NUMERICAL INVESTIGATION OF INTERACTION BETWEEN INTERNAL MIXING AIR AND SPRAY OF THREE KINDS OF FLUIDS

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The widespread use of atomizers for fuel spraying in combustion chambers or water spraying for cooling purposes has made them attractive subjects for research. This study investigates the interaction of internal mixing high-velocity airflow with the spray of three fluids in a pressure swirl atomizer. The research was conducted using the numerical solution method, supported by experimental data, which demonstrated good agreement between the simulation and experimental results. The findings revealed that adding 0.02 kg/s of high-velocity airflow at 300 K to the spray of three liquids—namely water, normal heptane, and kerosene—each at a mass flow rate of 0.08 kg/s, reduced the fluid film thickness (T) by 79.82%, 77.36%, and 76.87%, respectively. This reduction subsequently resulted in a significant decrease in the Sauter mean diameter (SMD) by 96.99%, 96.12%, and 95.94%, respectively. Additionally, the results indicated that the addition of high-velocity airflow slightly increased the spray cone angle for kerosene and normal heptane, but caused the water spray to collapse and move out of its intended pattern. The study also found that high-velocity airflow dramatically increased the turbulence kinetic energy (TKE) for the spray of all three liquids, with a more pronounced effect observed in the water spray. These results can guide researchers in understanding the effects of high-velocity airflow on spray dynamics and assist engineers in designing and manufacturing atomizers with optimal performance.

Keywords*: interaction, internal mix, high-velocity airflow, kerosene, normal heptane, fluid film thickness, SMD.*

1. Introduction

Pressure swirl atomizers (PSAs) are known for their reliability, cost-effectiveness, and effective atomization, making them widely utilized in sectors such as aircraft and rocket engines, pharmaceuticals, and cooling systems [1-3]. Liu et al. [4] investigated the spray characteristics of PSAs under varying injection pressures, while Gad et al. [5] analyzed changes in spray cone angle, concentration distribution, and intensity at different air-to-liquid ratios in swirling air blast atomizers. Garai et al. [6] studied how droplet size and velocity distribution vary in different locations within the spray. Musemic et al. [7] explored the effects of simple sharp-edged and Coanda deflection outlets, finding that high swirl decreases sheet thickness but increases energy loss at Coanda outlets. Bhattacharjee [8] evaluated the impact of the Weber number on the breakup of liquid spray jets, which was influenced by viscosity, surface tension, and gravitational forces. Martínez et al. [9] study on Air-Core-Liquid-Ring (ACLR) nozzle indicated that the internal flow and the external spray instabilities can be correlated with each other. Jing et al. [10] researched how pressure waves affect injection stability, using relative standard deviation (RSD) as a measurement tool, and proposed modifications to improve injector stability and fuel efficiency. Dianhao et al. [11] introduced a new electric injector featuring a controllable inflow orifice designed to enhance dynamic response and reduce cavitation and fuel return, thereby improving the stability of the needle valve and reducing torque imbalance. Calzada et al. [12] designed a hydraulic turbine based on a pressure swirl chamber using Ansys CFD, while Abdul Hamid et al. [13] focused on determining the optimal number and size of tangential ports for achieving the widest spray. Kulshreshtha et al. [14] examined the assisted pressure swirl atomizer's spray cone angle and penetration length under varying injection pressure differentials. Dikshitl et al. [15] experimentally analyzed how discharge orifice diameter, nozzle angle, and injection conditions affect the spray cone angle. Malý et al. [16] utilized Laser Doppler Anemometry (LDA) and high-speed imaging to study the spray formation process in a transparent atomizer. Jedelsky and Jicha [17] evaluated two atomizers with different helical swirlers to see how they affect the spray cone angle. Domnick et al. [18] researched internal mixing twin-fluid atomizers for cavity wax applications, and Gad et al. [19] looked at how geometric parameters impact the spray characteristics of air-assisted PSAs, noting that air assistance shifts the maximum spray concentration inward. Khani et al. conducted extensive studies on PSAs, exploring various configurations like tangential and spiral inlets. Through experimental and simulation methods, they assessed how multiple geometric parameters—such as the number of inlets, spiral angle, swirl chamber length, and outlet nozzle diameter—affect spray characteristics [20-22]. They also investigated how flow parameters, including inlet pressure, Reynolds number, fuel type, and temperature, influence key spray metrics like spray cone angle, Sauter Mean Diameter (SMD), and discharge coefficient. Their research highlighted significant effects of these parameters on spray characteristics [23-25]. In follow-up studies on air-blast atomizers, Khani et al. [26,27] analyzed spray characteristics under conditions resembling real engine operations, introducing a new dimensionless number for better result comparison, which enhanced the understanding of atomization factors and contributed to optimizing atomizer design for improved efficiency. In another study by [28] they improved upon a previous study conducted in the twin-fluid nozzle domain.

