



Primary atomization of liquid-fuel jets in confined turbulent pipe-flows of air at elevated temperatures

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ABSTRACT

The primary atomization of evaporating laminar liquid jets of either pure *n*-pentane or *n*-heptane injected continuously from a circular nozzle concentrically and axisymmetrically into high-temperature turbulent coflows of air in confined a pipe has been studied experimentally. Fuel-jet bulk velocities up to 2.7 m/s, air coflow bulk velocities up to 37 m/s and temperatures up to 1150 K were investigated within a 25 mm round pipe. In the near-field region of the injector nozzle, liquid fuel jets were formed whose length increased with the fuel injection velocity and decreased with the air velocity. Smaller droplets were formed at both higher fuel and air velocities. Droplet diameters within the range from 200 to 900 μm were measured, indicating the polydispersed nature of the fuel spray. The mean droplet diameter increased non-monotonically with increasing axial distance from the nozzle due to a complex competition between droplet coalescence and evaporation. No significant effect of the air inlet temperature was observed within the investigated range of conditions on the jet length and droplet size. However, smaller droplets were obtained in flows with lower turbulence intensities and longer longitudinal integral length-scales. Analysis of the data reveals that the mean droplet diameters can be predicted by the empirical expression $(d_{\text{mean}}/d_{\text{jet}}) = 34 \times 10^3 We_{\Delta}^{1.29} Re_{\Delta}^{-3}$, independent of the two perforated plates selected and used in the present work. The resulting data can contribute towards a better understanding of interfacial dynamics, and the development and validation of advanced multiphase-flow and reacting-flow models.

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1. Introduction

Liquid fuels are employed in many practical applications. In chemically reacting multiphase flows featuring liquid jets, important processes such as jet break-up, atomization, droplet evaporation, turbulent mixing and chemical reactions occur simultaneously, which presents significant challenges in terms of design and prediction. This paper focuses on the primary atomization of an evaporating and reacting liquid fuel jet injected coaxially and axisymmetrically from a circular nozzle into a continuous stream of preheated turbulent pipe-flows of coflowing air at elevated temperatures (up to 1150 K).

Post-evaporation, the air and fuel mix and at a certain distance downstream of the injection location, autoignition occurs in the form of 'spots' if the temperature is high enough. This configuration, which has been previously employed for experimental studies of the autoignition of gaseous fuels [1–3], allows independent

control of parameters in a well-defined flow configuration, and is relevant to practical systems such as diesel engines, gasoline direct injection engines, and lean-burn gas turbine combustors. The liquid-fuel droplet size distribution and spray spatial distribution can strongly affect the characteristics of the resulting phenomenon, and therefore an understanding of the spray characteristics (jet break-up, droplet dispersion) as a function of inlet conditions is important.

Turbulent sprays and related reacting-flow phenomena have been studied by a number of research groups. Refs. [4–11], for example, provide excellent reviews of such studies. The spray formation process is important to the reaction characteristics and generally involves two liquid break-up stages – primary and secondary atomization. Primary atomization involves break-up of a liquid jet or sheet into fragments and droplets, while during secondary atomization, these droplets further break-up into smaller droplets [12,13]. In the presence of a high-speed coaxial gas stream, the primary atomization of liquid jets issuing from a nozzle is fundamentally different from that in a stagnant gas [14,15]; the break-up behavior depends on the relative properties of the liquid jet and surrounding coflowing air velocity [16]. Laminar and weakly-turbulent

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air-assisted jet break-up has previously been studied by Engelbert et al. [17], and Lasheras and Hopfinger [15], but the effect of flow temperature and velocity (both of the gas and liquid) on primary atomization in well-defined turbulent coflows at elevated temperatures has not received sufficient attention.

For non-reacting sprays in cold air coflows, Kourmatzis and Masri [16] investigated the effects of grid-generated turbulence on the primary atomization and subsequent droplet deformation of laminar liquid methyl esters, acetone and diesel jets. Velocity fluctuations were found to randomize the break-up process. Further, O'Loughlin and Masri [18] studied the autoignition characteristics of dilute turbulent spray flames formed in hot coflowing stream of vitiated combustion products. Measurements of the mean temperature, velocity and droplet fields (droplet number density, volume flux, droplet diameter via phase Doppler anemometry) were made for ethanol (and also for methanol in O'Loughlin and Masri [19]) at various axial and radial locations. Similarly, Rodrigues et al. [20] experimentally studied ethanol pressure-swirl spray flames in a coflow of either air or hot-diluted oxidant. They observed immediate disruption of the liquid jet when introduced into the hot diluted coflow. The atomization mechanism in these coflows was different to expectations our knowledge of liquid-fuel atomization in coflows of pure ambient cold air.

The research reported herein applies high-speed shadowgraphy to observe primary atomization under hot reacting conditions in the near-field region of the injector nozzle, (while autoignition reactions were occurring, but further downstream of the region of interest). A systematic study is presented that allows us to study the effects of various inlet conditions such as the bulk air inlet temperature, bulk air inlet velocity, liquid fuel injection velocity, and turbulence characteristics of the flow (which were varied by using different turbulence-generating perforated plates upstream of injection) on the primary atomization process of pure *n*-pentane and *n*-heptane liquid jets, while other mean flow conditions are maintained constant. All investigated liquid jets were laminar and jet break-up occurred in the same nominal break-up regime. The results from this work provide insight into the conditions leading up to autoignition in these flows (and various observed phenomena [21,22]), and constitute a valuable dataset for validating and developing computational models of spray formation, and non-premixed two-phase turbulent reacting flows.

2. Experimental methods

2.1. Apparatus

Fig. 1 shows a schematic of the experimental apparatus, which has previously been used to study the autoignition of liquid *n*-pentane and *n*-heptane jets in preheated turbulent pipe-flows of air at high temperatures [21,22]. A summary of the apparatus, that is relevant to the current droplet characterization experiments, is provided below.

2.1.1. Background hot-air preparation

Dried and filtered compressed air, controlled and metered by a Bronkhorst digital mass-flow controller (air flow range 0.5–24.1 kg/h) was heated by an industrial-grade Osram Sylvania (rating 8 kW) high temperature inline heater to temperatures up to 1150 K. A temperature measurement from a welded-tip twisted-pair K-type thermocouple at the air heater exit was used as a feedback input to a PID controller, which was used to control the power input to the electric heater through a thyristor assembly.

The hot air leaving the heater passed through a stainless-steel perforated plate with 1 mm diameter holes and 75% solidity. Further downstream, a second turbulence-generating perforated plate of hole diameter M was used to set the vary the turbulence

characteristics into the main pipe test-section. Two different perforated plates, both with a 60° hole arrangement, were used: (i) a large perforated plate (LPP), with: $M = 3$ mm, solidity = 42%, pitch = 3.7 mm; and (ii) a small perforated plate (SPP), with: $M = 1.2$ mm, solidity = 55%, pitch = 1.7 mm. Here, pitch denotes the center-to-center spacing of adjacent holes. The perforated plate location was fixed at $z = -63$ mm, where $z = 0$ corresponds to the fuel injection location, where z denotes the axial direction coordinate.

The entire preheating assembly was heavily insulated with a 10 cm thick layer of high-temperature refractory insulation wool. A 1.5 mm diameter mineral-insulated N-type thermocouple was embedded into the assembly to monitor the thermal state of the apparatus during the heating up process and to confirm the attainment of thermal equilibrium before any experiments were performed and measurements made.

2.1.2. Main pipe test-section

The hot air stream from the preheating assembly passed directly into an optically accessible and vertically mounted custom-made test-section that consisted of a 65 cm long central quartz tube (referred to as the 'quartz tube' and abbreviated as 'qz' in the rest of this paper) of inside diameter $d_{qz} = 25.0 \pm 0.2$ mm and outside diameter $D_{qz} = 28.0 \pm 0.2$ mm. The tube's exit was open, exhausting into the laboratory, such that the pressure in the tube was maintained at ambient conditions. A quartz jacket of square cross-section enclosed the quartz tube along its entire length. The square shape of the surrounding jacket was selected to minimize the optical distortions caused due to curved surfaces. Hot air from a second process air heater that was horizontally mounted near the exit of the tube flowed in a counterflow direction to that of the upwards flow of hot air inside the central quartz tube, and exited through a port near the base of the test section. The test-section arrangement, therefore, took the form of a counterflowing double-pipe heat exchanger, acting to reduce the heat losses from the test section to the ambient.

