Evaluation of a twin-fluid atomizer for FCC feeding system with atomizing medium under transonic flow.

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Abstract

This paper presents a theoretical-experimental approach of a typical twin-fluid atomizer injector for liquid feedstock in oil fluid catalytic cracking plants (FCC).Those feed nozzles research and development has been highly motivated world-wide over the last decade. Such devices play an important role on high valued oil fractions conversion such as gasoline and diesel oil. By means of fluid mechanics and gasdynamics this work seeks the relationship between droplet size and the atomizing medium conditions, especially under transonic flow. Such an experimental approach demanded prototype and test rig design and manufacturing and the usage of quantitative droplet sizing techniques such light scattering. Based upon a comprehensive test data-base this paper finally presents a predictive model for droplet Sauter mean diameter of the spray.

1. Introduction

Many industrial processes from chemical, physical up to petrochemical and fuel conversion demand several reagents under multiphase streams. It is well known that cost effective processes are strongly dependent on reaction conversion yields among other parameters. Mainly in oil plants and refineries, especially in Fluid Catalytic Cracking Plants (FCC) the hydrocarbon feedstock injection system has important relationship with high cost products conversion yields like cracked naphtha [1].Modern FCC plants use catalyst under fluidized beds for cracking the feedstock [2]. Feedstock is fed into risers as a high momentum droplet spray. High surface areas are achieved and so better vaporization and interphase contact. The riser injection system uses feed nozzles in order to spray heavy hydrocarbon stream. In fact FCC feed nozzles are twin fluid atomizers specially designed for generating and keeping the spray under certain condition. The main target is to promote a contact between feedstock and catalyst as even as possible and keep the reaction zone under control. Some authors do confirm the relationship between spray and catalyst interaction and conversion yields [1,3]. The oil-catalyst contact, vaporization and residence time in the riser environment are all involved with inlet oil spray pattern. Some of the most important figures on feeding quality such as the droplet diameter, mass flow distribution on spray and momentum depend on the FCC atomisation nozzle [2,3,4].

The feed nozzle design may use one or more atomization techniques. The most used nozzle atomizer type is the twin-fluid atomizer. Those devices use a high velocity atomizing fluid which impinges on a liquid traverse flow. The high relative velocity between the two fluids causes a very rapid deformation of the liquid film, the sheet break up, the formation of ligaments, drops and droplets. The atomizing medium is steam under a pressure and temperature condition in order to achieve high relative velocity through nozzles.

2. Twin-fluid atomization

Among several parameters involved in twin-fluid atomization which leads to a certain spray pattern the Sauter mean droplet diameter (SMD), mean velocities, mass flow distribution and spray shape are especially important in FCC feeding. Above all the droplet SMD and velocity have the most important role because the vaporization time is closely linked with such characteristics. So a good FCC feed nozzle design must consider those two parameters [1].

The twin-fluid atomization is mainly based on the atomizing medium dynamic pressure and some liquid physical properties such as surface tension and viscosity [7,8]. Some non-dimensional relations like Reynolds and specially the Weber number represent the gas to liquid dynamic interaction [6,7,9].The final spray SMD depends on the gas to liquid relation firstly (Weber number) but drop to drop impact downstream nozzle is not less important. Some papers say that for a Reynolds number of 500 – 1000 the critical value for Weber number is around 17 [11]. Some side-effects like droplet coalescence or secondary atomization may take place downstream the nozzle and so concurrent droplets may result diverse final SMD after impact. Small relative velocities may lead to “quasi-elastic” impact and both droplets may go on separately. By increasing the relative velocity up to a critical level two droplets “melt” after impact and one coarser droplet will result. Such behaviour may take place up to a relative velocity level when the impact leads to secondary atomization and fine droplets are formed.

Finally twin fluid atomization evolves complex phenomena and the experimental investigation is still the best approach for spray studies. This paper shows results from an experimental approach of twin-fluid atomizers specially designed for FCC feed nozzles. Also a comparative study has been done for atomizing medium under transonic flow and the relationship with final spray SMD.

