DROPLET SIZE AND VELOCITY CHARACTERIZATIONS OF A SUPERHEATED TWO-PHASE FLASHING JET

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ABSTRACT

Liquid flashing phenomena holds an interest in many areas of science and engineering. Accidental releases from a chemical industrial reservoir through a superheated liquid jet are one of these interesting but dangerous examples. This illustrative case will be also the topic of the present study where violent boiling and aerodynamic fragmentation are the key words controlling the disintegration of a liquid jet. The initial, flashing stage of the jet, where the system is furthest from equilibrium is least understood. To investigate theoretically these source processes for design and safety assessments, knowledge of accurate and reliable data such as the distribution of droplet size, velocity and temperature are mandatory.

In the present work, a study on the sensibility of the initial conditions on the two-phase jet characteristics downstream the orifice is presented. The working fluid is a liquefied R134-A experiencing a sudden release from a reservoir. Due to the non-equilibrium nature of the droplets in the region of the release, to conduct an accurate data measurements campaign for droplet size and velocity is a challenging task. In order to fulfil this goal, a laser-based optical technique like Phase Doppler Anemometry (PDA) is used to obtain at the same time distribution of particle diameter and velocity evolution. Sensibility to initial parameters such as pressure, temperature and orifice diameter is studied. A high-speed video camera served to observe the disintegration of the jet giving qualitative information.

1) INTRODUCTION

In many areas of science and engineering, two-phase flows hold a special interest. This is especially true in the safety field where any unexpected event is undesirable. As an example, one can mention the accidental release of flammable and toxic pressure-liquefied gases in chemical or nuclear industry. The failure of a vessel or a pipe in the form of a small hole may result in the formation of a two-phase jet containing a mixture of liquid droplets and vapour. When both violent boiling and aerodynamic fragmentation control the two-phase behaviour, the flow experiences the “flashing phenomenon”. The initial stage of this phenomenon, where the system is furthest from thermodynamic equilibrium is least understood. To investigate theoretically these source processes, models need to be validated with accurate and reliable data such as distribution of droplet size, velocity and temperature. The Commission of European Communities launched a series of projects under the Fifth Framework programme on the understanding of the source processes with emphasis on flashing release of flammable pressurized liquids. The present study takes part in that framework.

The main objective of this work is to assess the influence of initial flow conditions such as liquid storage pressure (called “backpressure” or “driving pressure” hereafter), nozzle diameter and superheat on the spray characteristics after the atomisation. To reach this goal, a non-intrusive technique like Phase Doppler Anemometry is used to collect droplet size and velocity of the droplets when high-speed imaging served to observe the jet disintegration.

Organisation of the paper is the following, after an introductive section, the Section 2 will give description of the experimental set-up and measurement campaigns. The results and discussions based on spray statistics obtained with PDA and high-speed imaging are explained in Section 3. Section 4 describes the conclusions of the experimental results.

1.1) Flashing Mechanism

To experience flashing phenomenon, a liquid should find itself in a state where it enters in thermodynamic non-equilibrium and becomes superheated (i.e. the temperature of the liquid is above the boiling temperature for the pressure that surrounds it). It may be heated to a higher temperature while its pressure is maintained (Case 1) or depressurised rapidly so that its thermal inertia ensures the internal temperature remaining nearly constant and above the saturation temperature associated to the new pressure (Case 2). Under most practical circumstances, the superheated liquid will return to its equilibrium condition through evaporation. Under adiabatic conditions, the vapour to be formed can obtain its latent heat of vaporization only through the superheat of the remaining liquid. If the superheat within the depressurised liquid can be conducted to the liquid surface, the latent heat will be released through surface evaporation. If, however, the heat cannot be conducted at a sufficiently high rate to the surface, evaporation will occur inside the liquid through bubble growth. This process can be extremely violent and explosive. (see [1], [2],

[3], [4], [5] for detailed review). Because of the relatively large vapour pressure of the material, a combination of hydro dynamics instabilities and thermo dynamical non-equilibrium will then lead to break-up into small droplets for maximum surface exchange. Equilibrium will be reached when the fraction of the liquid converted to vapour has extracted enough energy from the residual liquid.