2.1.3. Liquid fuels and injection system

Pure *n*-pentane (99+% pure, CAS number: 109-66-0) and *n*-heptane (99+% pure, CAS number: 142-82-5) were used as liquid fuels. *N*-heptane is a commonly employed single component fuel representative of kerosene and has been used in a large number of studies given its relatively well-known chemical mechanism. It has also been used in prevaporized form in earlier work in the same flow configuration reported in Markides [3] and Markides et al. [23]. *N*-pentane was selected to study the effect of its relatively higher volatility (relative to *n*-heptane) on the examined phenomena.

An in-house water-cooled injector nozzle was used that comprised three concentrically arranged stainless-steel hypodermic tubes. The innermost tube carried the liquid fuel and was cooled by cold water flowing around it in the other tubes, within which it was enclosed. Hence, the final injector had an inside diameter $d_{inj} = 0.311 \pm 0.019$ mm and outside diameter $D_{inj} = 3.048 \pm 0.025$ mm. A 0.25 mm diameter mineral-insulated N-type thermocouple was used to measure the temperature at the outside wall of the inner injector tube at the injection location, which was used as an estimate of the fuel temperature at injection (T_{fuel}). The liquid fuel was delivered to the injector nozzle from a stainless-steel syringe mounted on a programmable Harvard Apparatus syringe pump.

2.2. Key experimental conditions/variables

For each experiment, three key measurements were recorded: the bulk air inlet temperature T_{air} , the bulk air inlet velocity U_{air} , and the liquid fuel injection velocity U_{fuel} :

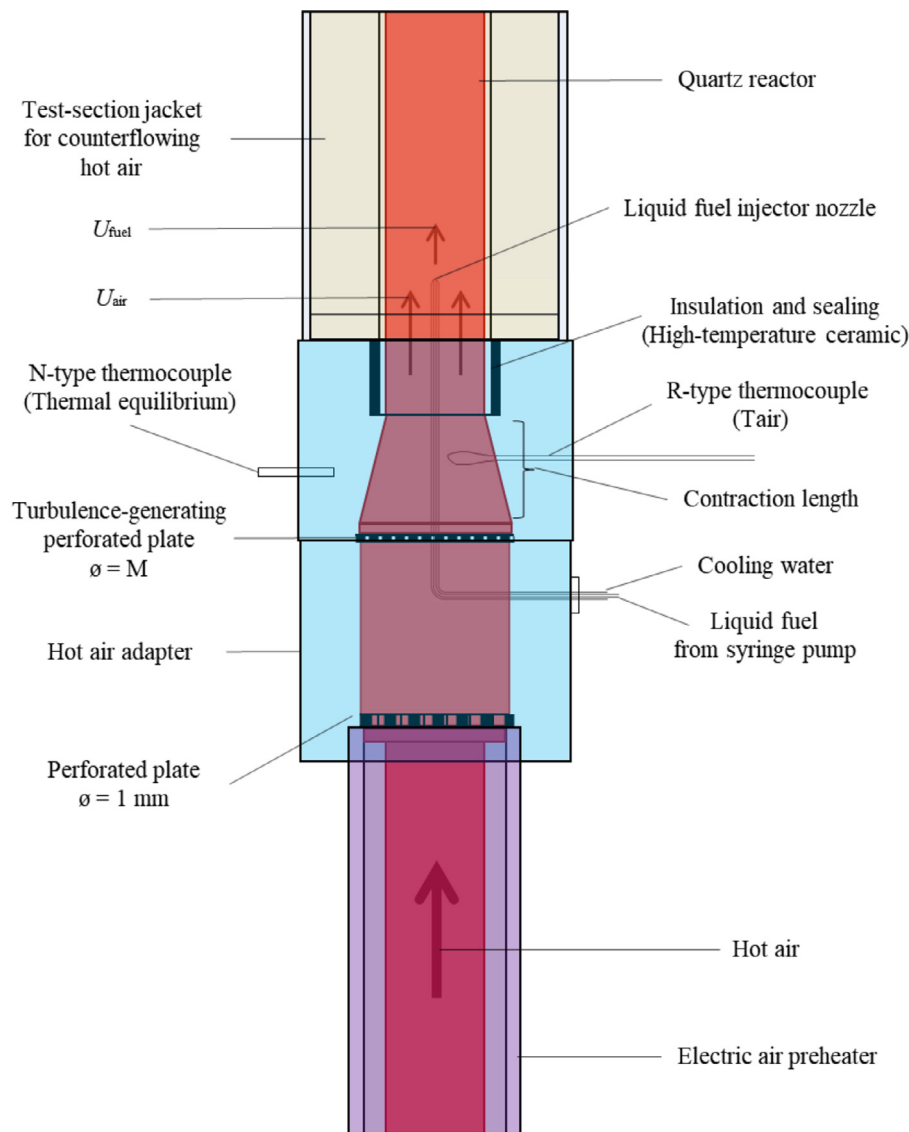


Fig. 1. Schematic of the experimental apparatus [21,22] with key parameter and variable definitions.

The bulk air inlet temperature T_{air} was measured at the inlet of the quartz tube (which was located at $z = -40$ mm), with a 0.25 mm bare wire (unsheathed) butt-welded R-type thermocouple (Pt/13% Rh-Pt), whose junction was located 9 ± 1 mm from the wall into the flow i.e., at $r/r_{\text{qz}} = 0.3$; here $r_{\text{qz}} = d_{\text{qz}}/2$. A 16-bit multifunction National Instruments USB-6259 data acquisition system with SCB-68 connector blocks was used to record all thermocouple measurements. The raw temperature measurements of the R-type thermocouple were corrected for conduction and radiation losses, as per Appendix A of Markides [3], in order to obtain T_{air} . The maximum correction was ± 4 K i.e., 0.4% of T_{air} .

The bulk air inlet velocity U_{air} , defined as the average air velocity over the annular cross-sectional area between the fuel injector nozzle and quartz tube, was based on the imposed mass flowrate of air $\dot{m}_{\text{air}}$ as directly measured by the air mass-flow controller. At T_{air} , U_{air} is given by $U_{\text{air}} = \dot{m}_{\text{air}} / (\rho_{\text{air}}[(\pi/4)d_{\text{qz}}^2 - (\pi/4)d_{\text{inj}}^2])$ where, $\dot{m}_{\text{air}}$ is the mass flowrate of air and, ρ_{air} is the density of air at T_{air} and atmospheric pressure.

The liquid fuel injection velocity U_{fuel} is the average velocity over the cross-sectional flow area of the injector tube and was calculated from $U_{\text{fuel}} = (Q_{\text{fuel}}\rho_{\text{amb,fuel}})/(\rho_{\text{fuel}}(\pi/4)d_{\text{inj}}^2)$, Q_{fuel} is the volumetric flowrate of the liquid, $\rho_{\text{amb,fuel}}$ is its density at ambi-

ent temperature ($= 296$ K), ρ_{fuel} its density at T_{fuel} , and d_{inj} is the inner injector diameter.

2.3. Experimental procedure

About 90 min of heating-up time was required for the apparatus to reach the temperatures necessary for the realization of the experiments. When the desired T_{air} was reached, the heaters were operated for another 45–50 min to bring the entire apparatus to thermal equilibrium, after which U_{air} and U_{fuel} were set to their desired values. Fuel injection was initiated a few minutes before measurements were made to minimize transients.

2.4. Optical measurements

Optical measurements of the jet and droplet field were made to obtain the jet break-up length, droplet size and location data. Imaging was conducted using a high-speed camera with a bright light-source for back illumination, which allows us to obtain shadowgraphs under hot reacting conditions in the near-field region, i.e., between $z = 0$ and $z = 50$ mm, while autoignition was occurring further downstream. An Olympus iSpeed3 monochrome high-

speed CMOS camera with a maximum resolution of 1280×1024 at 2 kHz equipped with an AF-S Nikkor 85 mm 1:1.4 G lens (f/1.4) and two extension rings (12 mm and 20 mm) was used. The camera was mounted approximately 0.15 m from the quartz tube. A 100 W white LED floodlight was used as the light source, with a 10 mm thick sheet of polystyrene foam acting as the light diffuser. Shadowgraphs were recorded at 2 kHz and an exposure time of 50 μ s. For each experimental run corresponding to a set of condition, 10,000 images were recorded. Over 250 independent experimental runs were performed across all conditions investigated in this work resulting in about 2.5 million high-speed images.

The high-speed images were analyzed to extract the sizes and positions of droplets in each frame. To compensate for any distortions due to defects in the tube, the quartz jacket, or projection through the lenses, the images were corrected using calibration images of a graticule (i.e., a printed screen with known pattern) inserted inside the tube. Rolling pixel-wise temporal median was used as the background model to segment out the droplets. Pixels sufficiently different from this background were classified as foreground (or pixels inside droplets). To refine the estimated area of droplets and discard any pixels inside shadows which move along with the droplets, a secondary refinement of the temporal segmentation based on pixel intensity differences was performed. This employed the GrabCut algorithm [24] initialized with the coarse temporal segmentation. Finally, a fully convolutional neural network [25], trained to predict the locations of droplet centers, was employed to separate out the droplets in contact with each other into distinct entities.

