Development of a New Two-Phase Fluid Atomizer Nozzle in Pilot Scale for Fluid Catalytic Cracking Process

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ABSTRACT: *The uniform atomization of FCC feed causes to produces desirable products like gasoline and decreases undesirable products like coke and dry gas. The atomization process caused the selectivity and efficiency of main products to increase. So Design and manufacturing of optimum atomizer system in FCC process are important. According to this idea, A new twin fluid low-pressure atomizer nozzle including the air-assets type of Nozzle was manufactured in RIPI (Research Institute of Petroleum Industry-NIOC Iran) from small to large scale. The nozzles sizes were categorized with small to large sizes according to water flow rate(4-50 kg/h). The analysis of spray nozzles pattern and droplet size was made by use of Doppler method with using of Doppler laser analyzers. Many tests were carried out for each size of nozzles, and a flow rate of 50 kg/h a specified nozzle was manufactured and introduced. The general configuration of the nozzle is introduced in this manuscript. The experimental data evaluation for nozzles shows that for a water flow rate of 50kg/hr and air of flowrate 1.4 kg/h, The quantity value of Sauter mean-diameter (D_{32}) and arithmetic diameter (D_{10}) for water droplet particles becomes 150 µm and 50 µm respectively. The following assessment on the pilot-scale will help to develop a new atomizer nozzle on large scale. It shall be mentioned that the development of a new atomizer on a large scale is according to experimental data at the pilot plant scale. Minimization of Sauter means diameter (D32) and arithmetic diameter (D10) for water droplet particles will be variables parameters to optimized atomizer nozzle dimension and configuration.*

Keywords: *Nozzle, Fcc, atomization, Laser, Doppler, Low pressure, Fluidized.*

INTRODUCTION

Fluid Catalytic Cracking (FCC) is one of the most flexible and profitable refinery upgrading processes. While commercialized more than 70 years ago, FCC has maintained a preeminent position by evolving to meet changing product, environmental and operational demands quickly and profitably. Several recent hardware developments are aimed at debottlenecking unit constraints to improve financial performance. Specific developments including the following items are carried out for FCC process as elimination of post-riser thermal cracking, stripper modifications to reduce coke make, and high-efficiency feed and catalyst mixing. The feed injection system is one of the keys to yield optimization and profitability. Catalytic cracking reactions occur in the vapor phase

on the active catalyst surface. Therefore, a well-designed feed injection system must provide quick vaporization and intimate contact between catalyst and oil. Poor feed vaporization and mixing create localized regions of high and low catalyst-to-oil ratios and induce back mixing which increases coke formation. Improvements in feed injection can reduce coke and light gas production, resulting in higher conversion and improved selectivity toward premium products. Gasoline yield increases as high as 5 vol% and conversion increases of over 4 vol% have been observed commercially with the Kellogg/Mobil ATOMAX feed injection system [1]. Rapid feed vaporization requires atomization into small droplets with a narrow size distribution. Smaller droplets vaporize faster than larger droplets. The feed injection system must also efficiently use the available liquid pressure drop to reduce operating costs or provide optimum atomization within fixed feed supply pressure constraints. The spray pattern from the nozzle must evenly distribute the oil within the riser to provide rapid and uniform oil and catalyst mixing. Oil should be sprayed into a dense phase of the catalyst to ensure high local catalyst-to-oil ratios. The feed must have sufficient momentum to penetrate the flowing catalyst without causing erosion of the riser wall or excessive catalyst attrition.

Feed atomization system

The feed injection is by far the most critical part of modern FCC riser reactor design. An atomizing nozzle for injecting fluid catalytic cracking (FCC) feed into a cracking riser comprises a spray nozzle for breaking up the feed to form a conical, atomized spray of feed which is confined within an open-ended nozzle pipe surrounding the spray nozzle and which extends downstream from the spray nozzle. Atomizing gas, usually steam, passes around the spray nozzle to promote further atomization and vaporization of the feed, and the mixture of feed droplets and atomizing gas is passed through an orifice plate at the tip of the spray, nozzle pipe to expand the spray across a greater axial distance. The atomizing system provides improved feed atomization and contact with the cracking catalyst with relatively low-pressure drops.

The atomization in FCC are completed and optimized according to the following steps:

● The first generation of modern FCC feed nozzles was introduced in 1980,s [2]. The design was based on producing a high-velocity liquid jet and shattering liquid jet to droplet upon hitting the target and conveying the droplets with steam to nozzle exit. As a result, this nozzle requires high feed pressure and high steam usage to achieve desirable feed atomization. Also, this design belongs to *Lefebvre* [3]

● The second generation of modern FCC feed nozzles was introduced in the early 1990[4] which all belongs to *Lefebvre* [3]. Definition of internal mixing, twin fluid atomizers. The atomization mechanism of these designs was based on internally mixing the steam and liquid feed upstream of the nozzle exit, using some form of mixing device, and conveying a two-phase mixture to nozzle exit. This design was an improvement over the first generation of feed nozzle, particularly in reducing the requirement of high feed pressure. However, all internal mixed twin-fluid atomizers have a common drawback. The two-phase mixture will stratify during conveying to the nozzle outlet. Regardless of how mixing two phases initially leading less efficient atomization in the exit. RIPI also developed its twin fluid nozzle according to this nozzle, experimental data, and spray nozzle pattern has shown efficient atomization and its result was not in accord with the above sentences.

● The newest optimized generation of FCC feed nozzles was introduced in the late 1990,s which are twin fluid atomizers using two-phase chocking as the atomization mechanism[5,6]. In these nozzles, atomization steam is mixed with stream before the final outlet of the nozzle, preventing the stratification of two-phase flow. As the homogenous two-phase flow passes through the final outlet, the sudden expansion of the two-phase flow shatters the liquid into fine atomization.

● *Jabreli Jolodar et al* [7] and RIPI Atomizer development team performed the design and manufacturing of a two-phase nozzle at the scale of 4 kg/h water flow rate. The sketch of the atomizer nozzle as shown in Fig. 1. The manufactured nozzle had the third part as follows: a) Primary mixing b) Hard mixing c) Atomization

