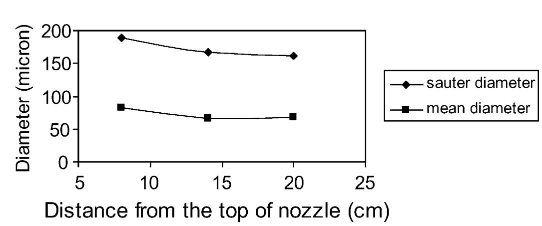

Fig. 12. Sauter and mean diameter variations with distance Z in upward condition.

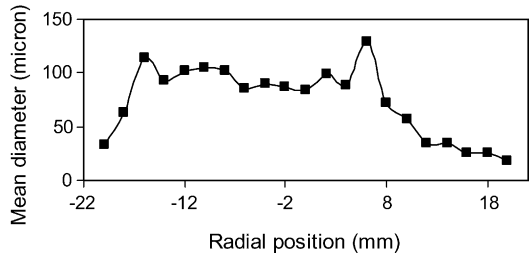

Fig. 13. Mean diameter profile at $Z = 14$ cm in upward condition.

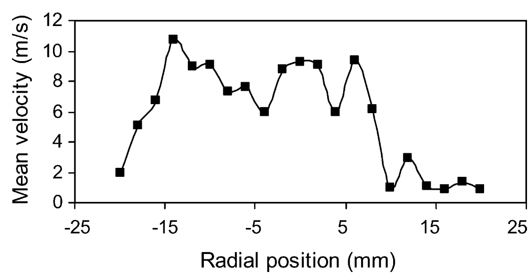

Fig. 14. Mean velocity profile at $Z = 14$ cm in upward condition.

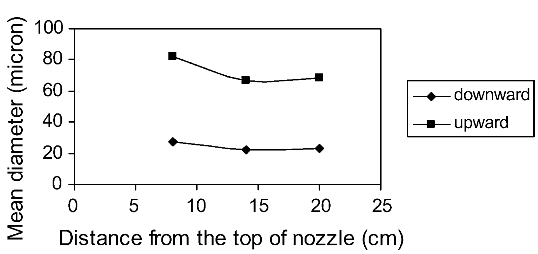

Fig. 15. Mean diameter variations with distance Z in upward and downward condition.

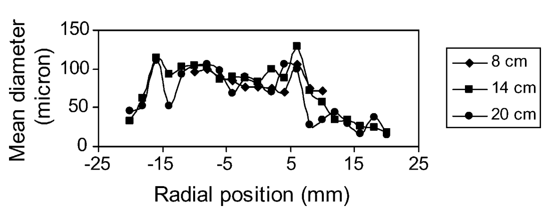

Fig. 16. Size distributions of droplets as a function of distance in upward condition.

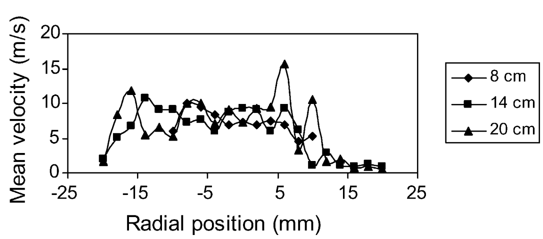

Fig. 17. Velocity distributions of droplets as a function of distance in upward condition.

duced by optimized atomizer in upward condition at different distances from the atomizer tip.

7. Conclusion

A lab-scale atomization system has been designed and developed for the study of various parameters on produced spray. A two-phase atomizer has been constructed and optimized to provide the best atomization with the lowest average droplet size. The effects of atomizer design parameters on spray quality were also investigated. Orifice shape, orifice depth and pressure of the mixture were the most important effective parameters in atomizer design. The droplet size and velocity distributions in several distances from the atomizer tip were measured by the particle dynamic analyzer (PDA) in two upward and downward conditions.

The SMD obtained by the optimized nozzle were measured to be 78.48 and 166.68 μm in downward and upward conditions, respectively. The mass flow rate ratio of air to water in the optimum conditions was 4.1% that is a proper amount for the FCC process.

The spray mean diameter at 14 cm distance from the atomizer tip was measured 18.21 and 66.84 μm in downward and upward conditions, respectively.

The Sauter and mean diameter patterns with respect to spray distance from the atomizer tip in upward and downward conditions are the same but the average size of droplets in the upward is larger than the downward spray.

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