The primary focus of these studies is to enhance engine efficiency, which leads to economic benefits such as lower fuel costs and better vehicle performance. Moreover, optimizing combustion processes [29, 30] can help reduce air pollution and harmful greenhouse gas emissions like carbon dioxide (CO_2) and methane (CH_4), addressing critical environmental issues linked to climate change. It is essential to recognize that while combustion is a major source of these emissions, other sectors—such as industry, agriculture, and transportation—also contribute significantly, highlighting the need for a comprehensive strategy to improve air quality and tackle climate challenges [31,32]. As researchers continue to explore combustion complexities [33,34], they are not only working on improving injectors and atomizers but are also considering alternative fuels and innovative combustion techniques that can further reduce emissions. Thus, ongoing research and development in atomizer technology, applicable in various military and civilian sectors including aviation, aerospace, gas turbines, and power generation [1-3], aims to enhance engine performance while promoting a sustainable future that balances economic and environmental objectives and more recent detailed studies in spray technology further support these goals [35-40].

1.1. Necessity, Objectives, and Innovative Aspects

- ❖ In summary, by reviewing the research background in the field of pressure swirl atomizers, previous studies can be classified as follows:
  - Studies that mainly aimed to understand the effect of geometric parameters of the atomizer, including the diameter of the inlet duct, outlet orifice, and swirl chamber; the length of the inlet duct, outlet orifice, and swirl chamber; as well as the number of inlets, etc., on the spray characteristics [20-22].
  - Studies that investigated the effect of fuel and liquid flow characteristics, such as inlet pressure and mass flow rate of fuel, fuel density, fuel temperature, etc., on the spray parameters [23-25].
  - A handful of studies evaluated the effect of airflow on spray characteristics [1, 14, 19, 40].
- ➢ Therefore, the existence of research gaps in this scope is quite evident and indicates the need for more detailed studies. The present study aims to fill one of these gaps, and its key difference from previous studies and its novel aspects, which are also the objectives of the present study, are: comparing the effects of adding high-velocity airflow to the spray of three liquids, namely water, kerosene and normal heptane, or in other words, the interaction of the spray of the three mentioned liquids with high-velocity airflow.

2. Key Equations Related to the Spray Main Characteristics

The provided text offers a brief summary of equations relevant to the spray parameters of pressure-swirl atomizers:

According to Rizk and Lefebvre [41], a relationship is established to estimate the spray cone angle, taking into account geometric factors, fluid properties, and operational conditions, as described in equation 1:

$$\theta = 6\left(\frac{D_s D_o}{A_p}\right)^{0.15}\left(\frac{\Delta P_L \rho_L D_o^2}{\mu_L^2}\right)^{0.11} \tag{1}$$

Equations 2 and 3, as suggested by Babu et al. [42], are recognized as reliable methods for estimating the Sauter Mean Diameter (SMD):

$$\text{For} \quad \Delta P_L < 2.8MPa \rightarrow SMD = 133\frac{FN^{0.64291}}{\Delta P_L^{0.22565}\rho_L^{0.3215}} \tag{2}$$

$$\text{For} \quad \Delta P_L > 2.8MPa \rightarrow SMD = 607\frac{FN^{0.75344}}{\Delta P_L^{0.19936}\rho_L^{0.3767}} \tag{3}$$

Equation 4 presents a mathematical estimation of the flow number (FN), while equations 5 and 6 are widely utilized formulas for this purpose [41]:

$$FN = \frac{\dot{m_L}}{\sqrt{\rho_L \Delta P_L}} \quad (4)$$

Equation 5 relies on experimental data, while Equation 6 provides improved dimensional accuracy [41]:

$$FN = 0.395(\frac{A_p^{0.5} D_o^{1.25}}{D_s^{0.45}}) \quad (5)$$

$$FN = 0.395(\frac{A_p^{0.5} D_o^{1.25}}{D_s^{0.25}}) \quad (6)$$

Additionally, the mass flow rate, an essential parameter in atomizers, can be calculated using Equation 7 [43]:

$$\dot{m}_L = C_D A_O (2\rho_L \Delta P_L)^{0.5} \quad (7)$$

Lastly, various equations have been proposed to estimate the fluid film thickness (T), including equation 8 by Suyari and Lefebvre [44], which closely aligns with experimental findings:

