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LAMINAR SWIRL SPRAY EMANATING FROM SIMPLEX ATOMIZERS WITH VARIOUS DISCHARGE ORIFICE DIAMETERS

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ABSTRACT

Studies of swirl spray have received considerable attention due to its importance in numerous applications such as combustion, agriculture, drug delivery, and perfumes. The present study investigates the characteristics of sprays emanating from a simplex atomizers with different diameters of discharge orifice and flowrates. Spray cone angle, breakup length and air core diameter are recorded repeatedly and their respective averaged values along with the standard deviation are presented. It is found that the size of the discharge orifice does play a significant role in determining the characteristics of the emanating sprays, while the role of flowrates (i.e. the injection pressure) is only prominent for determining spray cone angle and breakup length.

Keywords: swirl atomization, spray angle, breakup length, air core diameter.

INTRODUCTION

An atomizer is a device that produces fine spray from a stream of liquid [1]. The bulk liquids are forced through the discharge orifice of the atomizer in a swirling motion to form ligaments downstream of the orifice due to instability. This is defined as primary atomization. The ligaments are then atomized into fine droplets, in which the size and distribution is depending on the geometrical parameters of the atomizer, as well as the operating conditions. This is defined as secondary atomization [2].

Atomizers are used in various applications, such as to meter the flowrate, speed and pressure of the stream of liquid that emanating from it. Atomizers are also used in medical and pharmaceutical industries, where it applied in asthma inhalers and nebulizers. The main function is to deliver drugs through nasal cavity at a specified dosage [3]. In agricultural industries, the atomizer is used in plant spray and pesticides application. Besides that, atomizers are also used in applications of combustion system, for cleaning supplies, perfumes and kitchens. Thus, clear understanding of spray characteristics of atomizer is important for the improvement of technologies.

The present investigation focuses on the characteristics of spray emanating from simplex atomizers, i.e. spray angle, break up length, air core diameter and discharge coefficient. In general, a swirl stream of the fluid in a simplex atomizer is persuaded by move the fluid into a swirl chamber through tangential ports, that will results in the fluid moving downstream in a swirling motion and producing an air-cored vortex [4]. The swirling motion through the discharge orifice can be decomposed azimuthal and axial components.

The spray angle is the angle of the liquid spray from the discharge orifice of the atomizer to a maximum angle of spray created. The geometrical parameters that effect the spray characteristics of spray angle include the width of swirl chamber, diameter of discharge orifice, depth of inlet port, length of swirl chamber and length of orifice [5]. It was reported that the larger the diameter of discharge orifice increases the spray angle but the discharge coefficient decreases [6]. The increase in swirl chamber diameter, however, produced narrow spray, contradicted to that of the orifice size [7].

The breakup length of the spray is the distance of the bubble bursting prior to the discharge orifice of the simplex atomizer. The variations of injection pressure affect the elongation of the spray breakup length of the atomizer. As the injection pressure increases, the spray angle will increase but it will form the shortest spray break up of atomizer [8]. The relative velocity between the liquid and the air additionally influences the droplet sizes. The fluid's velocity is created by pressure in the atomizer. It also shows that when the fluid pressure increases, the velocity increases and the average droplet size decreases [9].

The air core that is created in swirl chamber of atomizer is significant source that influence the liquid film thickness [10]. A research by Liu, Huang, and Sun [11], concluded that when the length of swirl chamber is decreased, the air core becomes larger. Thus, the increasing of the air core diameter also led to decreasing the liquid viscosity. It is also reported that the stability of the air core is one of the most significant performance metrics of swirl atomizer [12].

In order to visualize the formation of the air core in the swirl chamber, the high speed camera system is used to investigate the variations and stability of the air core [13]. However, due to the limitation of visualizing the internal flow of the atomizer, researchers have simulated the flow for the prediction of air core size using numerical analysis [14].

EXPERIMENTAL SETUP

A series of cold flow tests were conducted at Laser Laboratory, Faculty of Machanical Engineering, UiTM. Water is used as a simulation fluid. The simplex atomizer (marked (7) in Figure-1) is installed at the end section of water piping systm. The components involved

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in this experiment are centrifugal pump (marked (1) in Figure-1), supply tank,valves (marked (2) in Figure-1), digital pressure gauge (marked (3) in Figure-1), water flowmeter (marked (4) in Figure-1), water collection tank (marked (5) in Figure-1),water pipe, and water pump switch (marked (6) in Figure-1).

