Studies on the effect of air temperature on lean premixed prevaporised turbulent sprays

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Abstract

Lean, partially premixed and prevaporised turbulent sprays of n-heptane/air mixtures are studied experimentally for various temperatures of the coflowing air at ambient pressure. Air temperature is changed by steps of 20 K from 313 K until 393 K. We can change the liquid fuel flow rate and the atomising air flow rate. Measurements are performed for three global equivalence ratios ($\phi = 0.65$, 0.72 and 0.79) and for four atomising air flow rates ($\dot{m}_{AI} = 0.063$, 0.090, 0.115 and 0.140 g/s). For all flames, phase Doppler anemometry (PDPA) is used to characterise the droplet velocities and diameters and to observe the influence of the coflowing air temperature on the droplets in the spray. Laser tomography allows us to visualize the spray.

1. Introduction

Lean premixed and prevaporised combustion appears to be a promising technology in significantly reducing NO_x emissions for a large number of propulsion applications and principally from gas turbines because vaporisation and mixing of fuel and air under lean conditions upstream the reaction zone lead to a low temperature flame which reduces the production of nitrogen oxides [1, 2]. Important physical processes involved in combusting sprays, such as interactions between droplets, between the droplets and the gas phase, the vaporisation of the droplets associated with heat release, are not completely understood because they are all coupled. In order to contribute to the analysis of vaporisation and mixing in partially premixed and prevaporised spray and to build a rather complete data base for model validation, an experimental study of lean premixed prevaporised turbulent spray is conducted at the laboratory.

In a first work we studied lean premixed prevaporised turbulent spray flames for air at room ambient conditions of temperature and pressure [3] and then for various air temperatures [4]. Here we present the influence of the temperature of the coflowing air on the characteristics of the droplets in the spray. The droplet velocity and size distributions are characterised by Phase Doppler Anemometry and the visualization of the spray is realised by laser tomography.

2. Experimental methods

2.1. Experimental facility

A schematic of the burner used for the present study is presented in figure 1. An air-assisted atomizer (plain-jet type, figure 2) of outer diameter 8 mm is placed coaxially at the centre of a square tube of inner diameter 24 mm, downstream of a grid generated turbulent coflowing air. The atomizer exit hole has a diameter of 0.8 mm. At the exit of the burner, an annular premixed methane-air pilot flame is used to stabilize a spray flame.

The distance from the atomizer tip to the burner exit, L_{TE} , may be varied, increasing the residence time of the droplets inside the burner and thus the duration of prevaporisation and premixing. In the present study, we consider only the distance L_{TE} of 160 mm, which corresponds to a residence time close to 18 ms for air at ambient temperature. This is the shorter distance possible to stabilize a flame because below this value, we observe a flashback of the flame.

The burner is mounted vertically on a three dimensional traverse system with vertical and radial displacements. The flow is going upward and is axisymmetric. Liquid fuel is supplied from a pressurised tank (~1.5 bars) and air from a compressor line. Calibrated flow meters are used to measure all flow rates. For this study, we use two different liquid fuels : n-heptane and n-decane but the results presented here concern only n-heptane.

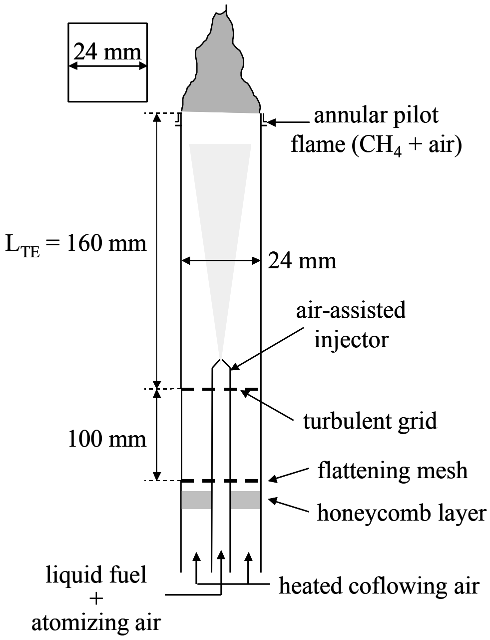


Figure 1. Schematic of the burner.