Many researchers have conducted studies on the flashing process of a liquid jet and the measurements along the area where the liquid disintegrates to gain thermodynamic equilibrium have been reported as optically very challenging. Many of earlier drop size measurements reported, involved the use of photography ([1];[6]) or light scattering techniques such as the diffraction methodology in the form of Malvern Particle Analyzer ([7],[8]) or Phase Doppler Anemometry ([9]; [10]). Brown and York [1] conducted a study on the behaviour of superheated water and Freon 11 jets in atmospheric conditions, employing different forms of nozzles. Miyatake et al.[11] performed measurements on a superheated water jet issuing from a circular tube nozzle into a low-pressure environment. The effects of superheat degree, flow rate and nozzle diameter on spray flashing were investigated. Peter et al. [3],[4] studied the different shattering patterns of superheated water released in a low pressure region and tried to provide temperature and droplet size distributions with the influence of superheat, pressure and nozzle type. Balachandar et al. [9] provided radial mean velocity and droplet size profiles for superheated water at two different axial locations for a single initial condition. Hervieu and Veneau [10] undertook measurements on an example of large-scale blow down of a LPG release addressing the flashing problem. They provided pressure, temperature evolutions in the vessel during blow down and droplet size-velocity evolutions of the two-phase jet with effects of nozzle diameter and initial pressure. Allen [8] used a modified Malvern system to characterize flashing propane releases and provided relative droplet size profiles and their variations for qualitative discussions of the jet characteristics. However, it is stated that quantitative accuracy requires improvement, and indicate that alternative droplet size methodologies may prove successful. Lately, Gemci et al. [12] conducted a study on the flash atomisation of a hydrocarbon solution containing n-hexadecane and n-butane. Nitrogen was used as propellant gas. They studied the break up patterns and spray characteristics with the effect superheat, butane concentration and nitrogen flow rate.

2) EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUES

2.1) Test facility

Fig. 1 shows the experimental installation, which allows the pressurization of liquid R134-A under different pressure values. The liquefied R134-A is stored at a pressure above its vapour pressure corresponding to the ambient temperature (i.e. 6.6 bars at 25°C). Nitrogen gas is introduced into the R134-A tank to control the driving pressure. A pressure transducer monitors the pressure history in the tube connecting the R134A and N2 tanks. At the connection with the R134-A tank, a two-entrance valve allows pressurization with N2 (in) and flow of R134-A (out) simultaneously. The liquid R134-A flows from the tank through a horizontal tube. At the end of this tube, a pneumatic ball valve system is installed and it is operated using pressurized air. A thermocouple is introduced in the tube to measure the temperature of the liquid R134-A before the exposure to the ambient. Different nozzle geometries can be mounted on the pneumatic valve.

2.2) Measurement campaign

The high speed imaging campaign helped to understand the break up process of the two-phase flashing jet. The changes in the flow patterns were observed with the changing initial parameters such as nozzle diameter and superheat. The test conditions are presented in Table 1. The backpressure is the storage pressure of the liquid R134A in the vessel and the superheat is defined as the difference between the initial liquid temperature and the boiling temperature at the final atmospheric pressure.

Table 1 Test conditions for high-speed imaging

Test no	Nozzle diameter (mm)	Superheat (ºC)	Back pressure (Bars)	Frame rate (Images/sec)	Exposure time (µsec)	Image size (pxl(H) x pxl(V))	Pixel /mm
1	1.00	43.4	8.2	32700	10	480x120	3
2	2.00	43.4	8.2	38400	10	608x80	3
3	4.00	43.5	8.2	33300	10	256x200	4
4	1.00	47.9	9.42	40000	5	512x64	4
5	1.00	49.8	8.86	40000	5	512x64	4

The droplet size and velocity measurements of the spray were acquired thanks to Phase Doppler Anemometry (PDA) technique. It allows the simultaneous measurements of the velocity and the size of the particles (in present case of the droplets). For transparent particles, light scatter at 30° in the forward direction is dominated by refraction. The receiver off-axis angle may change of about +/-2° introducing an error in the droplet size estimation up to 3 % ([13]). Considering the difficulties met in this flow (very dense flow, droplets with high non-sphericity, liquid ligaments etc.) this error is considered as negligible. Before taking the measurements, the optimum values of three of the PDA parameters (diameter range, velocity range and photo multiplier high voltage) had to be selected. For this purpose, preliminary runs were performed aiming to cover the diameter and velocity ranges of the most representative droplet population with both the highest acquisitions (events/s) and validation rates. Thus measurements ranges (10.33µm-377.3µm) and (0.27m/s-28.41m/s) were found to be reasonable. In this article, the radial direction stands for the

"Y" direction sketched on Fig.1. Present authors are aware that gravity may play a role in vertical radial profiles. Such measurements will follow in a future communication.