3. Results and discussion

3.1. Temperature-field characteristics

Measurements of the radial profiles of the local mean air temperature at different axial distances z were made with a 75 μ m bare wire bead-welded K-type thermocouple without fuel injection. The results, shown in Fig. 2, reveal that at $z = 0$ a thermal boundary layer was present extending a distance 0.2–0.3 r_{qz} from both the injector and quartz tube walls, the latter due to heat losses from the quartz tube to the laboratory. The thermal boundary layer over the tube wall grew further downstream. All of the jet and droplet phenomena reported in this work are confined within a spatial region that extends from the centerline of the quartz tube to a radial distance of 0.3 r_{qz} from the centerline. From Fig. 2, we observe the axial temperature decay increases at

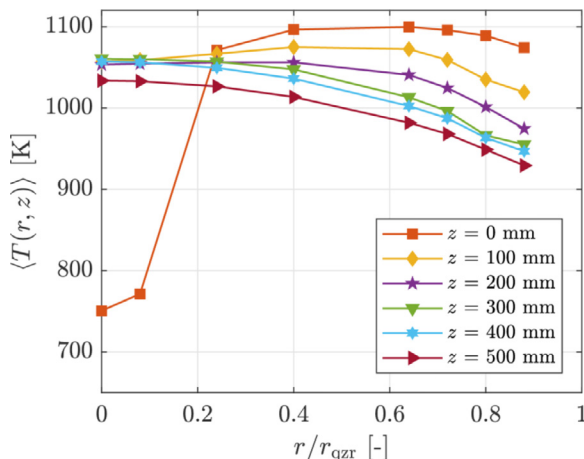


Fig. 2. Radial profiles of mean air temperature $T(r,z)$ for $T_{air} = 1127$ K, $U_{air} = 40.3$ m/s.

radial distances further away from the centerline. A worst-case average axial temperature decay due to heat losses of about 9 K per 100 mm was observed between $z = 0$ to 400 mm at the extreme radial distance of 0.3 r_{qz} .

The temperature fluctuations were random with probability density functions (PDFs) that closely matched Gaussian distributions. The root mean square (RMS) of the temperature fluctuations $T'(r,z)$ was measured to be 2.3 ± 1.7 K at the injection plane. More detailed information on the temperature field is available in Gupta [21], and Gupta and Markides [22].

3.2. Velocity-field characteristics

The apparatus presented in this work is identical to that used for the autoignition of gaseous fuels in Markides and Mastorakos [1,2], and Markides [3,3x]. In those studies, the velocity field was characterized by employing a hot-wire probe and constant temperature anemometer system. Similar velocity characteristics are expected in the quartz tube of the current work, especially at the inlet and until this is affected by the liquid fuel evaporation and reaction.

In Markides and Mastorakos [1] and Markides [3,3x], it was found when employing the LPP that the radial profiles of the axial velocity component were uniform over the region $r/r_{qz} = 0.15$ –0.8 for $z = 2$ –42 mm, with the local mean axial velocity remaining inside the range $U/U_{air} = 1.12 \pm 0.02$, due to a velocity boundary layer that grew along the walls of the quartz tube and the fuel injector. Over the radial region $0.4 < r/r_{qz} < 0.7$ and close to the injector exit, the flow turbulence intensity u'/U was inside the range 0.11–0.14, where u' denotes the velocity fluctuation RMS, and the longitudinal integral lengthscale L_{turb} was 3.5 ± 1 mm. When using the SPP, L_{turb} was 5–7 (± 1) mm at the same location [2].

3.3. Primary atomization regime

Optical measurements were made of the jets and droplet fields for *n*-pentane and *n*-heptane, and with both the SPP and LPP. A representative time sequence of raw shadowgraphs is presented in Fig. 3. In these experiments, each fluid stream, i.e., air and fuel, can be characterized by the bulk velocities, U_{air} and U_{fuel} , along with a set of non-dimensional numbers given by Dumouchel [13], Lasheras and Hopfinger [15], Kourmatzis and Masri [16]:

$$Re_{air} = \frac{d_e U_{air} \rho_{air}}{\mu_{air}} d_e = 4 \frac{\left[\left(\frac{\pi}{4} d_{qz}^2 \right) - \left(\frac{\pi}{4} D_{inj}^2 \right) \right]}{\pi (d_{qz} + D_{inj})} \quad (1)$$

$$Re_{jet} = \frac{d_{inj} U_{fuel} \rho_{fuel}}{\mu_{fuel}} \quad (2)$$

$$Oh = \frac{\mu_{fuel}}{\sqrt{\sigma d_{inj} \rho_{fuel}}} \quad (3)$$

$$We = \frac{\rho_{air} U_{air}^2 d_{inj}}{\sigma} \quad (4)$$

$$M = \frac{\rho_{fuel} U_{fuel} \left(\frac{\pi}{4} d_{inj}^2 \right)}{\rho_{air} U_{air} \left[\left(\frac{\pi}{4} d_{qz}^2 \right) - \left(\frac{\pi}{4} D_{inj}^2 \right) \right]} \quad (5)$$

$$P = \frac{\rho_{air} U_{air}^2}{\rho_{fuel} U_{fuel}^2} \quad (6)$$

where Re_{air} is the hot air Reynolds number; d_e the equivalent diameter based on the annulus between the quartz tube and the fuel injector nozzle; ρ_{air} the air density; μ_{air} the air dynamic viscosity; Re_{jet} the liquid fuel jet Reynolds number; ρ_{fuel} the fuel density; μ_{fuel} the fuel dynamic viscosity; Oh the Ohnesorge number; σ the

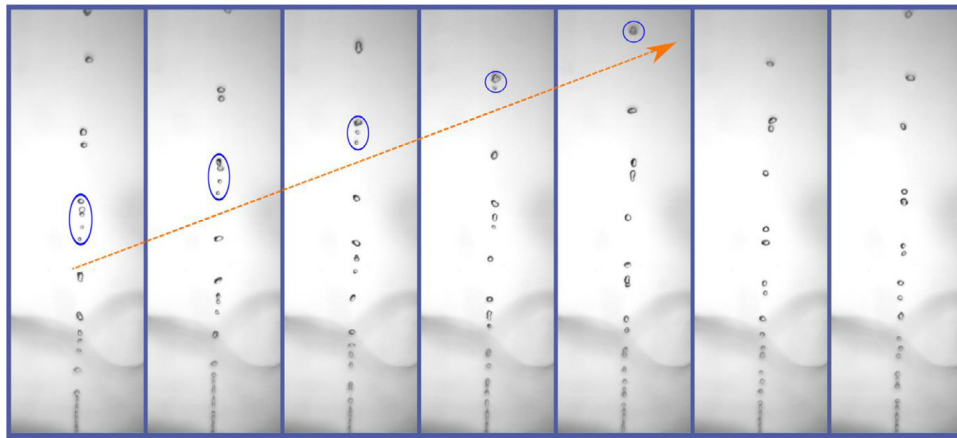


Fig. 3. Representative high-speed time-sequence shadowgraphs of pure liquid *n*-pentane jets with the LPP. Liquid fuel jet atomization and downstream motion of the droplets thus formed can be traced; the blue circles show tracks of coalescing droplets. The time between consecutive images is 2.5 ms and each image corresponds to 16 mm × 42 mm (radial × axial). The flow direction is upwards. Flow conditions: $T_{\text{air}} = 1115$ K, $U_{\text{air}} = 14.4$ m/s, $Re_{\text{air}} = 2243$, $U_{\text{fuel}} = 1.3$ m/s, $Re_{\text{fuel}} = 1090$, $Oh = 0.004$, $We = 1.3$, $P = 0.06$, $M = 0.03$.

surface tension; We the aerodynamic Weber number; M the mass flux ratio; and P the momentum flux ratio.

The We and Oh numbers describe the interaction of the jet stabilizing (inertia and viscous forces) and destabilizing (surface tension) processes [14,17,26]. For $We < 15$ [13] and $P < (7 \times 10^6 / Re_{\text{air}}^{1.9})$ [27], Rayleigh-type jet break-up regime is identified; for the entire dataset generated in this work, a Rayleigh-type jet break-up regime was observed. An $Oh > 2$ –4 dampens the jet break-up causing instabilities [14]; the Oh values recorded in this work were three orders of magnitude smaller (0.003–0.006), suggesting an inevitable jet break-up. The main liquid core of the jet became weakly wavy just before breaking into ligaments, from which further droplets of small diameter broke away. All the liquid fuel jets were laminar with a Re_{jet} between 600 and 1100. Finally, the air flow conditions were varied such that T_{air} was in the range 1100–1150 K and U_{air} in the range 14–40 m/s (up to 45 m/s only for *n*-pentane), while U_{fuel} was varied between 0.7 and 2.7 m/s.

