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Performance Evaluation of a Twin Fluid Air-Blast Atomizer for the FCC Feed System: An Experimental Study

Deepak Kumar[1], Abhijit Kushari[2], Pramod Kumar[3], and Hemant Mishra[4]
[1,2]Indian Institute of Technology Kanpur
Department of Aerospace Engineering, Kanpur, India
deepakkr@iitk.ac.in; akushari@iitk.ac.in
[3,4]Hindustan Petroleum Corporation Limited
Bangalore, India
Hemant.Mishra@hpcl.in; pramodkumar@hpcl.in

Abstract **-** This paper investigates the spray characteristics of a specially designed nozzle tailored for riser applications. Through experimental analysis, the study aims to identify optimal operational parameters for the nozzle design. An extensive experimental evaluation is conducted to assess the atomizing performance of a twin-fluid air blast atomizer and its potential integration into contemporary FCC feed systems. The novel conceptual air blast atomizer incorporates an impactor bolt positioned at varying distances in front of the liquid jet, aiming to enhance mixing dynamics and atomization performance. Utilizing water and compressed air as working fluids, droplet sizes and velocities are measured using a phase Doppler particle analyzer. Results indicate a reduction in droplet size, as evidenced by a decrease in the Specific Mean Diameter (SMD), attributed to the impactor bolt positioned 5 mm away from the center of the air injection orifice. Furthermore, the shift in spray axis, opposite the impactor bolt's placement, influences droplet mean velocity.
Keywords**:** Phase Doppler Particle Analyzer, FCC, Impactor bolt, Atomization, Twin Fluid Injector

1. Introduction

Fluid catalytic cracking (FCC) is the primary conversion of the feed (low-grade oil) into a variety of high-value products. The FCC unit is composed of two reactors, a riser, and a regenerator. Vacuum gas oil is typically the feed that is to be converted into products such as LPG, petrol, and diesel [1,3]. The feed (vacuum gas oil) atomize system is based on the bottom of the riser and is supplied into the riser with the help of an atomizer in the form of fine droplets. The feed atomized system plays a major role in the modern FCC riser design and fine atomization from the feed atomized system ensures mixing thoroughly with the hot catalyst. In modern FCC, a highly active zeolite catalyst is used so that the reaction time has been reduced to very few seconds. As soon as liquid hydrocarbon feedstock is vaporized, and mixed, the feed vaporization must take place so quickly for the catalytic cracking reaction to complete in a few seconds [4]. On the other hand, the feedstock is heavy oil having higher viscosity and boiling points. Hereof, better atomization of heavy feed is desired to convert into very tiny droplets. Different types of arrangements are used to improve the quality of atomization or to improve the performance of atomization units. These atomizers are widely used in many spraying systems for domestic and industrial applications. These injectors are categorized as Air-blast and Air-assist atomizers based on the quantity and relative velocity of the gas phase. Most of the FCC nozzle systems used in the modern FCC units are twin-fluid atomizers that are widely used to atomize the liquid.

Twin fluid injectors have demonstrated successful applications in the Fluidized Bed Catalytic Cracking (FCC) process. Guo [5] observed that, at a specific gas pressure, the spray angle gradually rises with increasing liquid phase velocity. Conversely, at a given liquid pressure, the spray angle decreases as gas pressure rises. Chen and Lefebvre [6] explored the relationship between spray cone angle and gas to liquid mass ratio (GLR), noting that at low ambient pressures, the spray cone angle increases with higher GLR, reaching a maximum at intermediate GLR under higher pressures. They explained the reduction in cone angle at high GLRs as resulting from the transition of two-phase flow within the atomizer exit orifice. Kushari [7, 8] investigated the injector's ability to control flow rate and spray characteristics independently, finding that a small airflow into the liquid stream is sufficient for atomization. They concluded that decreasing the injection area of air and increasing the injector's length result in smaller droplet sizes. Ju [9] examined air-assisted atomizers for heavy oils using sonic compressed air at 0.4 MPa to control fuel flow rate, achieving separate control of fuel flow rate with a fine spray and desirable flame length. Kin [10] studied the effect of mixing chamber geometry, observing that atomization mainly occurred due to the breakup of the liquid film on the top and side surface of the mixing chamber. Nguyen [11] studied two types of atomizers and proposed a relation for volume drop diameter with atomizer geometry and operating conditions, observing volume median drop diameters as low as 10 µm at air-liquid ratios (ALR) less than unity. Kufferath [12] showed that flow characteristics strongly influence the radial distribution of the Sauter mean diameter and mass density, with maximum D_{32} for laminar velocity found on the spray axes, and nearly radial profiles in turbulent flow. Karnawat [13, 14] systematically evaluated the performance of twin fluid atomizers. Ferreira et al. [15, 16] found that SMD decreases with increasing airflow rate, with the smallest SMD produced by the channel diameter under choked conditions. They presented design optimization for twin fluid injectors for heavy oils. Lal [17] reported controlled atomization for twin fluid atomizers, especially in fire suppression applications. Broninaz [18] investigated the atomization process of water-oil emulsions, showing that SMD increased with increased volume fraction of oil in the emulsion as well as emulsion viscosity. Deepak [19-20] studied the role of the impact plate in the atomization process in twin fluid injectors for FCC applications and the that the impactor plate has affect the primary atomization.

The objective of this study is to comprehensively investigate the spray characteristics and assess the atomizing performance of a newly developed twin-fluid air blast atomizer, particularly focusing on its suitability for integration into current FCC (Fluid Catalytic Cracking) feed systems. The study aims to analyze the influence of various operational parameters, including nozzle flow parameters and structural variables, on droplet size, velocities, spray forms, and primary breakup mechanisms. Additionally, the impact of an integrated impactor bolt positioned at different distances from the liquid jet on mixing dynamics and atomization performance will be examined. Measurements and comparisons of droplet sizes and velocities will be conducted using a phase Doppler particle analyzer under different experimental conditions

2. Experimental Rig and Methodology

A cutting-edge twin-fluid air blast atomizer has been innovatively engineered, featuring the integration of an impactor bolt to significantly enhance atomization efficiency within FCC feed systems. Delve deeper into this ground breaking development as we meticulously outline the atomizer's design intricacies, provide insights into the experimental setup, and elucidate the comprehensive array of test parameters meticulously selected to rigorously evaluate its performance.

