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Experimental Characterization of Transcritical Spray with Varying Fuel Temperature and Injection Pressure

Kaushik Nonavinakere Vinod¹, Robert Kempin¹, Tiegang Fang^{1}*

¹Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, USA.

**Corresponding Author Email: tfang2@ncsu.edu*

Abstract: The spray characteristics of fuels when sprayed under superheated and elevated fuel pressure are markedly different than traditional fuel injection sprays. Studying fuel sprays under these conditions will help us understand the complex behaviors that may provide us with information to optimize future applications of certain technologies like supercritical spray combustion. In this work optical diagnostics are used to study the behavior of Jet A-1 under subcritical, transcritical, and supercritical sprays into open air test chambers. The experimental setup includes a high-pressure air driven pump to create the required high fuel pressure and a special heated injector to increase the temperature of the fuel inside the injector before injection to the required temperatures. Optical techniques like Schlieren and backlit shadowgraph are used to capture and study the sprays from a single hole high pressure diesel injector. A combination of 4 different temperatures and 4 different pressures are tested and the resultant images are processed to obtain quantitative measurements such as spray penetrations, spray cone angle, and spray optical density for each case. Moreover, the spray plume structure transition with changing parameters from subcritical, transcritical, and supercritical states for the fuel are also studied. The results show that with the fuel being in a transcritical state before injection there is a measurable variation in the spray cone formation and penetration for any fixed pressure. At this state the spray cone shows a bimodal spray angle distribution with increasing penetration. An increase in vapor turbulence is also observed indicating the occurrence of flash boiling of the fuel. With the fuels pushed to a supercritical state, the spray shows a thinner spray jet near the injector with a reduced overall penetration and reduced optical density near nozzle. The transition between the three different states as shown in this study gives us an interesting relationship between the spray penetration, spray cone angle and the spray optical density. This can be used as an indicator in understanding spray atomization of the fuels under supercritical spray conditions.

Keywords: *Supercritical fluid, Fuel injection, Spray, Flash boiling, Superheated*

1. Introduction

With recent developments in automobile propulsion technologies there is huge focus on improving the efficiency and emission characteristics of the internal combustion engine (ICE) [1]. The unparalleled energy density, relative ease of manufacture, and fuel flexibility of an ICE makes it an essential energy source for the foreseeable future. In particular, road vehicles rely primarily on ICE technologies while being responsible for the bulk of the transport sector energy consumption. Increasing strictness of emission control combined with the recent developments in finding alternative and “clean” fuels have created a need for the ICE to adapt and employ new technologies and several optimizations to existing technologies [2].

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Optimizations to the fuel delivery systems like gasoline direct injection (GDI), and spark assisted compression ignition (SACI) have shown to improve both fuel efficiency and reduce overall NO_x and CO₂ engine out emissions while improving engine performance with traditional fossil fuels [3]. Homogeneous charge compression ignition (HCCI) strategies further can drastically reduce particulate matter (PM) emissions, with the main obstacle to widespread implementation being a relatively limited operating range [4]. Optimizations to advanced fuel delivery systems and additions of forced induction systems have created a recent focus shift to study the improvements in combustion quality based on new techniques in air-fuel mixing inside the combustion chamber [4]. These approaches are of interest since they require changes only to the ICE system without requiring a change to the fuel logistics system.

One such new technique of great potential is supercritical and transcritical spray combustion [5,6,7]. Recently, high pressure fuel injections in the order of 400 to 500 bar have been widely used to improve combustion quality. Studies show that further increase in operating pressure of the fuel system can benefit the fuel atomization process by generating finer droplets which can help reduce emissions and improve combustion quality [8,9,10]. However, there is an inverse correlation between increasing the fuel pressure and the cost of application. Higher pressure fuel systems require more robust components and raise more serious safety concerns. Thus, it is desirable to achieve these gains through other means. Supercritical and transcritical fuel injection systems can thus be beneficial for improving system cost effectiveness. With a supercritical spray, the fuel being sprayed will have better evaporation, atomization, dispersion, and diffusion than that of a subcritical high pressure injection system. Since the density of a supercritical fluid is relatively higher, the cost of fuel delivery can be optimized for the relative performance gains [11,12,13]. A fuel spray can be considered supercritical if the fuel in the injector before injection has the temperature and pressure above the critical point of the fuel. Several studies have been performed showing the effect of hydrocarbon based fuels at supercritical state being sprayed into a subcritical atmosphere [14]. Studies performed with the fuel heated and pressurized beyond the supercritical point in a gasoline direct injection system (GDI) show that there can be reductions in particulate matter emissions in the engine exhaust which could be caused by the improved fuel atomization and reduced mean droplet size of the spray [15].