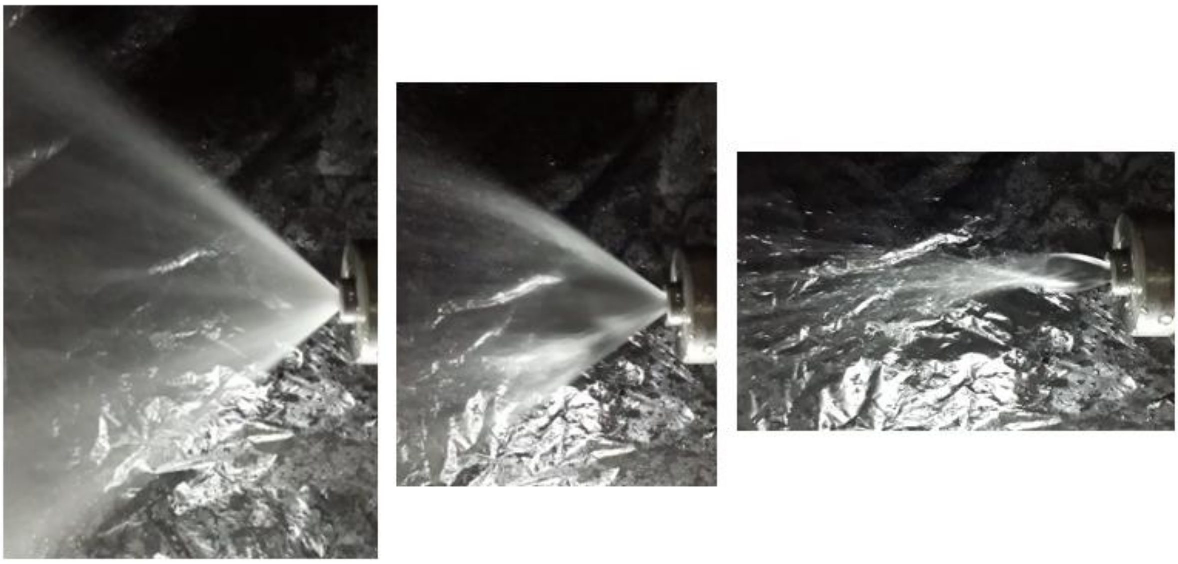
$$T = 2.7(\frac{D_o \dot{m_L} \mu_L}{\rho_L \Delta P_L})^{0.25} \quad (8)$$

3. Design and Experimental Testing

This section describes the design and testing of a tangentially-fed pressure-swirl atomizer, with a focus on its geometric measurements and operational parameters. The experimental test results are presented in Figure 1 and Table 1. The design process, which assumes ideal flow by neglecting viscosity effects, adheres to established guidelines. The atomizer operates with a fluid mass flow rate of 0.08 kg/s, a pressure differential of 3 bar, and a spray cone angle of 90°, using kerosene as the working fluid which is a common fuel in various industries, including aerospace and design outcome was D_o=4.4 mm, D_s=15.35 mm, D_P=2.35 mm, L_o=3.3 mm, L_s=11.75 mm, L_P=7 mm, with 4 tangential inputs which can be seen in Figure 2. The atomizer test was conducted with water, which is cheap and readily available, instead of kerosene. In the experimental setup, a Pentax PM45 pump was used to apply pressure in water and test of atomizer at different inlet pressures. At each inlet pressure, the amount of water sprayed was collected over a specific time-period, and the mass flow rate was calculated. The spray image was photographed at different inlet pressures with a Canon EOS R6 camera, and the spray angle was measured from the photographs, an example of which can be seen in Figure 5. The use of high-speed cameras and image restoration techniques [45] can increase the accuracy of spray angle measurements by capturing high-resolution images. Table 1 shows the results of atomizer testing at various pressures, including the design pressure. In this table, an inlet pressure of 4 bar is equivalent to a pressure difference of 3 bar, i.e., the design pressure difference, because the spray is discharged at ambient pressure, which is 1 bar. The difference between the experimental test results in the design pressure and the design data is due to three reasons: The first and most important reason is that the design was based on kerosene, but the experimental test was based on water, which its density is significantly higher than kerosene and its viscosity is approximately half that of kerosene. Naturally, the higher density and lower viscosity caused the mass flow rate in the experimental test to be significantly higher than the design case. However, the spray angle is more affected by the geometric dimensions of the atomizer, so the spray angle of the experimental test is in good agreement with the design case (Referring to Equations 1 and 7 will help to better understand this argument). Second, the design was based on an ideal fluid and, the effects of viscosity were ignored. Third and last, despite the effort to manufacture the atomizer with high precision, its dimensions certainly have tolerances and are not exactly equal to the design output dimensions. In general, the results indicated that the spray cone angle and fluid mass flow rate initially increased with inlet pressure but later reached a saturation point. Further design and test details are described in [25].

Table 1. Data obtained from experimental testing.