3. Methods and Materials

3.1 Experimental plan

The method used here has demanded tests and measurements in a test rig specially designed for spray investigation. In order to reach the correlation factors of a parameters group on the final spray SMD this study would have to produce a proper droplet diameter predictive model. Several tests have been carried out in order to set a proper data-base, data reduction and correlation by statistical approach. Besides, by exploring the gas-liquid relative velocity effects under transonic flow this paper proposes a nozzle study by means of the Gasdynamics Theory.

Experimental plan:

- Dimensionless predictive model for droplet diameter;
- Test rig design and mounting;
- Prototype design using several geometries with convergent or convergent/divergent nozzles for compressed air and water as test fluids;
- Factorial test plan;
- Test performance and data-base formation;
- Data reduction and analysis by means of a non-linear regression;
- Conclusions and predictive model;

3.2 Dimensional analysis

The twin-fluid atomization process depends on a set of parameters from the two fluids and the traverse flow conditions [10].The SMD predictive model was based on dimensionless group set as a functional SMD=F(related parameters). By means of the Buckingham-PI Theorem and the twin-fluid atomization theory the relation between SMD and all other parameters can be easily achieved. In fact such a Theorem teaches the relationship between dimension parameters with all others by dimensionless groups [10]. The main liquid physical properties in twin-fluid atomization are the density, surface tension and viscosity [7,8]. By another hand the interaction parameters involved in the process are the relative velocity (V_g - V_L) and the air/liquid mass flow relation (ALR). Considering all fluid related properties, flow and geometry dependence the droplet diameter functional may finally be written as follows:

$$D = f(r_g, d_g, V_g, \dot{m}_g, r_L, d_L, V_L, \dot{m}_L, s_L, m_L) \qquad (1)$$

Where subscript "*g*" is for gas (compressed air) and "*L*" for the liquid (water).A typical twin-fluid atomizer geometry with two water inlets and one air inlet has been adopted. In fact such a geometry is from an updated, commercial FCC feed nozzle named UltraMist™ (proprietary).

Parameters nomenclature:

- Atomizing medium (compressed air)

r_g	density
d_g	discharge diameter
V_g	velocity
$\dot{m}_g$	mass flow rate

- Liquid

r_L	dendsity
d_L	outlet diameter
V_L	velocity.
$\dot{m}_L$	mass flow rate
s_L	surface tension
m_L	viscosity

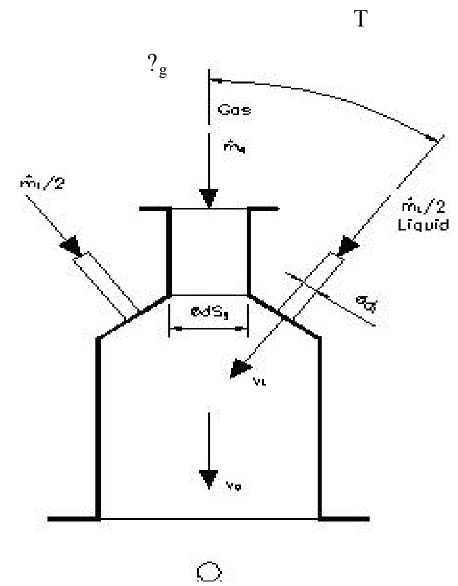

fig.1-Typical twin-fluid atomizer prototype.