While studies involving supercritical sprays have focused on characterizing the droplet diameter under a selected temperature and pressure, few studies show the effect of supercritical spray on the spray plume generated after injection. Understanding the changes in the spray plume can be beneficial in designing combustion chambers and injector nozzles for better atomization. Moreover, the transition state between subcritical and supercritical states, called the transcritical state, is of great interest as it can be achieved more reliably with very little modifications to existing high pressure fuel systems and can provide benefits in atomization of fuel due to flash boiling effects of the fuel but at elevated temperatures. In this work, several different fuel sprays ranging from subcritical to supercritical states before injection were characterized using high speed imaging. Jet A-1 was used as the fuel for this study due to its atomization properties. A single hole diesel injector was used with a custom heater and injected into ambient atmospheric conditions. The penetration lengths and spray angle were studied to characterize the different sprays.

2. Methodology

For this study a commercial Bosch high pressure diesel injector is used to spray fuel. A single hole injector nozzle with a diameter of $200\text{ }\mu\text{m}$ is installed. Injector control is provided by a custom injector driver. The injector is secured inside a heater block fitted with two 500 W heaters. This apparatus can heat the whole injector up to a maximum operating temperature of 650 K . Fuel pressure is generated by a high-pressure air driven pump capable of generating 420 MPa . The pressure and the temperature of the injector are controlled by closed loop controllers to ensure accurate and repeatable settings. For this study four temperature and pressure conditions are evaluated. A maximum pressure of 150 MPa and maximum temperature of 573 K are considered, reaching into the supercritical regime of the Jet-A1 test fuel. The injector was suspended in an open-air test cell maintained at a temperature of 297 K at atmospheric pressure. The resulting spray from the injector is recorded using a Phantom VEO 710 high speed camera. The spray is backlit using a diffused LED light source to generate the desired shadowgraph. The injector driver is synced to the camera trigger ensuring repeatable synchronization. Figure 1 shows a schematic of the experimental setup. The fuel lines leading to the injector are heated using a strip heater to 390 K to ensure the fuel inside the injector can have a stable temperature even when there is flow inside the fuel return from the injector to the fuel tank.

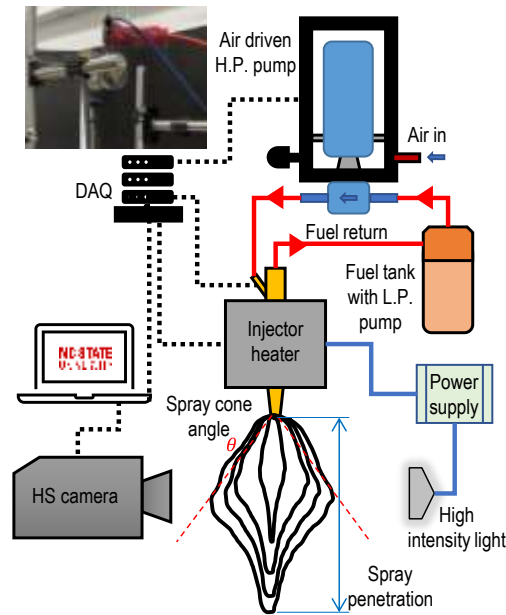


Figure 1: Experimental setup used for testing showing the spray measurement techniques.

At the beginning of every experiment the pump is activated to pressurize the injector while the heater is commanded to heat the injector block to the set temperature. Once the temperature is reached, the system is left idle to reach an equilibrium. After the system is holding steady the injector is triggered to spray and the cameras are thus triggered to record the images. Following acquisition the system is reset for the next experiment, to be triggered once an equilibrium is determined to be reestablished. Table 1 shows the experimental conditions tested in this study. Due to the small fuel quantity injected, it is expected that the fuel temperature in the nozzle is similar to the injector nozzle temperature.