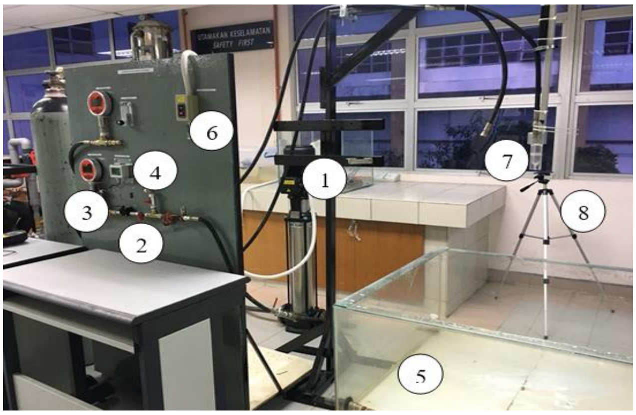

Figure-1. Experimental setup.

Water from the water supply tank is delivered to the atomizer by using centrifugal pump through the water pipeline. In order to control the water flowing out of the pump, the valve has been installed at the waterline between the pump and digital pressure gauge. Due to the fact that any unwanted substances have to be avoided from passing through the meter as well as the atomizer, the connection of the water strainer has to be established properly at the outlet of the water supply tank and at the water flowmeter inlet. As the water flowrate is varied in this experiment, the water flow meter has been installed to measure the desired value of water flowrate. The digital pressure gauge also has been installed to measure and control the pressure of water as well as in the scope of project which to ensure it will not exceed 4 bar.

A digital single-lens reflex camera Nikon D7000 model was placed about 1 meter from the atomizers to avoid water vapor reach the camera lens. The images were captured using the following settings: shutter speed of 1/250 µs, focal length of 6.3 and with ISO100. This is the optimum setting giving the sharpest and clearest images for the given laboratory environment. The flash reflector (marked (8) in Figure-1) is located behind the atomizer to eliminate direct, harsh light and shadows, and soften the light in order to record the water spray clearly.

The simplex atomizer consists of 3 inlet ports which are in the tangential direction. There are 3 parts of the atomizer, which are head, swirl chamber body, and discharge orifice body. These parts are connected together to form one simplex atomizer. The head consists of main inlet for water to flow inside all the 3 inlet ports. The swirl chamber body consists of 3 inlet ports that the water will flow swirly into the swirl chamber. While the discharge orifice body consists of spin chamber and discharge orifice. The discharge orifice body is designed and fabricated at 3 different types of diameter of discharge orifice which are 3mm, 5mm and 7mm. The material used to fabricate the head is aluminum while the swirl chamber body and discharge orifice body are using acrylic.

Table-1 summarizes the geometrical dimensions of the simplex atomizers tested in the experiment. There are 3 nozzles with different discharge orifice diameter. The length of the spin chamber at 3 nozzles also are different due to the constant of angle of spin chamber which are 30° for every nozzle.

Table-1. Dimension of the simplex atomizer.

Geometrical parameters	**Nozzle 1**	**Nozzle 2**	**Nozzle 3**
No. of inlet port	3	3	3
Diameter of inlet port (mm)	3	3	3
Length of swirl chamber, L_s (mm)	87	87	87
Length of spin chamber, L_c (mm)	14.7	13.0	11.3
Length of discharge orifice, L_o (mm)	15	15	15
Diameter of swirl chamber, d_s (mm)	20	20	20
Diameter of discharge orifice, d_o (mm)	3	5	7
Angle of spin chamber (mm)	30°	30°	30°

The geometrical parameters are defined in **Figure-2** for clarity.