2.1. Air- Blast Atomizer

In the laboratory, a groundbreaking conceptual air blast atomizer has been meticulously designed and developed. Illustrated in Figure 1, the schematic showcases the intricacies of this pioneering atomizer. Comprising a cylindrical mixing chamber, an impactor bolt, and a drain tube featuring a single nozzle tip, the injector embodies a sophisticated engineering marvel. Water ingress into the mixing chamber is facilitated through a 3 mm orifice on one side..

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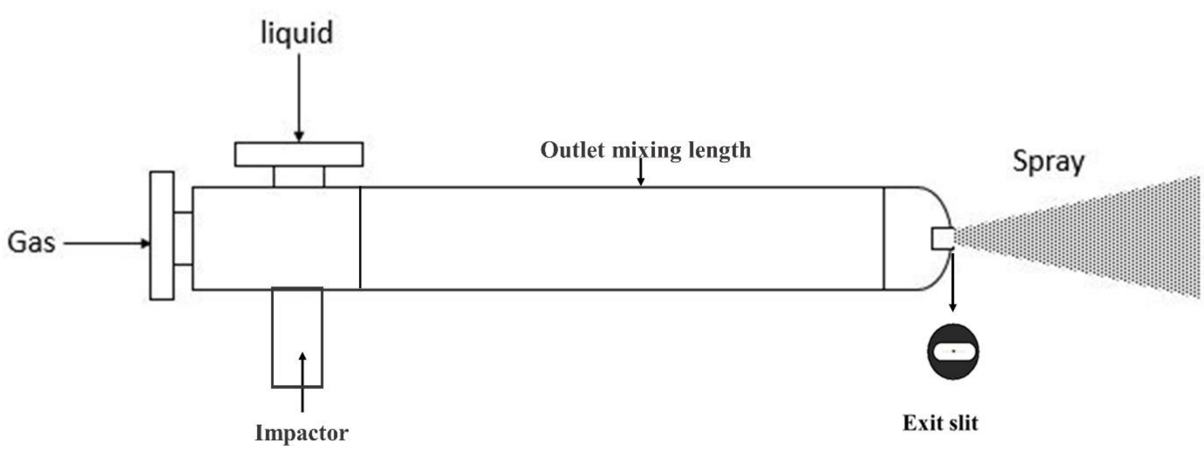

Fig. 1: Schematic of the Injector.

Central to the design is the inclusion of a 5 mm diameter impactor bolt within the mixing chamber, offering versatility through adjustable positioning. Meanwhile, compressed air is introduced through a 6 mm diameter inlet at the cylinder's apex Beneath the mixing chamber lies a lengthy cylindrical structure with a 12.5 mm inner diameter, serving as the conduit for the expelled mixture into the spray chamber post-passing through a honeycomb structure. The interaction between the incoming water and air initiates primary breakup within the mixing chamber, aided by the impactor bolt's strategic positioning. By aligning the bolt to the center of the air injection orifice, heightened interaction between water and air is achieved, thereby elevating the atomizing prowess of this pioneering atomizer.

2.2. Experimental Rig

The experimental setup encompasses a comprehensive water and air delivery system alongside an injector assembly, exemplified in the design depicted in Fig. 2. Central to this arrangement is the spray chamber, measuring 0.75 m x 0.75 m x 1.25 m, equipped with optical access, meticulously tailored for Particle Dynamics and Phase Analysis (PDPA) as well as visualization experiments. Positioned atop the spray chamber, the assembled injector serves as the focal point for evaluating atomization performance across various spatial and operational conditions. Water is propelled to the injector from a dedicated tank via compressed air, with pressure regulation facilitated by a pressure regulating valve and digital gauge. To mitigate mist formation within the test section and prevent interference with both the primary spray and optical measurements, a honeycomb structure is strategically deployed at the spray chamber's base, as illustrated in Fig. 2.

Water delivery, facilitated by compressed air, is closely monitored through a water flow meter, ensuring precise control and measurement of flow rates. Conversely, the compressed air, filtered and dried by a moisture separator and air heater, is supplied from a storage tank via a high-pressure conduit, regulated by a rotameter, needle valve, and pressure regulating valve. Density adjustments are meticulously calibrated by monitoring pressure levels with a gauge boasting 1% full-scale accuracy. For further insights into the Phase Doppler Particle Analyzer (PDPA), refer to the detailed description provided in reference [19-20].

