

THE SUB- AND SUPERCRITICAL BEHAVIOR OF FUEL DROPLETS

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1.0 Abstract

A new research facility for studying droplet behavior at high temperatures and pressures was designed in the Combustion and Emissions Control Laboratory at Clark Atlanta University. The mass emission rates and combustion characteristics of ~1.5-mm-diameter suspended droplets of a series of hydrocarbons ranging from hexane (C_6) to tetradecane (C_{14}) were measured at sub- and supercritical pressures and temperatures and under quiescent environments using a high-speed image system. The images of droplet gasification and combustion revealed interesting phenomena and provided better understanding of the droplet behavior in sub- and supercritical pressure and temperature environments. Buoyancy effect on the combustng droplet was more pronounced above the critical pressure. The gasification rate of a droplet proportionally decreased with the molecular weight of the hydrocarbon under system pressures below and above the hydrocarbon critical pressure. The oscillatory deformation of a free droplet, the buoyancy effects and flame propagation of a combustng free-droplet were found to be directly influenced by the system pressure and temperature. Increasing the system's oxygen partial pressure led to enhanced ignition, combustion rate and flame stability of the free droplets.

2.0 Introduction

Extensive literature review on both experimental and theoretical research is available on the subject of droplet evaporation and combustion in a stagnant environment or under forced convection conditions at atmospheric or near atmospheric pressures [1]. In many industrial applications, droplet evaporation at elevated pressures and temperatures is important, especially when the pressure and temperature get close to and beyond the critical point. Its potential importance is so well recognized that numerous theoretical and experimental studies aimed at improving the basic understanding of the physics have been pursued. In recent years, diesel engine manufacturers have striven to increase the ambient chamber density, and thereby the pressure, during fuel injection. This effort is motivated by the understanding that increased ambient density relative to the density of

the injected fuel results in better mixing and increased rates of combustion [1]. As these trends lead to even greater chamber pressures and temperatures, it becomes even more imperative that there is a clear understanding of supercritical processes which would lead to improved vaporizing and combusting spray models.

Significant experimental work was conducted in the early 20th century by Sato et al. [2], Norton et al. [3], Litchford et al. [4], Parigger [5], Woodward et al. [6,7], Chauveau et al. [8], Stengele et al. [9], and Mikiami et al [10], Hara and Kumagai [11].

It is believed that the actual path taken by the fuel droplets depends on the severity of the conditions to which the droplets are exposed. The direct experimental observation of supercritical droplet behavior, particularly under different environments, is essential to resolving unanswered questions and enhancing the understanding of spray and droplet combustion. To seek conclusive evidence regarding the behavior of single and multi-component droplets in both inert and oxidizing atmospheres and at different sub- and supercritical environments through simplified and systematic experiments, is of urgent importance and is the major task of the research efforts in this area at Clark Atlanta University. Such experimental efforts will provide the much needed information for data validation of modeling results.

3.0 Experimental

Analytical grade hexane, heptane, decane and tetradecane were used for the molecular weight, temperature and pressure variation experiments. The droplet combustion experiment hardware, designed and built at Clark Atlanta University is shown schematically in Figure 1, while Figure 2 shows the droplet formation and release system.

The experiments were conducted using the following procedures: (1) The combustion chamber was insulated with a Miraflex multi-project thermal and noise control insulation material. The heater was heated to the desired temperature using a variable autotransformer. (2) The combustion chamber was pressurized to the desired value with compressed air, and the liquid pump was started which pressurized the liquid fuels. (3) For the gasification rate measurements, a suspended droplet was used. The droplet diameters were calculated as the diameter of the sphere of equivalent volume as the observed ellipsoid, in the case where the droplet shape was ellipsoidal and not spherical. The droplet size was calculated using the equation: $d = 2(ab^2)^{1/3}$. The inlet needle valve on the liquid feeding line was opened first and the flow rate carefully adjusted until a droplet hung on the tip of the thermocouple (see Figure 2). Then, the needle valve was quickly closed. The droplet image was then recorded using the video system. (4) For the combustion tests, a free-falling droplet was used. While the free droplet was falling through the igniter's filament ring (see Figure 2), it was ignited. The burning droplet continuously fell downward or floated back upward depending on the system conditions. The whole process was recorded by the high-speed video system and analyzed. The video images were taken at a speed of 1000 frame pictures per second with an exposure time of $\sim 30 \mu\text{s}$.

