International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 43, No. 1, February, 2025, pp. 209-218
Journal homepage: http://iieta.org/journals/ijht

Experimental Study of Droplet Evaporation of Different Hydrocarbon Fuels

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https://doi.org/10.18280/ijht.430122

Received: 16 November 2024
Revised: 6 February 2025
Accepted: 18 February 2025
Available online: 28 February 2025

Keywords:
droplet evaporation, droplet lifetime, hydrocarbon fuel, free-flying droplet, high-speed photography, mass diffusion

ABSTRACT

This work experimentally investigates the evaporation process of kerosene, gasoline, ethanol, and acetone hydrocarbon fuels, and water for comparison. The experiments were performed on free-flying droplet, under gravity force only, in a cylindrical evaporation chamber at atmospheric pressure and controlled temperatures from 25 to 100°C. Diffusion controlled evaporation is the only mode considered in this study by keeping the chamber temperature less than the boiling temperature of the fuels. The droplet was photographed as it flew down using a high-speed camera. The extracted images from the camera were analyzed using MATLAB code. The droplet is assumed to be spherical. The results showed that the evaporation rate increases logarithmically with the increase in the temperature of the evaporation chamber for all tested fuels. When the temperature was raised from 25 to 45°C, the droplet lifetime of acetone, ethanol, gasoline, kerosene, and water decreased by 63%, 66.7%, 59.1%, 67.7%, and 70.5%, respectively. Increasing the temperature leads to an increase in the rate of evaporation and thus reduces the lifetime of the droplet. The evaporation constantly rose by 0.00767, 0.02159, 0.00693, 0.02, and 0.015 mm^2/s for every °C for kerosene, acetone, water, ethanol, and gasoline, respectively.

1. INTRODUCTION

The evaporation and combustion of liquid fuel droplets play a significant role in various fields of science and technology, such as power and process industries, chemistry, medicine, and environmental processes. Research work in the area of droplet evaporation has been going on for decades. Phenomenal progress has already taken place in the theory of evaporation and combustion of liquid fuel droplets and sprays. The theoretical progress includes the development of physical models and computer codes capable of solving model equations. The experimental advances, on the other hand, involve the development of improved instruments for calibrating the model predictions and for investigations of several complex phenomena occurring in the process of droplet evaporation and combustion. Many investigations carried out in the field have contributed well to the scientific understanding of the subject. A liquid droplet (in the context of evaporation/ combustion study) can be classified into three categories based on its constituents. Ma et al. [1] studied the evaporation and combustion of hydrocarbon droplets under different pressure conditions. Higher ambient pressure in sub-critical conditions led to faster droplet combustion controlled by phase equilibrium. In super-critical conditions, combustion time stabilized, influenced by the diffusion coefficient. The critical pressure determined super-critical combustion. Evaporation was completed earlier in super-critical pressure environments, indicated by a decreased evaporation-to-combustion time ratio. In their experiment, Patel and Sahu [2] studied the impact of fuel composition and air turbulence on bi-component fuel droplet evaporation. They suspended droplets made of n-heptane and ethanol mixtures in a turbulence box and observed that turbulence positively influenced the evaporation rate. The effect varied based on fuel vapor mass diffusivity and initial fuel composition. The first stage of evaporation was sensitive to turbulence and composition, while the second stage showed composition-specific trends.

Dai et al. [3] conducted an experimental study on the evaporation behavior of diesel/cerium oxide nanofluid fuel droplets. The experiments were performed at ambient temperatures of 673 K and 873 K, normal gravity, and atmospheric pressure. Results showed that at 673 K, the nanofluid fuel and diesel exhibited similar evaporation behavior. However, at 873 K, the nanofluid fuel droplets expanded and exploded more easily, with a shorter evaporation duration. This behavior was attributed to the presence of ceria nanoparticles near the droplet surface, reducing partial surface tension and promoting micro-explosion, thereby significantly reducing the evaporation time. Wang et al. [4] examined the evaporation characteristics of a nanofluid fuel with varying concentrations of ceria nanoparticles. At 873 K, the addition of nanoparticles led to intense micro-explosions and increased evaporation rate compared to pure diesel, with the highest enhancement at 0.25% to 1.25% concentrations. However, at 5%

concentration, the enhancement decreased. At 673 K, the nanoparticle accumulation inhibited evaporation by forming a porous shell on the droplet's surface. The researchers proposed an evaporation mechanism model based on their findings. Yadav et al. [5] investigated the potential of using trans-esterified waste transformer oil (TWTO) as a replacement for diesel fuel to reduce costs. They refined waste transformer oil through a two-stage trans-esterification process to obtain TWTO with suitable properties for diesel engine use. The evaporation characteristics of TWTO-diesel blends were evaluated using a suspended droplet experimental facility. Results indicated that B50 (50% TWTO and 50% diesel) exhibited superior droplet regression, evaporation constant, and droplet lifetime compared to B100 (100% TWTO). In a diesel engine, TWTO-diesel blends, particularly B25, demonstrated comparable performance, combustion, and gaseous emissions (CO, smoke, NOX) to diesel, making it an optimal blend for unmodified engines. Magaril et al. [6] investigated the effect of multifunctional surface-active nano-additive on the gasoline characteristics and engine performance. The measurement results confirmed the effective reduction of the surface tension of gasoline at the boundary with air, improving the mixture formation in the engine. On the other hand, the saturated vapor pressure was significantly decreased, which dramatically reduced evaporation losses and air pollution by light hydrocarbons.

Valiullin et al. [7] conducted simulations to analyze the ignition and combustion characteristics of coal-water slurry-containing petrochemicals (CWSP) and oil droplet groups surrounded by water droplets. They observed that reducing droplet distances, typical for fuel droplet size, decreased ignition delay times by 30%. Increasing water droplet distance reduced evaporation times by 25%. Placing a combustible droplet with water droplets increased ignition delay times for oil and CWSP.