P_{in}(bar)	1.2	1.6	2	2.5	3	3.5	4
$\dot{m}$(gr/s)	46.58	57.72	67.85	84.56	98.23	104.30	107.34
θ(deg)	41.71	51.58	59.63	67.68	72.80	78.66	84.90

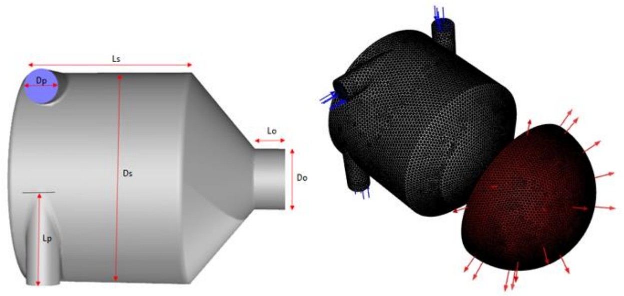


P_{in}=4 bar P_{in}=3 bar P_{in}=1.2 bar

Figure 1. Three samples from atomizer testing at different inlet pressures.

4. Research Method

Today, the use of numerical analysis methods has become an integral part of research in various fields due to their high accuracy and cost-effectiveness in terms of economy and time [46-49]. In this study, ANSYS FLUENT 18 was used for simulation. A mesh sensitivity analysis showed that a mesh size of 600K provided stable numerical results so the 600K mesh was selected for numerical analysis to minimize computational time while maintaining result accuracy which can be seen in Figure 3. The RNG-k–ε turbulence model was chosen for its superior accuracy in simulating swirl flow compared to other models, particularly for different declination angles [50, 53]. This model effectively predicts axial and tangential velocity characteristics, making it suitable for swirl flows. The research used a pressure-based approach with the volume of fluid (VOF) model to simulate two-phase flow, a common technique for spray simulations [54-60]. While VOF method's widespread use is attributed to its strong correlation with experimental results and is effective for interface tracking, it struggles with fine droplet breakup, necessitating the use of a specific Sauter Mean Diameter (SMD) equation derived from experimental tests for accurate predictions. Therefore, using equations obtained from experimental tests, such as equations 2 and 3, in measuring and calculating SMD will yield more accurate results. Therefore, in the present study considering the design pressure difference which is 3 bar, SMD was obtained using the equation 2. Simulations for different states including water, kerosene, and normal heptane with the same mass flow rate leads to different pressure differences for each state due to their differences in density and viscosity. By substituting the pressure differences obtained from the simulation into equations 2, 4 and 8, the SMD, flow number, and fluid film thickness can be calculated. It is important to note that estimating and measuring the diameter of spray droplets is a very complex physicochemical phenomenon that [61-63], despite numerous studies, still requires more detailed studies [64-66]. With the help of the liquid volume fraction contour at the atomizer outlet, which actually shows the spray formation, the spray angle can be measured (as in Figure 5). The fluid film thickness and spray droplet size can also be measured from the liquid volume fraction contour, but it will not be very accurate because these parameters are extremely small and measuring them manually from the contour is hardly possible to produce accurate results. Key convergence criteria included maintaining residuals below 1e-04 and achieving mass flow rate equilibrium at the inlet and outlet. The atomizer's inlets were set with a specified kerosene flow rate, while the outlet was defined as a pressure outlet, with stationary wall conditions applied to ensure smooth flow. Initial simulations with water validated the model against experimental data before subsequent tests with kerosene and normal heptane examined the effects of adding high-velocity air and its interaction with the mentioned fluids-spray. The simulation results shown in Figure 4 indicated the low-pressure region in the central part of the atomizer and spray, which caused the airflow to be sucked into the atomizer in the central part of the spray. In addition, the spray pattern was in the form of a hollow cone, with the highest velocity at the edges of the spray.



a b

Figure 2. Atomizer modeling(a), and its meshing(b).