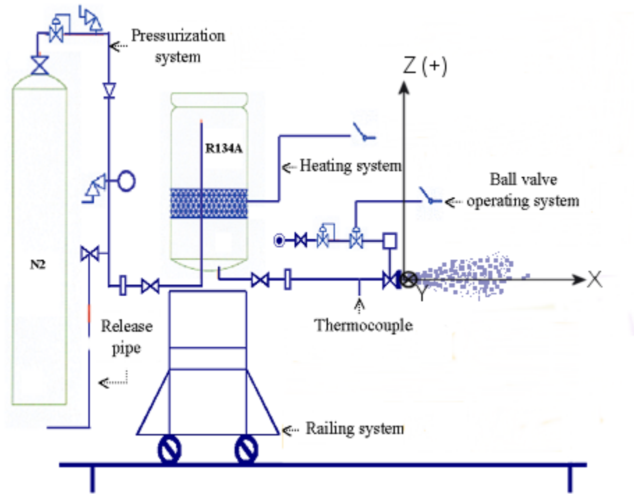

Fig. 1 The experimental facility

3) RESULTS AND DISCUSSIONS

3.1) Spray Characteristics

Spray characteristics are obtained by means of Phase Doppler Anemometry (PDA) at relatively far fields in axial distance. The high rejection rate of data due to the existence of liquid core, ligaments and non-spherical droplets pushes the measurement probe volume away from near nozzle region. For a jet issuing from a 1 mm nozzle with a driving pressure of 7.15 bars and a superheat of 46.5-47.0ºC, the variation of the arithmetic (D_{10}) and Sauter (D_{32}) mean diameters along the radius is given on Fig. 2 (left) for two axial stations (x/D=187 upstream and x/D=507 downstream). The radial velocity distributions for the same conditions are displayed in Fig. 2(right). The mean values are obtained over 20000 droplets. At both axial distances, the droplet sizes and velocities are larger on the axis and they decrease in the radial direction. The droplet sizes and velocity mean values decrease going further from the nozzle. Similarly, Reitz [6] was able to observe that the jet has a core region consisted of big droplets and a surrounding fine spray region. Balachandar et al. [9] found a similar trend in the arithmetical mean droplet diameter and velocity evolutions along the radius but they found an opposite behaviour concerning the evolution of Sauter mean diameter evolution along the axial distance. They indicated that the Sauter mean diameters are increasing moving further from the nozzle. However, one has to keep in mind that the compared measurement points for the case of Balachandar et al. [9] were at x/D=800 and x/D=2400 which are far downstream from the measurement points presented on Fig. 2. Disappearance of a large percentage of small particles by evaporation may explain their observation.

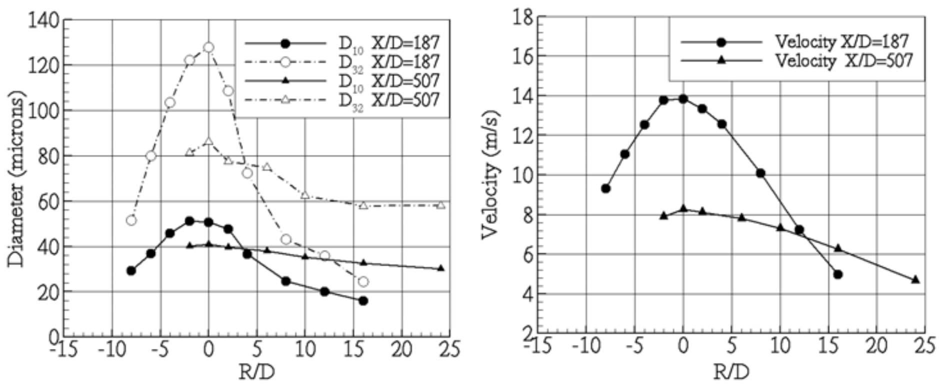

Fig. 2 Droplet size (left) and velocity (right) distributions at x/D=187 and x/D=507, z/D=-1

