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Theoretical and Experimental Investigation for Optimizing Spray Angle of Plain Orifice Nozzles

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Abstract

Spray nozzles are used in many applications such as cleaning, cutting and spraying. Spray nozzles come in many varieties and are usually classified according to the specific mode of atomization. This paper is focused on plain orifice nozzle. This kind of atomizer is the most common and simple type. Plain-orifice atomizers are widely used for injecting liquids into a flow stream of air or gas with normally circular pattern. The injection may occur in a co-flow, a contra-flow, or a cross-flow stream. An enormous variety of processes make use of plain orifice nozzles such as diesel engine, jet engine, afterburners and ramjets. The best known application of plain-orifice atomizers is perhaps diesel injectors. This type of injectors is designed to provide a pulsed or intermittent supply of fuel to the combustion zone for each power stroke of the piston. In the case of high pressure flow, fuel injectors these nozzles to generate finely atomized sprays. Droplet size and spray angle are critical because the large surface area and finely atomized spray enhance fuel evaporation area. Dispersion of the fuel into the combustion air is critical to maximize the efficiency of these systems and minimize emissions of pollutants. One of the most noticeable limitations of plain orifice is its narrow spray angel. Therefore, a little discrepancy between theoretical and practical data caused effective changes in engine performance. Unfortunately the available equations predict spray angle recklessly.

Keywords: Atomization, Optimization, Plain Orifice, Nozzle, Spray Angle

Fluid Mechanics

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Abstract
Spray nozzles are used in many applications such as cleaning, cutting and spraying. Spray nozzles come in many varieties and are usually classified according to the specific mode of atomization. This paper is focused on plain orifice nozzle. This kind of atomizer is the most common and simple type. Plain-orifice atomizers are widely used for injecting liquids into a flow stream of air or gas with normally circular pattern.
The injection may occur in a co-flow, a contra-flow, or a cross-flow stream. An enormous variety of processes make use of plain orifice nozzles such as diesel engine, jet engine, afterburners and ramjets. The best known application of plain-orifice atomizers is perhaps diesel injectors. This type of injectors is designed to provide a pulsed or intermittent supply of fuel to the combustion zone for each power stroke of the piston [1]. In the case of high pressure flow, around 25 bar, fuel injectors these nozzles to generate finely atomized sprays. Droplet size and spray angle are critical because the large surface area and finely atomized spray enhance fuel evaporation area. Dispersion of the fuel into the combustion air is critical to maximize the efficiency of these systems and minimize emissions of pollutants. One of the most noticeable limitations of plain orifice is its narrow spray angel. Therefore, a little discrepancy between theoretical and practical data caused effective changes in engine performance. Unfortunately the available equations predict spray angle recklessly. Therefore this paper focuses on the analysis of equations to reach the most useful and acceptable relation, in order to predict spray angle of plain atomizer as accurate as possible [1,2].

Keywords: Atomization, Optimization, Plain orifice, Nozzle, Spray angle

Introduction

When a continuous liquid stream disintegrates into droplets, a spray is formed. This process plays an important role in a large number of technical operation, ranging from agricultural purposes through painting technology to combustion one. Its importance in many of these areas made spray formation a subject of technical research already more than a century ago.
In last decades, the evolution of measurement technology and the development of investigation methods enabled deeper understanding of the processes related to liquid disintegration. There is still no uniform theory that would describe the entire process of spray formation, and there is especially lack of such theories that would account for a wide range of physical circumstances, representative of different applications, e.g. operation conditions in diesel fuel injection. On the other hand, the increase in understanding has been paralleled by a continuous growth in demand for accuracy and a wish for more details, all these related to systems, that are permanently evolving themselves as well, making it continuously harder to be modeled. In last years, many researches deal with methods to improve operating quality of combustion engines [3, 4], as an example you can see in "Figure 1"[5]. The initial phase of mixing of liquid fuel is the disintegration of liquid by the process of atomization. Homogeneous mixing involves the rate of production of fine atomization of fuel to prevent single droplet combustion and spatial distribution of the fuel spray within the combustor. Ignitability and flame stability are dependent on the drop size distribution and air-spray mixture close to the atomizer. The mixing of spray and surrounding air depends on the size distribution of the spray produced by the atomizer, the spray angle, the flow field created by the atomizer and the fluid dynamic properties of the fuel and air mixture [1,2]. Therefore, the design of the atomizer and the nature of the atomization play a key role in the efficient burning of fuel and the overall design of a gas turbine combustor. Previous researches proceeded technical information about penetration length [1-3 and 6], droplet size [2-5] and SMD[1][1-3 and 6] cavitations [2,4 and 7] and effects of different factors on performance of such atomizers completely. But there is still no acceptable and qualified relation for calculation of spray angle. In this regard, previous researches were investigated. Having analyzed theoretical relations, e.g. Siebers [2], Arai & Hiruyaso [7,8] and Heywood [9], Reitz & Bracco [10] led us to optimize the best equation. After that, optimized equation to assumption of spray angle [1-4], according to specifications of injection and target medium checked with experimental data. Furthermore, the results of this analysis and experimental works will be mentioned in this paper [11].