● A new type of twin-fluid injector is designed and developed by *Kumar D. et al* [9]. They incorporate an impactor plate with rectangular slots inside the injector. For FCC, they reviewed the process and mentioned that the main component of FCC system is the atomization injection system. They were mentioned that FCC feed injection system is the most critical hardware component of FCC unit to get desired product yield by minimizing
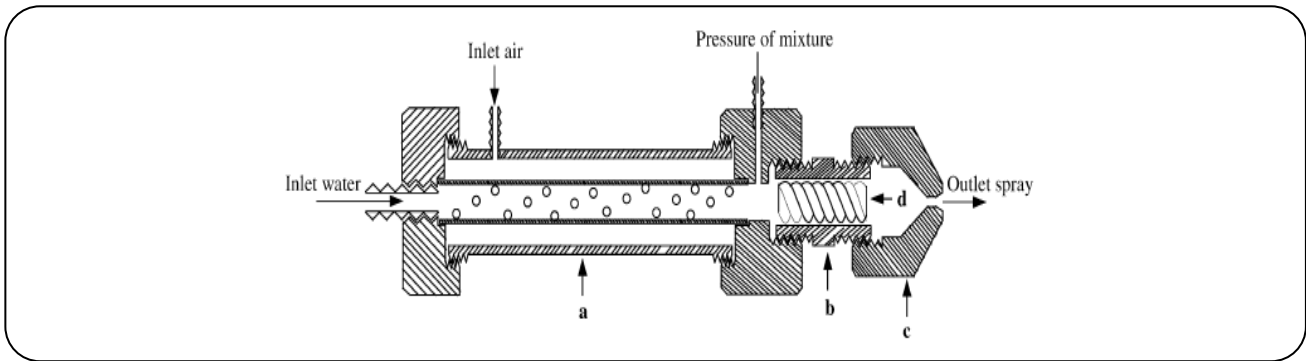
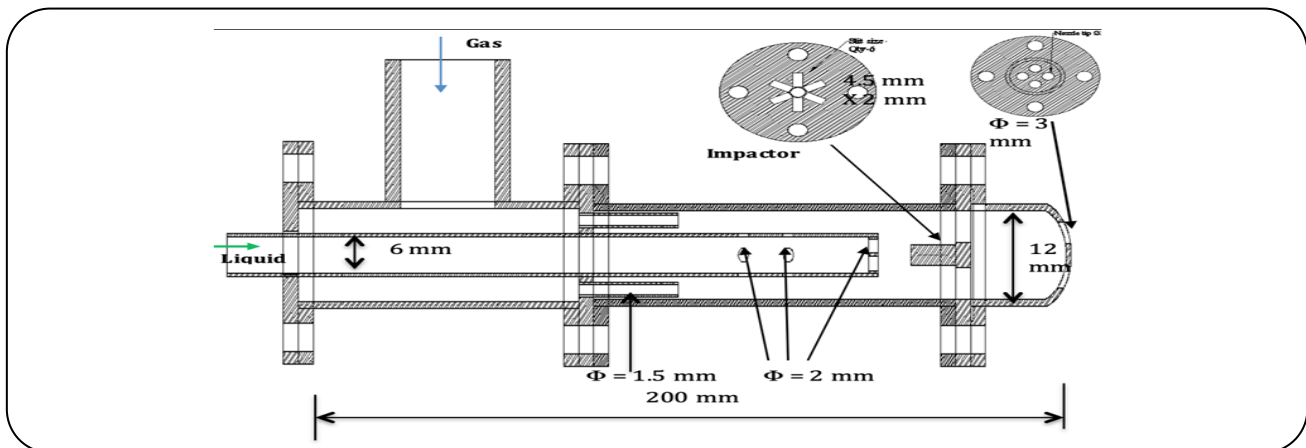*Fig. 1: Manufactured of two-phase atomizer nozzle by Jabreli Jolodar et al [7].*

Fig. 2: Schematic diagram of the developed two-phase injector (atomizer nozzle) by Kumar et al [9]

the undesirable dry gas and coke yield. Typically, twin-fluid nozzles (hydrocarbon and stream) are used to atomize the feed. In their study, a twin-fluid injector, with an internal impactor to minimize the droplet size and velocity, is designed, developed, and characterized. The method and system that were used are the same as *Jabrelia Jolodar et al* [7] and *Sadeghipour Khameneh* [8]. They manufactured a two-phase nozzle as depicted in Fig. (2) [9].

The set-up used by *Kumar et al*. [9] is depicted in Fig. 3. According to their investigation a relation for Sauter mean diameter(SMD) of the droplet with Air-Liquid Ratio(ALR) are developed :

SMD(mm)=53.55(ALR) $^{-0.31}$

According to the designed nozzle, Primary atomization is due to the impingement of water jet onto the impactor plate. The droplets thus produced are convicted downstream by the air. According to their tests, the water flow rate is independent of the airflow rate. This feature makes the developed injector unique among the twin-fluid atomizers. The droplet size is seen to be a function of ALR

produced by the atomizer is a solid cone spray with smaller droplets at the center and larger droplets away from the center followed by a further reduction in the droplet size towards the edges of the spray. [9]

● Experimental and numerical investigation of spray characteristics of a swirl Fluid Catalytic Cracking (FCC) feed nozzle was presented by *Qilong* and *Jinxian* [10]. In the experiments, the spray angle and Sauter Mean Droplet (SMD) were measured by them. Then pressure drop on each section of the nozzle was verified. Volume of Fluid (VOF) method by using fluent software and Gambit was used to simulate the gas-liquid flow process in swirl FCC feed nozzle.

● In Computational Fluid Dynamics (CFD), the Volume of Fluid (VOF) method is a free-surface modeling technique, i.e. a numerical technique for tracking and locating the free surface (or fluid-fluid interface). It belongs to the class of Eulerian methods which are characterized by a mesh that is either stationary or is moving in a certain prescribed manner to accommodate the evolving shape of the interface.
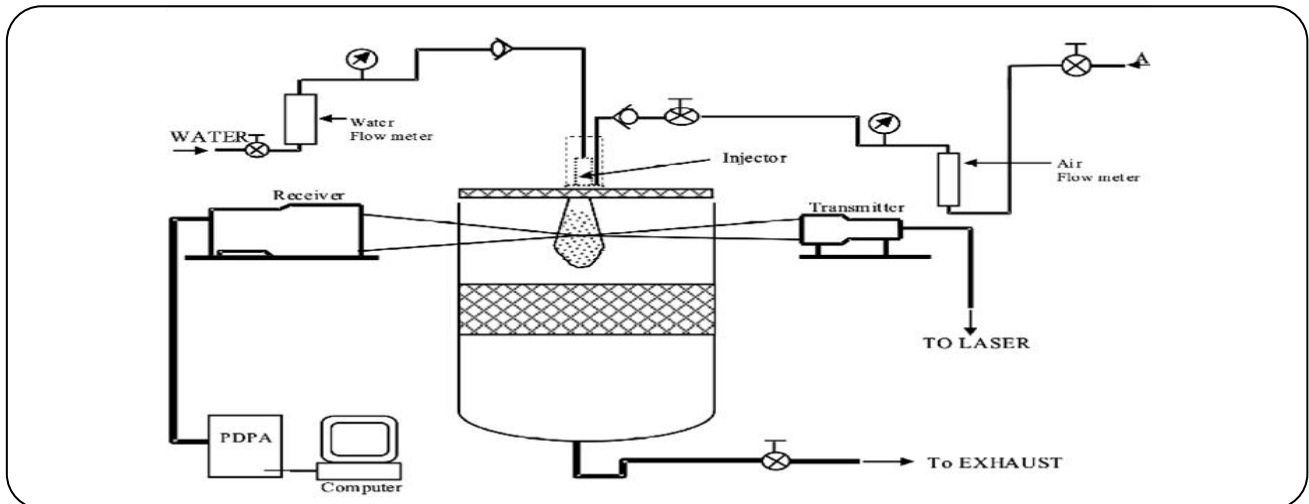
Fig. 3: Schematic diagram of the set-up used by Kumar et al [9]. It consisting of water flow measurement, airflow measurement, phase Doppler particle analyzer(PDPA) system, Receiver and transmitter, laser, and computer system.
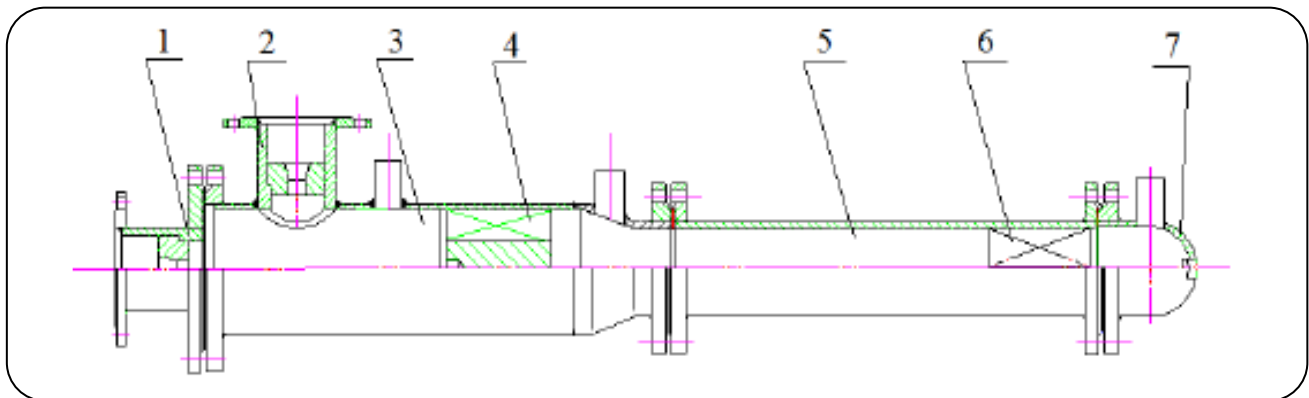