3.4. Liquid fuel jet morphology

The 5th percentile of all the droplet axial (z) locations obtained during an experimental run (from 10,000 high-speed images) was considered as a robust measure of the liquid jet break-up length L_{jet} , with the standard deviation of L_{jet} ranging from 0.01 to 0.12 mm (0.1–1.3%) across all experimental conditions. The momentum flux ratio P is known to be the primary parameter determining L_{jet} , with L_{jet} being inversely proportional to P [15].

Fig. 4 presents L_{jet} as a function of P for a range of conditions, and includes results for both *n*-pentane and *n*-heptane jets. It can be observed that L_{jet} increased monotonically with decreasing P for smaller P values (below ~ 0.2) but then plateaued at higher values, as U_{fuel} was varied at fixed U_{air} and T_{air} . For *n*-heptane, L_{jet} was consistently longer than for *n*-pentane. Furthermore, Fig. 5 shows L_{jet} as a function of We for *n*-heptane as U_{air} was increased at two different fixed U_{fuel} . The higher U_{fuel} is associated with longer L_{jet} , and for a given U_{fuel} (and consequently a constant Re_{fuel} and fuel momentum flux), L_{jet} decreased monotonically with increasing We (and U_{air}) at about 2 mm per unit increase in We . Kourmatzis and Masri [12] also observed a similar effect for liquid acetone jets injected into of coflowing air (cold) in a wind tunnel with different turbulence-generating grids.

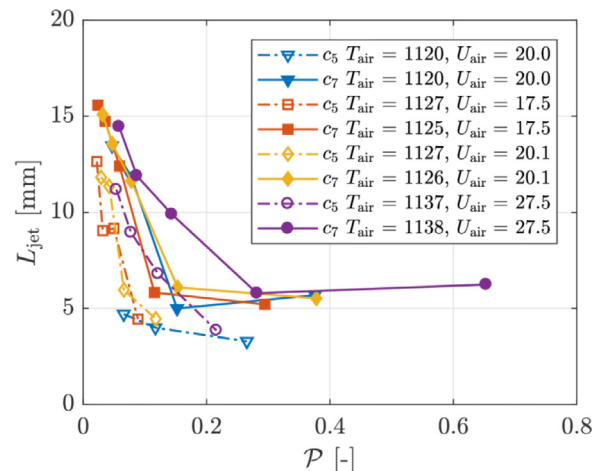


Fig. 4. Effect of P on L_{jet} for *n*-pentane ('c5') and *n*-heptane ('c7') at various fixed T_{air} and U_{air} . N.B.: P increased from 0.02 to 0.7 as U_{fuel} increased from 0.7 to 2.7 m/s. Legend: T_{air} in K; U_{air} in m/s.

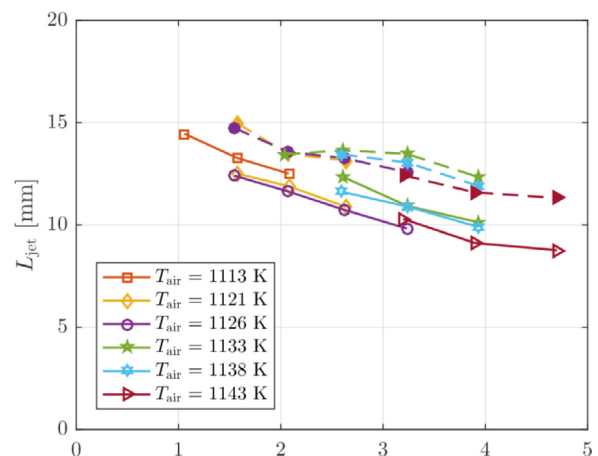


Fig. 5. Effect of We on L_{jet} for *n*-heptane at $U_{\text{fuel}} = 1.6$ m/s (solid lines, empty markers) and $U_{\text{fuel}} = 2.0$ m/s (dashed lines, filled markers) at various fixed T_{air} . N.B.: We increased from 1.0 to 4.7 as U_{air} was increased from 14 to 30 m/s.

Table 1

Conditions in the liquid fuel droplet characterization experiments (Dpf: droplets/frame; PP: perforated plate).

Figure	Fuel	PP	T_{air}	U_{air}	Re_{air}	U_{fuel}	Re_{jet}	Dpf	L_{jet}	J	S	Oh	We	P	M
#			[K]	[m/s]	[-]	[m/s]	[-]	[-]	[mm]	[-]	[-]	[-]	[-]	[-]	[-]
7(a)	<i>n</i> -pentane	LPP	1133	20.0	3030	1.3	1206	9.0	5.7	1.3	1450	0.004	2.6	0.11	0.02
–	<i>n</i> -pentane	LPP	1134	27.5	4168	1.3	1215	6.8	7.4	1.7	2100	0.004	4.9	0.22	0.02
7(b)	<i>n</i> -heptane	LPP	1132	20.0	3032	1.1	662	10.4	5.8	3.9	1050	0.006	2.0	0.15	0.02
–	<i>n</i> -heptane	LPP	1133	27.5	4175	1.1	686	6.1	4.9	2.9	500	0.005	3.9	0.28	0.01
7(c)	<i>n</i> -heptane	SPP	1133	27.5	4177	1.1	671	15.6	15.3	1.2	475	0.006	3.9	0.28	0.01
7(d)	<i>n</i> -pentane	SPP	1133	27.5	4175	1.1	1025	9.6	11.3	1.4	1650	0.004	5.0	0.31	0.01

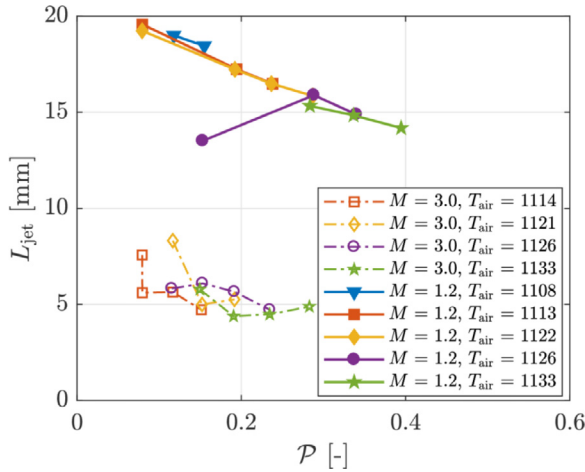
**Fig. 6.** Effect of P on L_{jet} for *n*-heptane with LPP and SPP at $U_{fuel} = 1.1$ m/s and various fixed T_{air} . N.B.: P increased from 0.09 to 0.4 as U_{air} increased from 14 to 30 m/s. Legend: M in mm; T_{air} in K. Corresponding conditions in same color; LPP: empty markers, dash-dot lines, and, SPP: filled markers, solid lines.

Fig. 6 compares L_{jet} for *n*-heptane measured from experiments of jets downstream of the LPP and the SPP for a fixed $U_{fuel} = 1.1$ m/s. It is interesting to note that the L_{jet} values measured with the SPP are at least twice as long as those with the LPP, irrespective of P (and hence U_{fuel}) at similar conditions of T_{air} and U_{air} (Re_{jet} , Re_{air} , Oh , We , and M were also equal). This suggests that the primary liquid jet break-up was strongly affected by the turbulence character of the background air flow.

With the SPP, the air velocity fluctuations are smaller and the longitudinal integral lengthscales L_{turb} longer compared to the LPP (from Markides and Mastorakos [2], and Markides [3,3x]). Kourmatzis and Masri [12,16] also suggested that liquid jets in an air-assisted Rayleigh breakup regime were influenced by fluctuations of the gas phase velocity (and hence the local We and Re). A qualitative parallel on the effect of the perforated plate design can also be drawn from the mixing field results of gaseous acetylene plumes from Markides and Mastorakos [2,2y,2z], where the larger turbulence lengthscales in flows downstream of the SPP caused the fuel plume to meander without appreciable mixing, resulting in narrower and longer plumes. In view of this, the longer jets when employing the SPP could be a result of jet thinning [12] owing to larger L_{turb} . Lastly, for all the data presented above, no significant effect of T_{air} on L_{jet} was observed, at least within the range of conditions investigated in this work.