Luo et al. [8] conducted an experimental study on the influence of an electric field on droplet combustion. The electric field had notable effects on the droplet's shape, flame temperature, and combustion time. The application of an electric field elongated the droplet's shape, brightened the flame, stabilized the droplet shape, and decreased the flame height. Combustion time was reduced by 14.9%. Flame temperature initially increased and then decreased with higher electric field intensity, while droplet and evaporation temperatures decreased. The maximum flame temperature increased by 17.6%, while the maximum droplet temperature and evaporation temperature decreased compared to no electric field condition. However, the electric field did not significantly affect the combustion rate. Rosli et al. [9] investigated the evaporation behavior of gas-to-liquid (GTL) diesel fuel blends with varying percentages of GTL fuel. Their study revealed that G100 showed no puffing, while G20 had no micro-explosions. The remaining blends exhibited both phenomena, with G50 having the highest micro-explosion intensity. Adjusting the detection threshold affected the number and size of child droplets, with G50 having the highest number. Overall, a 50% GTL fuel blend yielded the best droplet micro-explosions.

Kastner et al. [10] studied the diameter variations of single droplets dried in an acoustic field. They faced challenges in determining the rate of evaporation but found it easier to track the rate of size change. They divided the droplet drying process into two stages based on volume changes. In the first stage, they estimated the evaporation rate using droplet volume, while in the second stage, with minimal volume reduction, they measured the evaporation rate by observing changes in the position of droplet particles in the acoustic field. Brenn et al. [11] estimated the rate of evaporation using changes in droplet diameter. The evaporation rate was not taken into consideration in the reports by Mondragon et al. [12, 13]; instead, the droplet drying behavior in the acoustic field was assessed by the size changes, with the effects of drying conditions and initial droplet conditions on the final particle properties being investigated. to make it easier to measure the rate of droplet evaporation in the SDD processes that use sonic levitation. For the purpose of accomplishing a continuous, online measurement of the droplet moisture content while drying progressed, Groenewold et al. [14] included a dew point hygrometer in the system. Calculating the partial vapor pressure of outflow air converted the experimental data into droplet drying curves [15, 16]. A droplet with a diameter of 1 mm is suspended from the end of a thin glass or glass capillary tube and placed in a regulated air stream in a contact levitation experiment. A camera and a thermocouple (one placed in the core of the droplet and the other in the tube) are used to evaluate drying variables such as the droplet's mass as well as diameter reductions [17].

Many studies analyzed the discrete component model or individual components to simulate fuel droplet heating and evaporation [18-22]. They found that the discrete component model gives the highest accuracy. A multi-dimensional quasi-discrete model was utilized in several investigations [23, 24]. A modest number of representative components were used in place of a huge number of other components in this modeling.

Giyad and Shahad [25] conducted a comprehensive review of previous research about droplet evaporation. One of their conclusions is that the evaporation process can be enhanced by the addition of nanoparticles to the fuel.

The objective of the current investigations is to experimentally measure, explore, and compare the evaporation of a free-flying droplet of different liquids since the evaporation process of the droplet affects the mixing of fuel and oxidant, which in turn affects the efficiency of the combustion process. Droplet evaporation also affects droplet drying behavior. Droplet Faster evaporation means shorter combustion duration. Four different types of liquid hydrocarbon fuels and water have been considered. Water is chosen as the basis for comparison. The free-flying droplet technique is used with the help of high-speed photography and is adopted in this research. The MATLAB code is used in photographs and video analysis. The free-flying technique is adopted since it resembles droplet evaporation in diesel engines. The results of this study will help to choose the appropriate fuel for certain combustion applications.

2. EXPERIMENTAL SETUP

An experimental test rig was constructed, as depicted in Figure 1 and schematically in Figure 2, to observe the evaporation process of a falling droplet. It consists of: 1- Evaporation cylinder, 2- Droplet injectors, 3- Temperature sensor, 4- Air heater, 5- Air blower, 6- Control panel, 7- High-speed camera, 8- PC.

The high-speed photography technique is used to follow the falling liquid droplet and the change in its size due to evaporation. Therefore, a cylinder of heat-resistant, transparent Pyrex glass was used as an evaporation chamber.

The cylinder dimensions are 175 mm inner diameter, 180 mm outer diameter, and 1300 mm length. It is installed vertically. The cylinder is closed and supported by an iron flange from its lower end. The flange has an opening in its center to allow air hot circulation. The upper end of the cylinder is also closed by an iron flange with a central opening to allow for air circulation. On this flange, the thermocouple and droplet generator are mounted.

A low-pressure air is used to push the fluid into the droplet generator only. Then, the droplet is formed on a very fine needle with 0.26 mm diameter and falls freely under gravity force only into the evaporation chamber, which is at atmospheric pressure. The droplet size and shape are affected by various parameters such as the liquid physical properties (density and surface tension), nozzle size and geometry, and the flow rate. The size of the droplets produced by a pressure-driven droplet generator can vary from a few micrometers to several millimeters. The droplet generator is shown in Figure 3.

The evaporation process of the falling droplet is recorded by a high-speed camera type AOS-Q-PRI with an image resolution of 3 Megapixels. The internal memory is 1.3 GB, and the frame rate is 16000 FPS. The camera setting used in the experiment is 500 FPS and the total time of recording is 2 sec, 10% of which is set as pre-triggering to ensure that all evaporation process is recorded.