Fig. 4: Schematic diagram of two-phase flow swirl feed nozzle developed by Qilong and Jinxian [10].
(1) Center gas inlet(2) Side liquid inlet(3) Mixing chamber(4) Cyclone, (5) Injection tube, (6) Cross grille (7) Spherical head.

As such, VOF is an advection scheme—a numerical recipe that allows the programmer to track the shape and position of the interface, but it is not a standalone flow solving algorithm.

The simulation exhibited the process of two-phase flow filling feed nozzle. The nozzle pressure was predicted using fluent simulation, which was validated by the experimental data with good agreement. The results show that: the SMD size of droplet particles feed nozzle was 59-74μm; nozzle with short sheet had the smallest SMD; cross grille in nozzle effectively inhibited the flow rotation.

Swirl Feed Nozzle Structure.[10].

AT Fig. 4, a swirl feed nozzle is depicted. Under the crushing of high-speed airflow, the film was fractured. After passing through the injection tube, the nozzle atomization process completes.

The nozzle test system was used by *Qilong* and *Jinxian* [10]. is shown in Fig. 5. The test medium is water and compressed air. Using pump-type water supply system and required air from gas source through the valve. SMD and particle velocity were measured by a three-dimensional laser Phase Doppler Particle Analyzer (PDPA). It was used a digital camera to shoot the atomization on the side of the nozzle. The real-time pressure data of the nozzle were collected by pressure sensors.

Developments have made the feed injection system increasingly important because of the following items [11]:

● Due to the development of a highly active zeolite FCC catalyst, the reaction time has been shortened to a few seconds in the modern riser reactor.

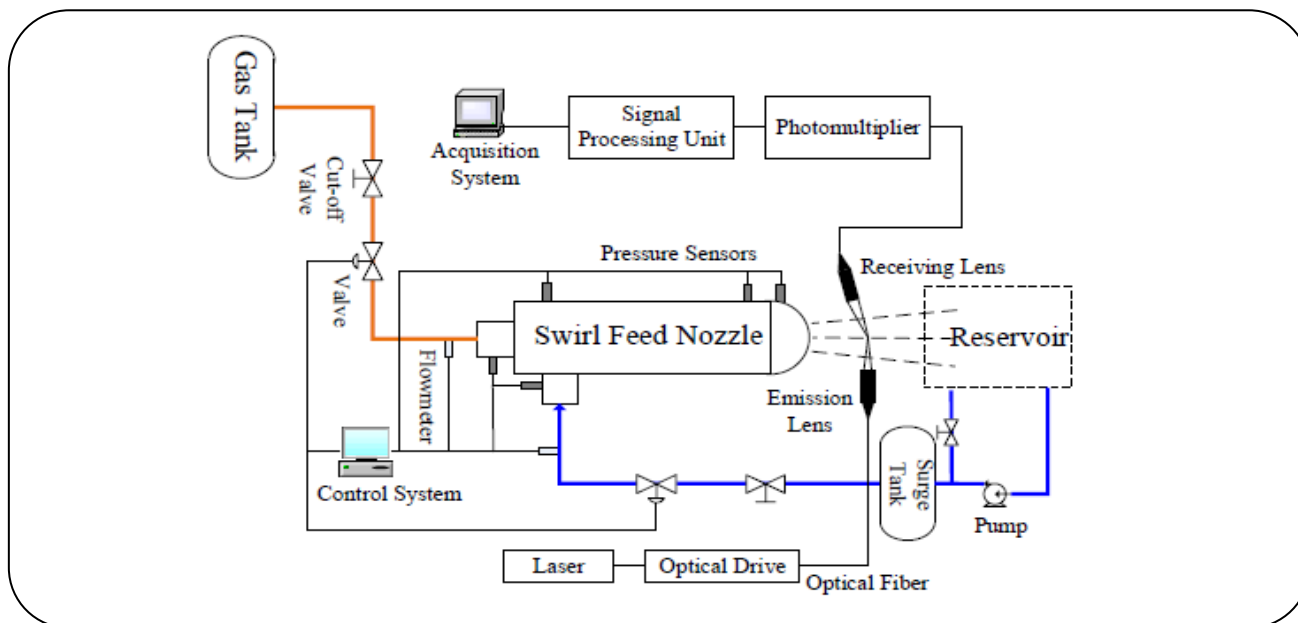●The regenerator temperature is getting higher to achieve

Fig. 5: Schematic diagram of the set-up used by Qilong and Jinxian [10].

more complete catalyst regeneration. The typical modern riser top temperature is in the range of 510–566ºC, but the typical regenerated catalyst temperature is much higher, in the range of 677–760 ºC. Feed injection reduces thermal cracking reactions by cooling off the lower riser quickly through fast mixing and vaporization of the feed.

● FCC feedstock is getting heavier, which makes feed vaporization more difficult

The new generation of the atomizer

The newest generation of side-entry FCC feed nozzles generates more uniform feed distribution as a result of better control of homogeneity of two-phase flow and atomization at the nozzle exit using two-phase choke flow. Some older FCC units still retain the original feed injection system located at the bottom of the riser (bottom-entry nozzles). A new generation of feed injection technology uses a similar side-entry atomization mechanism. For catalyst circulation, the bottom-entry nozzles have the advantage of reducing pressure drop through the riser. This system also enables longer riser residence time if riser height is limited. The newest generation of FCC feed nozzles also provides faster mixing with a catalyst because of the sudden expansion of two-phase choke flow at the nozzle exit, creating a strong suction to draw in the catalyst. Commercial experience has shown that the feed injection angle also plays a significant role in catalyst