Following the Buckingham-PI theorem, eight dimensionless groups (π_1 to π_8) can be set. Note Reynolds and Weber numbers naturally come up as the two most important dimensionless relations as follows:

$\pi_1 = f\,(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)$.

$$\frac{D}{dS_L} = f\left(\frac{r_g}{r_L}, \frac{dS_g}{dS_L}, \frac{V_g}{V_L}, \frac{\dot{m}_g}{r_L V_L dS_L^2}, \frac{\dot{m}_L}{r_L V_L dS_L^2}, \frac{1}{We_L}, \frac{1}{Re_L} \right) \quad (2)$$

Reducing some relations, and replacing ALR = $\dot{m}_g / \dot{m}_L$ (3) , gives:

$$\frac{D}{dS_L} = K \left(\frac{r_g}{r_L} \right)^a \left(\frac{V_g}{V_L} \right)^b * ALR^c * We^d * Re^e \quad (4)$$

This is the functional relationship between dimensionless parameters for the twin–fluid atomizer geometry on figure 1.The proportional K factor and a, b, c, d, and e constants are determined from non-linear regression of the experimental data-base.

3.3 Air nozzles

The atomizing medium velocity V_g through the air outlet is one of the most important parameter in twin-fluid atomization [8] and so in this study. The air velocity may range from subsonic, sonic to supersonic flow pattern by means of convergent-divergent nozzles. In order to get three levels of Mach number a set of nine prototypes has been designed: eight with fixed throat area and one with adjustable area by a conical needle plug. Such design allowed getting different compressible flow pattern keeping ALR parameter under control. Other fluid properties like surface tension and viscosity have been set by temperature and pressure control.

The nozzles design and V_g velocity calculation were based on the isentropic flow theory. Wullis [15] presented the "action" equation (5) based on the Thermodynamic First Law. The prototype air nozzle design was based on the "geometric action" dA/A as follows:

$$\frac{dV}{V}\left(M^2 - 1\right) = \frac{dA}{A} - \frac{d\dot{m}}{\dot{m}} - \frac{k-1}{a^2} dq_{out} - \frac{1}{a^2} dW_{mec} - \frac{k}{a^2} dW_{fric} \quad (5)$$

Figure 2 shows a typical convergent-divergent nozzle used on prototype design. Calculations have been made by isentropic flow theory.

By means of the gasdynamic approach and measuring stagnation and the misture zone pressure it is possible to calculate any thermodynamic property at any section, even more the flow pattern and velocities.

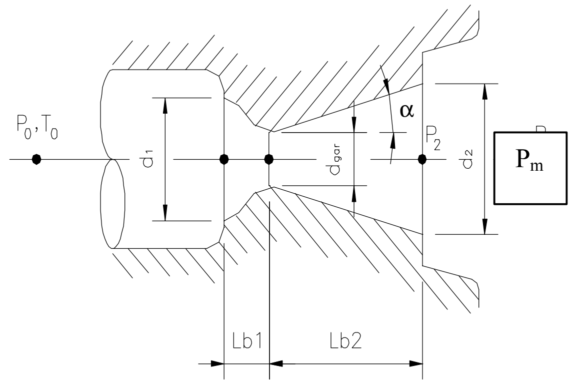

Fig 2 – Typical convergent-divergent nozzle

By changing operating conditions, mainly stagnation pressure p_0 was possible to get several flow patterns. By the other hand the pressure in the mixture zone p_m depends on the relation $ALR = \dot{m}_g / \dot{m}_l$ .Because of the very small prototype dimensions it was not possible to perform direct gas velocity measurements. Prototypes dimensions and throat diameters $\boldsymbol{d_{gar}}$**,** throat and outlet areas A_{gar} and A_2 have been precisely measured due to the relative area function $q = A_{gar} / A_2$ and the final V_g calculations [13].

3.4 Test rig

Considering the experimental approach this paper presents the test rig flow-sheet on figure 3. Because the dependence of fluid properties pressure, temperature and flow rates have been precisely measured in the test rig. High pressure compressed air, up to 30 Bar were used for tests in order to achieve Mach numbers from 0.8, 1 up to 2.25, keeping ALR and other parameters constants. For droplet sizing the 5 mW laser light scattering sizer by Malvern has been used.