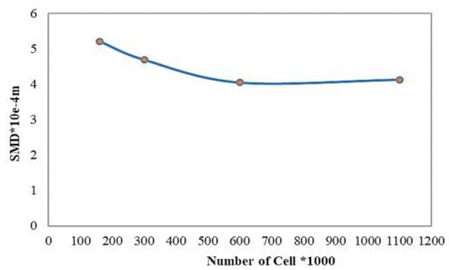
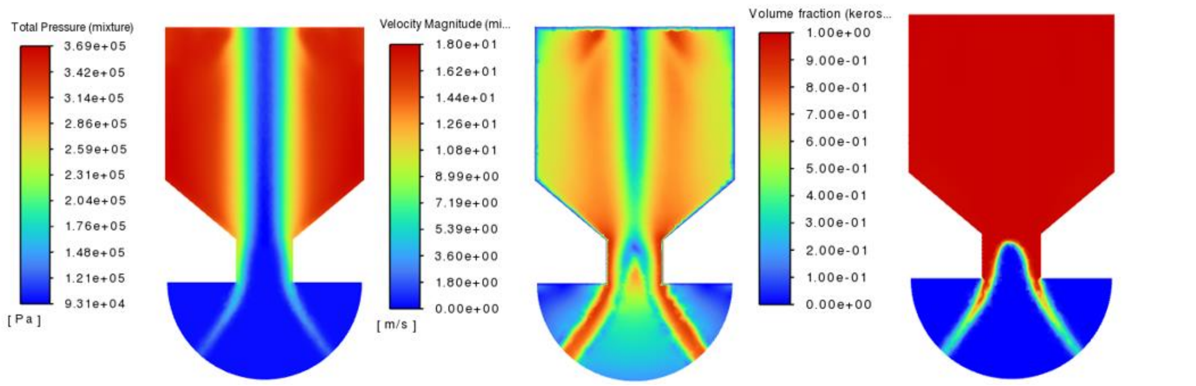


Figure 3. SMD for different mesh.



Total pressure contour Velocity magnitude contour Kerosene volume fraction contour

Figure 4. Some simulation results at the design point.

5. Validation

The accuracy of the simulation results was confirmed by the satisfactory agreement between the numerical solutions and the experimental data, as shown in Figure 5, which shows a sample of the comparison of the simulation results with the experimental test at inlet pressure of 3 bar. At this inlet pressure in the experimental test, the spray cone angle and the mass flow rate were 72.80^o and 98.23 gr/s, and the same parameters were in simulations 75.62^o and 100.11 gr/s, indicating a good agreement of the simulation results with the experimental test outcomes.

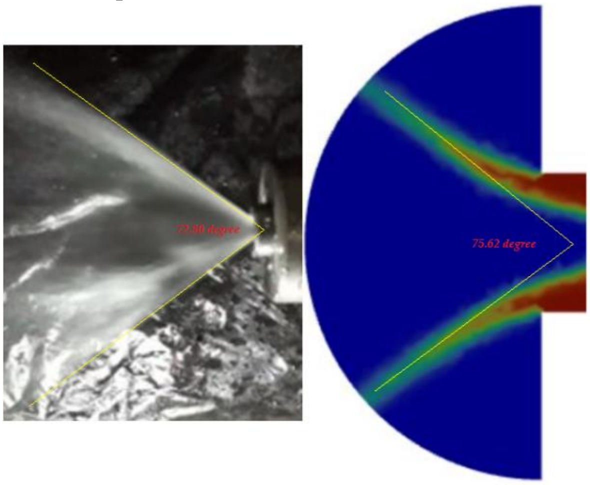


Figure 5. Sample of validating simulation results with experimental testing (P_{in}=3bar, and water as working fluid).

6. Results and Discussion

In this section, the effects of the interaction of adding internal mixing high-velocity airflow with the mass flow rate of 0.02 kg/s and the temperature of 300 K to the spray of water, kerosene, and normal heptane with the same mass flow rate of 0.08 kg/s are investigated. The reason for choosing these three liquids is that kerosene and normal heptane are the main components of fuels in various industries, including the aerospace industry, so studying them is of great importance. Although water is not a fuel, studying it is important for other reasons. The widespread use of water for cooling purposes and the fact that water is often used instead of fuel in experimental testing of atomizer because water is cheap and available. Another reason for choosing water for the study was to compare the difference in the interaction of high-velocity airflow with water and fuels. The results are presented in Figures 6-8 and Table 2, which indicate the significant effects of adding a high-velocity airflow on the spray of the three liquids. Figure 6 shows the volume fraction contours of water, kerosene, and normal heptane at the atomizer outlet. Comparing the label numbers of the contours in the air-mixed mode with the airless mode indicates that the addition of high-velocity airflow causes a significant reduction in the volume fraction for all three mentioned liquids, and also that the air core grows in the orifice and advances into the atomizer. Adding of high-velocity airflow causes the water spray to collapse and remove it from its proper pattern, but in the case of kerosene and normal heptane, the situation was different and the high-velocity airflow causes a slight increase in the spray cone angle, which can be understood with Equation 1 because Equation 1 indicates that the spray cone angle depends more on the geometric dimensions of the atomizer than on the flow conditions. Previous studies [25] have shown that increasing the inlet pressure (pressure difference inside the atomizer) up to a certain limit causes an increase in the spray angle, but after a kind of saturation state is created and the increase in pressure does not have a significant effect on the spray angle. Another important point is the range of addition of high-velocity airflow that causes spray collapse. The study [40] has shown that under conditions similar to the present study, high-velocity airflow with the mass flow rate of 0.03 kg/s causes kerosene spray collapse, while the present study showed that spray collapse occurs at an air mass flow rate of 0.02 kg/s. This indicates that due to the physicochemical characteristics such as density, viscosity, surface tension, intermolecular forces, etc., the water spray is more effective than the high-velocity airflow compared to the kerosene spray, and in other words, the interaction of water with the high-velocity airflow causes more severe changes. The results of Table 2 and Figure 7 confirm this and show that adding 0.02 kg/s of high-velocity airflow with the temperature of 300 K to the spray of three liquids including water, normal heptane, and kerosene with a mass flow rate of 0.08 kg/s reduces the fluid film thickness (T) by 79.82%, 77.36%, and 76.87%, respectively, which subsequently leads to a reduction in the Suater mean diameter (SMD) by about 96.99%, 96.12%, and 95.94%, respectively.