3.5. Liquid-fuel droplet characteristics

Table 1 lists representative flow conditions in the droplet characterization measurements, with the main results shown in Figs. 7 and 8. Specifically, Fig. 7 shows 2-D PDF maps, 2-D mean droplet

diameter maps, and droplet size distributions at different z . Furthermore, Fig. 8 tracks the evolution of droplet diameters with z . Such plots were obtained for each experimental run. The 2-D PDF and mean droplet diameter maps were constructed using a square area bin measuring $300 \mu\text{m} \times 300 \mu\text{m}$ ($\sim d_{jet}$ which was approximately $311 \mu\text{m}$).

The narrow radial spread of the PDF in Fig. 7 (top) indicates that the majority of droplets travelled close to the centerline of the tube. In Table 1, J represents the radial spread of the droplets at $z = 34$ mm, and calculated as the difference between the 95th and 5th percentiles of r locations of all droplets in $32 < z < 36$ mm. For the conditions investigated in this work, $J \leq 5$ mm i.e., the fuel droplets were confined inside a radial region of $\pm 8 d_{jet}$ for z up to 34 mm. The small values of J support the near-axisymmetric injection of fuel into the quartz tube. A common feature of the 2-D droplet diameter maps (such as that in Fig. 7 (middle)) was that larger droplets were concentrated near the centerline, while smaller satellite droplets were observed at the radial periphery of the spray. Friedman and Renksizbulut [28] also observed that the annular air jet assisted in confining large spray droplets. The satellite droplets moved downstream at relatively ($\sim 40\%$) higher velocities than large spray droplets.

Next, droplet diameter distributions were obtained at z between 20 and 40 mm in steps of 5 mm. The PDF of droplet diameter d_{drop} at a given z in Fig. 7 (bottom) was obtained from d_{drop} of all droplets located within the axial distance $z \pm \Delta z$, where $\Delta z = 2$ mm. The droplet diameters ranged from 200 to $900 \mu\text{m}$, indicating the polydispersed nature of the fuel spray. Also, the droplet size distributions were broad, with only small changes within the investigated axial region, which suggests significant evaporation of the liquid fuel had not occurred up to $z = 40$ mm. A simple estimate of the rate of evaporation of the droplets based on the specific heat capacity and latent heat of vaporization of the fuel, and the size of the droplets, suggested that the fuel droplets at these flow conditions are expected to evaporated at a rate of about 2.5% by mass up to $z = 40$ mm.

In Fig. 8, the mean droplet diameters $d_{mean}(z)$ were obtained from their corresponding PDFs (Fig. 7(bottom)). It was noted that $d_{mean}(z)$ increased non-monotonically with increasing z in the observed axial region up to $z = 40$ mm. The blue circles in Fig. 3 identified coalescing droplets with increasing z . Coalescence of droplets in turbulent gas-liquid coaxial flows was also reported by Lefebvre [29] and Kourmatzis and Masri [12]. It can be concluded that the observed increase in $d_{mean}(z)$ was due to the formation of larger droplets through the collision and coalescence of smaller droplets.

Lastly, droplet size and inter-droplet distance both affect combustion behavior [30]. Table 1 lists the mode of the inter-droplet distance S , computed as the distance to the nearest droplet in the same image, for droplets downstream of $z = 25$ mm. The mean S was found to be $1200 \mu\text{m}$ (with a standard deviation $\sim 650 \mu\text{m}$) i.e., of the same order of magnitude as d_{mean} . This suggested that the existing sprays must be categorized as dense sprays

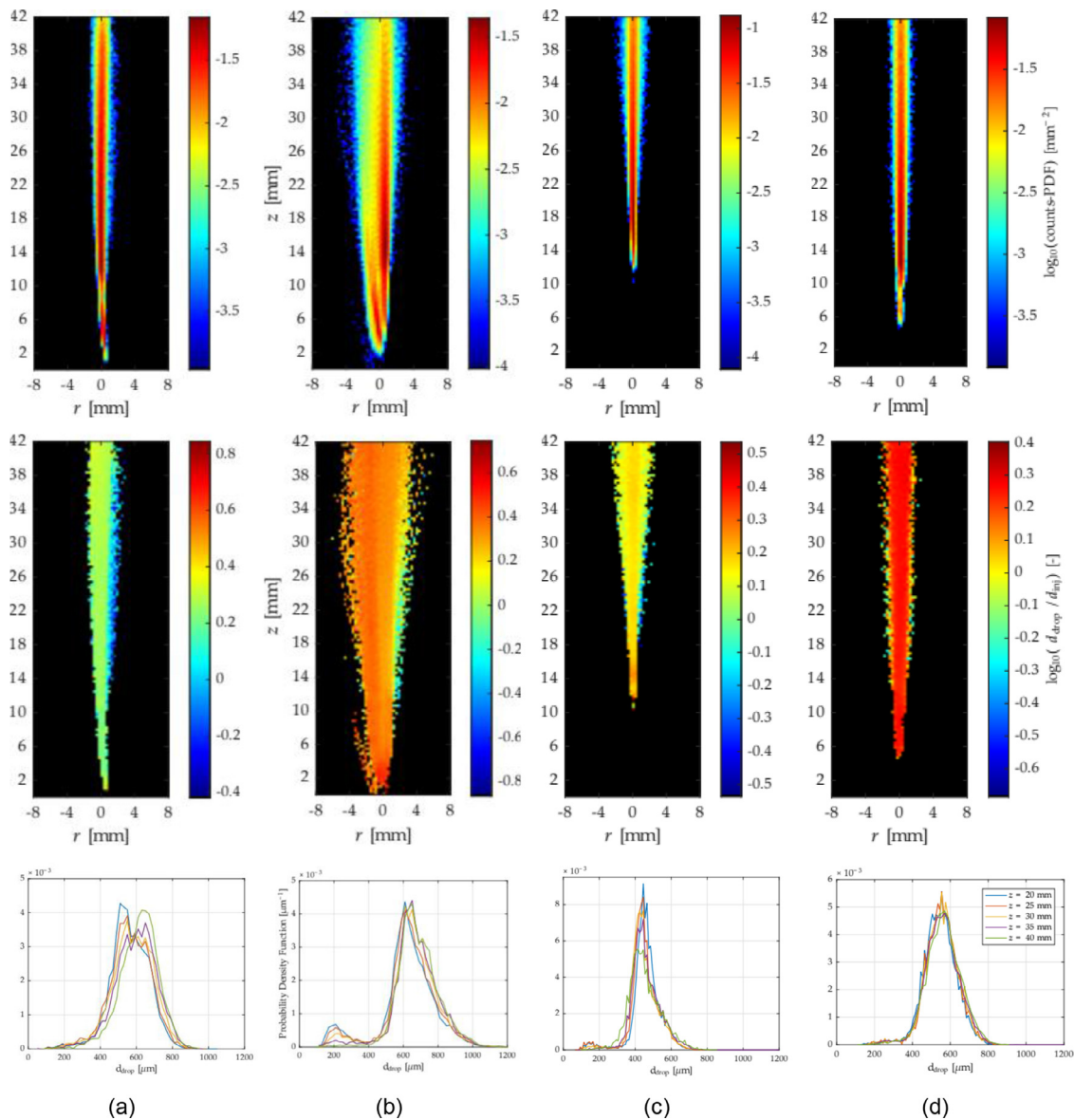


Fig. 7. Liquid fuel droplet spatial and size characteristics: (top) PDFs of spatial location of the droplets; (middle) spatial distribution maps of mean diameter d_{drop} ; and (bottom) PDFs of droplet diameter d_{drop} at z between 20 and 40 mm in steps of 5 mm. The full set of conditions is summarized in Table 1.

for $z < 42$ mm. The observed coalescence of droplets was an indicator of droplet-droplet interaction – a typical feature of dense sprays [10].

3.6. Effect of inlet flow conditions on droplet size

The primary jet break-up and atomization under all experimental conditions was complete upstream of $z = 20$ mm. Therefore, $z = 20$ mm was the most upstream z location common across all experimental conditions where liquid fuel droplets existed. The effect of inlet flow conditions such as T_{air} , U_{air} , U_{fuel} and perforated plate on d_{mean} at $z \pm \Delta z$ ($z = 20$ mm and $\Delta z = 2$ mm) was examined. A parallel analysis of the effect of the inlet flow conditions on z locations downstream of 20 mm, suggested that the overall effect of the flow conditions on d_{mean} remained the same. Hence, d_{mean} at $z > 22$ mm are excluded from discussion here. The standard deviation of d_{mean} ranged from 0.2 to 7.3 μm (0.04–1.33%) across all experimental conditions. Note that all autoignition phenomena were observed much further downstream,

at $z > 350$ mm [21,22]. Due to the non-uniqueness and large number of non-dimensional parameters in these complex flows, the results are presented as a function of the true experimental variables; the non-dimensional parameters can be extracted by scaling using the definitions described above.