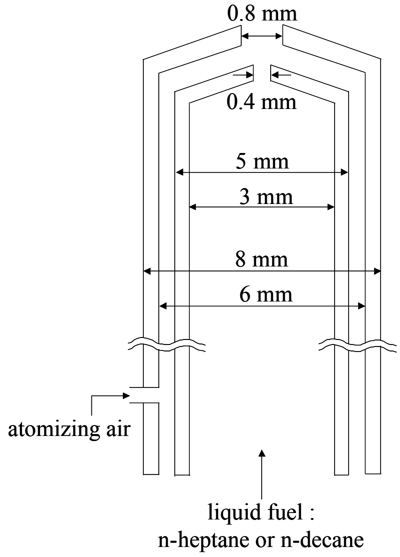


Figure 2. Schematic of the atomizer.

The coflowing air flow rate is maintained constant for all cases (1.98 g/s) but we change the atomising air flow rates to vary the initial spray droplet diameter, and the fuel flow rates to change the global equivalence ratio. The flow rates for each condition studied are shown in table 1, the air to liquid ratio corresponding is indicated in table 2.

$\dot{m}_{liq}$ (g/s)		$\dot{m}_{AI}$ (g/s)			
		0.063	0.090	0.115	0.140
ϕ	0.65	0.088	0.089	0.090	0.091
	0.72	0.097	0.099	0.100	0.101
	0.79	0.107	0.108	0.110	0.111

Table 1. Atomising air and liquid heptane flow rates.

RAL		$\dot{m}_{AI}$ (g/s)			
		0.063	0.090	0.115	0.140
ϕ	0.65	0.72	1.01	1.28	1.53
	0.72	0.65	0.91	1.15	1.39
	0.79	0.59	0.83	1.05	1.26

Table 2. Air to liquid ratios.

We study the influence of the coflowing air temperature by heating the air by the Joule effect. The air temperature is monitored by a K-thermocouple placed at the bottom of the burner. By heating the air, we indirectly heat the liquid fuel which flows through the atomizer. The heptane temperature is estimated by introducing a K-thermocouple inside the tube. The relation between the fuel temperature and the coflowing air temperature is indicated in figure 3 for the two extreme conditions. We mention the temperature of heptane in degree Kelvin on the left axis and this temperature normalised by the temperature of boiling of heptane on the right axis. We see that heating the air significantly changes the heptane temperature. Furthermore the relation is linear between these two temperatures as already observed by [5].

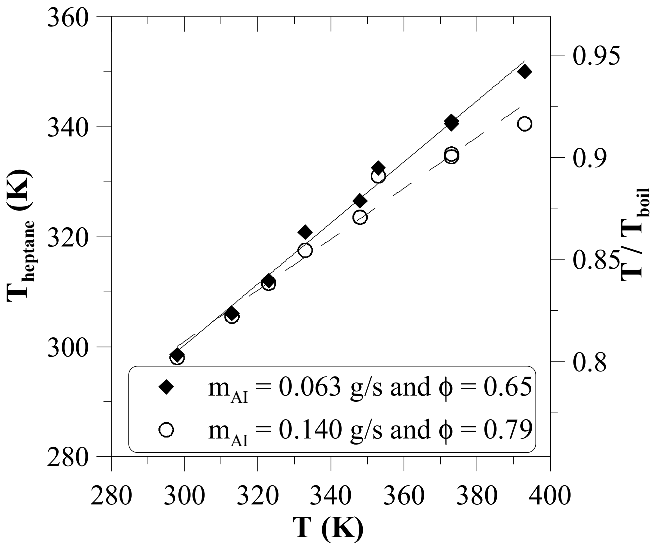


Figure 3 : Relation between fuel temperature and coflowing air temperature.

2.2. Instrumentation

2.2.1. Phase Doppler Anemometry

Simultaneous two-component droplet velocity and size measurements are performed with a TSI phase Doppler anemometer. We don't describe this diagnostic in this paper but further details are available in [4].

2.2.2. Tomography laser

A Nd:Yag laser beam of 4 mm in diameter passes through a convergent and a semi-cylindrical lenses to expand the beam into a collimated sheet. This laser sheet is 160 mm high and 50 µm thin. A colour high speed camera placed at 90° of the laser sheet is used to collect the light scattered by the droplets in the spray (figure 4).