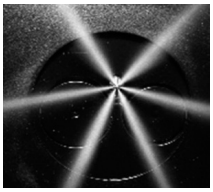

Figure 1: Diesel fuel injection

[1] Sauter Mean diameter, based on volume-to-surface ratio

Mathematical formulation

The spray angle of plain orifice nozzle is the narrowest one among other atomizers. The normal range of injection angle is around 5-30 degree. Therefore, a little difference between theoretical and practical results causes a lot of changes in operating condition and final result. Having investigated previous theoretical works, it is clearly understood that there is very large gap between these two types of considerations. In this regards some relations which predicted spray angle closer the real and experimental angles were selected.

In addition, some differences were seen between effective parameters of such relations. The value of parameters in each equation differs from others, as it can be seen below and in "Figure 2" [3, 8-11]:

$$\tan\left(\frac{\theta_1}{2}\right) = \frac{2}{3} \times \left[\frac{\pi}{3+\frac{L}{3.6\times D}}\right] \times \sqrt{3 \times \frac{\rho_{tar}}{\rho_{inj}}} \tag{1}$$

$$\theta_2 = 0.05 \times \left[\frac{\rho_{tar} \times \Delta P \times D^2}{\mu_{tar}{}^2}\right] \tag{2}$$

$$n = 0.0284 \times \left[\frac{\rho_{tar}}{\rho_{inj}}\right]^{0.39} \tag{3}$$

$$\theta_3 = 0.0676\left[\rho_{inj}\,.\,V_t.\frac{D}{\mu_{inj}}\right]^{0.64} \times \left[\frac{L}{D}\right]^{-n} \times \left[1-\exp\left(-0.023 \times \frac{\rho_{inj}}{\rho_{tar}}\right)\right]^{-1}$$

$$\theta_4 = 83.5 \times \left[\frac{L}{D_{up}}\right]^{-0.22} \times \left[\frac{D_{up}}{D}\right]^{0.15} \times \left[\frac{\rho_{tar}}{\rho_{inj}}\right]^{0.26} \tag{4}$$

$$We_{inj} = \rho_{inj} \times V_t{}^2 \times \frac{D}{\sigma} \tag{5}$$

$$\gamma = \left[\frac{\rho_{inj}\,.\,V_t.\frac{D}{\mu_{inj}}}{We_{inj}}\right]^{-2} \times \frac{\rho_{inj}}{\rho_{tar}}$$

$$F = \frac{\sqrt{3}}{6} \times [1-\exp(-10.\gamma)]$$

$$A = 3 + 0.2778 \times \frac{L}{D}$$

$$\tan(\theta_5) = 4 \times \frac{\pi}{A} \times \left[\frac{\rho_{tar}}{\rho_{inj}}\right]^{0.5} \times F$$

$$\tan\left(\frac{\theta_6}{2}\right) = 0.26 \times \left[\left(\frac{\rho_{tar}}{\rho_{inj}}\right)^{0.19} - 0.0043 \times \left(\frac{\rho_{inj}}{\rho_{tar}}\right)^{0.5}\right] \tag{6}$$

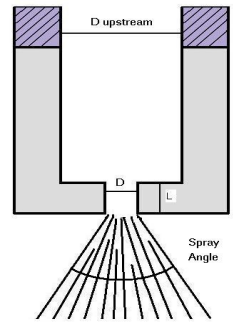

Figure 2: Plain-orifice nozzle main geometric parameters

So we decided to have more accurate theoretical analysis for two different purposes: 1) analyzing significant parameters to which one is the most effective 2) Recognizing which equation produces the closer result to experimental data. Practically however, when these relations were tested the results were not acceptable. To do so, experimental results of various test set-ups compared with output of these equations to reach the best one. Unfortunately, the results were very different from experimental data and in some cases such as the predicted angle of equations 3 and 4, the results were unacceptable. To make it clear, the final results of some practical tests will be explained in this paper.