The following system temperatures and pressures ranging from the subcritical regime to the supercritical regime were studied: (1) low P (0.1 MPa), low T (298 K); (2) low P, high T (up to 873 K); (3) high P (up to 6.9 MPa), low T; and (4) high P, high T.

4.0 Results and Discussion

4.1 Droplet Gasification

Figure 3 shows that the gasification rate obeys the d^2 -law, i.e., square of the diameter of the hexane droplet vs. time is a straight line in most parts of the gasification period. This linearity is due to surface effect. Figure 3 further indicates that after the diameter squared diminished to about 0.50 mm^2 ($\sim 0.8 \text{ mm}$ in diameter) at 1.38 and 5.52 MPa system pressures, the gasification rate increased by a factor of about 3. As the droplet diameter decreases, the escaping tendency of the molecules at the droplet surface becomes stronger, and its gasification rate per unit surface area increases. In addition, the gasification rate was measured from a suspended droplet. Because of the effects of gravity and the thermocouple wires, the droplet was found not to be a perfect sphere but with some deformation. As the droplet size decreased, the deformation was observed to increase in this study. The combination of these two effects is believed to be responsible for the change in gasification rate of the droplet as its size decreased beyond a certain value.

Figure 3 further shows that the hexane gasification rate near the critical pressure (e.g. at the 3.45 MPa system pressure) was more than double those at 1.38 and 5.52 MPa. The critical pressure of hexane is 3.01 MPa. The gasification rate of the suspended droplets of heptane and decane, like the hexane, also reached their maximum value at or near their corresponding critical pressures. The gasification rate was found to increase with increase in pressure at subcritical conditions to a maximum at or near the critical pressure of hexane and then decreased at supercritical pressures.

Figure 4 shows the variation of hexane droplet diameter with gasification time at different temperatures and ambient pressure. The gasification rate increases with increase in temperature at subcritical temperatures.

The hexane droplet behavior around the critical temperature was studied by suspending a droplet at the tip of the thermocouple and increasing its temperature from 673 to 773 K. It was observed that as the droplet temperature increased to $\sim 773 \text{ K}$, (critical temperature for hexane is 780.7 K) the droplet became unstable and disintegrated. This is attributed to the vanishing surface tension at the critical temperature.

The dependence of the fuel molecular weight on droplet gasification was also studied for fuels ranging from hexane to tetradecane. Figure 5 shows the variation of gasification rate with fuel molecular weight. At ambient temperature, the results indicate that the gasification rate of a hydrocarbon droplet proportionally decreases with the molecular weight of the hydrocarbon under a fixed temperature and pressure condition. This decrease occurs because as the molecular weight of a hydrocarbon increases, its size increases and its vapor pressure and activity decrease.

The combined effect of temperature and pressure on the gasification and combustion characteristics was studied. The results show that the gasification rate increases with increase in pressure and temperature up to the critical conditions. Above the critical pressure the gasification rate decreases.

4.2 Free Falling Droplet Tests

From replays of the recorded images at a much slower speed (e.g. 1 – 30 frames/sec), the shape and speed of the falling droplet were observed and measured. Oscillatory deformations of the droplet from circular to elliptical were observed. It was found that during falling, the shape of a droplet oscillated in the vertical direction. The magnitude of the oscillation changed with the system temperature and pressure. The deformation of the droplet was enhanced as the temperature and pressure increased.