mixing, impacting the temperature profile in the riser. Although most modern FCC units have feed nozzles installed through riser shrouds at a fixed angle, a new feed nozzle design, shown in Fig. 6, enables feed injection angle adjustment while using existing riser shrouds. This enables optimized mixing of feed and catalyst by adjusting the injection angle to optimize FCC performance. Commercial FCC operation has confirmed that using the newest generation feed nozzles optimizes the temperature profile in the riser and substantially reduces dry gas, thereby increasing gasoline yield. These results are in line with the expectation that better feed injection design reduces thermal cracking reactions, which are the primary source of dry gas. As a result, catalytic cracking reactions are maximized and more desirable products are produced. In many refineries, the Fluid Catalytic Cracking (FCC) unit serves as the primary conversion unit, converting, or cracking, low-value crude oil heavy ends into a variety of higher value, light products. In Iran and many other countries, the primary function of FCC units is to produce gasoline. Although FCC is a process that has been commercially deployed for over 70 years, the technology continues to evolve to meet new challenges, which include processing more difficult feedstock and meeting more stringent environmental regulations. Modern FCC units can process a wide variety of feedstock and can adjust operating conditions to maximize the production of gasoline,
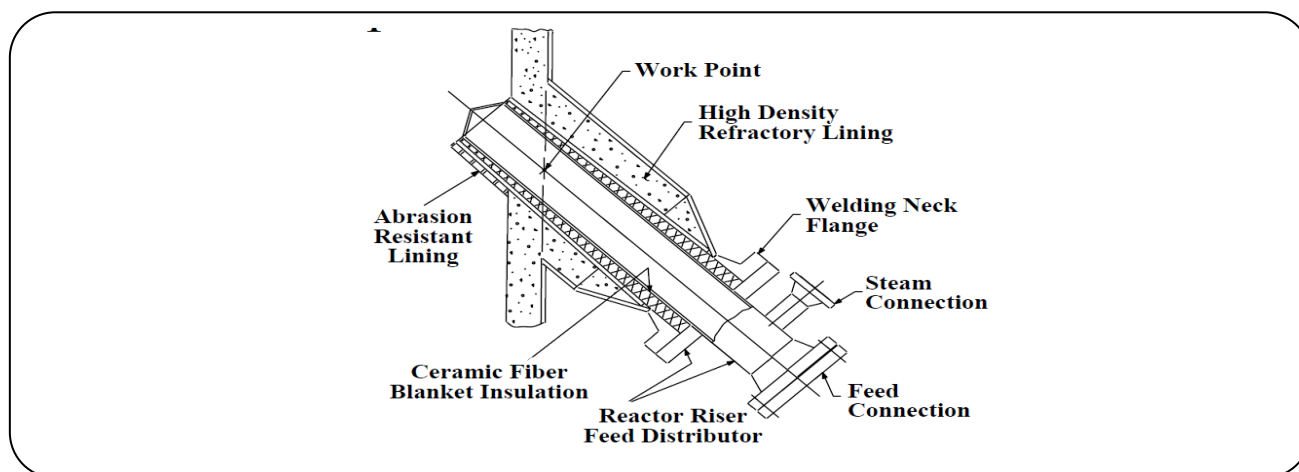
Fig. 6: Feed injection atomizer nozzle in riser reactor [11]. Feed nozzle including the following inlet point; steam and feed, Mixing of feed and steam shall be done before atomizing

middle distillate olefins (LCO) or light olefins to meet different market demands. *Farshi et al.* have been reviewed and experimentally investigated the FCC duties on Propylene demands [12,13]. These new challenges have inspired new technology breakthroughs [11].

Air atomizing nozzles

Air atomizing nozzles provide the finest degree of atomization and are available in four spray patterns: round, wide-angle round, 360° round, or flat. The spray pattern remains as long as the velocity of the atomizing air is maintained. The drops may evaporate completely, depending on size, exposure time, and other ambient conditions.

Internal mix

Internal Mix means that the liquid and air are mixed internally to produce a completely atomized spray. The liquid and gas streams are not independent and a change in airflow will affect the liquid flow.

External mix

External Mix means that the liquid and air streams are mixed outside of the nozzle. Air and liquid flow can be controlled independently. This is effective for higher viscosity liquids and abrasive suspensions. External mix can be siphon set-ups or pressure set-ups.

Spray Set-Ups

Each air atomizing nozzle series is available with a pressure spray set-up or siphon spray set-up. Each spray set-up provides a specific spray pattern with a specific capacity and sprays coverage range performance. Spray set-ups are interchangeable for each nozzle series.

Pressure set-up

The liquid is supplied to the nozzle under pressure. Air and liquid can internally mix to produce a completely atomized spray.

Siphon or gravity-fed liquid set-ups

The liquid is supplied by either a liquid siphon or gravity-fed. These set-ups are designed to draw liquid through the feed line into the airflow where it is atomized.

RIPI atomizing nozzle type

The pattern of the Manufacturing nozzle that was developed in RIPI is according to the internal mixing of air and water in the inner side of the nozzle.

Phase Doppler particle analyzer method

Large volume two-phase atomizers are used in many applications, such as industrial gas scrubbing and FCC atomization process, for which accurate drop size is important .due to high number density characteristics sprays from this nozzle are difficult. This has led to the cooperation of two companies of aerometric Inc. And spraying systems co. to work together to develop a reliable method for analyzing such sprays, using Phase Doppler Particle Analyzer (PDPA)[14]. They evaluate a method for characterizing large volume, two-fluid atomizers using the Phase Doppler Particle Analyzer (PDPA).
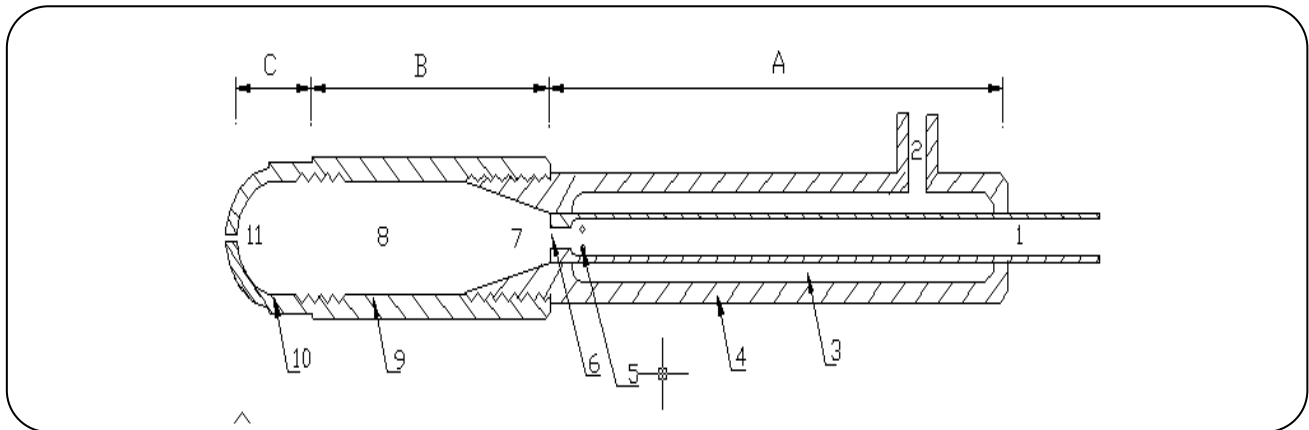
Fig. 7: The design of a two-phase atomizer nozzle with a capacity of 50kg/h [8]. Description of components: 1-Water inlet point, 2-Spray gas (air)inlet point3-Air follow section4-Structure primary mixing section5-Holes of spray air injection6-Mixer spray orifice 7-Primade part8-Expansion structure 9-Expansion section10-Nozzle head11-Outlet orifice

By using a laser of adequate power, errors due to obstruction and multiple scattering can be reduced. The PDPA photo multiplier's power can be set and optimized to ensure adequate data validation at the sampling area. The sampling method consists of collecting data at various radial locations throughout the spray.