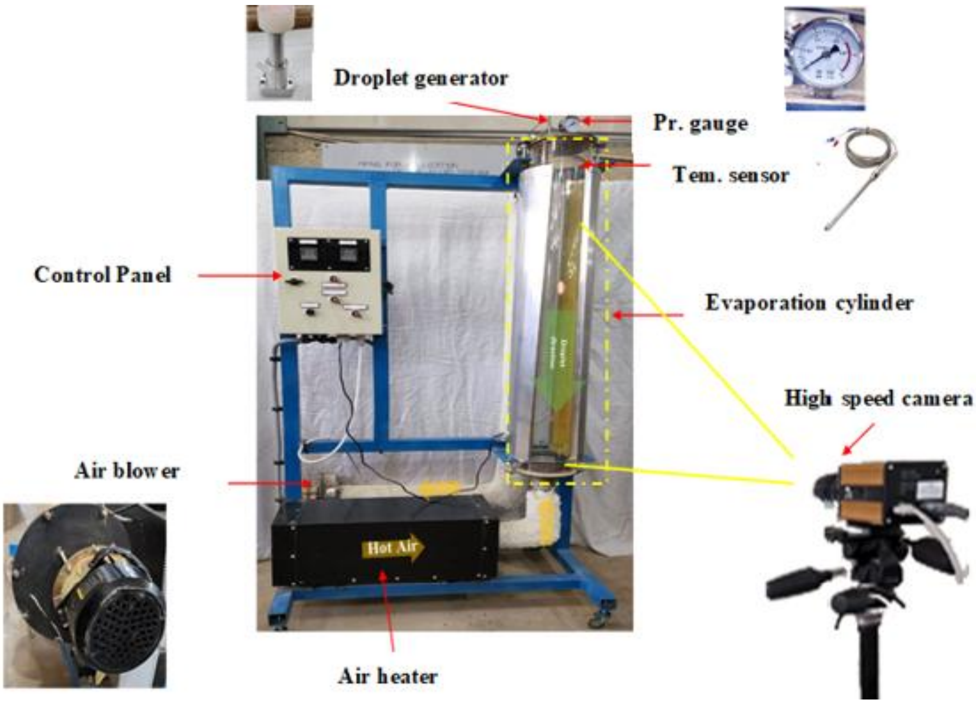


Figure 1. The experimental setup

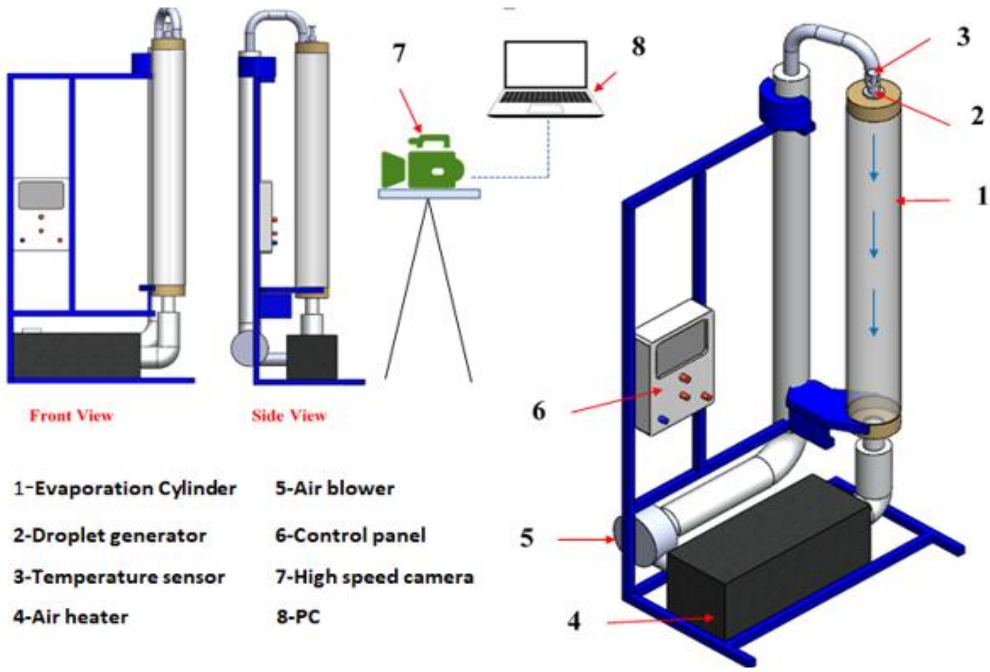


Figure 2. Schematic diagram outlining the experimental setup

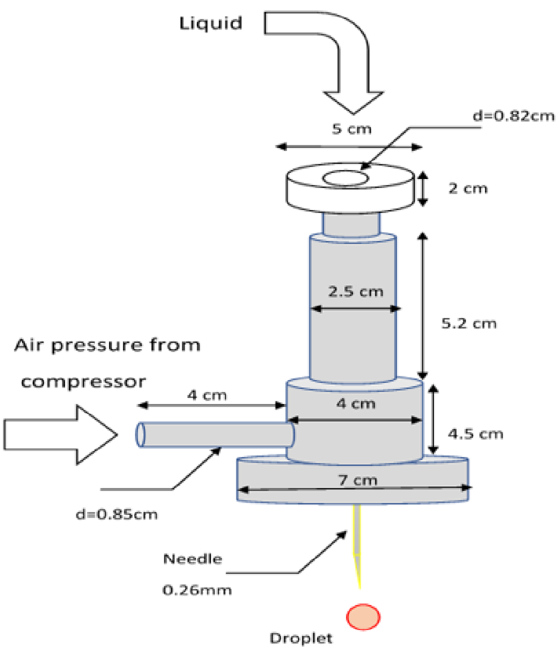


Figure 3. Pressure-driven droplet generator

3. DATA ACQUISITION

The experimental procedure is as follows:

i. The camera is installed at a distance of 103 cm from the evaporation chamber. The camera and the computer are connected via an interface unit.
ii. Set the evaporation chamber temperature.
iii. Switch on the air heater to heat the circulating air until the required set temperature in the chamber is reached, then, the heater is switched off by the control unit.
iv. Generate a droplet.
v. The camera is switched on to record the free-flying droplet as it falls through the chamber. Figure 4 shows an example of these recordings.
vi. At the end of the experiment, the chamber is flushed with fresh air to scavenge any remaining liquid.
vii. Repeat the previous steps but at another chamber temperature for the same liquid.
viii. Repeat the same procedure for other liquids.
ix. The captured video is transferred to the MATLAB program in AVI format by designing image processing code.

A code script is developed in MATLAB to analyze video data of a droplet and plots various graphs related to the variation of droplet size and evaporation rate at different times as the droplet falls through the evaporation chamber. As a result, the droplet diameter and volume are calculated at the end of each time step. So, the droplet evaporation rate can be calculated using the following relationship:

$$\dot{m} = \frac{\rho_l \Delta v}{\Delta t} \quad (1)$$

where, $\Delta v = v_1 - v_2$, $\Delta t = t_2 - t_1$.