Table 1: Experimental conditions tested.

Experimental parameter	Value
Fuel	Jet-A1
Fuel rail pressure	50 MPa, 100 MPa, 125MPa, 150 MPa
Injector nozzle temperature	473 K, 528 K, 548 K, 573 K

3. Results and Discussion

Data from the high-speed camera was processed in custom Matlab and ImageJ code to generate spray contours after removing the background. Using the spray contours the spray penetration and spray cone angle values were calculated for each case tested. The following sections discuss the data recorded in detail.

3.1 High Speed Spray Images

Figure 2 shows a sequence of spray images for different nozzle temperatures with increasing time after injection was triggered for a fuel injection pressure of 150 MPa. The 4 temperatures were chosen to showcase the three different regimes of the fuel spray. Nozzle temperatures of 473 K and 523 K show the subcritical spray, 548 K shows the spray at transcritical conditions, and at 573 K the spray represents a supercritical spray.

Looking at the three temperatures at early stages of the injection there is a noticeable difference in the fuel spray jet exiting the nozzle. With the temperature increasing there is a measurable change in the profile of the fuel spray. The effect of fuel flash boiling at the transcritical and supercritical states can also be clearly seen around the jet. After the initial jet has exited the nozzle, the spray development is affected by the change in the flash boiling effect between the different states. The lower temperature (subcritical) sprays show a relatively normal spray development with the spray containing mainly liquid droplets that are carried out by the pressure of injection and form a spray plume that is mostly pressure driven with minor diffusion along the outer boundary of the spray. This region of diffusion is shown as greener areas in the contour plots. The transcritical spray shows a central narrow liquid jet surrounded by a plume of fast vaporizing fuel as seen by the increased diffusion regions as the spray develops. With the 573 K case there is only a small narrow central jet that is made up of a liquid that is propelled by the pressure of injection. Around the central jet we can see a rapidly diffusing plume of fuel caused by the fuel potentially being in the supercritical state. With further increase in time, since the fuel in the transcritical state will lose temperature to the ambient it no longer shows the rapid vaporization and expansion present in the supercritical spray. The transcritical spray returns to developing a spray that looks more like a subcritical fuel spray jet which is mainly pressure driven. However, there is still a small section near nozzle that has increased fuel vaporization indicating the existence of flash boiling. The supercritical spray, however, shows a bimodal operation with the first ~2-4 mm showing a relatively narrow liquid jet with a rapidly vaporizing (flash boiling) plume around it and a wider plume afterwards with increased turbulence caused by the fuel rapidly diffusing and vaporizing.

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The initial narrow jet can be explained by the fuel jet being driven by the inertia from the pressure of injection and the quick change in the spray width results from the fuel rapidly boiling and diffusing as the temperature of the fuel should still be be relatively close to or above the critical temperature of the fuel.