EXPERIMENTAL SECTION
Developed low pressure twin-fluid internal mixing nozzle

RIPI (Research institute of the petroleum industry) begun its study on atomizer development in 2004, *Jabraieli et al.* [7] developed its atomization nozzle on a scale 4 kg/h water. Then *Sadeghi Pour Khamene* [8] scale-up atomization nozzle. Research and study of atomizing nozzle for a fluid catalytic cracking show that there is not standard formalize relation with information data for the design of nozzles. The licensor company usually designs the nozzle according to experimental data. The design of atomizer nozzle in RIPI is gathered from data of patents, review of structural of the nozzle in different industry and trial and error in manufacturing different atomizer. According to this idea to reach an optimized nozzle, a nozzle with changeable parts is manufactured, with changing different parts of nozzles all tests conducted in set-up.it is evaluated that each nozzle that could produce turbulent flow in the liquid jet can produce optimized atomization from liquid particle diameter and spray nozzle pattern viewpoint. [8]

Design Feature of Atomizer

The atomizer nozzle was designed according to some information from research, patents, and previous project.

The process variable of atomizer nozzles was water flowrate, air percentage ratio to water as 3%, and air velocity as 250*water jet velocity. The process variables parameters were calculated for atomizer nozzle with a water flow rate of 50 kg/h as the following list:

Airflow rate (1.5kg/h), with piping inside diameter(4.6mm), Jet liquid velocity(0.847m/s) ,Injected air velocity(212m/sec)

With the above technical data, an atomizer nozzle with changeable parts is made and tested in many laboratory tests.

At FFAs referred to in Fig. 7, the two-phase atomizer is designed with a capacity 50 kg/h [8]

This atomizer concept was the same as the atomizer manufactured by *Jabereil Jolodar et al.* [7], its content of the third section as already mentioned. Primary mixing section(A), Homogenized or hard mixing section (B) Atomizer outlet section (C)

Experimental Test Set-Up

An experimental setup is designed and manufactured. The atomization set-up containing the following section :

1-Feed injection section

2-Atomization section

Feed injection section including Feed tank, feed pump, pressure gauge, temperature gauge, air gas cylinder, mass flow meter, pressure, and temperature gauge.

Atomization section including Nozzle apparatus, laser Doppler particle dynamic analyzer, and computer.

The Schematic of nozzle experimental test set-up is shown in Fig. 8 [7,8].

T₁ - Water tank
P₁ - Water pump
V₀ - Water recycle valve
K.O.D. – Knock out drum
PI₀ - Inlet water pressure indicator
V₁ - Water valve
FI₁ - Water flow meter
PI₁ - Water pressure indicator
CV₁ - Water Chech valve
PIC - Air pressure indicator & controller
V₂ - Air valve
FI₂ - Air flow meter
PI₂ - Air pressure indicator
CV₂ - Air check valve
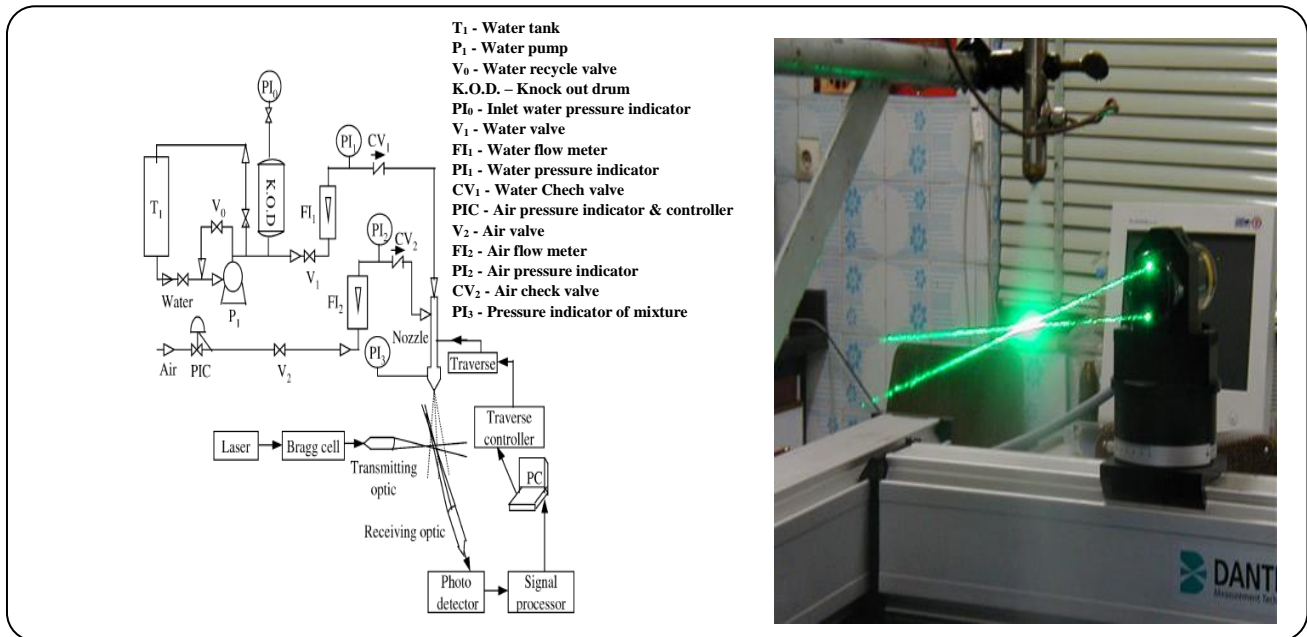**PI₃ - Pressure indicator of mixture**

Fig. 8: Atomizer nozzle experimental test set-up[7] with Picture of laser Doppler analyzer and computer [8]. All components of set-up are described besides of figure.

In Fig. 8 A picture of the Nozzle experimental test set-up with laser Doppler analyzer and computer is shown.

Experimental tests of the nozzle

There are different equipment for review and analysis of spray particles .usually they are categorized according to analyzing methods of particles that are used for study For the experimental study of particles the method of nozzle laser dynamic analyzer was used. laser equipment of Particle Dynamic Analyzer (PDA) has capable of analyzing together of velocity and diameter for spherical particles in gas and liquid phase. This equipment can measure the particle diameter of 0.5micro meter to a few mm size and velocity of lower than 500m/s. This equipment can also be capable to measure mass concentration and flux [14]. Measurement of diameter and velocity together causes that relation between parameters to be found. Velocity is measured according to frequency proportional of Doppler waves with Laser Doppler Anemometry (LDA). But measurement of diameter is done according to the comparison of two laser optical detectors that are installed at a different angle. Signals are received according to phase difference that is related to the location of laser accessories. These differences have directed relations to particles diameter. Generally, according to the type and behavior of a particle in a laser beam, three types of optical phases for the measurement of particle

diameter in PDA are described. These phases are categorized according to optic dispersion as following:

1-First order refraction

2-Reflection

3-Second order refraction

In the application of PDA it is usually the first-order refraction is used. for example, a particle of water and oil optic can pass in another selection method reflection (for a sample that optic of laser can not be passed) was used. The detailed description and theoretical effect of laser optic with the particle in water and oil will be given in reference [8].

Design and experimental data evaluation by Taguchi optimized method

For review, optimizing and design of atomizer, Taguchi method was used according to this technique the following parameters are selected: [8]

1-Number and diameter of holes of injection part of the air to water

2-Diameter of the spray hole

3-Diameter of outlet orifice hole for spray and water

 4-Air and water flow rate as the independent variable.

And according to the first laboratory tests and previous experiments, three levels were described (Table 1).

With referring to the reported variable in Table 1 Orthogonal arrays of L₁₈ for the design of tests with the Taguchi method

Research Article

Table 1: The Main Factors of Design Parameters of Nozzle and Three Orthogonal Levels of Them.