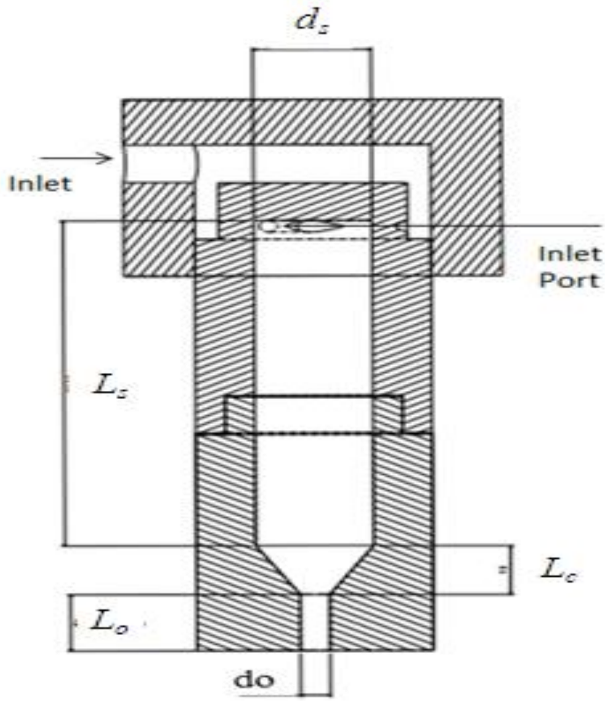

Figure-2. Schematic representation of the atomizer with geometrical definitions.

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MEASUREMENT OF SPRAY ANGLE, BREAKUP LENGTH AND AIR CORE DIAMETER

The spray angle is defined as the angle of the water spray that exits from the discharge orifice of simplex atomizer. Image J software has been used to process the original image (

Figure-3(a)) using Canny edge detection algorithm to make the edges of the emanating spray more visible. Once the image is processed, two straight lines are drawn coinciding with the edge of the swirl spray on both sides (as depicted in

Figure-3(b)) and the angle between the two lines is measured. It is important to note that the resulting sprays are rather unsteady, hence the measurements are repeated using 10 images taken at different instantaneous times and the average values are reported along with the standard deviation (represented by the error bars on the plots). The same procedures were applied for the measurements of spray breakup length and air core diameter.

The spray breakup length is a vertical distance from the atomizer's discharge orifice to the point where the liquid sheet disintegrated into ligaments (primary atomization). Similar to the abovementioned procedure, the image is first processed using canny edge detection algorithm to make the edges of the emanating spray more visible. Then, a straight vertical line is constructed from the discharge orifice of atomizer to the point of primary atomization, as depicted in

Figure-3(c).

The formation of air core is one of the spray characteristics that have been investigated in this experiment. A horizontal line is drawn connecting the two edges of the air core (as depicted in

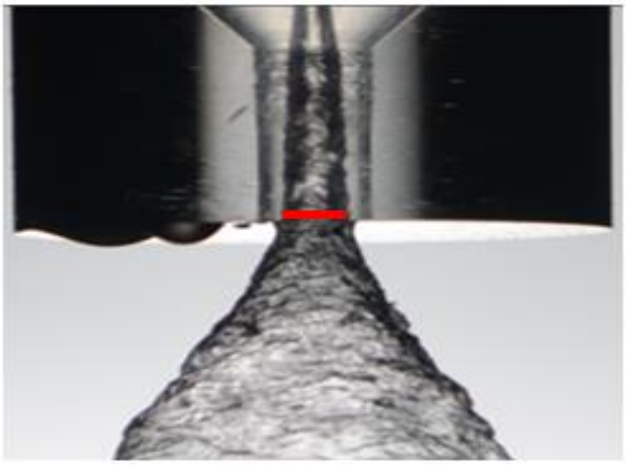
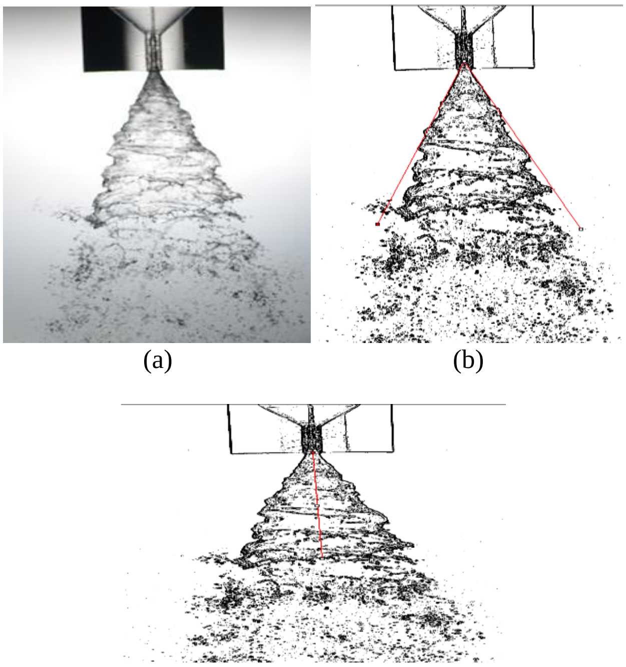


Figure-4). The length of this line is then measured, indicating the diameter of the air core at the discharge orifice.