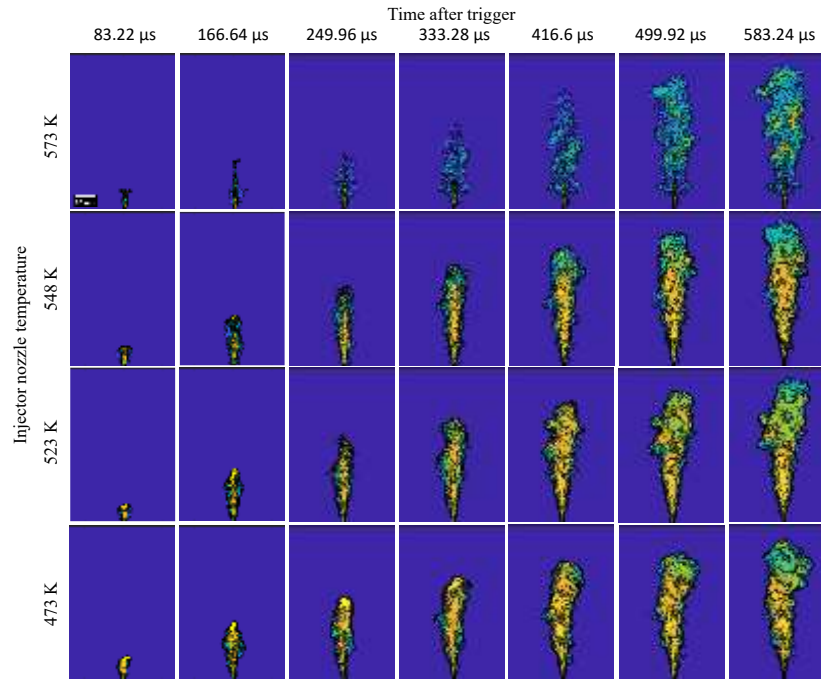


Figure 2: Spray contours showing the spray penetration with time for different temperatures

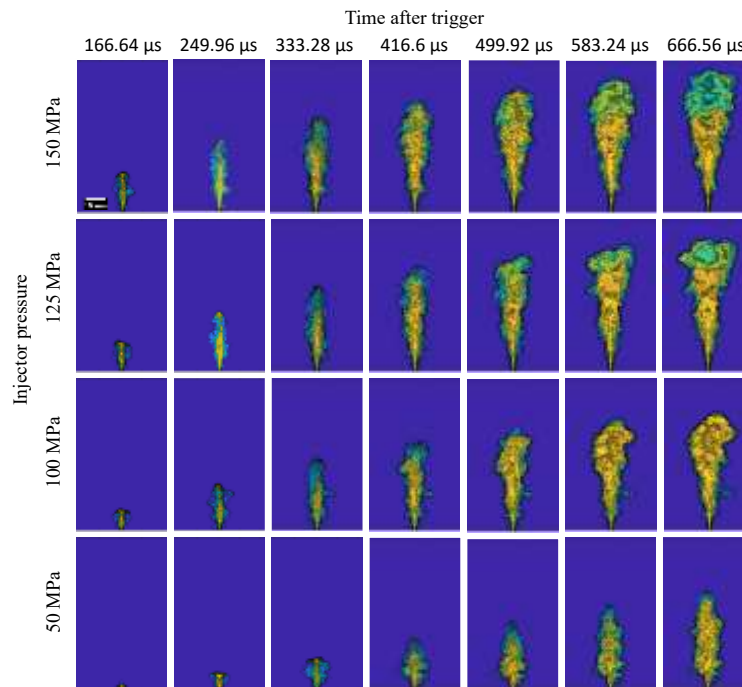


Figure 3: Spray contours showing the spray penetration and development with time for different pressures for an injector temperature of 548 K

Figure 3 shows a similar sequence of images with changing pressures for a fixed temperature of 548 K. This temperature was chosen for discussion due to its interesting behavior in the transcritical region. The temperature of the fuel is below the critical point, but the combined effect of elevated fuel injection pressures and the temperatures forces the fuel to diffuse faster than compared to the fuel being cooler. With increasing pressure, it is clear that the spray jet exits the nozzle faster with greater penetration in the early stages of the spray. For the same time after injection a higher injection pressure shows a narrower spray jet in the early stages. This is caused by the inertia of the fuel at higher pressures. At lower pressures the fuel jet starts spreading wider while still consisting mostly liquid droplets with a narrow region of vaporizing fuel along the outer boundary. With increasing time, the lower pressure sprays show a reduced penetration length with a wider plume while the higher-pressure spray shows a narrow spray with increased diffusion area with increasing penetration. With the temperature increased further towards the critical point of the fuel, the effect of pressure is diminished.

3.2 Spray Cone Angle

Figure 4 shows the mean spray cone angle measured for all the sprays tested in this study. The inset inside figure 4 A and B shows an expanded view of the first 250 μs after triggering the injection event.