Figure 6 shows that the effective acceleration of a hexane free droplet, α , was found to be inversely proportional to the increase of the system pressure from ambient (0.1 MPa) to 8.27 MPa. This proportionality is due to buoyancy. For a free falling droplet, the gravity was the driving force, and the buoyancy the resistance force. As the system pressure increased, the resistance force increased, while gravity remained constant. This balance is shown in Figure 6. The resistance force was calculated according to $f = (V \cdot \rho) \alpha$, where V and ρ are the volume and density of the droplet, respectively. The effect of temperature on hexane droplet acceleration and resistance force at ambient pressure was also investigated. The effective acceleration of a free-falling droplet of hexane was found to increase linearly with increase in temperature at subcritical temperatures, while the resistance force decreased with increase in system temperature at ambient pressure.

4.3 Free Falling Droplet Combustion Tests

From the recorded video images, it was observed that the system pressure had significant effects on the combustion of a free falling droplet. As the system pressure increased, the falling speed of a droplet proportionally decreased. When the chamber pressure was increased to a certain value (~ 1.38 MPa), after falling below the igniter ring for a distance, the burning droplet started to float upwards. As the chamber pressure increased, the distance that the burning droplet fell below the igniter ring before floating upwards decreased. As the chamber pressure approached the droplet's critical pressure, the free burning droplet virtually stayed at its ignited position. This phenomenon can be explained by the effect of buoyancy. After a free droplet was ignited, the gas around the droplet was heated and became less dense. Buoyancy force caused by the differences in densities of cold (unheated) and hot (heated) gases helped to push the droplet upwards. As the system pressure increased, the gas density in the combustion chamber increased, and the differences in densities between the hydrocarbon droplet and gas decreased.

The system pressure also had some effect on the flame life of a droplet, which is defined as the combustion time of the droplet. At pressures near the critical pressure, the hexane droplet had the longest flame. As the molecular weight of the hydrocarbons and the system pressure increased, the ignition of the free-drop droplets became more difficult, the combustion rates of the droplets decreased, and the flames of the combusting free-drop droplets became less stable. The size of concentrated vapor sphere of a droplet was found to be proportionally decreased as the system pressure increased, but no large change was observed after the system pressure passed through the hydrocarbon's critical pressure.

As the number of carbon atoms of a droplet hydrocarbon molecule increased to 14 (tetradecane), the free-drop droplets were ignited (except for decane) in all of the system pressure range from ambient to 6.89 MPa but with quite different behaviors. The free-drop droplets of decane (C₁₀) could not be ignited under any of the experimental conditions used, from ambient to 6.89 MPa of the system air (21% oxygen and 79% nitrogen) pressure and up to 14 igniter V (~1673 K). Additional experiments are needed before one can explain the observed puzzling behavior of decane droplet combustion. It was also found in this study that increasing the system's oxygen partial pressure led to enhanced ignition, combustion rate, and flame stability of the free-drop droplets.

5.0 Conclusions

- A versatile droplet experimental setup, developed at Clark Atlanta University, was used to study the combustion and gasification behavior of hexane droplet at ambient pressure. Because of its small size and compact design, the system can be used for both normal and microgravity tests in a ground station or in a microgravity environment.
- Free-falling non-combusting hexane and droplets exhibited a d^2 -law gasification behavior at sub- and supercritical experimental conditions. The system pressure, temperature, and the molecular weight of the hydrocarbon that formed the droplet had large effects on the gasification. At subcritical temperature, the maximum gasification rate occurred when the system pressure was close to the critical pressure. As the molecular weight of the droplet increased, the gasification rate decreased.
- The oscillatory deformation of a non-combusting free droplet of hexane at ambient pressure was enhanced as the system temperature increased. The acceleration of a free-drop droplet proportionally increased as the system temperature increased while the resistance force decreased.
- Buoyancy effect on the combusting droplet was more pronounced above the critical pressure. Under some conditions the falling combusting droplet reversed direction and floated upwards due to buoyancy effect.