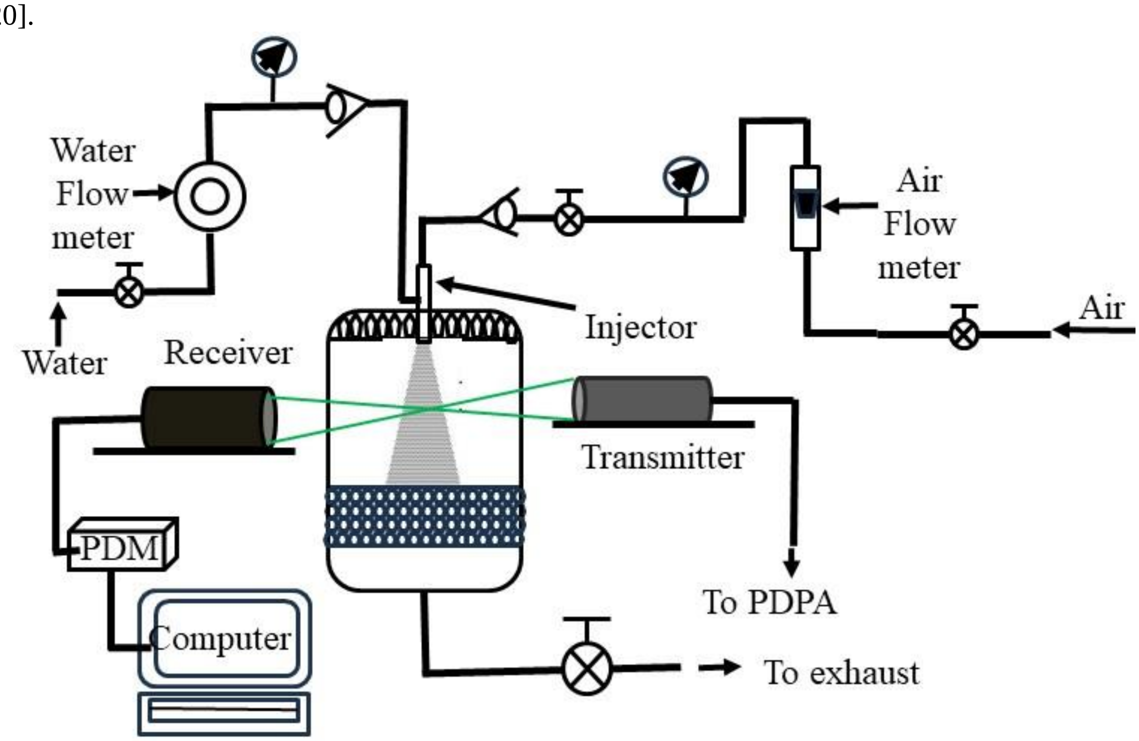

Fig. 2: Schematic of experimental laboratory facilities.

2.3. Operating conditions

The atomizing performance was systematically investigated through two distinct experimental scenarios. In the initial case, the liquid flow rate and injection pressure remained constant while the air flow rates, coupled with air pressure, were systematically varied, resulting in a range of non-dimensional air-to-liquid mass ratios spanning from 0.09 to 0.12. The crucial parameter under scrutiny was the Air-to-Liquid Mass Ratio (ALR), defined as the ratio of air mass flow rate to liquid mass flow rate and given by $ALR = \dot{m}_a/\dot{m}_l$. Subsequently, in the second case, the air flow rate was held constant at approximately 5.5 x 10^-3 kg/s, while the liquid flow rate was incrementally increased from 0.05 to 0.22 kg/s. This investigation aimed to discern the impact of varying liquid flow rates on atomization effectiveness. Detailed operational conditions for the investigated injector are meticulously outlined in Tables 1 and 2, providing comprehensive insight into the experimental parameters under scrutiny.

Table 1: case one

P_l (psi)	P_a (psi)	$\dot{m}_a$ (kg/s)	$\dot{m}_l$ (kg/s)	**ALR**
25	60	0.005	0.051	0.098
25	90	0.006	0.051	0.120
25	120	0.006	0.051	0.119

Table 2: Case 2

P_l (psi)	P_a (psi)	$\dot{m}_a$ (kg/s)	$\dot{m}_l$ (kg/s)	**ALR**
18	80	0.0055	0.0255	0.215
26	80	0.0055	0.051	0.107
25	80	0.0055	0.0761	0.071
37	80	0.0055	0.1	0.05

2.4. Measurements points and Target bolt positions:

To comprehensively assess the atomizing capabilities of the newly devised injector, two distinct cases were meticulously examined, as elaborated in the preceding section 2.3.

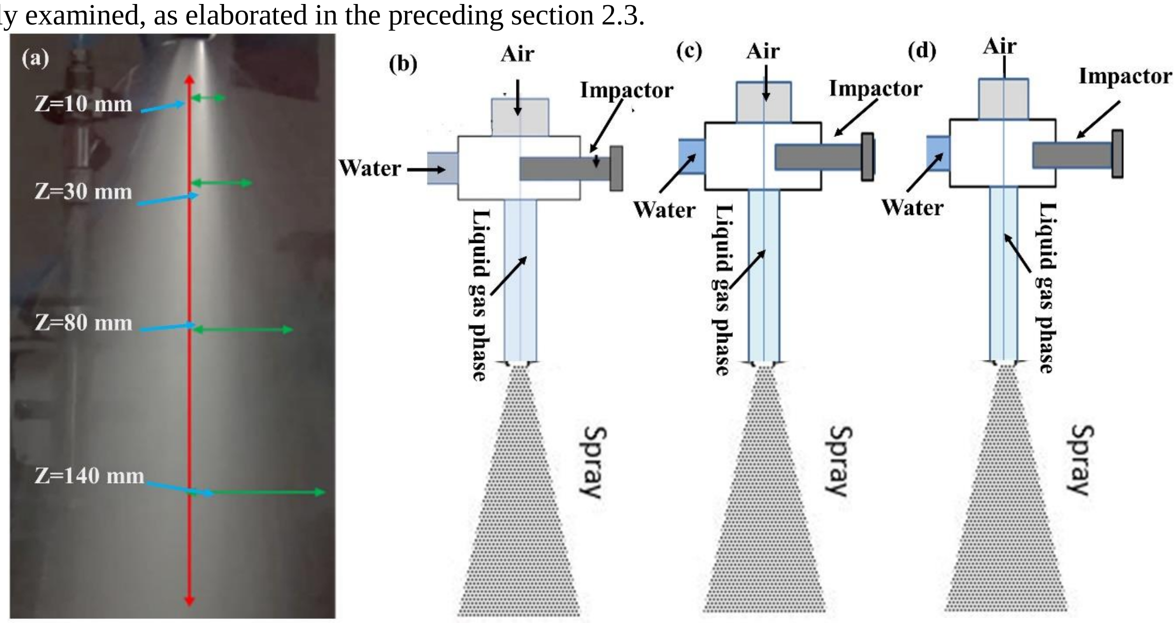

Fig. 3: Schematic a) Measurement points, b) centre position, c) 5 mm away from the centre, and d) 10 mm away from the centre.

In the first case, measurements were systematically taken along the spray's central axis, commencing 10 mm downstream of the injector and proceeding at 10 mm intervals up to 140 mm. In the second case, measurements were focused on four specific downstream positions (z=10 mm, z=30 mm, z=80 mm, and z=130 mm). Proximate to the atomizer exit, two positions were selected to encompass the primary atomization region, gradually traversing radially from the spray's center to its periphery at 2 mm increments. Conversely, farther downstream from the atomizer exit, two additional positions were chosen to encapsulate the secondary breakup region, extending from the center to the outer periphery at 3 mm intervals, as illustrated in Figure 3 (a). The impactor bolt's influence on atomizer performance was meticulously investigated by exploring three distinct bolt positions depicted in Figure 3 (b), (c), and (d). In the first configuration, the impactor is situated near the center of the mixing chamber, or equivalently, the midpoint between the air inlet and mixture outlet. Subsequently, the bolt was adjusted 5 mm away from the center for the second position, and again for the third position. These variations in impactor positioning alter the manner in which air impinges upon the liquid surface, potentially influencing the interaction between air and the liquid jet, thus directly impacting atomizing performance and the atomization process overall. The presence of the impactor bolt within the air-water injection zone may ultimately augment the capabilities of the existing injector.