In the first one, there is specified test setup with these below mentioned input parameters; $\rho_{Injection}$=651 (kg/m^3), ρ_{target} =30.2 (kg/m^3), $\mu_{Injection}$=0.0011 (kg/ms), μ_{target}= 0.00001657 (kg/ms), $T_{injection}$=577(°c), σ=0.0002 (N/m), ΔP=134200 (kPa), $D_{upstream}$=0.2 (m), D=0.0002 (m). Finally, the output spray angles of all equations in addition experimental angle compared in "Table 1"[11].

Table 1: Spray angles from the first experimental test (test1)

θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_{Exp}
deg	deg	deg	deg	deg	deg	deg
26.1	32.27	161	95	26.1	15.9	24

Secondly test was repeated by above mentioned condition but pressure drop and temperature changed as follow; ΔP=131900 (kPa) and $T_{injection}$=723 (°c). The practical results illustrate in "Table 2" [11].

Table 2: Spray angles from the second experimental test (test2)

θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_{Exp}
deg	deg	deg	deg	deg	deg	deg
26.8	30	160	124	21	15.9	28

The third test was arranged with below mentioned input: $\rho_{Injection}$=756.2 (kg/m)^3, ρ_{target} =17.3 (kg/m)^3, $\mu_{Injection}$=0.0019 (kg/ms), μ_{target}= 0.0000175 (kg/ms), $T_{injection}$=20 (°c), σ=0.026 (N/m), ΔP=118500 (kPa), $D_{upstream}$=0.2 (m), D=0.0002 (m), L=0.0011 (m) the results illustrates in "Table 3" [3].

Table 3: Spray angles from the third experimental test (test3)

θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_{Exp}
deg	deg	deg	deg	deg	deg	deg
7.4	36	59.1	83	13.8	13.6	22

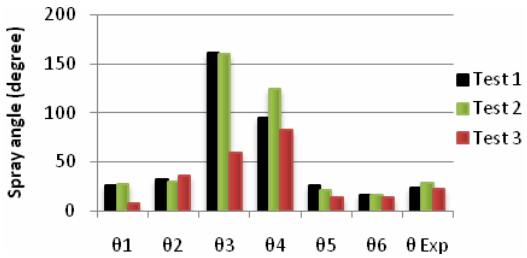

Figure 3: Theoretical and experimental results of tests

After considering the above mentioned relations and achieved practical results, this article tries to select the two best ones which are capable of producing the closer result to experimental output. As shown in "Figure 3", the predictions of equations 3 and 4 were so far from test results. After that, these equations were eliminated from analyzing and consideration because of the important properties of fluid neglected [11-17]

In contrast with relation 3 and 4, remained equations specially equations 1, 2 and 5 predicted spray angle more closer to practical output than others. To summarize, there are a number of reasons why these mentioned equations are chosen and the others are rejected. The most significant reason is that some parameters such as pressure drop, viscosity of target or injection mediums, surface tension etc affecting the spray angle of liquid injection considered in number 2 and 5 but is not thoroughly dealt with in the others.

The second reason is that the predicted angles are fairly closer to experimental results than the other ones. Therefore, this paper tries to give a solution to optimize existing relations. Based on effective factors and two selected relations, the result of experimental data led us to predict spray angle between the suggested ones by equation 2 and 5. This article offers modified equation represents in equation 7.

$$\theta_{recom} = 0.025\left[\frac{\rho_{tar} \times \Delta P \times D^2}{\mu_{tar}{}^2}\right] + \frac{\pi \times \frac{\sqrt{3}}{3}}{\left(3 + 0.2778 \times \frac{L}{D}\right)} \times \left[\frac{\rho_{tar}}{\rho_{inj}}\right]^{0.5}\left[1 - \exp\left(-10.\left[\frac{\rho_{inj}\cdot V_t\cdot\frac{D}{\mu_{inj}}}{\rho_{inj}\cdot V_t{}^2\cdot\frac{D}{\sigma}}\right]^{-2}\cdot\frac{\rho_{inj}}{\rho_{tar}}\right)\right] \quad (7)$$

To substantiate modified relation, experimental test setup was arranged. More information about achieved results will be represented below.

Experimental setup and procedure

Experimental results from other technical papers prepared suitable information to check and analysis equations. In addition, it made a beneficial background to consider equation 7. A schematic of the test facility is shown in "Figure 4".