3.2) Effect of the orifice diameter on distributions

Brown and York [1] studied the effect of nozzle geometry and superheat on break up patterns of superheated water jets at atmospheric conditions. For the same superheat and driving pressure, they observed that disintegration due to flashing occurs as sudden explosions for the jets exiting from larger sharp edged nozzles at distances differentiating from 2.5 to 12.5 L/D downstream whereas for the smaller nozzles the disintegration is further downstream and in a manner that cuts the jet into distinct sections with a slower disintegration. Peter et al. [3] found out that a superheated water jet exposed to a vacuum chamber through a cylindrical nozzle with larger inner diameters experiences flashing phenomena more easily than the ones with smaller inner diameters. The high-speed measurements, which are subject to the present work, support these observations. Based on Fig. 3, it is observed that the jet exiting from larger nozzle diameters presents a more violent break-up than the smaller ones for the same backpressure and superheat. Additionally, the disintegration of larger jets appears closer to the nozzle.

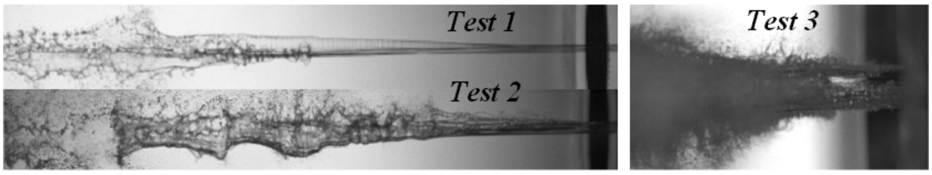

Fig. 3 High-speed image sequences for "Test 1: nozzle diameter 1 mm", "Test 2: nozzle diameter 2 mm" and "Test 3: nozzle diameter 4 mm"

According to Brown and York [1] smaller jet diameters seem to give bigger droplets diameter when the superheat and driving pressure were kept constant. On the contrary, Hervieu and Veneau [10] observed bigger droplet diameters for bigger nozzles if the absolute distance from the nozzle, driving pressure and superheat are kept constant. By looking at the radial evolution of droplet size and velocities at a distance of X/D=110 for jets initiated from 1 and 2 mm nozzles presented in Fig. 4, an increase in the droplet diameters with increasing nozzle size is seen. No significant change is observed on the velocity for the presented tests the superheat was kept between 46.6-47.2ºC and driving pressures were in the range 7.6-8.0 bars.

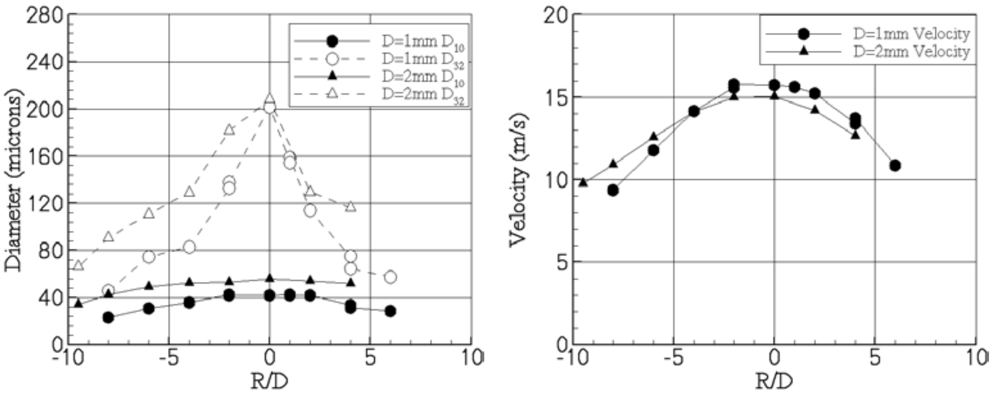

Fig. 4 Effect of the nozzle diameter on the droplet diameters (left) and velocities (right) at the same absolute axial distances from the nozzle)