The evaporation constant (K) is a parameter that describes the rate of evaporation of a liquid into the surrounding environment. The evaporation constant depends on various factors, such as the properties of the liquid, the temperature and humidity of the surrounding environment, and the flow conditions around the droplet. It is calculated as follows:

- Measure the initial droplet diameter, D_o, which is assumed to be spherical. The initial droplet diameter depends on the liquid density since it is generated in the atmospheric environment (no injection). Table 1 shows that water produces the smallest droplet since it has the highest density.
- Measure the change in diameter over the time step by using the MATLAB image process.
- Plot $\frac{D^2}{D_\circ^2}$ versus $\frac{t}{D_\circ^2}$ and fit a curve with a linear equation.
- The slope of the generated curve would be negative and equal to the evaporation constant (K) [26].

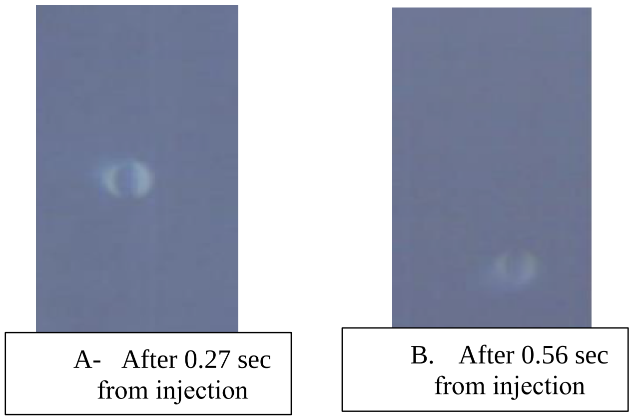


Figure 4. Ethanol droplet images as a sample of the high speed camera recording

Table 1. Initial droplet diameter for tested liquids

Liquid Type	Initial Droplet Diameter (mm)
Acetone	2.82
Ethanol	2.81
Gasoline	2.58
Kerosene	2.44
Water	2.12

A droplet's lifetime refers to the duration of time during which a liquid droplet remains suspended in the air until it is completely evaporated. The droplet lifetime depends on various factors, such as the size of the droplet, the ambient temperature and humidity, and the velocity of the surrounding air. The lifetime of the droplet, t_d, is calculated using the following equation:

$$t_d = \frac{D_\circ^2}{K} \quad (2)$$

4. UNCERTAINTY ANALYSIS

The standard uncertainty, Su, is calculated by the equation proposed by Bell [27] as:

$$Su = \frac{S.D.}{\sqrt{N}} \quad (3)$$

$$S.D. = \sqrt{\frac{\sum_{i=1}^{N}(X_i - X_{average})^2}{(N-1)}} \quad (4)$$

$$X_{average} = \frac{1}{N}\sum_{i=1}^{N} X_i \quad (5)$$

where, N is the total number of measurements, X_i represents the values for measurement data.

Each experiment was repeated three (3) times and the mean is considered in the analysis to reduce the uncertainty. The uncertainty results are shown in Table 2.

Table 2. Standard uncertainty for diameter measurement

Fuel Type	Uncertainty of Diameter Measurements (mm)
Acetone	0.00623
Ethanol	0.00582
Gasoline	0.00542
Ethanol	0.00582
Kerosene	0.00557
Water	0.00501

5. RESULTS AND DISCUSSION

5.1 Liquids physical properties

The most important physical properties of the used liquids related to the droplet formation, namely density and viscosity, are measured in the laboratories of the Materials Engineering Department/ University of Babylon. The results are shown in Table 3.

5.2 Repeatability analysis of measurements

The repeatability of the experiments is shown in Figure 5 for water droplets. The figure shows the variation of evaporation constant with temperature. It shows that there is an error in the rate of evaporation of the droplet ranging from 1% to 4% at 25°C and 8%-12% at 95°C, which is acceptable.

$$Error\ Percentage = \frac{\max value - \min value}{\max value} \times 100 \quad (6)$$

5.3 Results of droplet evaporation

The data obtained from the present set of experiments provides suitable conditions to explore the effect of prevailing temperature on the evaporation process for the different liquid droplets. The most important parameters that characterize droplet evaporation were calculated, which are the droplet diameter, the evaporation rate, the evaporation constant, and the droplet lifetime.

The variation of droplet diameter with time is due to the evaporation process as the droplet falls in the chamber. When a liquid droplet is released into the air, it immediately begins to evaporate by mass diffusion only without boiling, and the vapor diffuses into the surrounding air.

Figure 6 shows the decrease in the droplet diameter with time after injection into the evaporation chamber at different chamber temperatures. The Initial droplet diameters for the different liquids, acetone, ethanol, gasoline, kerosene, and water, are 2.82, 2.81, 2.58, 2.44, and 2.12 mm, respectively. As expected, it is clearly shown that the droplet diameter decreases with time for all liquids at all temperatures. The initial droplet diameter for the different liquids varies due to the differences in their densities. This figure shows that acetone and ethanol droplets evaporate faster than other liquids due to their larger surface areas and larger diffusivity in air, as shown in Table 3.

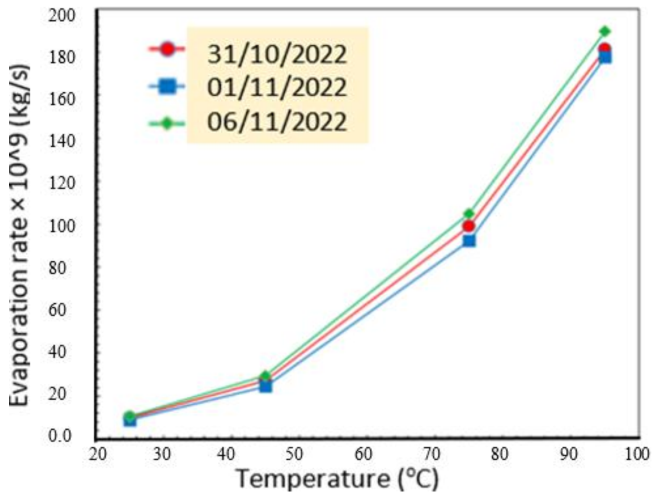
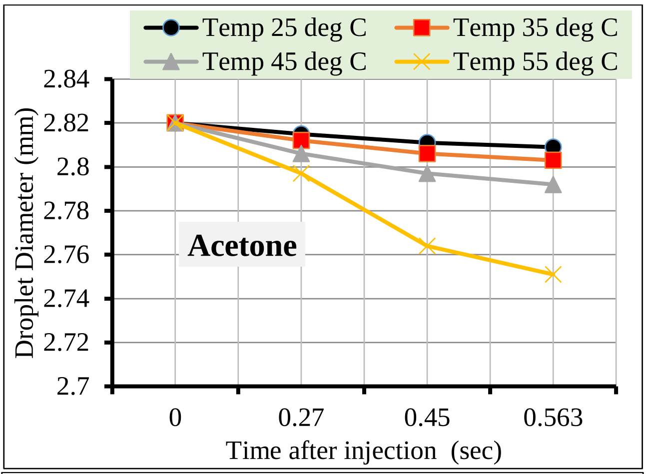