3. Results and discussion

Within the intricate dynamics of the spray system, droplet diameters were analyzed using two distinct parameters: the mean diameter, reflecting the average size across the spatial expanse of the spray, and the Sauter diameter, which quantifies the volume-to-surface area ratio. These measurements are crucial for a comprehensive understanding of spray behavior. While the initial breakup of liquid jets primarily occurs within the mixing chamber, the main focus of the study lies within the secondary atomization breakup region. Nonetheless, special attention is given to the vicinity of the injector's injection tip, where the spray exhibits a tightly compacted nature, posing challenges in accurately assessing droplet size and distribution. This study meticulously presents data collected at various downstream and radial positions from the injection tip.

3.1 Centreline variation and distribution of droplet diameter and velocities:

Figures 4(a) and (b) offer a comprehensive visualization of the mean droplet diameter and Sauter mean diameter variations along the spray centerline, while maintaining a fixed air-to-liquid mass flux ratio (ALR) of 0.09. The illustrated data reveals distinct zones that delineate the evolving dynamics of the spray. In the initial zone, extending up to 40 mm from the injector's tip, droplet sizes exhibit an increasing trend along the axial direction. This region presents challenges in accurate droplet size prediction due to the dense and compact nature of the spray. The presence of numerous non-spherical particles, unaccounted for by the Phase Doppler Particle Analyzer (PDPA), contributes to notably low data capture rates in this dense region. Moving downstream, a second zone emerges characterized by radial dispersion, likely induced by the formation of ligaments or larger droplets. This region, termed the atomizing zone, witnesses a decrease in droplet sizes with downstream progression until reaching a critical stage where further reduction becomes unlikely.

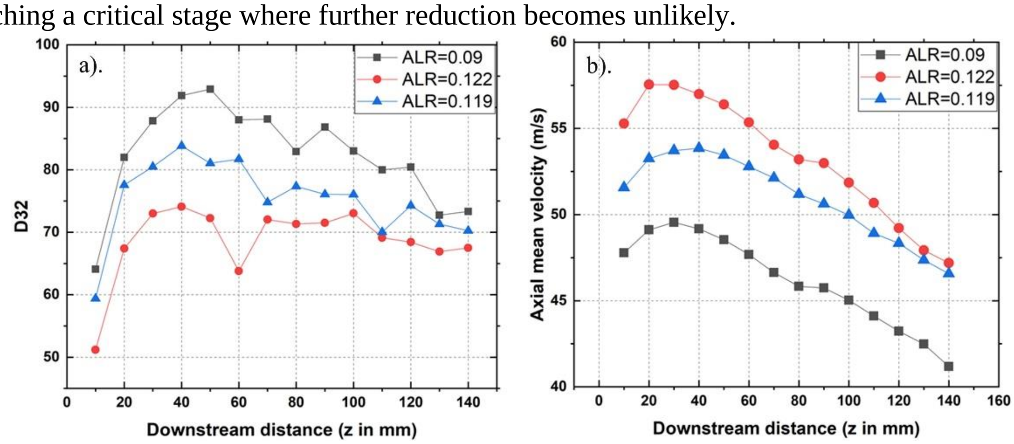

Fig. 4: Effect of ALR on droplet sizes

Observations reveal a gradual increase followed by a decrease in D32 within zone 1, with minor fluctuations attributable to a mixed mode encompassing column and surface breakup modes. Similar fluctuations are observed across various air-to-liquid mass ratios, indicating the presence of mixed modes leading to the simultaneous formation of fine and large droplets, resulting in fluctuating trends in SMD variation. Subsequent analysis delves into the breakup mechanisms influencing droplet formation and dynamics. Figures 5(a) and (b) further elucidate the centerline variation of mean droplet velocities, depicting a gradual decrease in axial velocity with downstream locations within the atomized zone, while radial velocity exhibits an almost linear increase. Further insights are gleaned from the probability density function (pdf) of droplet size and velocity distributions depicted in Figure 5. The pdf analysis confirms a leftward skew and upward peak shift in size distribution with downstream progression, signifying a decrease in droplet size and an increasing number of droplets. Similarly, the pdf of axial mean velocity displays a leftward skew and upward peak shift with downstream distance, indicating a reduction in droplet mean velocity and an increased prevalence of droplets dominating streamwise spray transport. Near the atomizer exit, radial mean velocity approaches zero, denoting minimal dispersion and a compact jet, gradually increasing as the spray disperses and more droplets emerge beyond the compact zone.

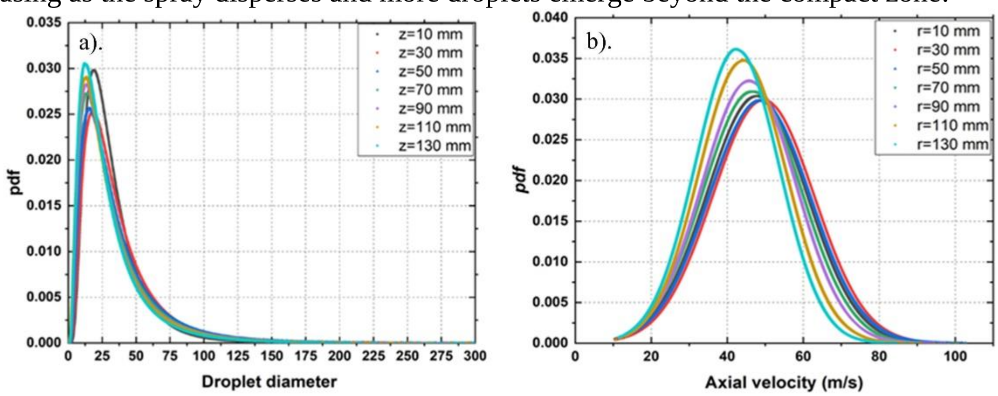

Fig. 5: Probability density function for droplet size and velocity distribution.