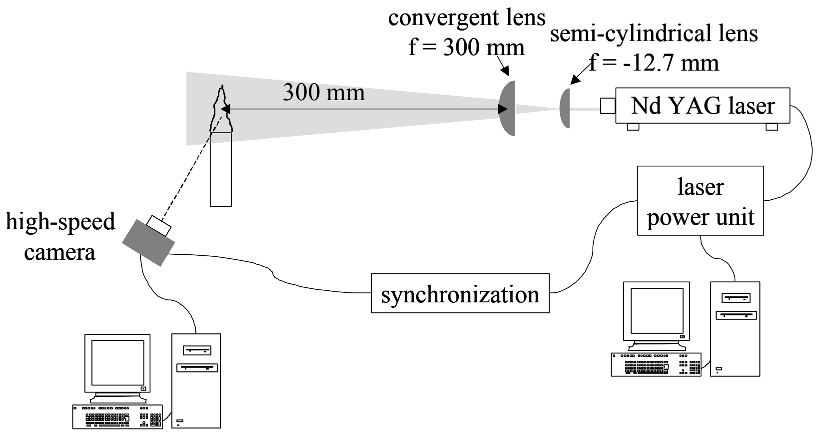


Figure 4 : tomography laser facility layout.

The dimension of the image recorded is 512×256 pixels^2 corresponding to an image of 6.5×3.2 mm^2 ; the acquisition is made with a recording frequency of 6200 images/s. The laser pulse energy varies between 1.5 and 3 mJ depending on the condition studied in order to avoid camera saturation. For all conditions, 2048 images are recorded.

From the measurements by laser tomography, we can determine the spray angle at the atomizer exit and the volumetric fraction of the liquid phase. The spray angle is determined directly from the sum of the 2048 images recorded. The volumetric fraction of liquid heptane is estimated as follow : each image is corrected from the laser beam intensity, an average is realised from the 2048 images, a median filter of 10×5 pixels^2 is applied to this mean image, the volumetric fraction is then obtained. All these treatments are made with the Matlab software.

3. Results and discussion

The influence of the air temperature on the droplet characteristics is presented for a spray of heptane and for an atomising air flow rate of 0.090 g/s and a liquid fuel flow rate of 0.108 g/s, thus an equivalence ratio of 0.79 and an air to liquid ratio of 0.83. The measurements are performed with air temperature between 313 and 393 K. First, we present the results obtained on the atomizer axis from the phase Doppler anemometry measurements.

3.1. Droplets characteristics

3.1.1. Velocities

The mean axial droplet velocities U (figure 5) increase with the temperature whereas the mean radial velocities V remain constant, close to zero. For the axial fluctuating droplet velocities (figure 6), there is an increase with the air temperature whereas the radial component v' is not affected by air temperature. The turbulence is not isotropic since u'>v'.

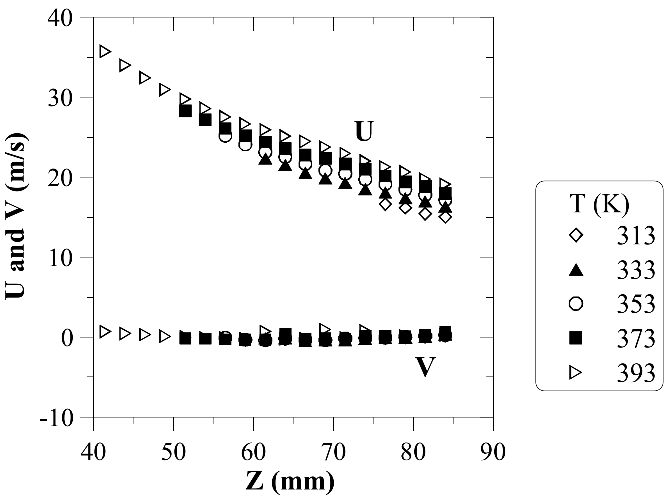


Figure 5 : influence of air temperature on droplet mean velocities.