3.6.1. Air velocity and temperature

Fig. 9 shows the effect of U_{air} on d_{mean} at various T_{air} and U_{fuel} with the LPP for both fuels. At all conditions, d_{mean} decreased with increasing U_{air} . For n -heptane at $U_{\text{fuel}} = 0.7$ m/s, d_{mean} decreased from about 800 to 600 μm as U_{air} increased from 15 to 20 m/s (Fig. 9(a)); at $U_{\text{fuel}} = 1.1$ m/s d_{mean} decreased about 50 μm , from 650 to 600 μm (Fig. 9(b)). For n -pentane, in Fig. 9(c) and (d), d_{mean} decreased from 700 to 400 μm for U_{air} between 15 and 30 m/s. Further, similar to the observation made for the effect of T_{air} on L_{jet} , no significant effect of T_{air} was observed on d_{mean} . At $U_{\text{air}} > 20$ m/s, d_{mean} was generally observed to be independent of T_{air} but varied by about 100 μm at U_{air} below 20 m/s (Fig. 9) – indicating some effect of T_{air} but only under certain conditions.

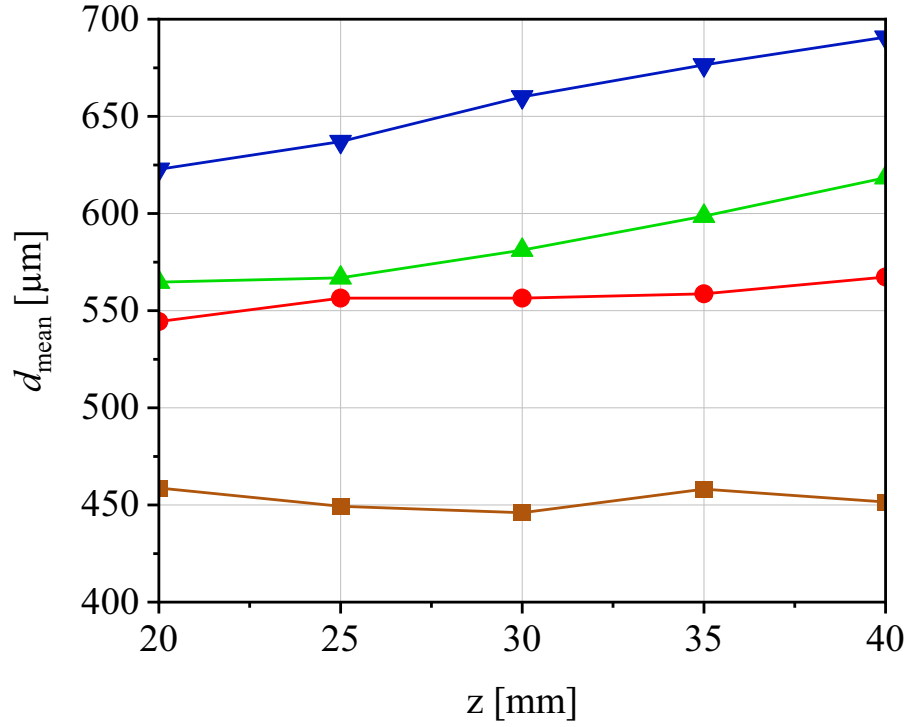


Fig. 8. Mean droplet diameters d_{mean} as a function of z . The conditions for the green, blue, red, and brown data are the same as in Fig. 7(a), (b), (c) and (d), respectively. The full set of conditions is summarized in Table 1.

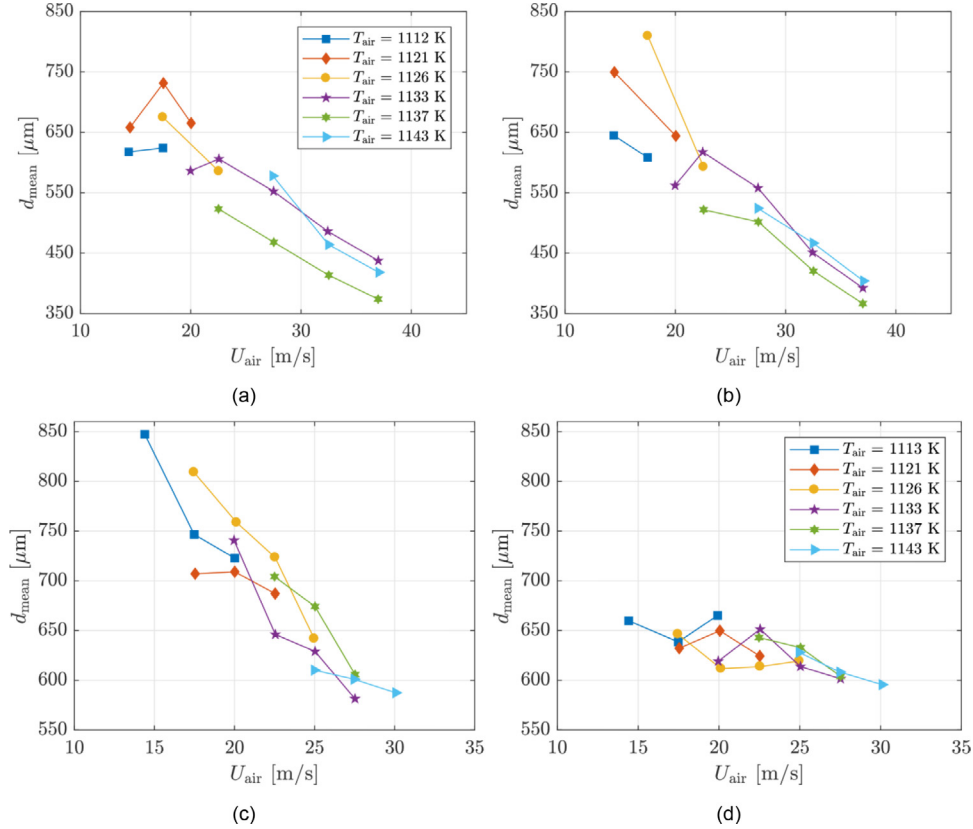


Fig. 9. Effect of U_{air} on d_{mean} for $n\text{-pentane}$ at: (a) $U_{\text{fuel}} = 1.3 \text{ m/s}$; (b) $U_{\text{fuel}} = 1.8 \text{ m/s}$ for constant T_{air} between 1112 and 1143 K, and $n\text{-heptane}$ at: (c) $U_{\text{fuel}} = 0.7 \text{ m/s}$; (d) $U_{\text{fuel}} = 1.1 \text{ m/s}$. Legend in (b) applies also to (a), and that in (d) applies also to (c). Here, d_{mean} is the arithmetic mean of the diameters of all individual liquid fuel droplets observed across the tube's cross-section area and inside the axial region defined by $z \pm \Delta z$ ($z = 20 \text{ mm}$ and $\Delta z = 2 \text{ mm}$) compiled over the entire experimental run.

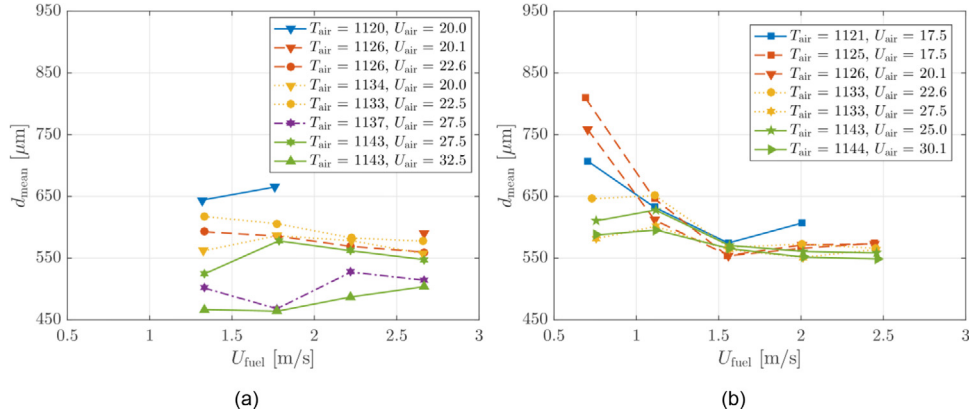


Fig. 10. Effect of U_{fuel} on d_{mean} for: (a) n -pentane; and (b) n -heptane, at various constant T_{air} and U_{air} . The conditions represented by each colour and line-style denote the same T_{air} , whereas each marker type denotes the same U_{air} . Legend: T_{air} in K; U_{air} in m/s. Here, d_{mean} is defined as in Fig. 9.