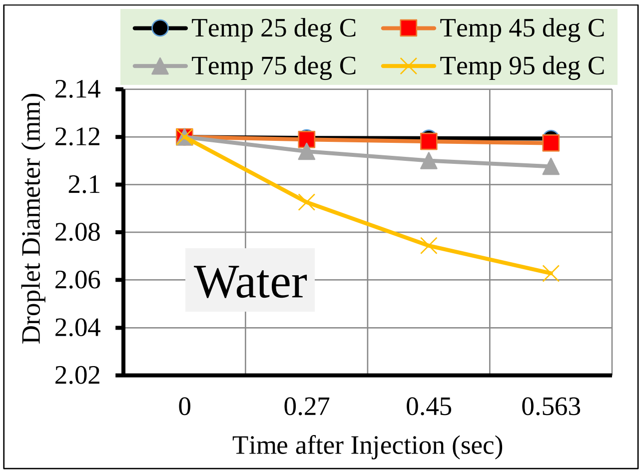
Figure 5. Repeatability test for water droplet experiments

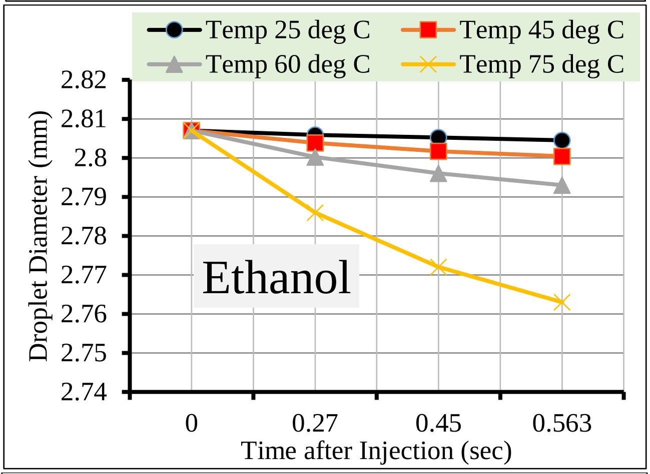
Figure 7 shows the variation of droplet diameter due to evaporation with chamber temperature for acetone, ethanol, gasoline, water, and kerosene, respectively, with time after droplet release. All figs show the same trend where the droplet diameter decreases with increasing the chamber temperature. As the chamber temperature increases and approaches the boiling temperature of the specific liquid, the rate of diameter reduction rises due to the high rate of evaporation, as will be seen later. The initial droplet diameter of acetone is 2.82 mm and decreases by 0.39% at a temperature of 25°C during 0.5625 sec, while when the temperature of the evaporation chamber is raised to 55°C, which is close to its boiling point, and during the same period, the percentage reduction increases to 2.446%. Likewise, a droplet of ethanol with an initial diameter of 2.807 mm decreases by 0.077% when the evaporation chamber temperature is 25°C after 0.5625 sec; while raising the chamber temperature to 75°C, the percentage reduction increases to 1.583%.

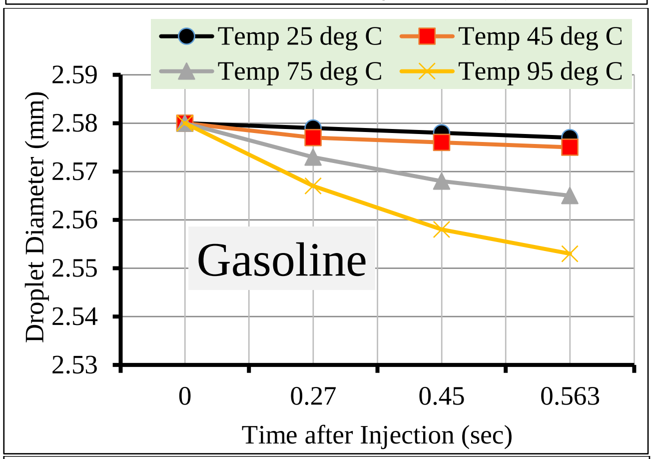
Table 3. Physical properties of used fuels

Liquid Type	Density (g/cm^3)	Surface Tension (mN/m)	Viscosity (mPa.s)	Boiling Temperature (°C)	Diffusivity (cm^2/s)
Acetone	0.7811	24.5	0.421	56	0.124
Ethanol	0.7862	21.55	0.316	78.37	0.12
Gasoline	0.7392	21.56	0.494	35-200	6.3×10^{-3}
Kerosene	0.7961	30	0.523	175-325	2.63×10^{-5}
Water	0.9895	72	0.89	100	2.299×10^{-5}