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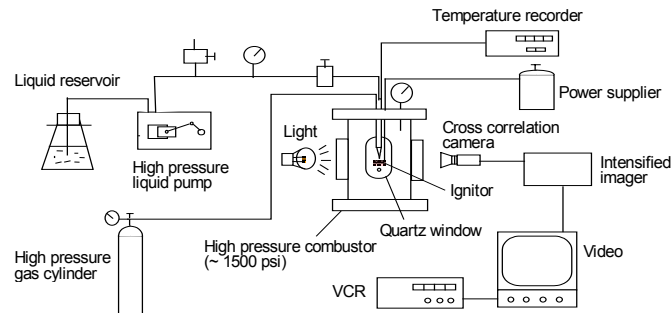


Figure 1. Schematic of the experimental setup

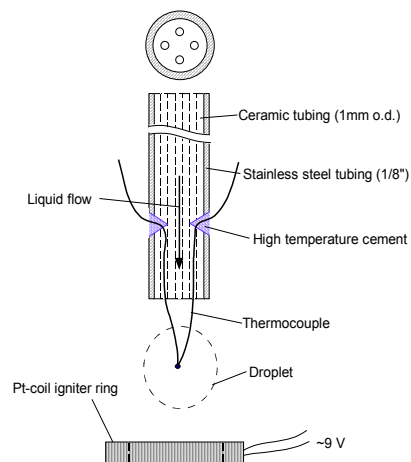


Figure 2. Droplet formation and release system and igniter

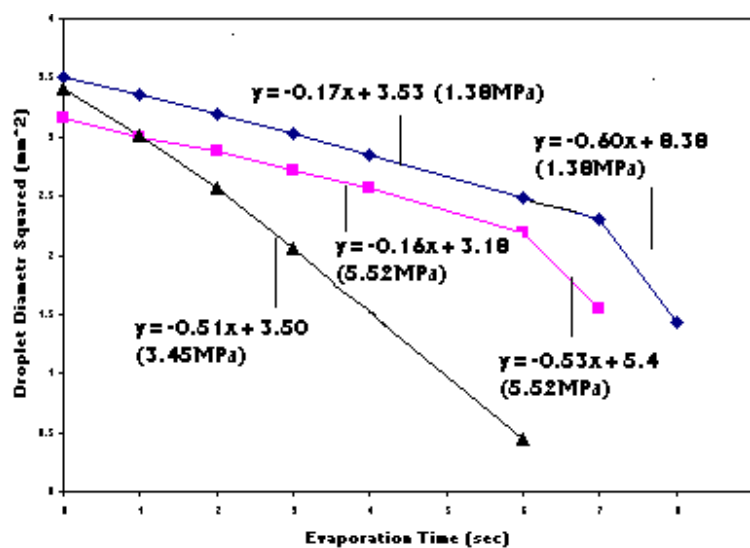


Figure 3. The changes of the surface areas (measured as diameter squared) of hexane droplets with gasification time at different pressures and ambient temperature.