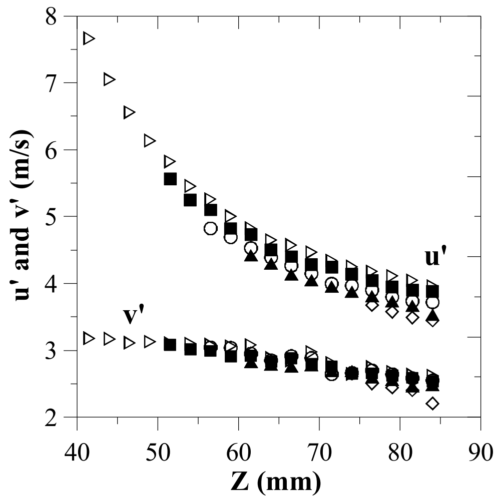
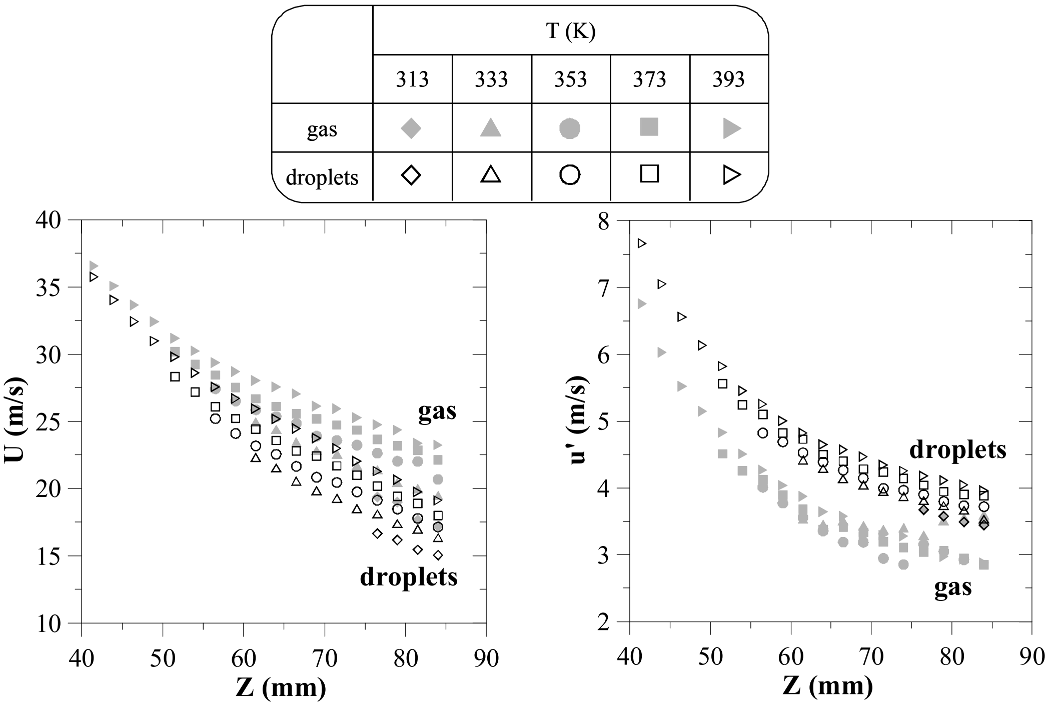


Figure 6 : influence of air temperature on droplet fluctuating velocities.

We can compare the droplets velocities to the gas velocities which can be determined from the droplet with a diameter less than 4 µm. The results obtained are presented in the figure 7. We observe that the gas velocities are higher that the droplets velocities for all temperatures and for each position above the atomizer exit (figure 7a). The difference is between 0.8 at Z ~ 40 mm and 4.2 m/s at Z ~ 85 mm. The droplets velocities decrease more rapidly that the gas velocities. Furthermore, the axial fluctuating velocities are higher for the droplets than for the gas (figure 7b).



(a) mean velocities (b) fluctuating velocities

Figure 7 : comparison droplet / gas.

3.1.2. Droplet diameters

The influence of the air temperature on the mean droplet diameters is presented in figure 8. For the arithmetic diameter D_{10}, the variation is small with the temperature : this diameter lies between 7 and 12 µm. By increasing the temperature, the diameter decreases. The Sauter mean diameter seems to decrease by increasing the temperature but the trend is not well pronounced. This diameters decrease may result from the reduction of droplet diameter caused by vaporisation.