(a) (b)

(c)

Figure-3. (a) Typical unprocessed image of instantaneous spray. Measurent of (b) spray angle and (c) breakup lengthwith the aid of Canny edge detection algorithm.

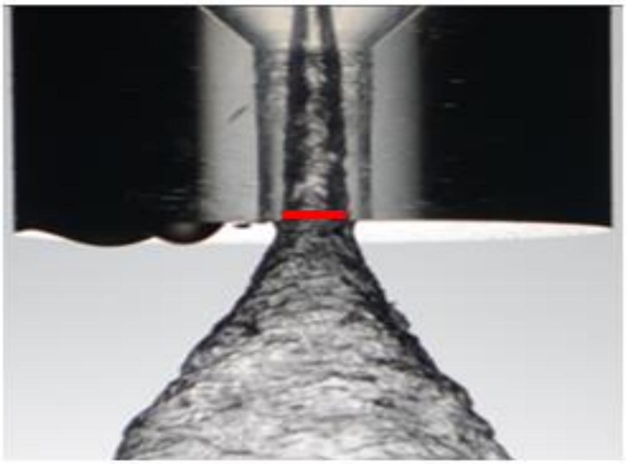


Figure-4. Close-up view of atomizer near the discharge orifice.

RESULTS AND DISCUSSIONS

The results of the experiments and calculations will be described in this section. The effect of the spray characteristics of the simplex atomizer will be analysed based on the different flowrate and diameter of discharge orifice. A total of 300 images were captured and the averages were calculated for each case to analyse the spray characteristics of the atomizer, i.e. spray cone angle, spray breakup length, and air core diameter. Furthermore, the discharge coefficient is also reported for each of the tested nozzle.

Figure-5 shows the relationship between the spray cone angle and discharge orifice diameter for various liquid flowrate. It is noted that the standard deviation of the spray angle and air core diamter data are exaggerated four times for clarity of error bars in the plot, while the standard deviation for the breakup length data is reported without exaggeration.

It can be seen that an increased in liquid flowrate resulted in a wider spray cone angle, and that the relation is almost linear. The reason for this observation is that high liquid flowrate leads to relative increase in azimuthal component of liquid flow in the swirl chamber, thus widening th reesulting sprays. It was observed that Nozzle 3, which has the largest diameter of discharge orifice produces widest spray cone angle compared to other nozzles. A previous study by [5] also reported that the resultant spray angle were affected by the discharge orifice diameter of the atomizer. Thus, in the present research, the relationship between the different discharge orifice diameter and flowrate on the spray angle are verified where the increases of flowrate and diameter of discharge orifice leads to wider the spray angle.

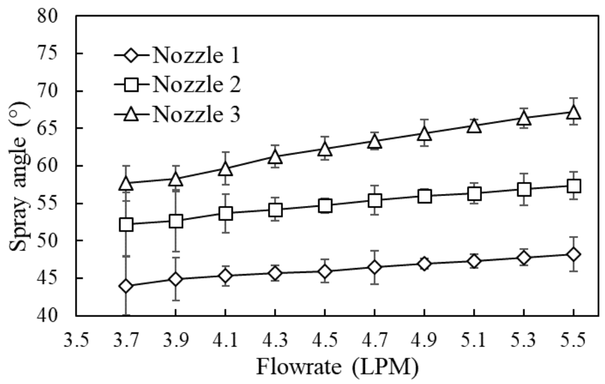


Figure-5. Spray angle plotted against flow rate.

The relationship between the spray breakup length and different diameter of discharge orifice as well as with liquid flowrate are shown in Figure-6.