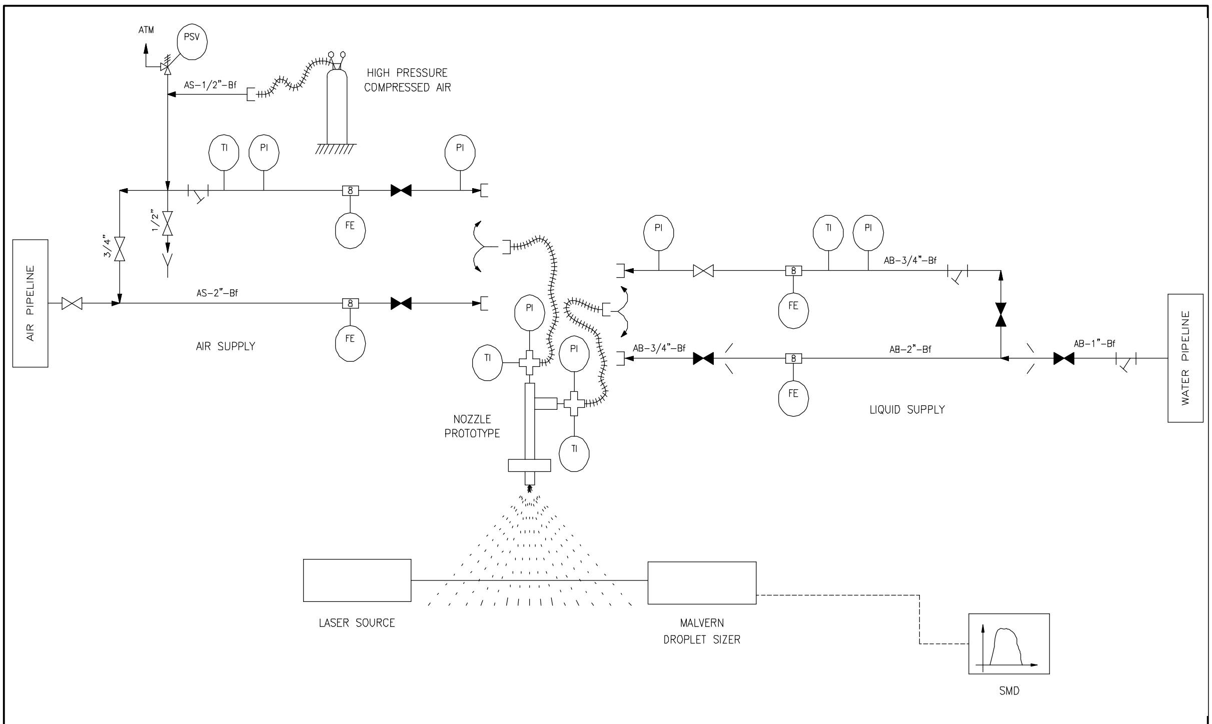

FIG.3 Test rig flowsheet

4. Results

The factorial test plan has been taken and the nine prototype set have been tested under several conditions. Around 500 tests have been carried out by changing one of the five dimensionless parameters on equation (3). However the "spray diameter" D had to be determined by criteria set based on the average SMD taken from several spray zones.

4.1 Measurement zone.

Firstly some tests have been carried out in order to fix the spray measurement points for the "D" calculation (figure 4).

Exploratory 492 measurements have been taken on 11 cross sections downstream the spray of a chosen prototype. A typical operating condition has been kept constant for all exploratory tests. Up to 12 measurements have been taken on each section cross, 6 above and 6 below the main spray axis. The SMD data base has indicated that some spray zones presented standard deviation of less than 10 %. Those nine spray zones at coordinates P(x,y) have been chosen for the SMD measurements and the final mean D = average [SMD at P(x,y)]