In the literature numerous studies concerned the influence of air temperature on droplets in a spray [5, 6, 7, 8]. These studies consider generally a variation of air temperature close to 100 K and all conclude to a decrease of arithmetic and Sauter mean diameters with temperature increase.

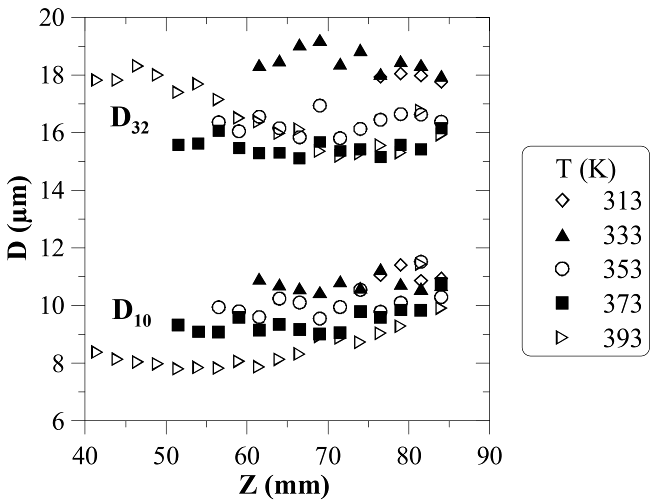
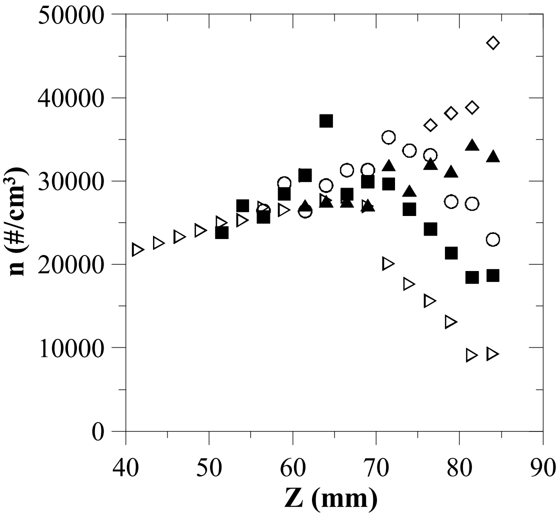


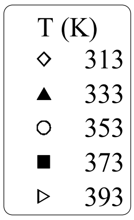
Figure 8 : influence of air temperature on droplet mean diameters.

3.1.3. Droplet number density and volume flux

The droplet number density (figure 9) increases then decreases when we move off from the atomizer exit. This evolution is already observed by [9, 10]. The increase can be explained by the transport of the droplets from the periphery of the spray to it centre. The decrease is due to the droplet vaporization.

When the air temperature increases, the number density (figure 9) decreases above Z = 70 mm, meaning that there is less droplets with hot air. For the volume flux (figure 10), there is also a decrease for all position above the atomizer exit.





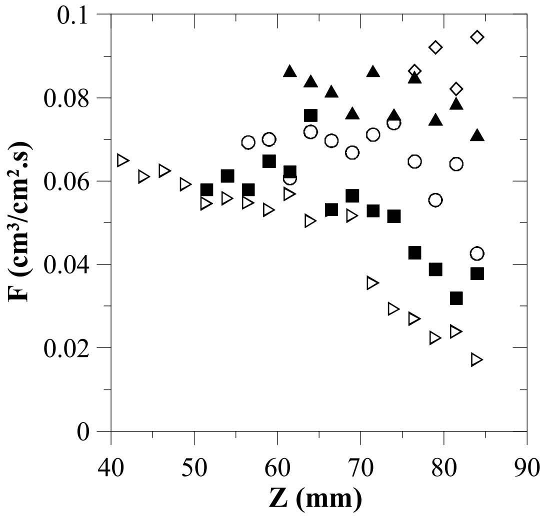


Figure 9 : influence of air temperature on droplet density.

Figure 10 : influence of air temperature on droplet volume flux.