3.2 Radial variation and distribution of droplet diameter and velocities

Figure 6 (a) and (b) illustrate the radial evolution of droplet size at various downstream positions. Droplet sizes exhibit a gradual decrease from the spray core towards the edges, followed by an increase as one approach the periphery. Notably, the largest droplets are observed at the peripheral locations of the spray. This behavior is characteristic of a swirl injector, where centrifugal forces propel larger droplets outward. The radial variation of droplet size delineates three distinct zones: the spray core, characterized by medium-sized droplets with higher axial velocity; the fine zone, comprising smaller or very fine droplets with moderate velocities; and finally, the outer zone, where larger droplets with lower velocities are observed, likely due to coalescence or radial dispersal of larger droplets. These zones and their corresponding droplet classes are depicted in Figure 7. Examining the radial variation of droplet velocities, as depicted in Figure 6 (c) and (d), reveals that axial velocity peaks in the core zone and gradually decreases towards the edges. In zone 2, axial mean velocity decreases nearly linearly with radial distance, while in zone 3, it decreases gradually or remains relatively constant. Figure 7 (c) portrays the radial evolution of radial mean velocity. Here, it is evident that in zone 1, droplet mean radial velocity is minimal and increases drastically to its maximum. In zone 2, the velocity approaches its maximum before decreasing, while in zone 3, the decrease is gradual or appears to plateau. Similar droplet distribution behavior was observed at both locations (z=30 mm and z=130 mm), with skewness continually decreasing, indicating the formation of larger droplets through coalescence or aggregation, which may or may not involve separation and exhibit significant drag, resulting in momentum loss.

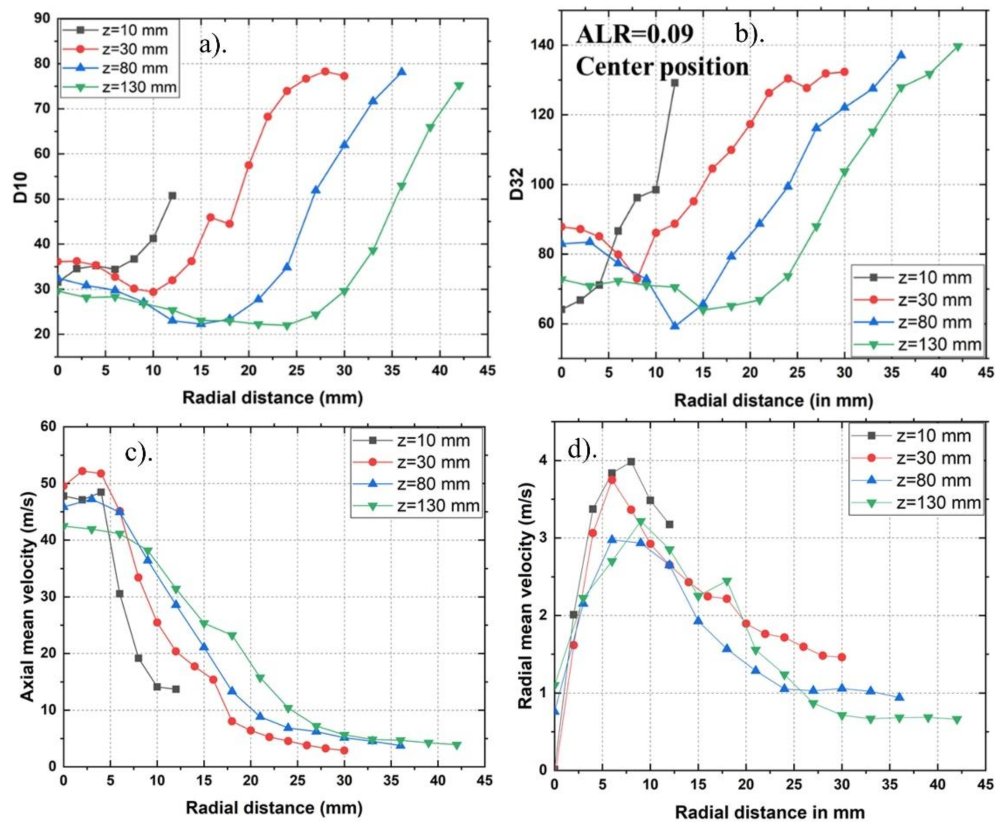

Fig. 6: Radial variation of droplet sizes and velocities.