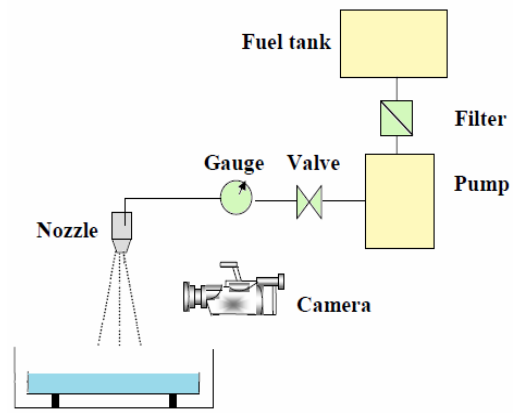

Figure 4: Schematic of test setup

Before test, the specifications of injection and target mediums are assumed as per available facilities and situation. The experimental set up constructed for investigation of spray angle as illustrated "figure 4". Input parameters for experimental test are assumed as:

$\rho_{Injection}$=1000 (kg/m^3), ρ_{target}=69.91 (kg/m^3),
$\mu_{Injection}$=0.0012 (kg/ms), μ_{target}=0.000127 (kg/ms),
Δ p=100 (kpa), T $_{injection}$=20 (°c), σ=0.06774 (N/m),
$D_{upstream}$=0.0340 (m), D=0.01427 (m), L=0.002 (m)

Now the result of our test, θ_{our} , was compared with relations 2, 5 and 7 and the results show in "Table 4".

Table 4: Experimental result of our test

θ_2	θ_5	θ_7	θ_{our}
degree	degree	degree	degree
27.25	33.91	30.6	30

Having compared the obtained results which is shown in table 4 and 5, led us to optimize predicted spray angle as accurate as possible.

Results and Discussion

To analysis the taken results from plain orifice nuzzles, depicts in "Table 5". In this regard, test setup prepared and arranges as per "Figure 4". It should be mentioned that for predicting the theoretical spray angles, there are some consumptions. Some important physical properties such as density, viscosity, surface tension, temperature etc assumed constant. In addition, experimental measured errors such as pressure drop and temperature etc were neglected.

In "Figure 5", the spray angle obtained from equations 2, 5, 7 and our experiment are illustrated. As shown, the result of optimized equation, θ_7, conforms extremely with experimental data, θ_{our}. Other results predict spray angle with more error.

In "Figure 6", the spray angle from equations 2, 5, 7 and all experiments (test1, 2, 3 and our test) are illustrated. It shows that not only for our test but also for other tests, the result of modified equation, θ_7, predicts spray angle closer to the experimental data.

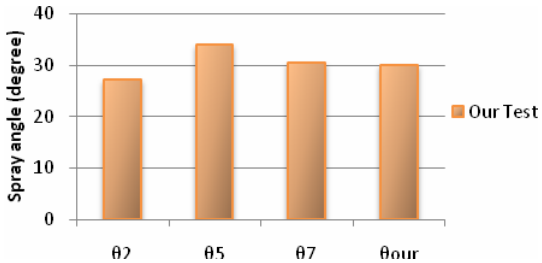

Figure 5: Comparison of our test and predicted angle

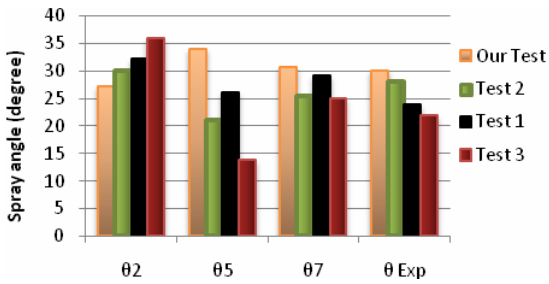

Figure 6: comparison for all tests and predicted angle

Conclusions

Available relations to predict spray angle of plain orifice nozzle need more analysis. Very various and not quite correct results from previous equations which sometimes were so far from practical and actual measurements led us to optimized them. Then, our modified equation for plain-orifice nozzles' spray angle in compare with other relations, predicts spray angle closer to the experimental data.

List of Symbols

A	Dimensionless number
D	Orifice diameter
$D_{upstream}$	Upstream diameter
F	Dimensionless number
L	Orifice length
n	Dimensionless number
P	Pressure
V_t	Outlet Velocity
We	Weber number

Greek symbols

σ	Surface tension
γ	Dimensionless number
Δ	Difference/drop
θ	Spray angle
θ_{exp}	Spray angle of previous experiment
θ_{our}	Spray angle of our test
μ_{inj}	Viscosity of injection medium
μ_{tar}	Viscosity of target medium
ρ_{inj}	Density of injection medium
ρ_{tar}	Density of target medium

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