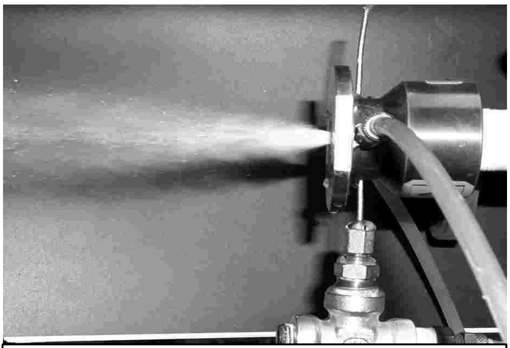

Fig.4 – Typical prototype

Later the results data-base has shown that the “low deviation standard” criteria measurement was quite precise for the final predictive droplet model. The chosen nine points P (x,y) were: (in millimetres): P1(20,0); P2(20,10); P3(20,-10); P4(45,15); P5(45,0); P6(45,-15); P7(105,20); P8(105,0); P9(105,-20).Where “X” is the main spray axis. All measurements have been taken traversing the spray cone by the sizer laser bean (Malvern). No radial droplet distribution has been made.

4.2 Effect of atomizing air velocity

As per figure 5 the D diameter decreases as the atomizing air velocity increases towards sonic flow. The two ALR levels have been chosen in order to avoid such a single effect. The overall diameter decreases rapidly as the Mach number reaches the unity however a lighter reduction was observed for supersonic flow (Mach >1).

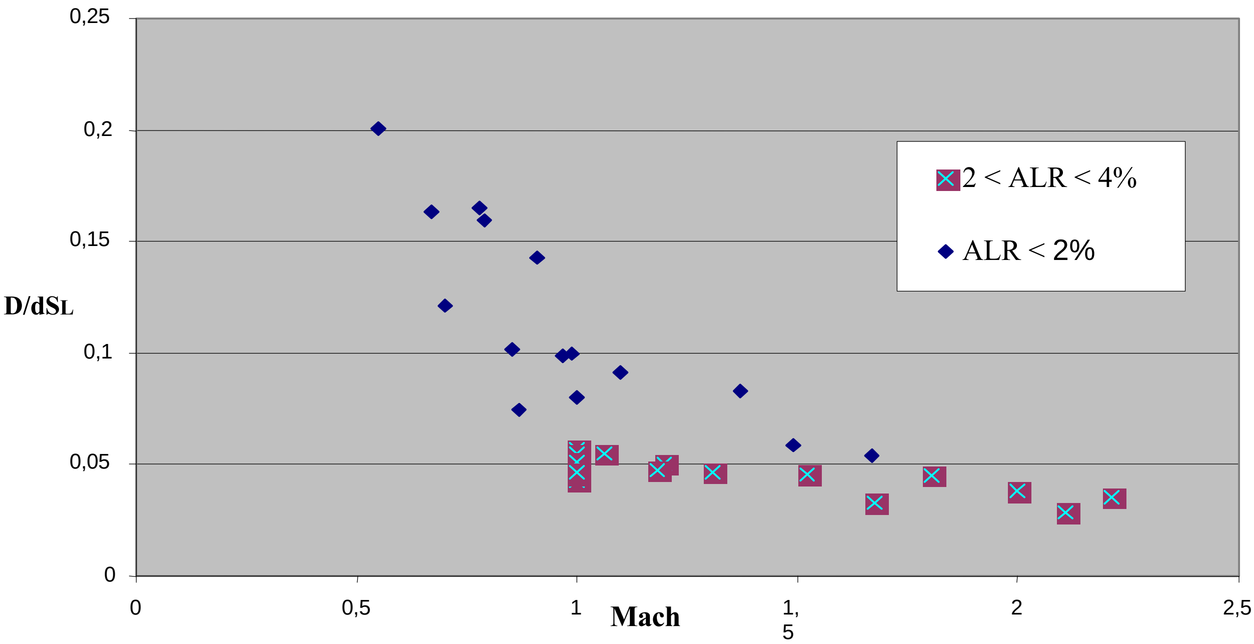

Fig 5- Effect of Mach number

5. Conclusions

The constants K, a, b, c, d and e in the equation (4) have been found by means of data reduction and non-linear estimation. The final predictive droplet model for the prototype sets is shown on figure 6 by equation (6). The regression factors have been calculated by the "quasi-Newton" method and deviation function by the least squares. The overall results have shown a coefficient of determination of 97% and low residuals.