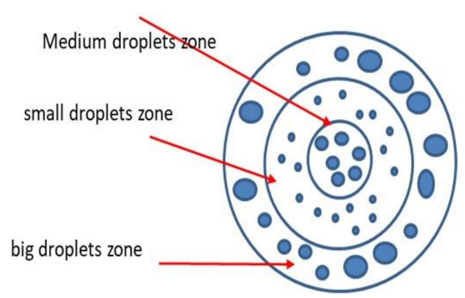

Fig. 7: Schematic of droplets classes

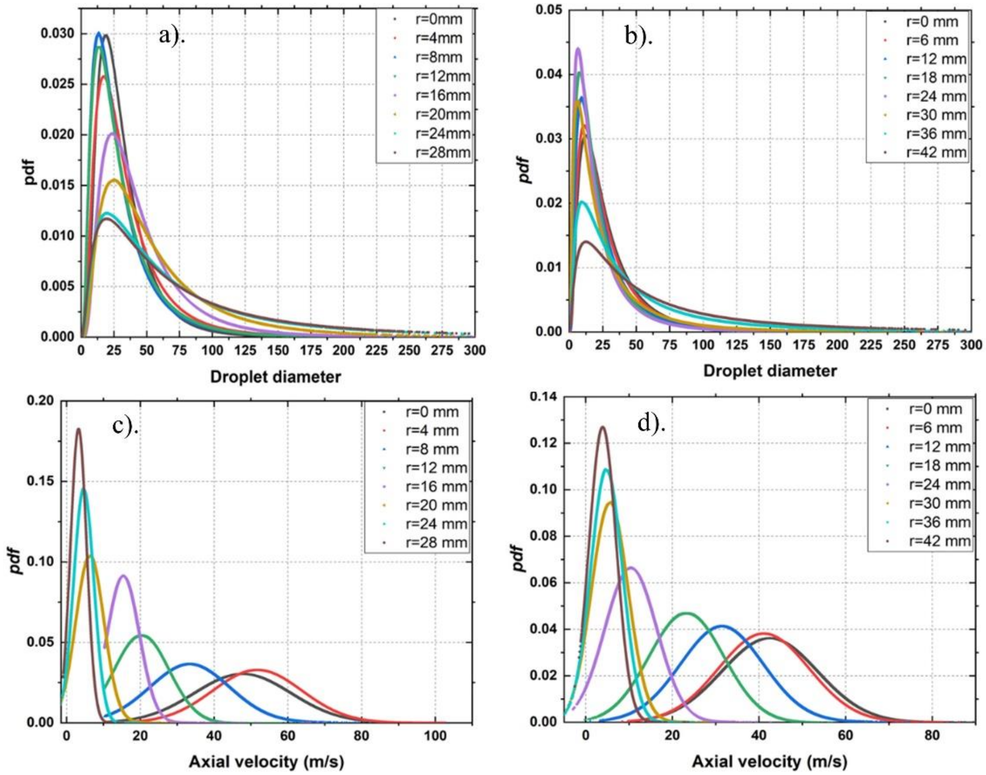

Fig. 8: Radial distribution of droplet size and velocities.

3.3 Effect of Water flow rates

Figure 9 (a) presents the influence of liquid (water) flow rates on droplet characteristics, including sizes, velocities, and data acquisition rates across various downstream locations. Specifically, it illustrates the axial variation of the Arithmetic Mean Diameter (AMD) of droplets for different liquid flow rates while maintaining a constant air flow rate. At lower liquid flow rates, the AMD gradually decreases, indicating ongoing secondary atomization processes without reaching the critical stage at the target locations. Conversely, at higher liquid flow rates, droplets appear to achieve the critical stage, resulting in uniform or minimally affected sizes, suggesting the completion or near-completion of secondary atomization. Notably, droplet size increases with liquid flow rates, with a significant decrement observed at lower flow rates due to higher energy transfer, while larger flow rates exhibit a more gradual decrease in Specific Mean Diameter (SMD), approaching the critical stage. Consistently, droplet velocities decrease with increasing water flow rates, reflecting the greater energy required for atomization at higher flow rates and consequently less momentum attained by droplets compared to lower flow rates. Figure 9 (d) displays the variation in data acquisition rates at different downstream positions for various liquid flow rates. Generally, droplet data rates exhibit a logarithmic increase with liquid flow rates, except at high flow rates ($\dot{m}_w = 0.1$ kg/s), where an almost linear increase is observed. This trend suggests an enhanced formation of spherical particles with downstream progression, indicative of improved atomization levels, while the number of tiny particles decreases with increasing flow rates. Overall, higher liquid flow rates adversely affect atomization quality, leading to a reduced rate of tiny droplet generation.

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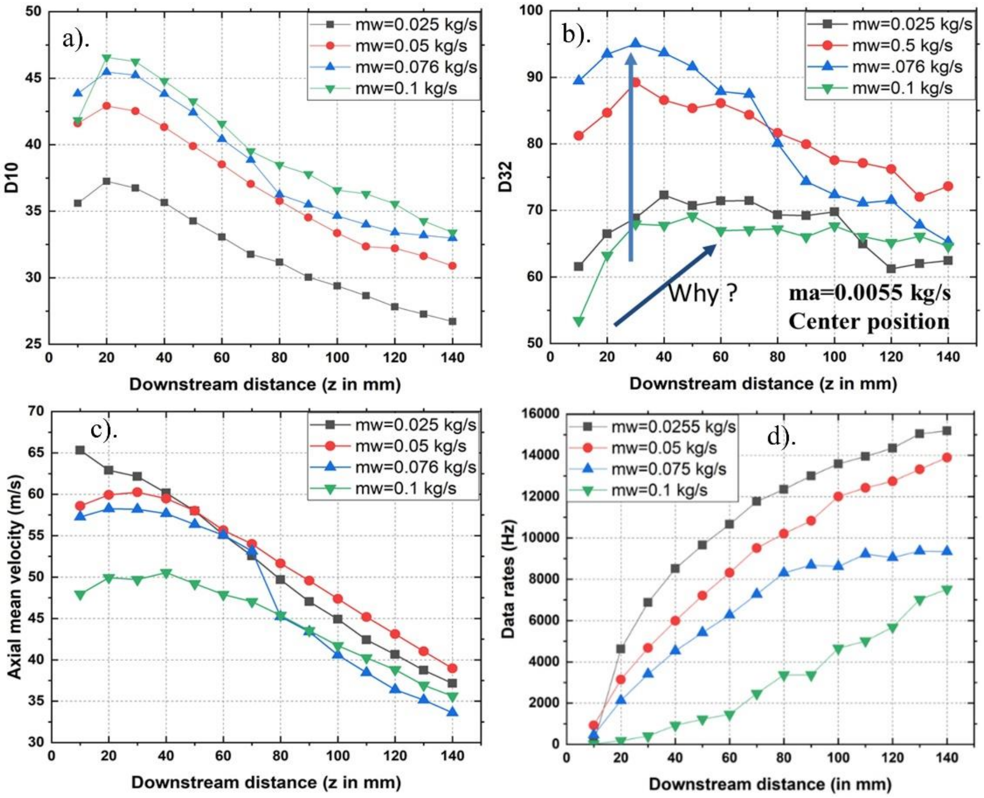

Fig. 9: Effect of liquid flow rate.

3.4 Effect of Impactor bolt's positions

In figure 10 (a) displays the axial distribution of Sauter Mean Diameter (SMD) across different impactor positions. Notably, a reduction in droplet size is observed, particularly within the atomized and critical zones, when the impactor is positioned 5 mm away from the center. This reduction is likely attributed to heightened shearing forces and droplet stripping, leading to the breakup of the liquid sheet column and surface, ultimately yielding finer droplets.