Variable	Level 1	Level 2	Level 3
Air injection hole numbers int(A)	2	3	4
Air injection hole diameter(mm)(B)	0.5	0.75	1
Atomizer Spray hole diameter(mm)(C)	2.5	3.5	4.5
Outlet orifice diameter(mm)(D)	1	1.5	2
Water volume flow rate(lit/hr)(E)	30	40	50
Mass flow rate of air(kg/hr)(F)	0.8	1.4	2

Table 2-Evaluating Spray Quality And Converting It To Quantity Value

Spray Quality	Spray Quality Sign	Spray Quantity Value
The spray distribution is completely homogenized, no pulsing, particle diameter is very low	A+	21
	A	20
	A-	19
The spray distribution is homogenized, low pulsing, the particle diameter is low	B+	17
	B	16
	B-	15
The spray distribution is homogenized, not medium pulsing, the particle diameter is high	C+	13
	C	12
	C-	11
The spray distribution is homogenized, not high pulsing, the particle diameter is high	D+	9
	D	8
	D-	7

is appropriate. the Orthogonal arrays L_{18} maximum for six factors of A, B, C, D, E, F with three layers are applicable and including of 18 numbers tests. The design of laboratory tests in two cases of quality and quantity are reviewed.

Laboratory quality tests

After the design of laboratory tests, the test was done for quality checking of spray. In each test, the result of the test was reviewed and given (Table 2). According to the following result the all problems are identified and with changing design conditions the tests have a good result. Therefore for designing the nozzle, it is required the quality result are converted to quantity value (Table 4). The designed laboratory test according to the Taguchi method in two series was done randomly and the result of the test are given in Table 5**.** This table shows how tests are done randomly [8].

Sauter Mean Diameter (SMD) and arithmetic mean diameter

The various mean calculations are defined in several standard documents. There are multiple definitions for mean because the mean value is associated with the basis of the distribution calculation(number, surface, volume). Laser diffraction results are reported on a volume basis. In fluid dynamics, Sauter's mean diameter (SMD D32 or D [15]) is average particle size. the equation for the surface means is shown below:

$$D[3,2] = \frac{\sum_{1}^{n} D_i^3 v_i}{\sum_{1}^{n} D_i^2 v_i} \qquad (1)$$

The generalized form of the equation is shown below equation:

Table 3: Result and Operating Condition Of Qualify Laboratory Tests with Taguchi Method.

Test no.	Randomly	Mass flow rate Kg/hr		Pressure drop Psig		Pressure operating Psig			Atomization qualification (first series)				Atomization qualification (second series)				Air %wt
		Water	Air	Air	Water	Atomizer	Air	Water	Distribution	Pulse	Size	Quantity	Distribution	Pulse	Size	Quantity	Air
1	1	30	0.83	6	3	46	51	48	B	C+	B	9	B	C	B	9	2.74
2	7	41	1.54	13	2	30	43	35	B	B	B	16	B	C+	B	16	3.76
3	13	50	1.92	5	1	16	21	17	A	B+	A	19	A	B+	A	19	3.85
4	2	41	2	10	2	44	54	46	A	B+	A	19	A	A-	A-	19	4.95
5	8	50.5	0.81	8	2	16	24	18	C	C	D	11	C	C	C	12	1.6
6	14	30.4	1.41	5	2	47	52	49	D	D	D	7	D	D	D	7	4.66
7	9	33.5	1.38	4	1	72	76	71	B-	D	B	15	B	D	B	15	4.1
8	15	32	2	9	3	22	31	25	B	D	B-	12	B+	D	B	13	6.25
9	3	39.1	0.83	7	5	8	15	13	C	C	D	8	C	B-	D	9	2.13
10	16	42	1.42	17	2	12	29	14	D	D	D	7	D	D	D	7	3.4
11	4	50	0.75	5	2	82	87	84	A	A	A	20	A	A	A	20	1.5
12	10	30.4	0.83	6	1	14	20	15	C	C	D	11	B	C	C	13	2.73
13	11	30	1.92	22	2	18	40	20	B+	B	B	16	B+	B	B	16	6.4
14	17	42	0.77	5	2	61	66	63	C	C	C	12	C	C	C	12	1.84
15	6	48	1.26	4	2	42	46	44	B	B+	B	17	A	A	A	19	2.62
16	18	51	0.81	4	1	20	24	21	C	C	C	12	C	D	C	12	1.58
17	5	31	1.45	10	3	10	15	13	C+	B	B	15	B	B+	B	16	4.77
18	12	40	1.48	3	1	80	83	81	C	D	15	12	D	D	C	11	3.72

$$\overline{D}_{pq}^{(p-q)} = \frac{\sum D_i^p}{\sum D_i^q} \qquad (2)$$

D=The overbar in D designates an averaging process

Where D the overbar in D designates an averaging process p-q (p>q) the algebraic power of D_{pq}

D_i= the diameter of the i_{th} particle $\sum$ =the summation of D_{ip} or D_{iq} representing all particles in the sample

D_{10} is arithmetic or number mean and D_{32} is volume/surface mean (also called the Sauter mean)[15]

RESULTS AND DISCUSSION
Laboratory tests certificate

After manufacturing optimum atomizer according to referred parameters in table 4,the laboratory tests with these factors in two series were carried out till confirmed taguchi metods. The mean diameter of spray particles by PDA equipment are 41.4 and 51.3 microns that the average of it is 49.35 micron. that this value has 10% error in comparison with taguchi method .

The result of average diameter ,sauter diameter and also average velocity of spray particles are given in Table 5.

Table 4: The Design Calculation for Atomizer at Scale 50kg/h.

Trial No.	Air injection holes numbers A	Air injection holes diameter B (mm)	Spray hole diameter C (mm)	outlet orifice diameter D (mm)	water flow rate E (kg/h)	Mass flow rate of air (kg/h)	Water pressure (Psig)	Air pressure (Psig)	Maximum pressre(psig)	water volumetric flow rate (L/h)	air volumetric flow rate (L/h)	Air velocity to water (m/s)	Water velocity (m/s)	Mixture volumetric in expansion area (L/h)	Mixture velocity in expansion area m/s	Velocity in orifice outlet (m/s)	D10 Micron	D32 Micron	Velocity (m/s)
Test 1-Nozzle (Small) 50 kg/hr	3	0.5	2.5	2	50	1.4	20	30	16	1081.3	458.03	216.10	0.80	567.72	32.14	100.09	53.8	142.2	22.5
Test 2-Nozzle (Small) 50 kg/hr	3	0.5	2.5	2	50	1.4	19	28	16	1081.3	471.63	222.52	0.80	567.72	32.14	100.09	54.3	138.3	22.6

Table 5: Condition and Result of Laboratory Test for Optimized Atomizer in Different Distance from Atomizer Outlet

number	%Wt		Mass flow kg/h		Operating pressure psig			Pressure drop Psig		Result of atomization tests		
	air	water	air	water	air	Atomizer	water	air	D10 (µm)	D32 (µm)	m/s
1	2.8	50	1.4	17	38	15	2	23	51.3	151	16.2
Repeating above test	2.8	50	1.4	17	38	15	2	23	47.4	146.5	16.4

In Table 6 all arithmetic mean & Sauter mean diameter and average velocity for different flow water (30-50 kg/h) from atomizer nozzle are given.