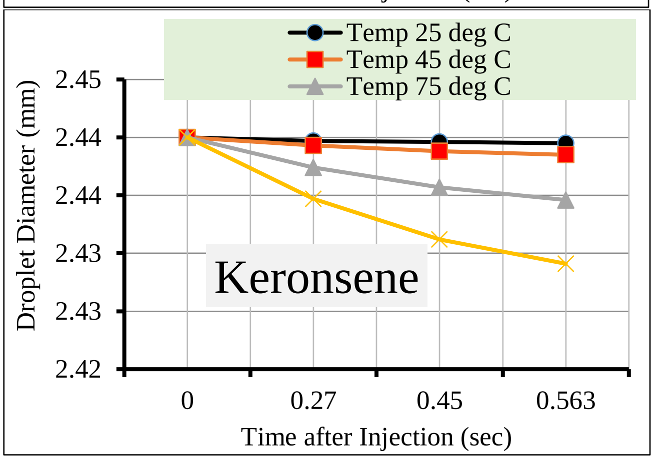
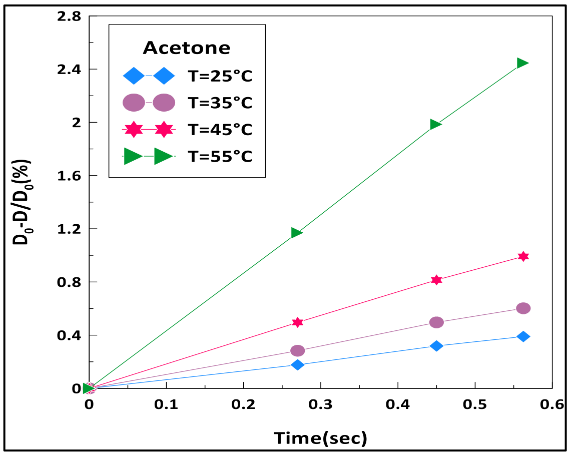
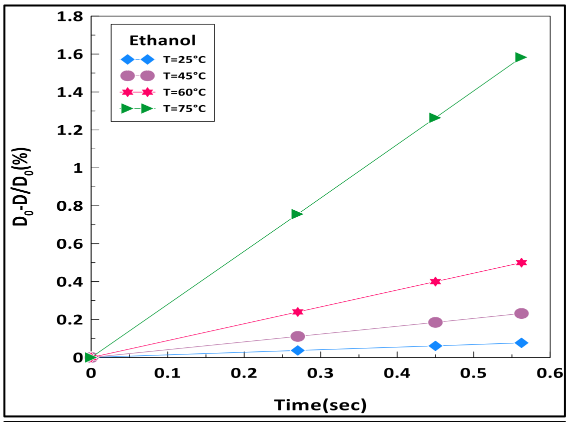
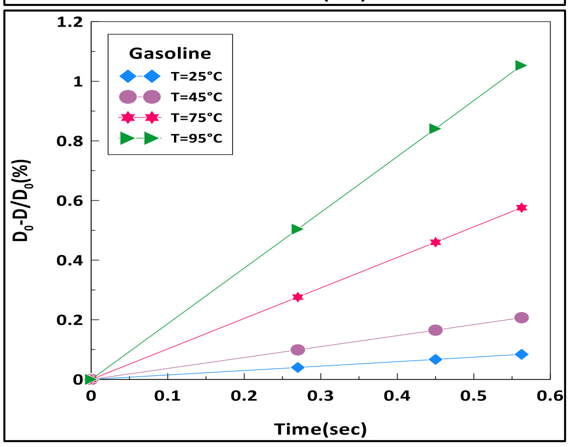


Figure 6. Variation of liquid droplet diameter with time







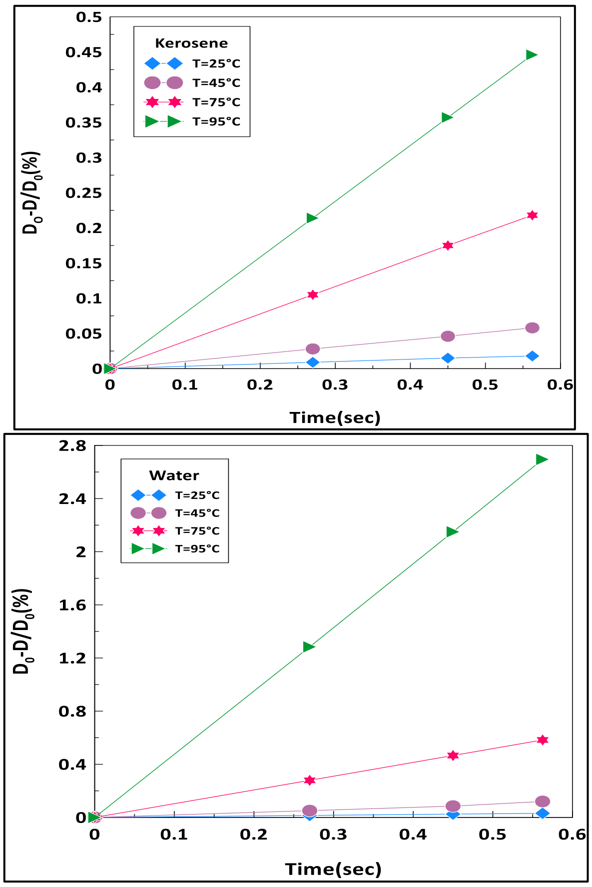


Figure 7. Percentage reduction in droplet diameter with time

For the same period and temperature, the diameter reduction for gasoline droplets is 0.084%, while the reduction rises to 1.053% when the temperature becomes 95°C. During the same period of 0.5625 sec, the reduction in droplet diameter of water at 25°C was 0.031% and became 2.69% when the temperature was raised to 95°C. Under the same initial temperature and during the same period, the reduction in the kerosene droplet diameter was 0.018% and became 0.446% when then the temperature was raised to 95°C. The variation in the maximum temperature is limited by the boiling temperature of the specific liquid at atmospheric pressure.

The results presented in Figure 7 show that the kerosene has the lowest reduction in droplet diameter (slower evaporation) since it is a mixture of many higher hydrocarbons and its very low diffusivity. This means longer droplet residence time in the combustion chamber and higher soot propensity. Higher soot propensity is a bad property of fuel.