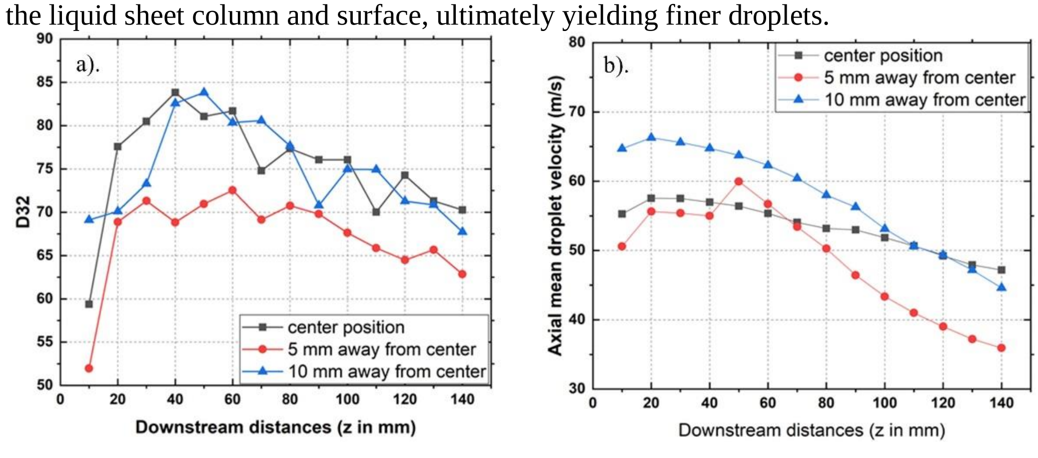

Fig. 10: Effect of impactor bolt's positions on sizes and velocity.

In figure 10 (b), the variation in droplet axial mean velocity is depicted, revealing higher velocities associated with injector positions located 10 mm away from the center compared to other positions. This discrepancy arises from the significant shift in the spray axis caused by the presence of the impactor bolt. Consequently, the spray trajectory adjusts in a direction opposing the positioning of the impactor bolt, thereby influencing the atomization dynamics of the injector.

3.5 Water- air interactions

Figures 11 (a), (b), and (c) depict the water-air interaction dynamics for all three positions of the impactor bolt the present atomizer setup. This interaction is particularly pronounced, leading to the breakup of the liquid jet column the interaction chamber by the high-speed transverse air jet acting on a conical liquid column. In Figure 11 (a), the bolt locations are situated almost at the center of the forthcoming air-jet injection orifice. As a result, the airflow deviates from its intended path due to the presence of the bolt. This deviation fosters a robust interaction between the air and water jets, with the air effectively enveloping a substantial portion of the water jet's interaction area. Consequently, both column and surface breakup modes become more prevalent, thereby enhancing the atomizer performance of the current injector by reducing droplet size and velocities. Moving to Figure 11 (b), the bolt is positioned 5 mm away from the center of the air injection orifice. Here, there is less interaction between air and water, with minimal deviation of the upcoming air jet from its intended flow field compared to the previous configuration. Consequently, column breakup becomes more dominant while surface breakup is less pronounced, as the diverted air flow strips off fewer droplets. Lastly, Figure 11 (c) illustrates the impactor bolt positioned 10 mm away from the center of the air injection orifice. In this configuration, there is no direct constriction in the airflow path. The air jet directly interacts with the water column, fracturing it into large chunks and a few droplets. Here, only the column breakup mode is predominant. With no loss of air momentum, droplet velocities attain high axial velocity due to significant momentum exchange. These large chunks subsequently mix with air and undergo further breakup into droplets, contributing to the overall mixing phases within the cylindrical passage.

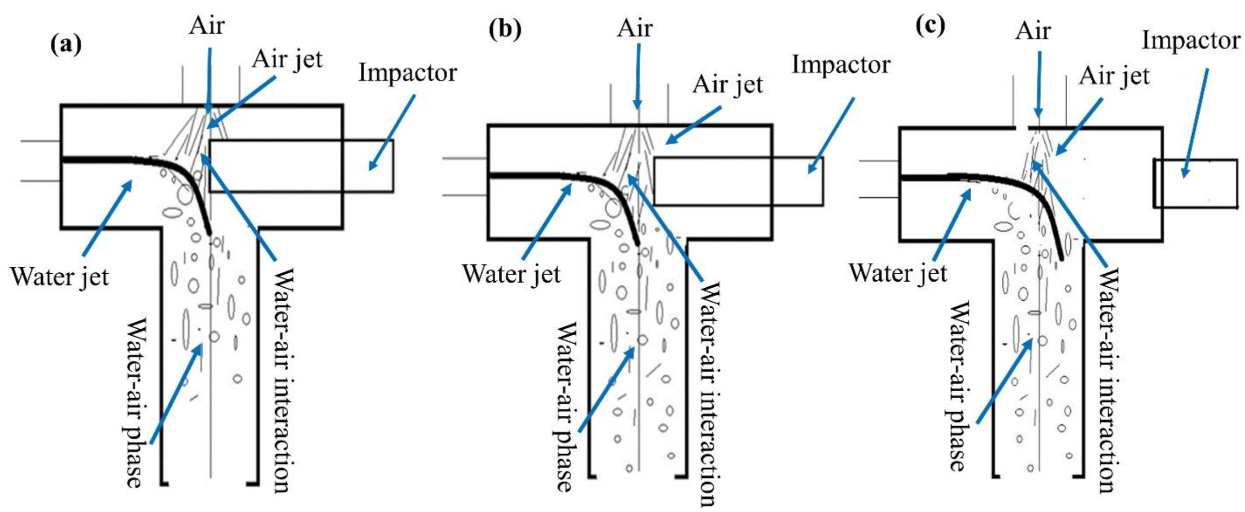

Fig. 11: Water-air interaction- breakup mechanisms (a) centre position (b) 5 mm away from the centre, and (c) 10 mm away from the centre.

4. Conclusion

A twin-fluid air blast atomizer was meticulously designed and crafted within an in-house laboratory setting, tailored for modern FCC riser applications. This innovative atomizer, featuring a variable structure and a strategically positioned target bolt within the mixing chamber, underwent rigorous experimental scrutiny to assess the impact of nozzle flow parameters and structural variables on droplet size, velocities, spray characteristics, and primary breakup mechanisms.