In Table 7 laboratory tests result for optimized atomizer at a flow rate of 50 kg/h are given. [8]

Experimental optimum tests in atomizer nozzle and result

In laser PDPA methodology measurement of particle diameter and velocity together as average mean and mathematical method of calculation diameter as Sauter Mean Diameter (SMD) or D_{32} are Carried out. In this method measurements at 28 points of spray in an area with a radius of 3mm that is located at a distance of 15cm from the spray outlet point are carried out. with reference to many diagrams that was sketched by PDA, it will be listed to some of them:

1- Diameter and velocity distribution in the center of spray for air and water

2- Three-dimensional distribution of mean diameter in spray surface for air-water system

3- Profile distribution of mean diameter in spray surface for the air-water system in x and y directions

4- Profile distribution of mean velocity in spray surface for the air-water system in x and y directions.

● A Three-dimensional Sauter diameter graph for the optimized nozzle is shown in Fig. 4, it is shown that the mean diameter is the same in spray surface area.

Change of particle means diameter and Sauter diameter is shown in Fig. 4 it is shown that the mean diameter of particles in the center is lower than the mean diameter of particles in spray around the area as the Sauter mean diameter is visa versa. (Fig. 9).

● Three-dimensional graph profile of mean velocity in spray atomizer of optimized nozzle shows that big particles have lower velocity than small particles. (Fig. 5).

The graph profile of mean velocity in spray atomizer of optimized nozzle shows that graph has

The Gaussian curve also shows that velocity in the center of spray has maximum value. .(Fig. 10) [8]

CONCLUSIONS

A pilot plant-scale atomizer nozzle has been designed and developed for the study of various parameters on

Table 6: The Result of Mean and Sauter Mean Diameter and Average Velocity of Spray in Different Point for Air-Water Mixture from Atomizer Nozzle is Shown.

Trial No.	Air side hole no.	Air hole diameter	Spray hole diameter	Outlet orifice diameter	Water mass flow	Air mass flow rate	Water pressure	Air pressure	Mixture pressure	Air flow rate	Air flow rate	Inlet air velocity to water	inlet water velocity	Mixture volume rate in expansion area	Inlet velocity of mixture air and water	Velocity in outlet orifice	Velocity	Particle diameter -D10	Particle diameter - D32
	A(mm)	B (mm)	C (mm)	D (mm)	E (kg/hr)	F (kg/hr)	Psig	Psig	Psig	Std (lit/hr)	lit/hr	m/s	m/s	lit/hr	m/s	m/s	m/s	Micron	Micron
1	2	0.5	2.5	1	30	0.8	42	47	42	617.93	160.17	113.36	0.48	190.17	10.77	229.27	16.2	31	133
2	2	0.75	3.5	1.5	40	1.4	27	30	24	1081.38	381.14	119.88	0.64	450.69	13.02	176.36	20.5	24.7	113
3	2	1	4.5	2	50	2	17	21	16	1544.83	716.27	126.73	0.80	789.60	13.80	141.09	20	40	129
4	3	0.5	2.5	1.5	40	2	46	54	44	1544.83	374.04	176.48	0.64	426.79	24.16	249.25	31.2	43.5	130
5	3	0.75	3.5	2	50	0.8	18	23	17	617.93	277.74	58.24	0.80	336.51	9.72	59.09	10.9	37	153
6	3	1	4.5	1	30	1.4	51	53	50	1081.38	241.90	28.53	0.48	275.64	4.82	393.27	36	71.7	140.5
7	4	0.5	3.5	1	50	1.4	76	78	75	1081.38	175.22	62.00	0.80	227.18	6.56	400.35	28	40	131.5
8	4	0.75	4.5	1.5	30	2	28	31	27	1544.83	531.73	83.63	0.48	574.48	10.04	247.67	21	24	95.5
9	4	1	2.5	2	40	0.8	13	15	8	617.93	327.89	29.01	0.64	440.12	24.92	58.20	9.8	43.5	164
10	2	0.5	4.5	2	40	1.4	12	28	10	1081.38	595.29	421.30	0.64	683.50	11.94	99.20	17	32	131.4
11	2	0.75	2.5	1	50	2	88	90	86	1544.83	221.07	69.53	0.80	275.46	15.60	564.34	21.2	25.7	122
12	2	1	3.5	1.5	30	0.8	12	15	11	617.93	340.17	60.19	0.48	383.41	11.08	101.90	14.5	23.4	136
13	3	0.5	3.5	2	30	2	19	40	17	1544.83	673.75	317.88	0.48	746.27	21.56	139.32	17	33.3	110
14	3	0.75	4.5	1	40	0.8	63	68	64	617.93	116.88	24.51	0.64	155.39	2.72	232.81		63.8	144.6
15	3	1	2.5	1.5	50	1.4	41	43	39	1081.38	285.33	33.66	0.80	345.96	19.59	177.93	26.4	46	134
16	4	0.5	4.5	1.5	50	0.8	20	24	20	617.93	261.73	92.62	0.80	311.73	5.45	105.05	15	35.7	148
17	4	0.75	2.5	2	30	1.4	12	14	10	1081.38	595.29	93.62	0.48	673.50	38.13	98.32	12.3	42	130
18	4	1	3.5	1	40	2	88	88	88	1544.83	221.07	19.56	0.64	261.07	7.54	560.80	35.7	65	140
Opt.	3	0.5	2.5	2	50	1.4	17	38	15	1081.38	501.39	236.56	0.80	585.15	33.13	100.09			

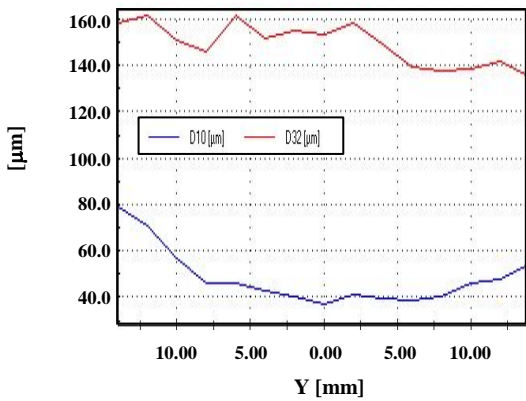*Table 7: Laboratory Tests on optimized atomizer Nozzle (50 kg)*

Test No.	Air Percentage	Liquid Velocity at Atomizer Outlet	Liquid Pressure	Air Flow	Water Flow	Pressure Drop		Sauter Mean Particle Diameter D32
						Liquid	Gas	
	Wt%	m/s	(Psig)	Kg/h	Kg/h	(Psig)	(Psig)	Micro meter
1	1.4	100	16	2.8	50	2	23	151
2	1.4	100	16	2.8	50	2	23	149
3	1.4	100	16	2.8	50	2	23	152.6
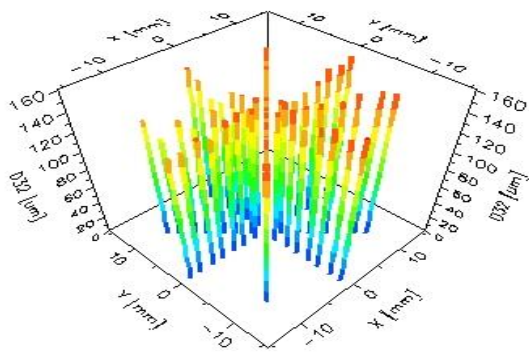
First series   Second series
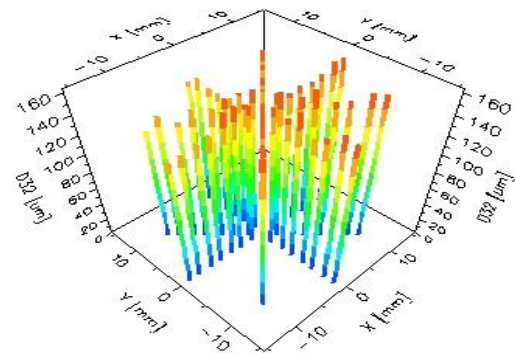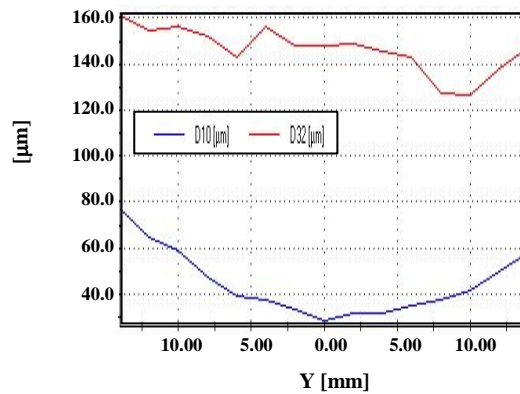
First series   Second series