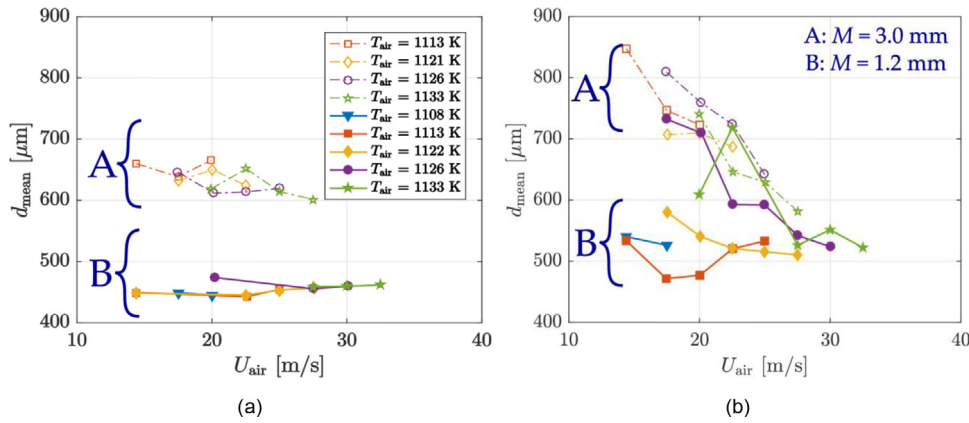


Fig. 11. Effect of U_{air} on d_{mean} for n -heptane with LPP and SPP: (a) $U_{\text{fuel}} = 0.7$ m/s; and (b) $U_{\text{fuel}} = 1.1$ m/s, at constant T_{air} conditions between 1113 and 1133 K. Legend in (b) applies also to (a). The LPP data are denoted by empty markers and dash-dot lines (Set A), whereas the SPP data are denoted by filled markers and solid lines (Set B). Here, d_{mean} is defined as in Figs. 9 and 10.

3.6.2. Fuel injection velocity

The effect of U_{fuel} on d_{mean} for n -heptane and n -pentane, with LPP, is shown in Fig. 10(a) and (b). The d_{mean} for n -heptane droplets decreased from about 800 to 570 μm when U_{fuel} increased from 0.7 to 1.5 m/s. This behavior was only exhibited for U_{air} up to 22.5 m/s; for $U_{\text{air}} > 22.5$ m/s, d_{mean} decreased by 50 μm . Increasing U_{fuel} beyond 1.5 m/s showed no appreciable change in d_{mean} . For n -pentane (Fig. 10(b)), d_{mean} showed a weak dependence on U_{fuel} for $U_{\text{air}} \leq 22.5$ m/s – d_{mean} decreased from about 600 to 550 μm as U_{fuel} increased from 1.3 to 2.7 m/s. No definite conclusion could be drawn about the dependence of d_{mean} on U_{fuel} for $U_{\text{air}} > 25$ m/s.

3.6.3. Effect of turbulence

Fig. 11 compares d_{mean} between the LPP and SPP experiments for n -heptane; d_{mean} for LPP is the same as that in Fig. 9. Irrespective of U_{fuel} , with SPP the n -heptane droplets were smaller compared to LPP at similar T_{air} and U_{air} . As mentioned previously, the larger L_{turb} and lower U_{air} with SPP, can result in liquid fuel jet thinning. The current observations of d_{mean} suggested that these longer and thinner n -heptane jets atomize into smaller droplets. The d_{mean} of n -heptane droplets for SPP at $U_{\text{fuel}} = 1.1$ m/s were 30% smaller than for LPP; the standard deviations were 40% smaller. Eggers and Villiermaux [31] also reported that thinner, stretched and corrugated liquid ligaments produced finer drops and a narrower droplet size distribution. The formation of smaller droplets with increasing jet thinning was observed by Kourmatzis and

Masri [12] for a finer grid. Similarly, with SPP, at $U_{\text{fuel}} = 0.7$ m/s (Fig. 11(a)) and $U_{\text{fuel}} = 1.1$ m/s (Fig. 11(b)), an increase in U_{air} resulted in smaller droplets. However, except for the decrease at $T_{\text{air}} = 1126$ and 1133 K at $U_{\text{fuel}} = 0.7$ m/s, this change in d_{mean} was not as pronounced as that observed with LPP. N -pentane also showed a similar behavior.

3.7. Development of droplet size correlation

Depending on the atomization mechanism, and for a given perforated plate (hole size, solidity, pitch, etc.), the factors that can influence the atomized droplet diameter are: the inside diameter of the injector nozzle (d_{inj}), the velocity difference between the air and fuel phases ($\Delta U = U_{\text{air}} - U_{\text{fuel}}$), the air (T_{air}) and fuel (T_{fuel}) temperatures, the air (ρ_{air}) and fuel (ρ_{fuel}) densities, the air viscosity (μ_{air}) and the surface tension (σ). Therefore, we can specify the functional dependence of the mean droplet diameter as:

$$d_{\text{mean}} = f(d_{\text{inj}}, \Delta U, \sigma, \rho_{\text{air}}, \rho_{\text{fuel}}, \mu_{\text{air}}, T_{\text{air}}, T_{\text{fuel}}) \quad (7)$$

The dimensional relation above contains 9 physical quantities and 4 primary dimensions, suggesting a functional dependence featuring 5 dimensionless quantities. Non-dimensional analysis applied to the above relation reduces this to:

$$\frac{d_{\text{mean}}}{d_{\text{inj}}} = f\left(\frac{1}{We_{\Delta}}, \frac{1}{Re_{\Delta}}, \frac{\rho_{\text{fuel}}}{\rho_{\text{air}}}, \frac{T_{\text{fuel}}}{T_{\text{air}}}\right) \quad (8)$$

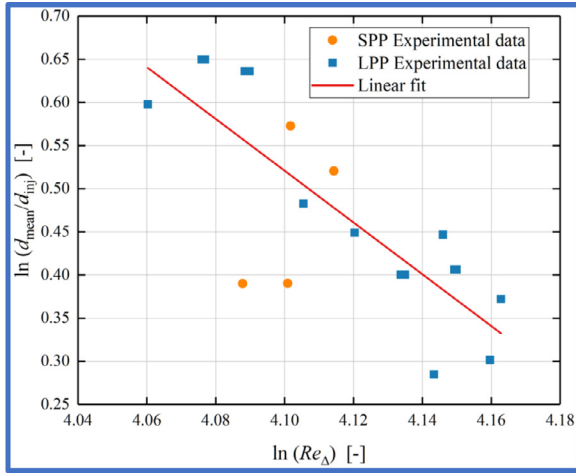


Fig. 12. Relationship between $\ln(d_{\text{mean}}/d_{\text{inj}})$ and Re_{Δ} ($R^2 = 0.63$) for all data generated using the two perforated plates (LPP and SPP), and when We_{Δ} is constant; SPP: square markers, and, LPP: circular markers.

where the changes in $(\rho_{\text{fuel}}/\rho_{\text{air}})$ and $(T_{\text{fuel}}/T_{\text{air}})$ are small, and can be ignored, such that:

$$\frac{d_{\text{mean}}}{d_{\text{inj}}} f(We_{\Delta} Re_{\Delta}) \text{ where, } \left(We_{\Delta} = \frac{d_{\text{inj}} \rho_{\text{air}} \Delta U^2}{\sigma} \right) \quad (9)$$

$$\text{and } \left(Re_{\Delta} = \frac{d_{\text{inj}} \rho_{\text{air}} \Delta U}{\mu_{\text{air}}} \right)$$

and for σ we can use a value associated with saturated fuel vapor at 1 atm.

Because of the significant velocity of the air stream (relative to the fuel) and the change in the air temperature, liquid atomization is more affected by the air stream properties (i.e., the viscosity and density of the air), which play a controlling role in the atomization process.

From Eq. (9), a power law with constants A , m , and n can be assumed of the form:

$$\frac{d_{\text{mean}}}{d_{\text{inj}}} = A We_{\Delta}^m Re_{\Delta}^n \quad (10)$$

where the constants can be determined from experimental data by taking logarithms, and plotting the best straight-line fits that correspond to the following linear equation:

$$\ln \frac{d_{\text{mean}}}{d_{\text{inj}}} = \ln(A) + m \ln(We_{\Delta}) + n \ln(Re_{\Delta}) \quad (11)$$

Specifically, the data can be used in two steps to obtain the 3 constants in Eq. (11). In the first step, we can obtain the relationship between $\ln(d_{\text{mean}}/d_{\text{inj}})$ and Re_{Δ} for a given We_{Δ} . During this process, and using all data including from the two perforated plates used in our work, we find that a value of $\ln(We_{\Delta}) = 1.85$ leads to the best linear correlation between $\ln(d_{\text{mean}}/d_{\text{inj}})$ and Re_{Δ} . The relationship between $\ln(d_{\text{mean}}/d_{\text{inj}})$ and Re_{Δ} is shown in Fig. 12.