- Key findings of the study elucidate that primary breakup of the liquid jet predominantly occurs within the mixing chamber, facilitated by the aerodynamic forces exerted by impinging air. Notably, positioning the impactor bolt at 5 mm away from the center of the air injection orifice fosters heightened turbulence in the flow field, augmenting mixing and interaction with the liquid jet. This results in the dominance of both surface and column breakup modes, leading to a reduction in droplet size and velocities, thereby enhancing overall atomization efficiency.

- Conversely, as the impactor bolt is displaced away from the center of the air injection orifice, the air jet tends to adopt a more linear trajectory, thereby diminishing mixing, turbulence, and interaction levels. Consequently, lesser momentum is transferred to the liquid phase, resulting in diminished atomizing energy and subsequently larger droplet sizes and velocities. At significant distances from the air injection orifice, the dominance of the column breakup mode is evident.
- Moreover, at higher liquid flow rates, the spray density increases, thereby leading to a reduced droplet population density and lower data rates, particularly notable at higher water flow rates. This discrepancy raises concerns regarding the accuracy of measured (SMD) at higher flow rates.
- Finally, the formed spray exhibits three distinct classes of droplet size distribution: medium-sized droplets within the core region, characterized by higher velocities owing to their large inertia-to-drag ratio; larger-sized droplets near the spray edges, displaying lower inertia-to-drag ratios and inability to synchronize with airflow; and smaller-sized droplets occupying the intermediate zone of the core and the spray edges.
- These findings underscore the pivotal role of nozzle design and structural parameters in dictating atomizer performance, with implications extending to improved spray quality and efficiency in practical applications.

Acknowledgements

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References

[1] B. Klaus a Venuto PB, Habib ET. “Fluid Catalytic Cracking with Zeolite Catalysts”. Marcel Dekker, New York,1979.

[2] K.N., Theologos, A.I. Lygeros, N.C., Markatos “Feedstock atomization effects on FCC riser reactors selectivity”, Chem Engg Sci.;54(22):5617–5625,1999.

[3] C. Mirgain, C. Briens, M.D. Pozo, “Modeling of Feed Vaporization in Fluid Catalytic Cracking. Ind Eng”, Chem Res., 39(11): 4392–4399, 2000.

[4] A. Gupta, D.S. Rao, “Model for the performance of a fluid catalytic cracking (FCC) riser reactor: effect of feed atomization”, Chem Eng Sci., 56(15): 4489–4503, 2001.

[5] L.J.Guo, G.J Li., B. Chen, X.J. Chen, D.D. Papailiou, and T.h. Panidis, “Study on Gas-Liquid Two-Phase Spraying Characteristics of Nozzles for the Humidification of Smoke”, Exp. Therm. Fluid Sci., 26: 715-722, 2002.

[6] A.H. Lefebvre, J.S Chin., “Flow Patterns in Internal-Mixing, Twin-Fluid Atomizers”. Atomization Sprays, 3(4):463–75, 1993.

[7] A. Kushari, Y. Neumeier, O. Israeli, E. Lubarsky, B.T Zinn., “Internally Mixed Liquid Injector for Active Control of Atomization Process”, J. Propul. Power, 4(17):878–82, 2001.

[8] A. Kushari, “Effect of Injector Geometry on the Performance of an Internally Mixed Liquid Atomizer”. Fuel Process Technol. 91(11):1650–4, 2010.

[9] S. C. Ju, X. W. Li, “Experimental study on Internal Mixing Sonic Flow Air Assist Atomizer for Heavy Oils”. In: International Gas Turbine and Aeroengine Congress and Exposition, June 11, 1990–June 14, 1990. Brussels, Belg: ASME, p. T6, 1990.

[10] S. Kim, S. Kondo, K. Nishida, H. Hiroyasu, “Effects of Mixing Chamber geometry and flow on spray characteristics from an internal mixing twin-fluid atomizer. Int. J. Fluid Mech. Res, 24(1–3):76–87, 1997.

[11] D.A. Nguyen M.J. Rhodes, “Producing Fine Drops of Water by Twin-Fluid Atomisation”. Powder Technol. 99(3):285–92, 1998.

[12] A. Kufferath, B. Wende, W. Leuckel., “Influence of liquid flow Conditions on Spray Characteristics of Internal-Mixing Twin-Fluid Atomizers”. Int. J. Heat Fluid Flow, 20(5):513–9, 1999.

[13] J. Karnawat, A. Kushari., "Controlled Atomization Using a Twin-Fluid Swirl Atomizer". Exp. Fluids, 41(4):649–63, 2006.
[14] J. Karnawat, A. Kushari, "Spray Evolution in a Twin-Fluid Swirl Atomizer". Atomization Sprays 18(5):449–70, 2008.
[15] G. Ferreira, F. Barreras, A. Lozano, J.A. Garcia, E. Lincheta, "Effect of the Inner Twin-Fluid Nozzle with an Internal Mixing Chamber". Atomization Sprays. 19(9):873–84, 2009.
[16] G. Ferreira, J.A Garciia, F. Barreras, A. Lozano, E Lincheta, "Design Optimization of Twin-Fluid Atomizers with an Internal Mixing Chamber for Heavy Fuel Oils". Fuel Process Technol.90 (2):270–8, 2009.
[17] S. Lal, A. Kushari, M. Gupta, J. C. Kapoor, S. Maji, "Experimental Study of an Air-assisted Mist Generator". Exp Therm. Fluid Sci. 34(8):1029–35, 2010.
[18] L. Broniarz-Press, M Ochowiak, J. Rozanski, S Woziwodzki., "The Atomization of Water-Oil Emulsions". Exp Therm Fluid Sci. 33(6):955–62, 2009.
[19] D. Kumar, T. Sikroria, A. Kushari, P. Kumar, and G. Sriganesh, "A twin-fluid injector for FCC feed injection", Int J Petrochem Sci Eng., 4(3):109–115, 2019.
[20] D. Kumar, T. Sikroria, A. Kushari, P. Kumar, and G. Sriganesh, "Spray Characteristics from a Twin-Fluid Atomizer with Internal Impactor" ILASS-Asia 2016, 18th Annual Conference on Liquid Atomization and Spray Systems - Asia, Chennai, India. 6- 9 Nov. 2016.