From figure 4 A it is evident that with increasing fuel temperature there is a noticeable change in the mean spray cone angle with all other conditions maintained constant. All the sprays tested show an increased spray angle right after the start of injection and a drop with eventual plateauing of the spray cone angle. With increasing fuel temperature this effect is exaggerated, and the sprays show a bimodal variation in the cone angle development. Both 548 K and the 573 K cases show a spray that has a wider spray cone for longer. This arises from the initially hot fuel from the injector diffusing into the atmosphere quickly as the fuel would be closer to transcritical or supercritical conditions. As the fuel is injected out, the temperature of the fuel inside the injector will drop slightly causing the effect of instant diffusion and flash boiling to reduce and settle into a balance causing the slight second increase in the cone angle before plateauing. From figure 4 A it is also evident that the extent of the fuel being closer to the critical temperature has a considerable effect in how fast the fuel can vaporize. With just a 25 K increase in temperature from 548 K to 573 K the spray shows a 50% increase in the cone angle at the same injection pressure of 150 MPa.

Figure 4 B shows the effect of changing the fuel injection pressure for a temperature of 548 K. At this temperature we can see the effect of pressure increase with the changes in the spray cone angle over time. At lower pressures, the spray spreads to a wider plume near nozzle due the effects of fuel boiling and vaporization. Over the course of the injection, the plume stays wide with reduced penetration. Increasing the pressures reduces the initial plume spread and increases the penetration. With further increase in pressure, we start to see the influence of flash boiling on the spray plume. A bimodal distribution of the spray cone angle is seen due to the near nozzle flash boiling of fuel. With increase in penetration, the flash boiling effect is reduced due to the slight decrease in the fuel temperature causing the spray cone angle to reduce until the effect of vapor diffusion increases the angle again.

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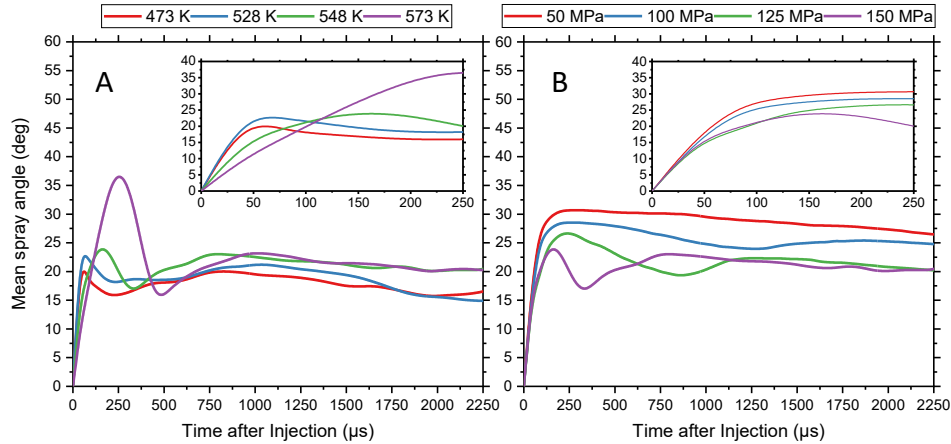


Figure 4: Spray cone angle as measured from the high speed imaging for A). changing temperatures and B). changing pressures.

3.3 Spray Penetration

Figure 5 shows the spray penetration over time after the start of injection for all the cases tested. Due to the camera and image capture setup and the high pressures of the experiment, the spray jets show penetration beyond the field of view of the cameras after a certain time. This distance is depicted by a dotted line at 121 mm in the figures.

From figure 5 A it is evident that there is a reduction in the rate of penetration with increasing temperature. This is caused by the fuel diffusing radially around the spray jet in the initial stages of injection due to fuel being transcritical or supercritical. At lower temperatures the fuel spray shows a relatively linear penetration rate with time. With the temperatures increasing to the transcritical temperatures for Jet-A1, there is a reduction in the penetration in the early stages of the spray. This is caused by the rapid boiling and diffusion of the fuel as noticed in the cone angle measurements. With fuel state being closer to the supercritical temperature of the fuel the initial penetration is substantially reduced. This reduction in penetration is accompanied by increases in spray diffusion and boiling, thus improving the vaporization and atomization characteristics of the fuel.

Figure 5 B shows the effect of changing pressures on spray penetration. Increasing the pressure shows an increase in the initial spray penetration. With lower pressures due to the diffusion caused by the increased spray cone angle, the penetration is reduced. The lower pressure spray also shows a slow spray at very early stages of injection. The spray accelerates over the course of the injection.