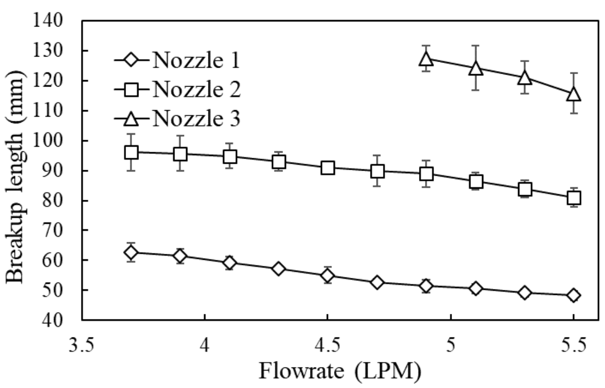


Figure-6. Effects of discharge orifice diameter on spray breakup length.

It can be observed that when the liquid flowrate increases, the breakup length is decreased. The decrease in breakup length is likely due to the increase in both axial and azimutahal velocity components at the exit orifice. The increase in these velocity components strecthed the liquid film at a faster rate, and thus resulting a shorter break up length. Nozzle with smaller diameter of discharge orifice tends to produce shorter breakup length. Nozzle 3 shows the highest value of breakup length due to stronger azimuthal component of velocity compared to the axial counterparts.

Referring to the Figure-6, the breakup length at the Nozzle 3 at liquid flowrate from 3.7LPM to 4.7LPM cannot be measured due to the spray pattern that emanating from the nozzle are not in fully developed stage. In this case, the spray is in “onion” stage when the flowrate at 3.7LPM due to relatively very weak injection pressure, as depicted in

Figure-7. The spray then changed to “tulip” stage when the flowrate starts at 4.7 LPM. The spray becomes fully developed when the liquid flowrate is increase to at least 4.9LPM. At this stage, the primary atomization can be clearly seen and hence the breakup length can be measured.

(a) (b)

Figure-7. The different stages of Nozzle 3 sprays at (a) 3.7 LPM and (b) 4.7 LPM.

Figure-8 shows the air core diameter plotted against liquid flowrate for all tested nozzles. It can be seen that the air core diameter is almost uninfluenced by the variation of liquid flowrate (or injection pressure). The observation can be attributed to the fact that at an increased injection pressure, the axial velocity componont of the swirling flow inside the swirl chamber is increased, thus conservation of mass dictates that the thickness of liquid film in the discharge orifice remain almost constant, thus the size of the air core. This argument is consistent with observation of shorter berakup length at higher injection pressure.

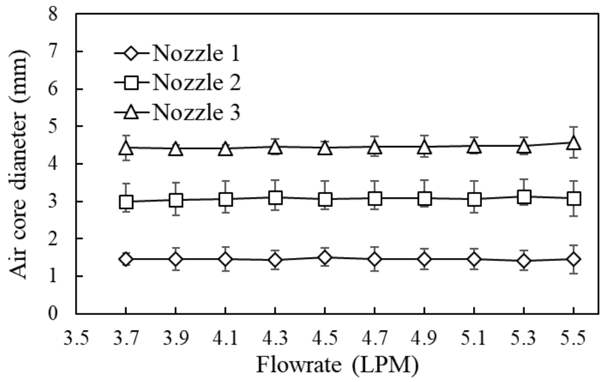


Figure-8. Air core diameter plotted against flowrate.

It is also observed that the air core is larger for a bigger dicharge orifice. However, it is intersting to note that the effect of discharge orifice size on the air core diameter is less prominent at a higher range of orifice diameter. This is likely due to the relative increase in azimuthal velocity component for a larger orifice, thus resulting in thicker film thickness in the discharge orifice. Consequently, the conservation of mass dictates that the axial velocity component of the spray must decrease. Again, this argument further supports the observation of wider spray angle for the nozzle with larger discharge oifice. In order to support the arguments regarding the axial velocity, conservation of mass principle is applied at the exit orifice to predict the variation of axial velocity with injection flowrate and exit orifice diameter, i.e.

$$V_{\text{axial}} = \frac{Q}{A_{\text{eff}} \cos \beta} \quad (1)$$

where V_{axial} is axial velocity component at the exit orifice, Q is volume flowrate, β is spray half angle and A_{eff} is the effective area of liquid sheet at the exit orifice, which is approximated by

$$A_{\text{eff}} = \frac{\pi}{4}(d_o^2 - d_a^2) \quad (2)$$

where d_o and d_a are orifice and air core diameters, respectively. The plot of the axial velocity against liquid flowrate is presented in Figure-9.