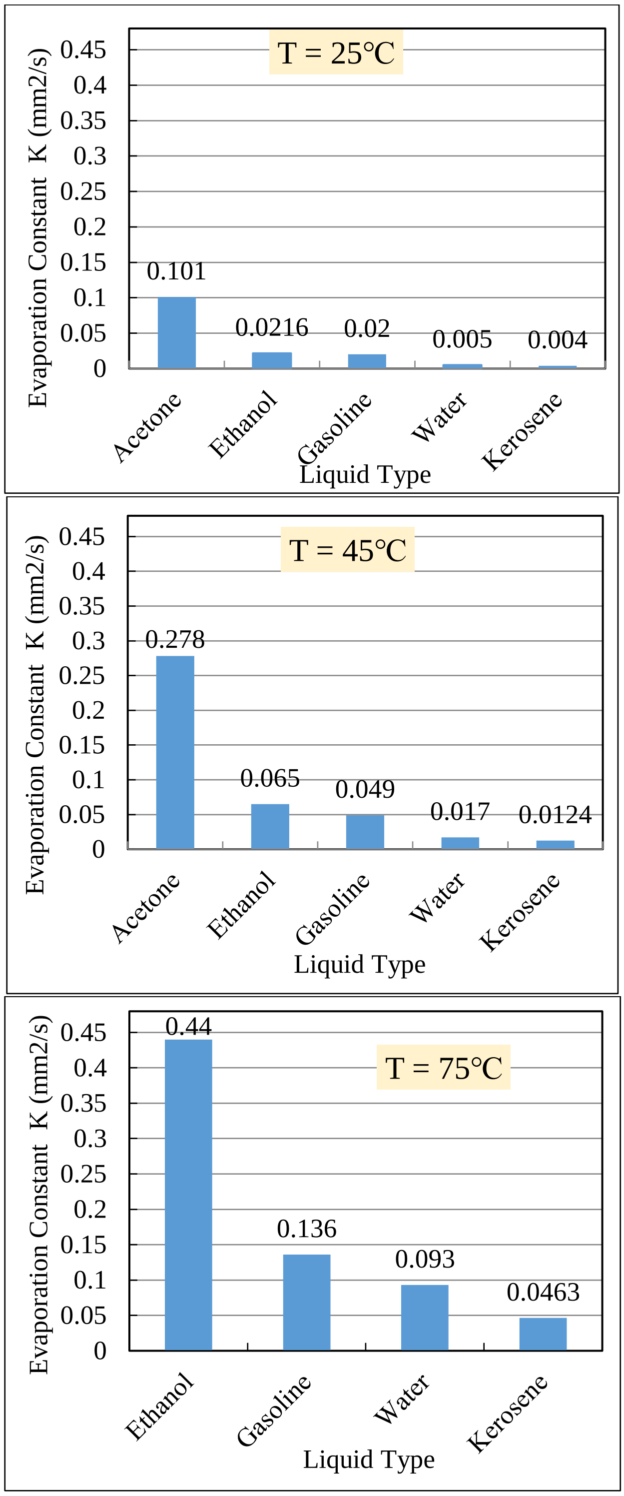
5.4 Effect of temperature on evaporation constant

Figure 8 shows the effect of temperature on the evaporation constant for all liquid droplets used in the experimental program. The value of the evaporation constant increases with increasing temperature as approximately a logarithmic relationship. This agrees with information in the literature as this constant is a strong function of temperature.

The evaporation constant of acetone droplet increases with increasing temperature, where at 25°C its value is 0.101 mm^2/s, and when the temperature of the evaporation chamber is increased to 55°C, the evaporation constant becomes 0.683 mm^2/s. The value of the evaporation constant for ethanol droplets at temperatures 25, 45, 60, and 75°C is 0.0216, 0.065, 0.14, 0.44, mm^2/s, respectively. This could be attributed to the fact that diffusivity increases with temperature for all liquids.

The same behavior is noticed for all other liquids but with different values. However, it is mentioned that the evaporation process is affected by the humidity of ambient air especially for water, since it affects the mass diffusion process.

Figure 9 shows that the higher rate of increase in evaporation constant starts at a lower temperature for acetone, followed by ethanol, gasoline, water, and finally, kerosene. This is due to the difference in the fuels' physical properties. The effect of the evaporation constant is reflected in the evaporation rate of the different liquids.



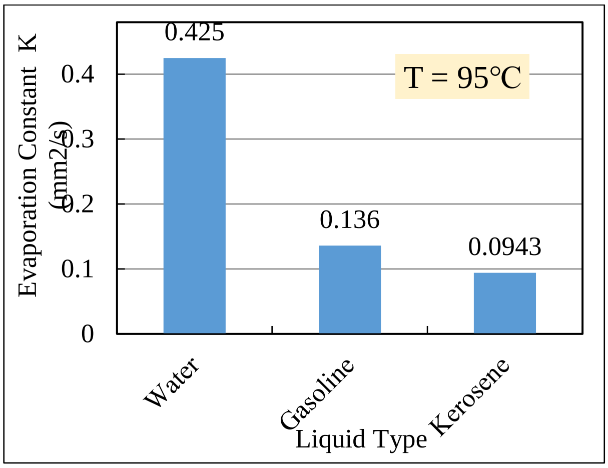


Figure 8. Variation of evaporation constant with temperature for different liquids

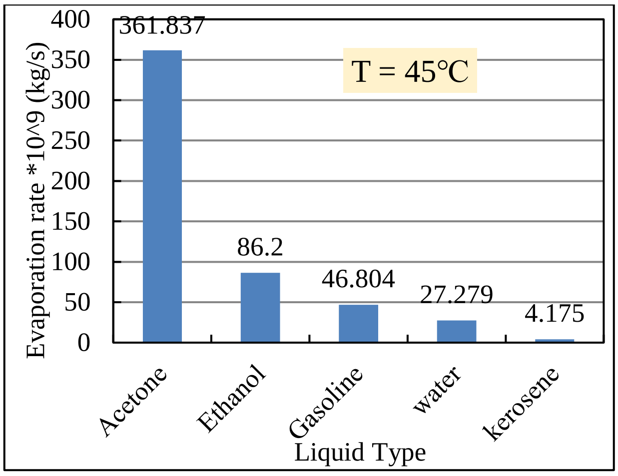


Figure 9. Evaporation rate for all liquids at 45℃

5.5 Droplet lifetime results

Droplet lifetime typically refers to the length of time that a liquid droplet exists before it evaporates completely. The droplet lifetime can vary widely depending on several factors, such as the size of the droplet, the ambient temperature, and the properties of the liquid. Smaller droplet tends to have shorter lifetimes as they have a large surface area to volume ratio and thus evaporate more quickly. Similarly, higher temperatures tend to accelerate droplet evaporation and reduce the droplet lifetime.