Fig. 9: The Graph of Three Dimensional Distribution /Distribution Mean/Sauter /Diameter in Spray Atomizer of Optimized Nozzle.

produced spray. A two-phase low-pressure 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. The main effect parameter in the atomizer is spray hole diameter and other affected parameters are as according the following arrangement: outlet orifice diameter, air injection hole numbers, water volume low rate,
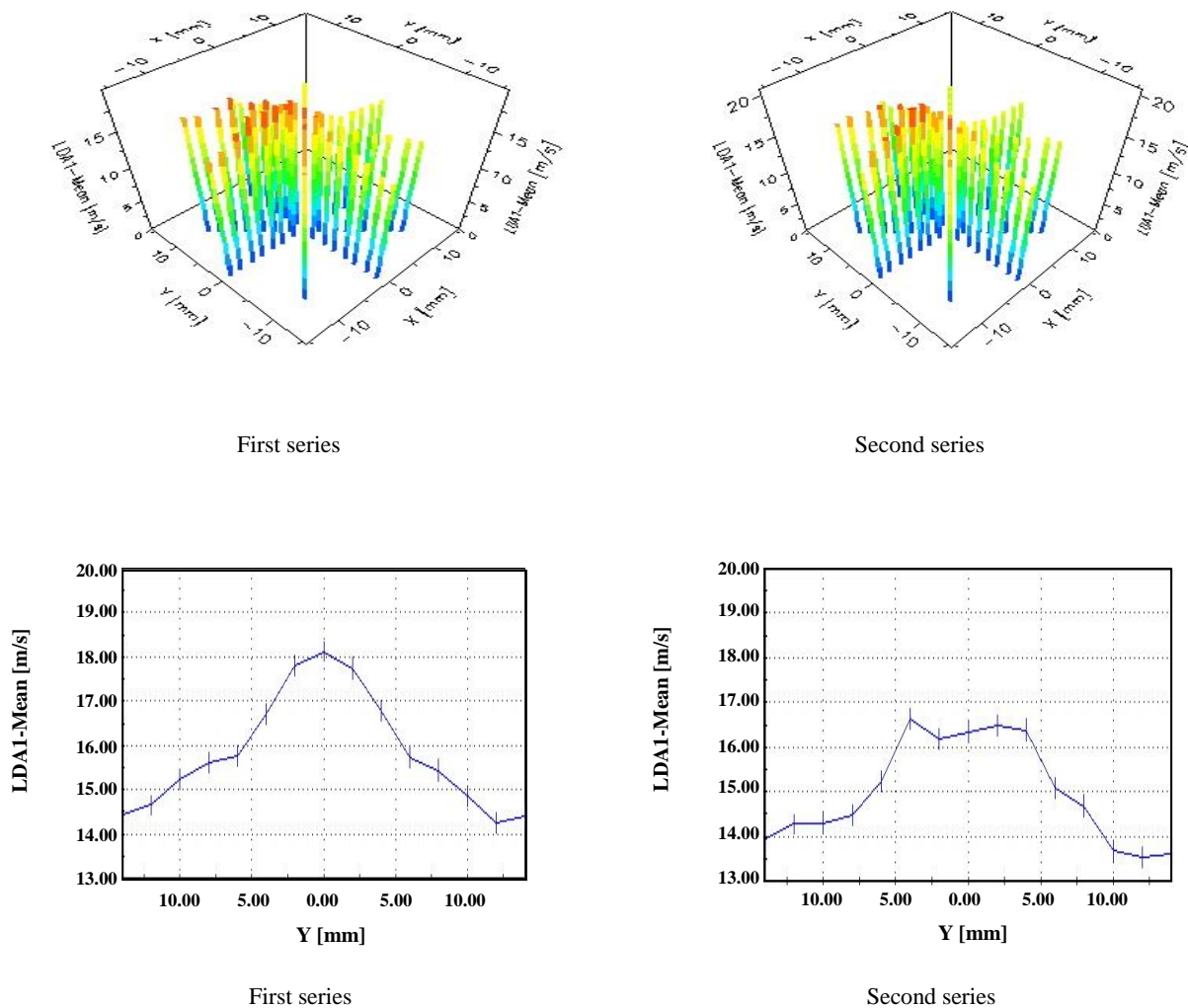
First series   Second series

First series   Second series

Fig. 10: The graph of three-dimensional distribution/distribution mean velocity in spray atomizer of the optimized nozzle.

spray hole diameter and outlet orifice diameter. For the design and optimized number of tests, the Taguchi methods were used. The main effective factor in the design of the atomizer was catches by using the Taguchi method. The spray atomization quality was investigated with quantity and quality methods**.** The droplet size and velocity distribution in several distances from the atomizer tip were measured by the Laser Particle Dynamic Analyzer (LPDA), measurement of the diameter and velocity together causes that relation between parameters are reached. Velocity is measured according to frequency proportional with Doppler waves with Laser Doppler Anemometry (LDA). But measurement of spray Particles diameter is done according to the comparison of two laser optical detectors that are installed at a different angle. The tests

number were optimum by the Taguchi method of orthogonal collocation arrays and errors were decreased by the optimizing method. All design parameters of the designed atomizer were optimized, and after it, the required tests for the water flow rate of 50kg/h were carried out. The result of data analysis for the nozzle with a water flowrate 50 kg/h and air flowrate 2.8 kg/h in the low-pressure nozzle (pressure lower than 2 bar) showed that the Sauter diameter (D_{32}) of droplet particles have a value of 150 µm and mean diameter (D_{10}) of droplet particle have a value of 50µm, water outlet velocity from nozzle tip is 100m/s. The researchers are continuing in two-phase low-pressure nozzles and nowadays FCC plants were equipped with this type of nozzles, detailed study of this type of nozzle will help to resolved industrial problems of low-pressure nozzles.

Nomenclatures

ALR	Air-Liquid Mass Ratio
CFD	Computational Fluid Dynamics
D32	Volume/surface means or Sauter Mean Diameter of Droplet Particle, mm
D_{10}	Arithmetic or Mean Diameter of Droplet Particle(mm)
FCC	Fluid Catalytic Cracking
LPDA	Laser Particle Dynamic Analyzer
LDA	Laser Doppler Anemometry
mw	Water mass flow rate, kg/s
NIOC	National Iran Oil Company
PDPA	Phase Doppler Particle Analyzer
RIPI	Research institute of the petroleum industry
SMD	Sauter Mean Diameter of Droplet Particle, mm
VOF	Volume of Fluid

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