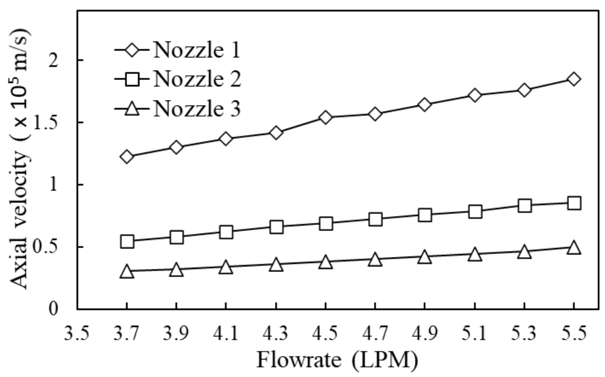


Figure-9. Estimated axial velocity component of emanating sprays at exit orifice plane.

It can be seen from Figure-9 that the axial velocity component of the spray increases almost linearly with liquid flowrate, and that the velocity decreases with larger exit orifice. These observations clearly support the previously mentioned arguments.

The discharge coefficient is another important spray characteristic of simplex atomizer in present study. It is calculated using

$$C_d = \frac{\dot{m}}{A\sqrt{2\rho\Delta P}} \quad (2)$$

where $\dot{m}$ is the mass flowrate, A is the dischargeorifice area of atomizer, ρ is the density of water and ΔP is the pressure drop across the nozzle. The data is presented in Figure-10.

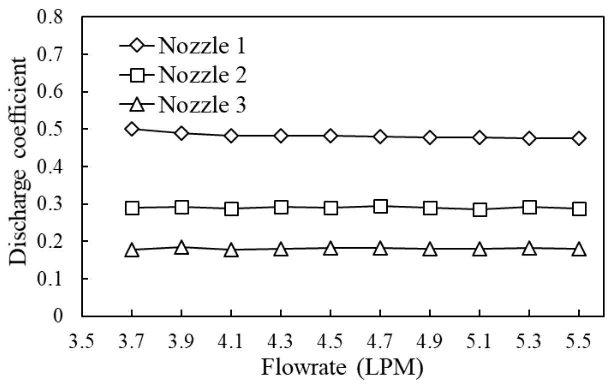


Figure-10. Discharge coefficient for all tested nozzles at various flowrate.

Referring to Figure-10, the discharge coefficient for all nozzles is almost independent of liquid flowrate. This observation is explained as follows: when the injection pressure is increased, both the axial and azimuthal velocity components of the swirling liquid sheet inside the nozzle are increased. The former tends to reduce the boundary layer thickness, thus reduces the resistance to the flow, while the latter increases the strength of swirl and thus the friction imposed on the fluid. This counterbalancing effect results in an almost constant value of C_d with flowrate.

Figure-10 also indicates that larger discharge orifice imposes greater resistance upon the flow. This observation can be related to the increased of air core diameter with the increased of discharge orifice diameter. A larger air core lowers the effective area of discharge and thus reduces the discharge coefficient of that nozzle.

CONCLUSIONS

A total of 300 cold flow test experiment was conducted to study the performance of the spray characteristic of the simplex atomizer with different parameters varied, which are the diameter of discharge orifice and liquid flowrate. In order to analyze the performance of the atomizer, the spray characteristics such as spray angle, breakup length, and air core diameter have been measured. The discharge coefficient has also been calculated and analyzed in the present study. It can be concluded that increases in liquid flowrate tends to widen the spray and shorten the breakup length. The air core diameter and discharge coefficient are, however, insensitive to the change of flowrate.

A larger discharge orifice tends to produce wider spray, larger air core and consequently lower discharge coefficient. Furthermore, the primary atomization occurs further downstream for a larger discharge orifice.

Most of the sprays are in fully developed stage, except for Nozzle 3 at relatively low flowrate, where the sprays are in “onion” and “tulip” stage. Hence, no primary atomization was observed.

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