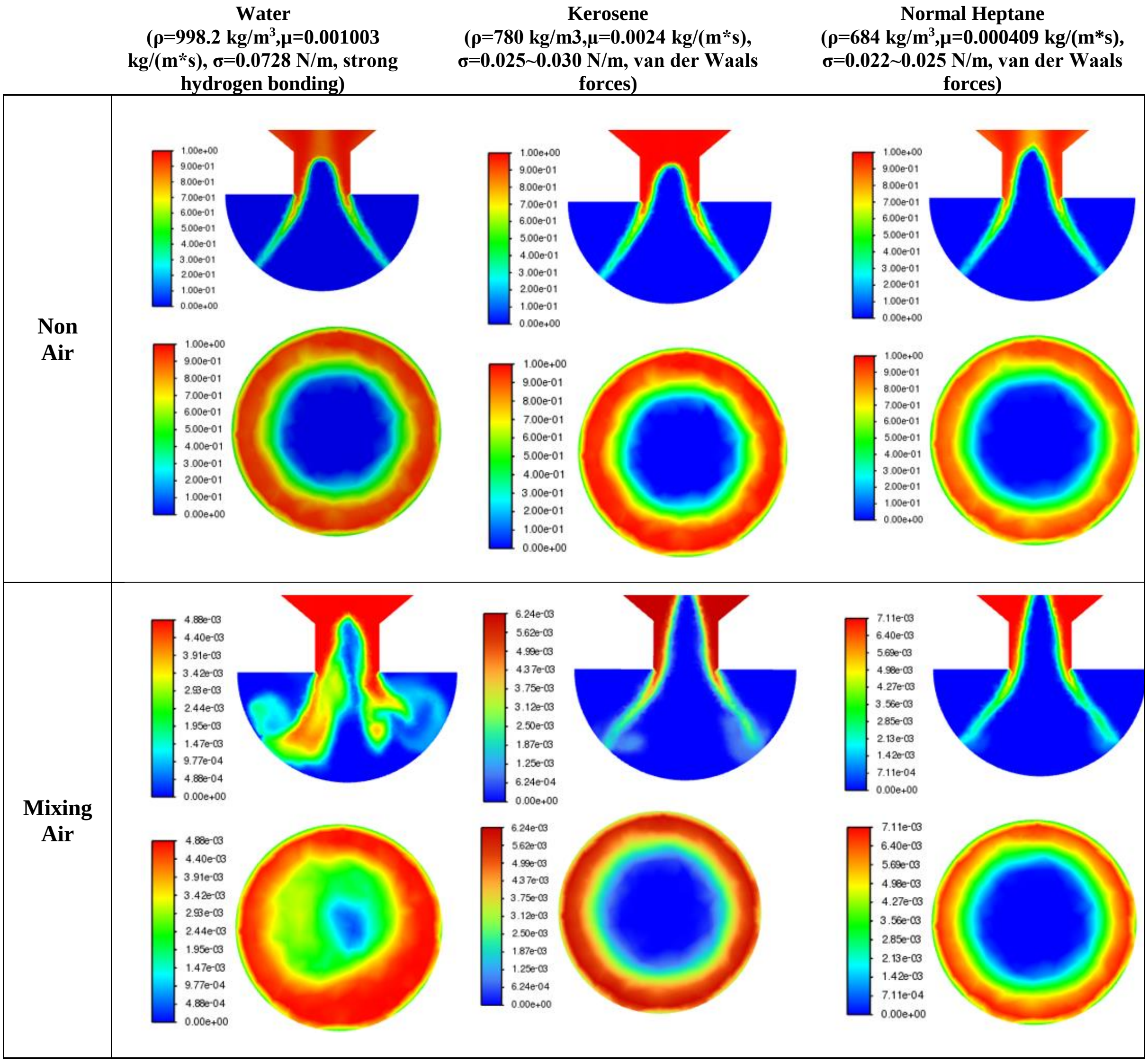


Figure 6. Comparison of the volume fraction of the three liquids at the atomizer outlet for the case of no high-velocity airflow and adding high-velocity airflow.