From fig 5 A and B we can see that at lower temperatures and medium pressures the fuel spray displays a high speed of penetration in the initial stages of the spray development. This can be explained by the relatively high concentrations of liquid fuel being propelled out of the nozzle by the pressure of injection with low diffusion or vaporization. As the temperature increases, we see a reduction in the speed as the effect of injection pressure is subdued by the reduction in the liquid fuel fraction in the spray jet. The increased vaporization/boiling and diffusion caused by the fuel being in a transcritical/supercritical state caused the slow penetration speed as larger quantities of

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fuel vaporizes rapidly around the spray jet. With increasing time, as the fuel inside the heated injector drops in temperature due to the injection process, the jet will accelerate as shown by the increase in the spray penetration speed.

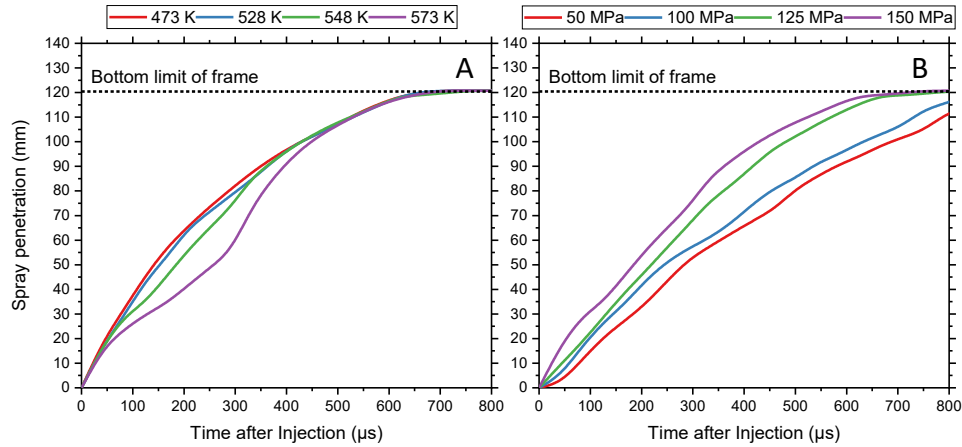


Figure 5: Spray penetration as measured from the high speed imaging for A). changing temperatures and B). changing pressures.

3.4 Spray Optical Density

Figure 6 shows the spray penetration for different temperatures at 2 different times after the start of injection for sprays with 150 MPa injection pressure. From the images, the change in the observed optical density of the spray shows an interesting behavior with the changing temperature. A simple threshold-based algorithm was used to identify the ratio of spray area that consists diffusing vapor to the spray area with predominantly liquid droplets. This ratio is defined as the spray optical density ratio, and it can be used as a simple identifier for studying spray mode transitions between the 3 states. From figure 6 we can see that as the temperature increases, there is a reduction in the intensity of the central plume and an increase in the distribution of low intensity vapor plume caused by flash boiling and rapid fuel vaporization. At 573 K injection temperature, we see only a fraction of the fuel spray having a high optical density suggesting that the distribution of the liquid droplets is much lower than the vapor phase.

Using this method, a time dependent variation of the spray optical density ratio can be plotted as shown in figure 7. At a lower temperature of 473 K, the ratio of vapor phase to the liquid phase in the spray starts out low and then increases to a steady value. This indicates that the amount of fuel vapor within the spray plume does not change with time. Meanwhile, with increasing temperature we see an increase in the ratio showing that there is a higher concentration of vapor in the spray plume at 528 K. There is also a small bump in the ratio around 90 μs showing that other factors, like flash boiling, are increasing the rapid fuel diffusion for a short time, thus increasing the ratio briefly. With further increase into the transcritical regime, we see that there is large increase in the ratio around 90 μs. This is due to the increase in the flash boiling effect causing more fuel to rapidly vaporize briefly before the temperature of the fuel drops due to the injection process. This reduction in temperature then causes the ratio to settle into a slightly lower value. When the fuel injection temperature is above the critical point of the fuel, the spray shows the highest peak ratio

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showing that there is much more fuel as a vapor than liquid droplet. The initial peak then reduces slightly though still maintaining a high ratio. Unlike the lower temperature cases, the effect of dropping fuel temperature with injection duration takes longer to have a measurable effect on the spray structure. This sustained elevated injection temperature results in the spray optical density ratio remaining high for most of the injection sequence before dropping. Thus, the spray plume in the supercritical case is predominantly vapor, differing from the subcritical/transcritical cases.