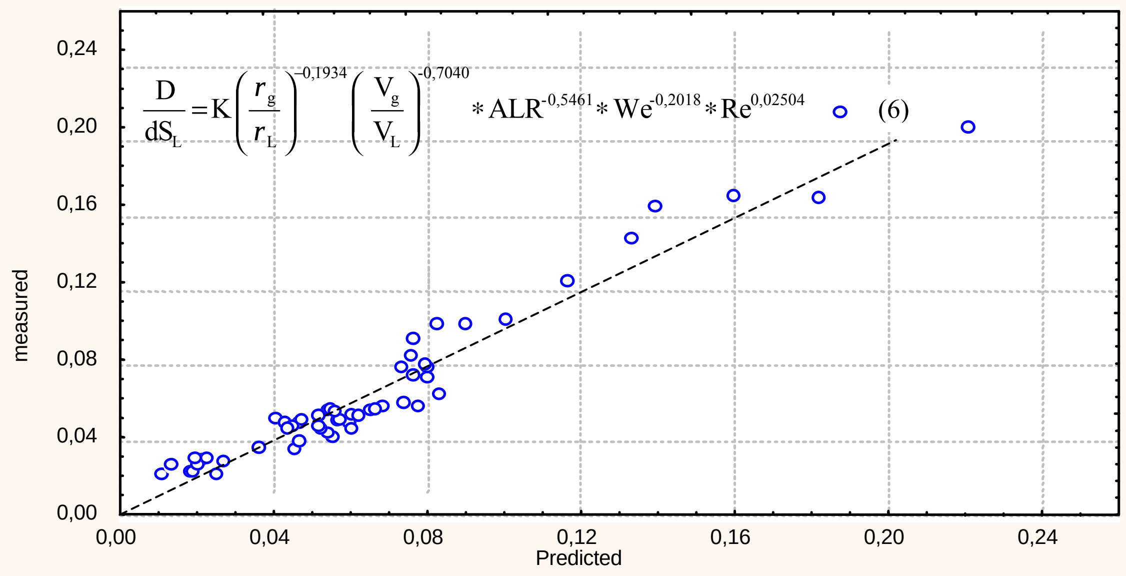

Fig.6 – Predicted and measured figures (D/dSL)

6. Nomenclature

a Sound velocity at point conditions, m/s
A Cross-section area of a nozzle, m^2
ALR Relation of mass flow, $\dot{m}_g / \dot{m}$
D Drop diameter
d Diameter, m
dS Discharge diameter
K Proportionality constant
k Isentropic coefficient = cp/cv
Lb1 Length of divergent section of a nozzle
Lb2 Length of convergent section of a nozzle
M Mach number, V/a
$\dot{m}$ Mass flow, kg/s
q Relative area function = A_{gar} / A_2
q_{out} Heat
P Pressure, Pa
Re Reynolds number, (ρ.V.dS)/µ

SMD Sauter Metter Diameter
T Fluid temperature, (ºC)
V Velocity, m/s
W Work, J
We Weber number, $(\rho.dS.(Vg-V_L)^2)/\sigma$
s Surface tension, kg/s^2
? Density, kg/m^3
µ Dynamic viscosity, kg/(m.s)
q(x) Area relation (gasodynamic function)
α Divergent section Semi-angle

Subscripts

g Gas
L Liquid
fric Friction
gar Nozzle throat
m Interaction zone index
mec Mecanic
0 Stagnation
1 Before nozzle throat
2 After nozzle throat

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