The results of T in Table 2 and Figure 7 indicated that for both airless and adding high-velocity air can be justified by comparing the viscosities of water, kerosene, and normal heptane. The increase in viscosity increases the adhesion of the flow to the atomizer wall and the liquid flow flows at a slower speed, which gradually increases as the flow layers accumulate on each other. The passage of the high-velocity airflow over the liquid layers causes the liquid layers in contact with the airflow to move, which leads to a decrease in T. The changes in SMD with the addition of high-velocity airflow are complex and indicate that although the SMD for the spray of all three liquids decreased sharply, the intensity of this decrease was greater for water, again emphasizing that the effectiveness of water spray is greater than that of high-velocity airflow compared to kerosene and normal heptane.

TABLE 2. Comparison of spray characteristics for two modes, Non Air: $\dot{m}_{Liquid}$=0.08(kg/s), $\dot{m}_{Air}$=0(kg/s) and Mixing Air: $\dot{m}_{Liquid}$=0.08(kg/s), $\dot{m}_{Air}$=0.02(kg/s).

Conditions	Non Air	Mixing Air	Non Air	Mixing Air
Key features of the spray	**SMD($*10^{-4}$m)**	**SMD($*10^{-4}$m)**	**T($*10^{-4}$m)**	**T($*10^{-4}$m)**
Water	4.571	0.1377	5.96	1.203
N-heptane	4.574	0.1773	4.686	1.061
Kerosene	4.036	0.1638	6.927	1.602

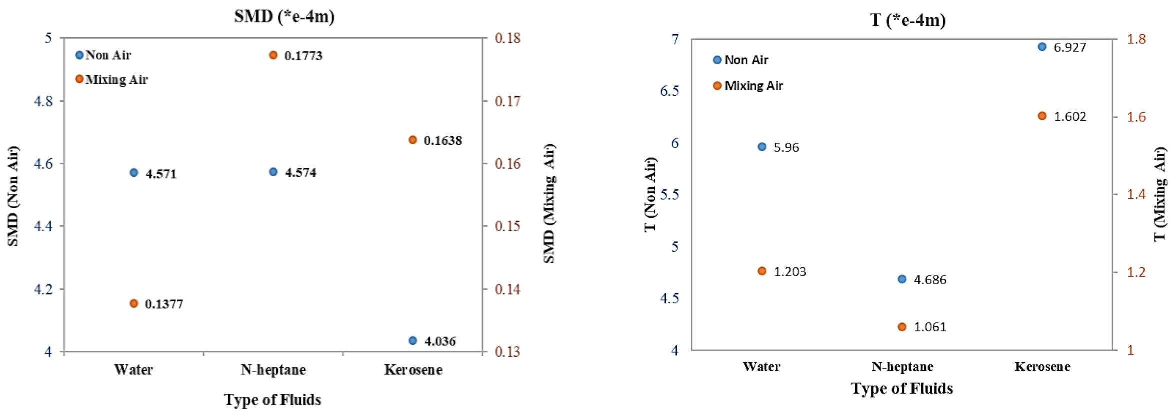


Figure 7. Changing of spray two key characteristics in the spray of three types of fluids by adding high-velocity airflow.

Studies have shown that the turbulent kinetic energy (TKE) in a spray has a significant effect on droplet size [67]. TKE primarily affects the dispersion and breakup of the liquid jet. A higher TKE can result in smaller droplet sizes and faster mixing of the spray with the surrounding gas, while a lower TKE can result in larger droplets and more localized mixing. In Figure 8, a comparison of TKE for the no-air and airflow conditions shows that high-velocity airflow significantly increases TKE in sprays of all three liquids, but the magnitude of this increase is significantly greater for water sprays, which could be the reason for the more dramatic reduction in water SMD with the addition of airflow, such that the SMD for water sprays is the lowest. The numbers on the TKE contour label for kerosene and normal heptane indicate that in the absence of airflow, the TKE of normal heptane is slightly higher than that of kerosene, but with the addition of high-velocity airflow, the TKE of both fuels reaches a nearly identical range, which means that the addition of high-velocity airflow increases the TKE of kerosene slightly more than that of normal heptane, which could explain why the SMD of kerosene is smaller than that of normal heptane with the addition of high-velocity airflow.