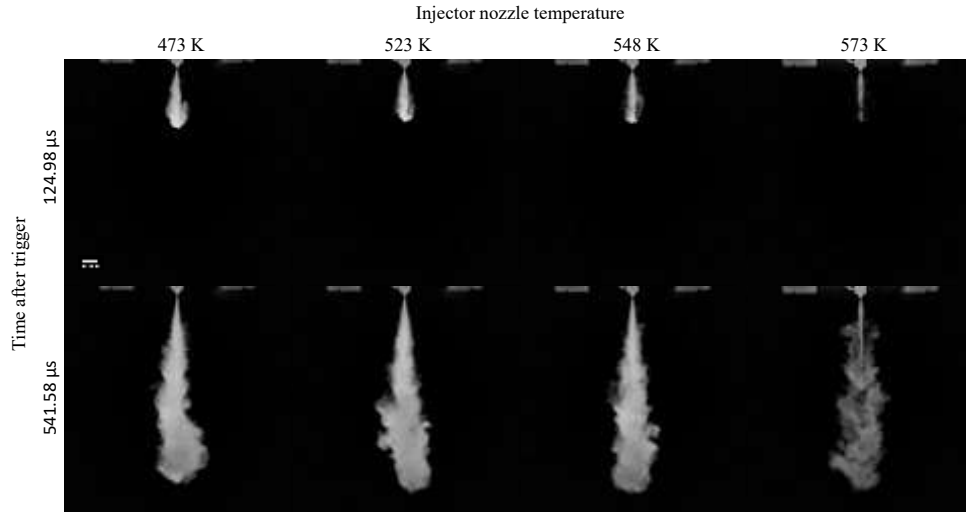


Figure 6: Spray penetrations at varying temperatures showing the spray optical density variation

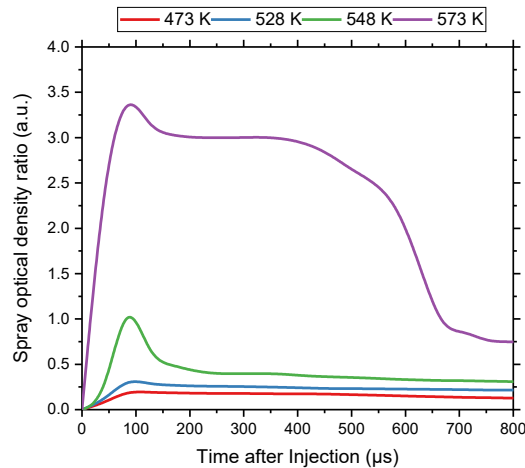


Figure 7: Spray optical density ratio variation with temperature.

4. Conclusions

In this study Jet-A1 fuel sprays are characterized for subcritical, transcritical, and supercritical spraying regimes with varying fuel temperatures and pressures. Optical diagnostics by means of backlit shadowgraphy was used to capture the spray jets in high speed and the resulting spray cone angle, and spray penetrations are measured. Spray optical density ratios were also calculated to help identify spray mode transition. Following are some key points of the study:

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- Increasing the temperature from subcritical to supercritical states increases the vapor concentrations in the spray.
- The spray under supercritical conditions shows two modes of dispersion, an initial pressure driven mode and a diffusion driven expansion mode.
- The spray cone angle measurements also show the same bimodal trend with increasing temperature. The effect is amplified with temperature increase.
- Increasing injection pressure also shows the same bimodal spray cone angle variation in transcritical and supercritical temperature regimes.
- With increasing temperatures, there is a sacrifice in spray penetration length and the speed of penetration as there is a reduction in liquid concentrations in the spray jet with fuel temperatures in transcritical or supercritical regimes.
- Spray optical density ratio shows good correlation with the changes in vapor to liquid distribution in the spray under different spray modes.

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