From Fig. 12, we obtain the constant n , such that:

$$\ln \frac{d_{\text{mean}}}{d_{\text{inj}}} + 3 \ln(Re_{\Delta}) = \ln(A) + m \ln(We_{\Delta}) \quad (12)$$

In the second step, we can now obtain the relationship between $[\ln(d_{\text{mean}}/d_{\text{inj}}) + 3 \ln(Re_{\Delta})]$ and We_{Δ} through linear fitting to all experimental data, which is done in Fig. 13.

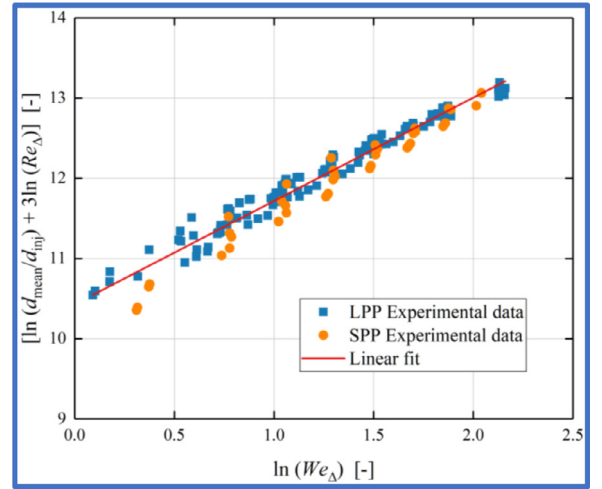


Fig. 13. Relationship between $[\ln(d_{\text{mean}}/d_{\text{inj}}) + 3 \ln(Re_{\Delta})]$ and We_{Δ} ($R^2 = 0.96$) for all data generated using the two perforated plates (LPP and SPP); LPP: circular markers, and, SPP: square markers.

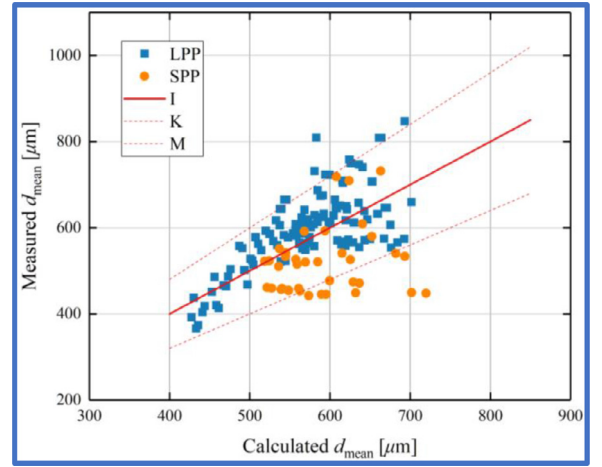


Fig. 14. Predictive performance of the calculated d_{mean} relative to experimental data for all data generated using the two perforated plates (LPP and SPP) in the present work; LPP: circular markers, SPP: square markers, I: prediction from Eq. (13), K and M: $\pm 20\%$ deviations from I.

From Fig. 13, we obtain:

$$\frac{d_{\text{mean}}}{d_{\text{inj}}} = 34 \times 10^3 We_{\Delta}^{1.29} Re_{\Delta}^{-3} | 1113 \text{K} \leq T_{\text{air}} \leq 1143 \text{K}, 25 \leq Re_{\Delta} \leq 75, 1.2 \leq We_{\Delta} \leq 8.6 \quad (13)$$

with an R^2 fitting correlation of 0.96.

Of note, referring to Figs. 12 and 13, is the further conclusion from these figures, which distinguish the plotted data according to the perforated plates with which they were generated (LPP: circular markers; SPP: square markers), that the functional relationship for the mean droplet diameter being developed here is not dependent of the perforated plate used, suggesting that within the region of our investigation, the relationship is general.

Finally, Fig. 14 shows a comparison of predictions from the mean drop diameter relationship above, i.e., Eq. (13), against measurement data. The dotted lines in the figure over and under the solid line that represents Eq. (13) represent $\pm 20\%$ deviations from this correlation. Since 95% of the data are contained within this region, it can be concluded from this figure that the prediction error of Eq. (13) is $\pm 20\%$ for the present dataset.

4. Conclusions

The primary atomization of evaporating liquid-fuel jets of either pure *n*-heptane or *n*-pentane injected coaxially (concentrically and axisymmetrically) from a circular nozzle into preheated turbulent pipe flows of air has been characterized through high-speed shadowgraphy imaging. The liquid phase was confirmed to take the form of a continuous, single-phase flow injected with velocities up to 2.7 m/s without bubbles at the injection nozzle, into air flowing with bulk velocities up to 37 m/s and at elevated temperatures up to 1150 K confined inside an insulated transparent tube of inside diameter 25.0 mm.

The effects of various inlet conditions, such as the liquid fuel injection velocity, the bulk air inlet temperature, velocity and turbulence characteristics, on the jet break-up and droplet formation and size distribution in the near-field region of the injector were studied. In particular, the turbulent character of the air flow was manipulated by introducing different turbulence-generating perforated plates/grids (with holes of a different size) into the air flow upstream of the injection location. The liquid jets were laminar with Re_{jet} between 600 and 1100, and jet break-up was observed to occur in the Rayleigh-type break-up regime.

The length of the liquid-fuel jets l_{jet} increased with increasing U_{fuel} (on average, by about 6 mm per m/s of U_{fuel}) but decreased with increasing U_{air} (on average, by about 0.5 mm per m/s of U_{air}). For the smaller perforated plate ($M = 1.2$ mm, solidity = 55%, pitch = 3.7 mm) used in the present experimental campaign, the observed fuel jets were twice as long as those observed with the larger perforated plate ($M = 3$ mm, solidity = 42%, pitch = 3.7 mm). This observation may be attributed to possible thinning of the fuel jet, owing to the longer longitudinal integral flow lengthscales associated with the smaller perforated plate.

From PDFs of the spatial distribution of the droplets formed after atomization, it was observed that the radial spread of the droplets was narrow across the investigated conditions, with the majority of the droplets travelling close to the centerline of the tube. The droplets were confined within a radial distance of ± 2.5 mm for z (axial distances from injection) up to 34 mm. Larger droplets were concentrated near the centerline, while smaller satellite droplets were observed at the radial periphery of the spray. Droplet diameters ranged from 200 to 900 μm , indicating the polydispersed nature of the fuel spray. The mean droplet diameters d_{mean} increased non-monotonically with increasing z up to $z = 40$ mm, suggesting finite and competing droplet collision and coalescence events to form larger droplets (i.e., strong droplet-droplet interactions). Such phenomena were confirmed by direct optical observations. The inter-droplet distance for droplets downstream of $z = 25$ mm was found to be 1200 μm (with a standard deviation equal to 650 μm); the existing sprays were categorized as dense sprays for shorter distances, i.e., $z < 42$ mm.

No significant effect of the bulk air inlet temperature T_{air} on the mean droplet diameter d_{mean} at $z = 20$ m/s was observed within the range of investigated conditions. However, d_{mean} decreased with increasing bulk air inlet velocity U_{air} . Specifically, when U_{air} was increased from 15 to 20 m/s, d_{mean} decreased by about 50 μm . Similarly, d_{mean} decreased when higher liquid fuel injection velocities U_{fuel} were used. Irrespective of U_{fuel} , the droplets for both *n*-heptane and *n*-pentane were smaller when using the smaller perforated plate compared to those generated with the larger perforated plate at otherwise similar air-flow conditions (i.e., T_{air} , U_{air}). The longer and thinner *n*-heptane jets with the smaller perforated plate were found to atomize into smaller droplets, with a d_{mean} of *n*-heptane droplets generated with the smaller perforated plate at $U_{fuel} = 1.1$ m/s being 30% smaller than with the larger perforated plate, while the standard deviation was 40% smaller.

Using linear regression, the empirical correlation $(d_{mean}/d_{jet}) = 34 \times 10^3 We_{\Delta}^{1.29} Re_{\Delta}^{-3}$ was developed for the mean droplet diameters measured in our experimental campaign. This correlation was shown as being capable of predicting the mean droplet diameter within $\pm 20\%$ deviations relative to the experimental data, and was found to be independent of the perforated plates selected and used in the present work.

The results from this work can be used to further our understanding of the two-phase flow physics of atomization in turbulent, high-temperature flows, and for developing and validating computational models of spray formation and two-phase turbulent reacting flows.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

CRediT authorship contribution statement

Ajay Gupta: Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Hongkun Guo:** Formal analysis, Writing – original draft, Visualization. **Ming Zhai:** Conceptualization, Formal analysis, Writing – review & editing, Supervision. **Christos N. Markides:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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