From the droplets distributions, we can obtain the volume cumulative distribution and we can thus determine the span factor which is defined by $\Delta = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}}$ where D_{Vi} is the drop diameter such that i% of total liquid volume is in drops of smaller diameter. We find that the span factor is not significantly influenced by the air temperature.

3.1.4. Percentage of evaporated liquid heptane

From the droplet volume flux, we can estimate the prevaporisation degree of the mixture by the formula $\Omega_{vapour} = 1 - \frac{\dot{m}_{fuel}}{\dot{m}_{fuel\ initial}} = 1 - \frac{\int_{-D/2}^{D/2} F(r)\, r\, dr}{\dot{m}_{fuel\ initial}}$ where $\dot{m}_{fuel}$ is the liquid heptane flow rate in one section (measured value) and $\dot{m}_{fuel\ initial}$ the liquid heptane flow rate initially injected. Figure 11 indicates the prevaporisation degree of the mixture for various air temperatures at various sections above the atomizer exit. When we heat the air the percentage of vapour heptane is more important, indicating that the vaporisation is better.

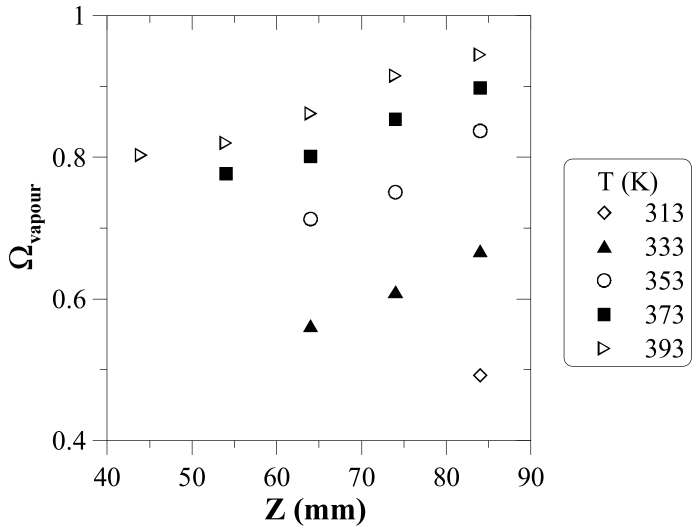
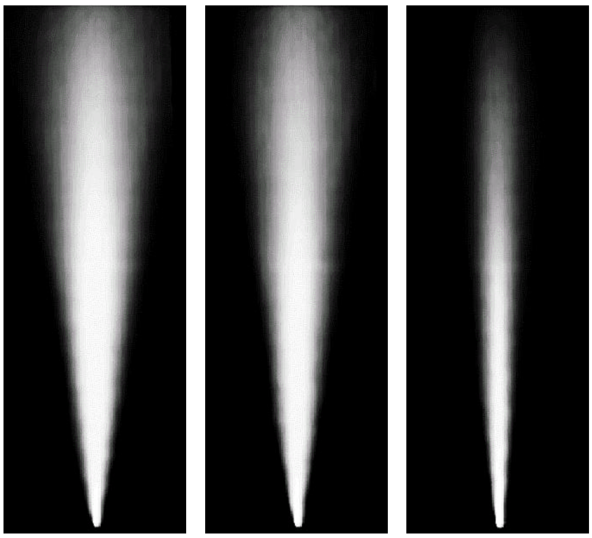


Figure 11 : influence of the air temperature on the percentage of evaporated liquid heptane.

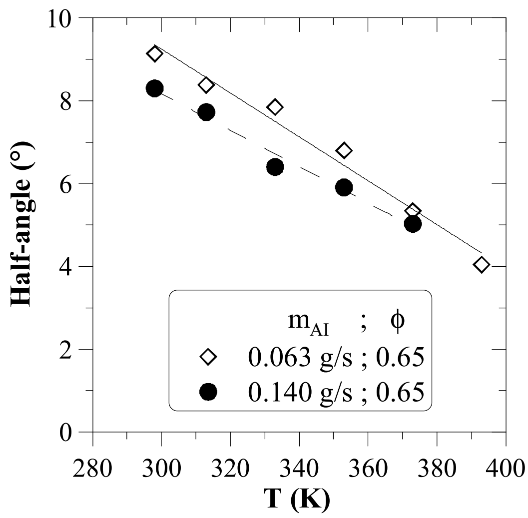
3.2. Spray visualization

From the laser tomography images, we can determine the angle of the spray at the exit of the atomizer. Examples of spray visualization are presented in figure 12a for various air temperatures whereas the values of the spray angle for two conditions are indicated in figure 12b for all air temperatures studied. We find thus that the spray angle decreases when the air temperature increases.