Figure 10 shows the effect of liquid type on droplet lifetime at different evaporation chamber temperatures. The figure shows that the lifetime of different droplets varies due to the difference in the droplet's initial diameter and the evaporation constant. Larger droplets experience longer droplet lifetimes and vice versa.

At a temperature of 25℃, the minimum droplet lifetime is fir acetone, which is about 78.736 sec. As for other liquids, gasoline, ethanol, water, and kerosene, the droplet lifetime is 332.82, 364.78, 898.88, and 1,488.4 sec, respectively. This is due to the fact that the rate of evaporation of acetone is higher than the rest of the liquids used, as the evaporation process reduces the size of the droplet until it fades and disappears.

As the evaporation chamber temperature increases, the droplet lifetime shortens for all tested liquids. The results show that at 95℃, the droplet lifetime of gasoline and kerosene is longer than that of water since water is a pure substance and boils at a constant temperature, while gasoline and kerosene are mixtures of different hydrocarbons with different boiling temperatures. For example, at the temperature of 95℃, the droplet of water shows the least lifetime compared to gasoline and kerosene, as the lifetime of a droplet of water is 10.575 sec, gasoline 26.84 sec, and kerosene is 63.134 sec.

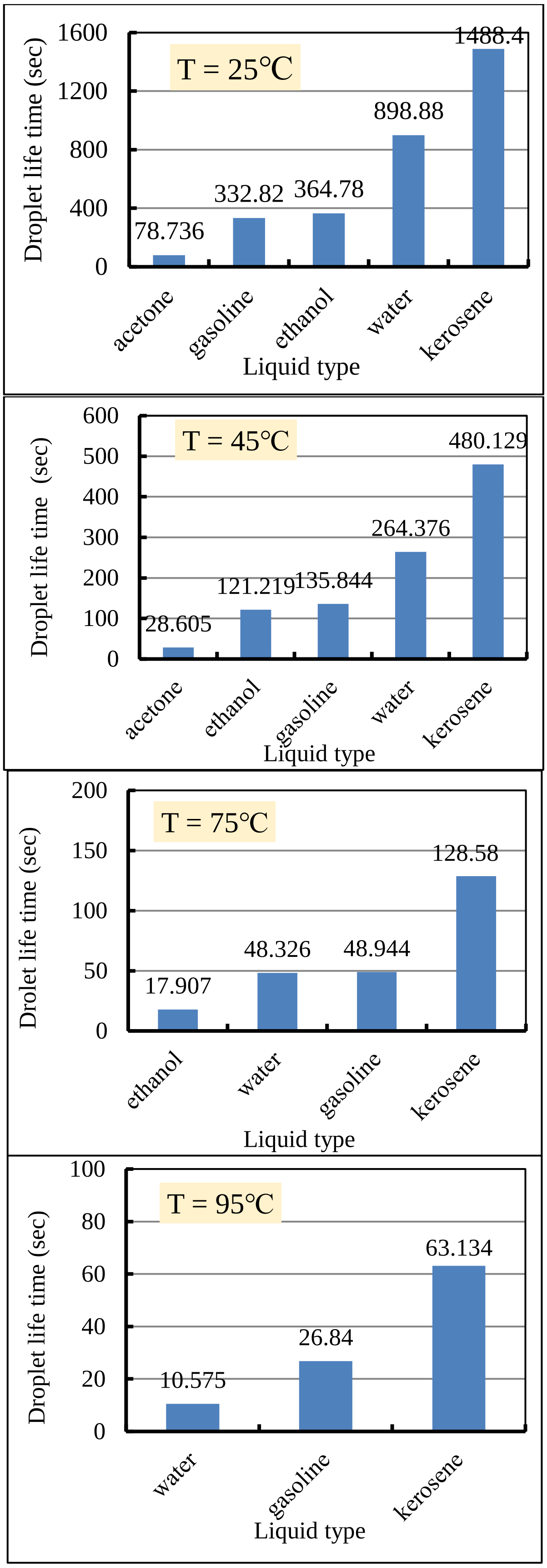


Figure 10. Liquids droplet lifetime at different temperatures

A longer droplet lifetime means that the droplet might leave the combustion chamber as a soot particle before burning completely. One of the worst characteristics of diesel engines is the appearance of soot in the exhaust. Therefore sooting fuel is not recommended as a fuel for diesel engines.

6. CONCLUSIONS

The experimental measurements reveal that droplet evaporation process depends on the liquid type and the prevailing temperature. It is shown that the evaporation rate increases logarithmically with the increase in the evaporation chamber temperature. It is also noticed that the evaporation constant for all tested liquids increases with temperature.

The droplet's lifetime depends on the droplet's initial diameter and the prevailing temperature. For example, the lifetime of acetone droplets decreases by 63.66% when the temperature is raised from 25 to 45℃. The acetone has the highest evaporation constant, followed by ethanol, gasoline, water, and kerosene.

Kerosene droplet has the longest lifetime compared to other tested hydrocarbons, and therefore, it has the highest soot propensity. Ethanol has a high evaporation rate; therefore, it is not a suitable fuel for diesel engines when used as pure since it causes knock.

Numerical modeling and simulation are suggested to be performed to extend the variables limits of droplet evaporation process.

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NOMENCLATURE

D	Droplet diameter (m)
D_o	Initial droplet diameter (m)
K	Evaporation constant (m^2/s)
$\dot{m}$	Droplet mass evaporation rate (kg/s)
t_1	Initial time (s)
t_2	Final time (s)
t_d	Droplet lifetime (s)
Δt	Time step (s)
v_1	Droplet volume at time t_1 (m^3)
v_2	Droplet volume at time t_2 (m^3)
ρ_l	liquid density (kg/m^3)

Abbreviations

GTL	Gas-to-Liquid