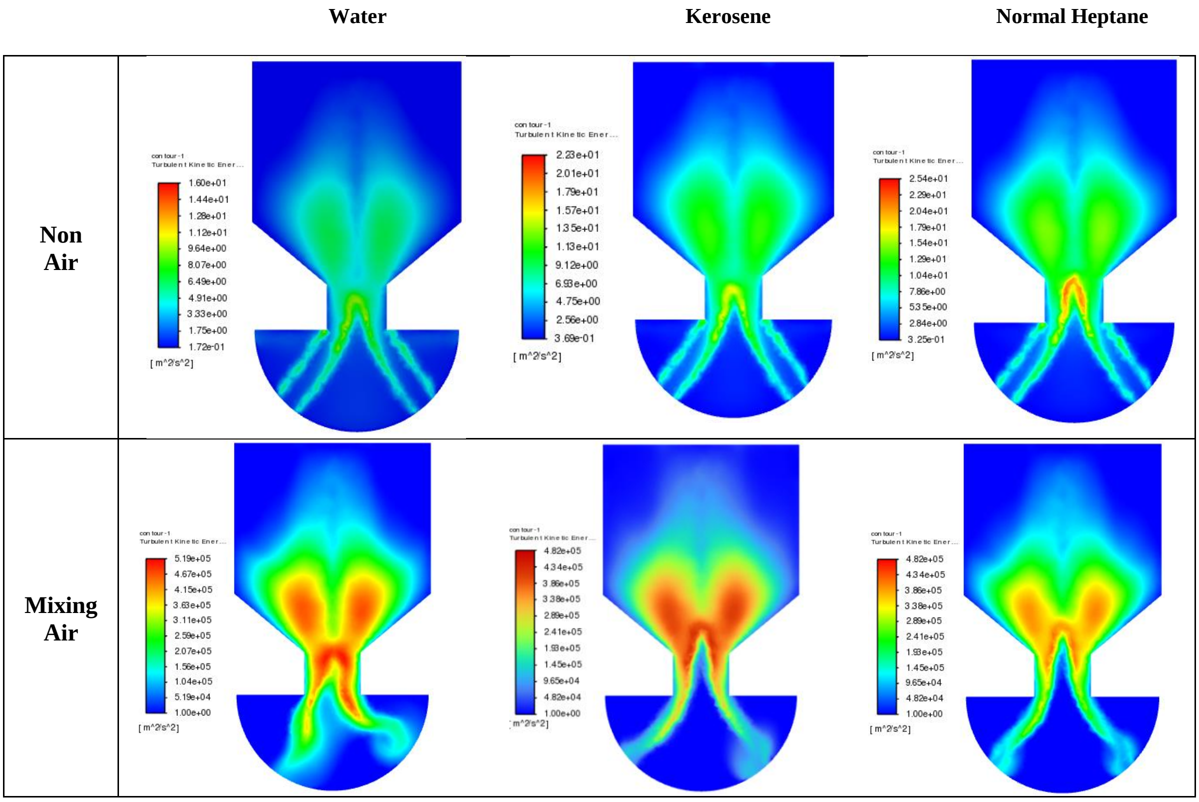


Figure 8. Comparison of the turbulence kinetic energy of the three liquids at the atomizer outlet for the case of no high-velocity airflow and adding high-velocity airflow.

In summary, the results of this section demonstrated that the adding of high-velocity airflow has a pronounced impact on the characteristics of all three types of sprays examined: water, kerosene, and normal heptane. However, it is important to note that the extent of these changes is particularly pronounced for the water spray. This disparity can be attributed to the differing physicochemical properties of the three liquids, such as their viscosity, surface tension, and volatility. These inherent differences influence how each liquid interacts with the high-velocity airflow, ultimately leading to varied outcomes in terms of spray formation, droplet size distribution, and dispersion patterns. Consequently, understanding these interactions is crucial for optimizing spray applications across different liquids in various industrial and environmental contexts.

Conclusion

In the present study, we investigated the interaction of internal mixing high-velocity airflow, with a mass flow rate of 0.02 kg/s and a temperature of 300 K, with the spray of three common fluids—namely water, kerosene, and normal heptane—each having a mass flow rate of 0.08 kg/s in a pressure swirl atomizer. The main results were as follows:

- A reduction in fluid film thickness (T) for the water, normal heptane, and kerosene sprays by 79.82%, 77.36%, and 76.87%, respectively.
- A reduction in the Sauter mean diameter (SMD) for the water, normal heptane, and kerosene sprays by 96.99%, 96.12%, and 95.94%, respectively.

- A slight increase in the cone angle of the kerosene and normal heptane sprays, while the water spray collapsed and deviated from its intended pattern.
- A significant increase in the turbulence kinetic energy (TKE) of the spray for all three liquids, with a more pronounced increase observed for the water spray.

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