T = 298 K T = 353 K T = 393 K

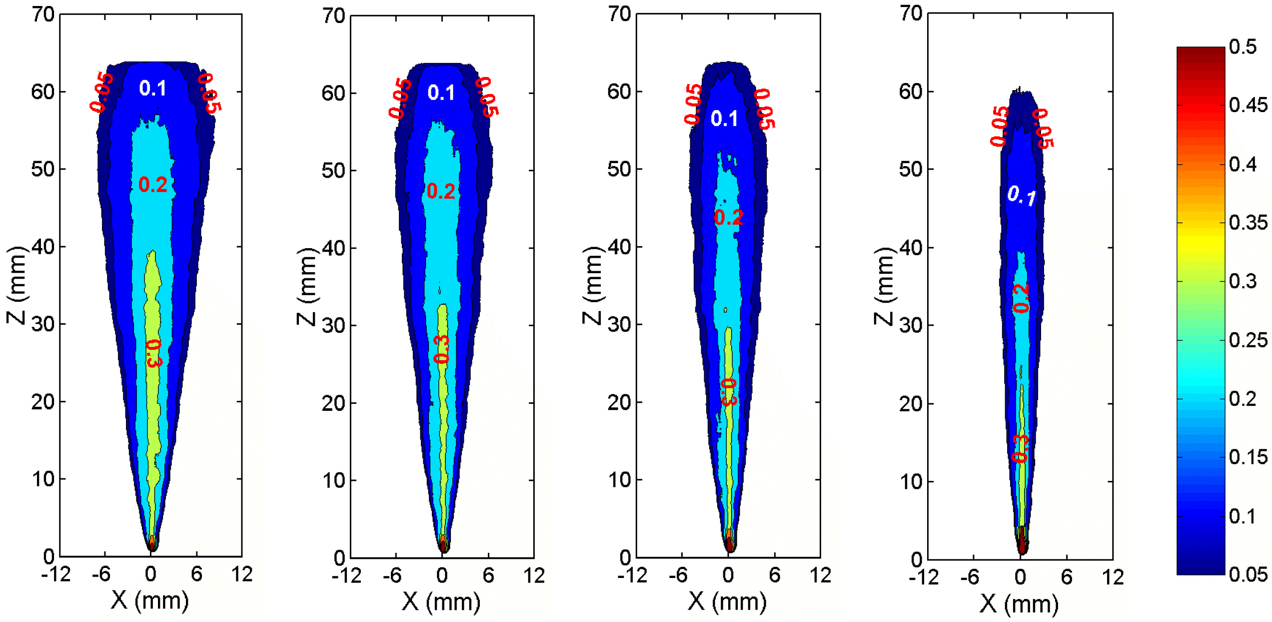
(a) spray visualization



(b) values of spray angle

Figure 12 : influence of air temperature on spray angle at the atomizer exit.

From laser tomography we can also obtain the volumetric fraction of liquid heptane as described above. We present in figure 13 the influence of the temperature on this parameter. We see that an increase of air temperature improves the droplet vaporisation since the volumetric fraction of liquid heptane is lower.



T = 298 K   T = 333 K   T = 353 K   T = 393 K

Figure 13 : influence of air temperature on volumetric fraction of liquid heptane.

4. Conclusions

We have presented a study on the influence of the coflowing air temperature on a lean partially premixed and prevaporised spray of n-heptane/air. The phase Doppler anemometry is used to observe the droplet characteristics in the spray and visualization of the spray is made by laser tomography. The results indicate that an increase of the temperature improves droplet vaporization : decrease of the droplet number density and of the volume flux, increase of the percentage of evaporated liquid and decrease of volumetric fraction of liquid heptane.

5. References

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