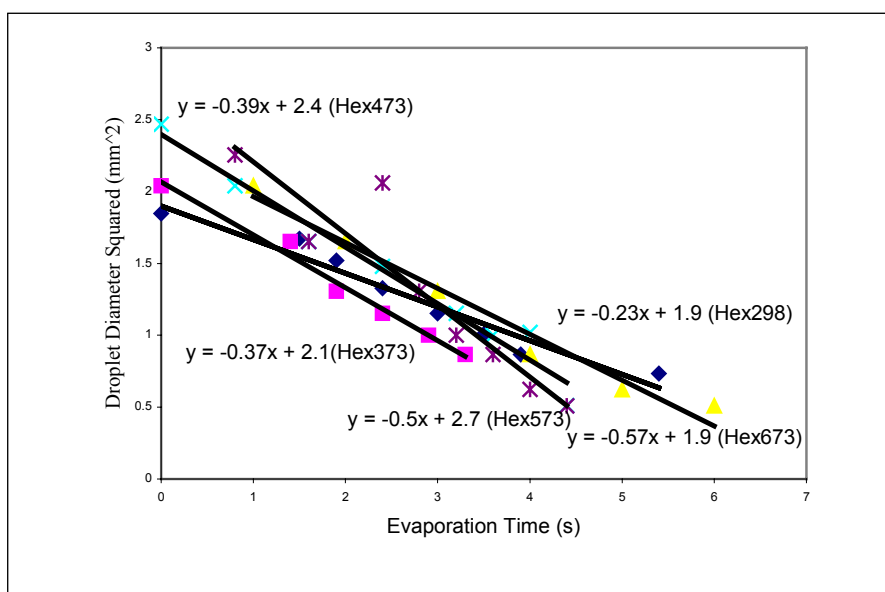


Figure 4. The changes in surface area of hexane droplet (measured as diameter squared) with gasification time at different temperatures and ambient pressure – (Note: Hex673, for example, implies data for hexane at 673 K).

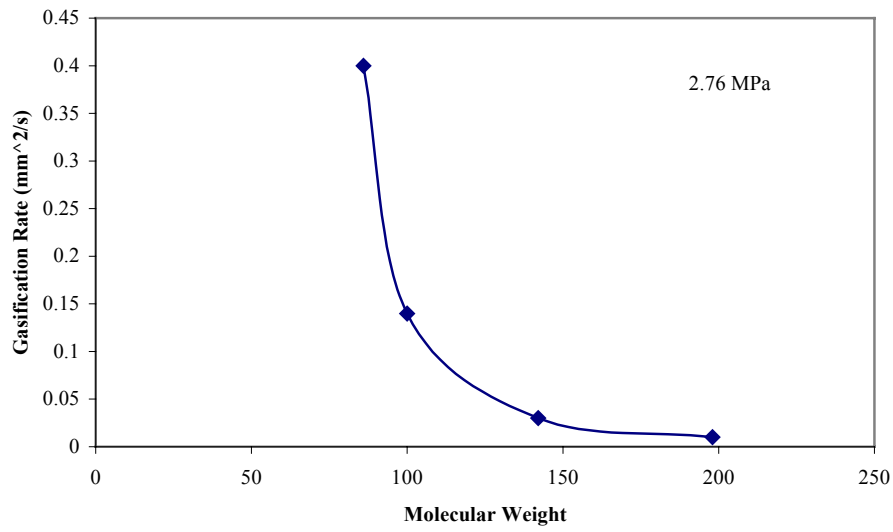


Figure 5. Variation of molecular weight of hydrocarbon fuels with gasification rate measured at 1.76 MPa and ambient temperature.

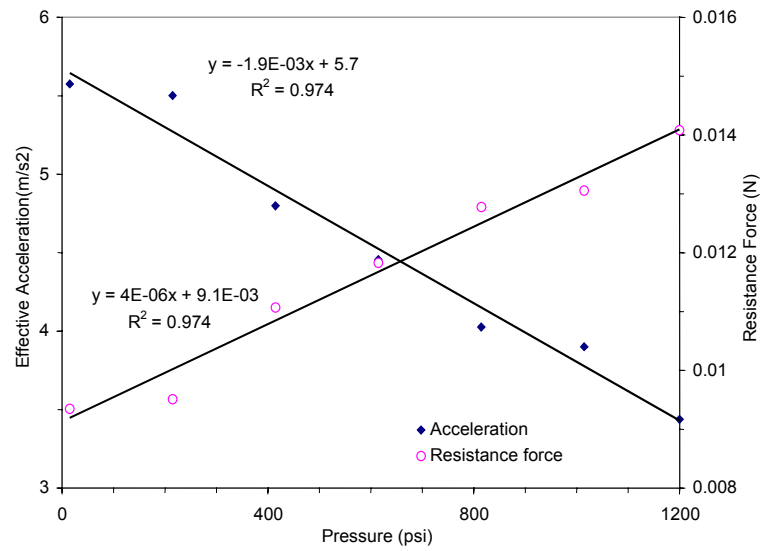


Figure 6. The effect of the system pressure on the effective acceleration and resistance force of a free-falling hexane droplet.