3.3) Effect of the temperature on distributions

Previous studies have shown that even very small changes in the superheat may change the break-up pattern drastically when the superheat effect on the jet break-up is concerned ([1], [3], [11]). Brown and York [1] observed that an increase of superheat with a narrow range of 5ºF (~2.8ºC) may provoke shattering of the jet due to flashing from an initial state where there is no effect of temperature. Miyatake et al. [11] noticed that with the increase of superheat flashing process becomes more violent and the liquid column near the nozzle exit becomes shorter. In the study of Peter et al. [3], the disintegration of the jet is defined in four different pattern as "non-shattering" (liquid column preserved for extended distances and non-dispersed ligaments falling parallel to the liquid core), "partially shattering" (liquid column retained in the centre and droplets shatters only from the sides), "stage wise shattering" (complete shattering after a distance downstream) and "flare flashing" (complete disintegration of the jet at the nozzle exit). They observed that an increase of ~10ºC in superheat transforms the non-shattering jet into stage-wise shattering jet and the transition from partially shattering to stage-wise shattering pattern may happen in a band of ~7ºC. Gemci et al. [12] also reported that the primary break-up length and ligaments get shorter upon increasing the superheat.

The high speed images presented in this study show the behaviour of the jet with superheat increment up to 6.4 ºC. Observing the jet exiting from the nozzle of 1 mm diameter with the lowest superheat (i.e. superheat=43.4ºC (Fig. 5-top: test 1)), a slow expansion downstream the nozzle is noticeable. From time to time, a group of bubbles growing very rapidly shatters the jet violently and locally. Applying a superheat increase of 4.5ºC (i.e. superheat=47.9ºC, Fig.5: test 2) generates an increase in the numbers of bubbles appearing all over the jet and breaking the jet gradually downstream with an apparent and intact liquid core at distinct sections. A further increment of 1.9ºC (i.e. superheat=49.8ºC, Fig.5: test 3) leads to complete shattering of the jet and a spray-like behaviour.

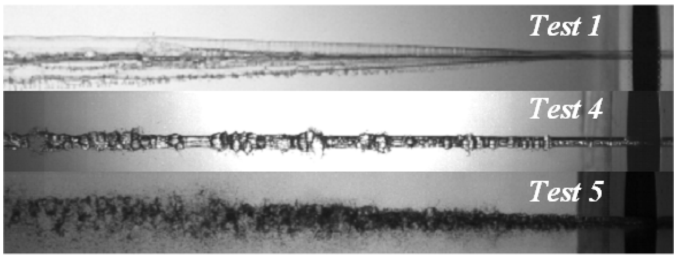

Fig. 5 High-speed image sequences for nozzle diameter of 1 mm "Test 1: superheat=43.4ºC", "Test 4: superheat=47.9ºC" and "Test 5: superheat=49.8ºC"

High-speed camera images have illustrated that even a narrow superheat increment such as ~2ºC may lead to significant changes in the break-up patterns. To investigate the influence of this small superheat increment on the mean droplet sizes and velocities, Fig. 6 displays the radial droplet size and velocity evolution of the jet issued from a 1 mm nozzle at x/D=187 for similar superheats presented in Fig. 5 (the location x/D=187 is more downstream than Fig. 5 where it is clearly seen that PDPA measurements are impossible). We can see that the smaller superheat leads to a radial distribution having a higher arithmetic mean diameter (D_{10}) at r/D=0 than the one of the higher superheat. The envelope of the spray at this axial position presents an expansion in radial distribution for increasing superheat. The expansion may result in a shift of some big droplets towards the radius (opening of the spray) and may explain why the arithmetic mean diameter (D_{10}) and Sauter mean diameter (D_{32}) show an opposite behaviour in the periphery than the centre for increasing superheat. The effect of this slight increase of superheat does not create a change in the velocity on the axis of the jet. The velocity change for the radial profile of the external part of the jet is due to jet expansion and higher presence of big droplets. Because the velocity distribution does not show a significant change, the differences in diameter distribution may be explained only by an atomisation process due to a higher production of bubbles than due to aerodynamic break-up effect. Brown and York [1], Peter et al. [3] and Gemci et al. [12] also observed a decrease in the mean diameter size with increasing superheat at constant capsule pressure.

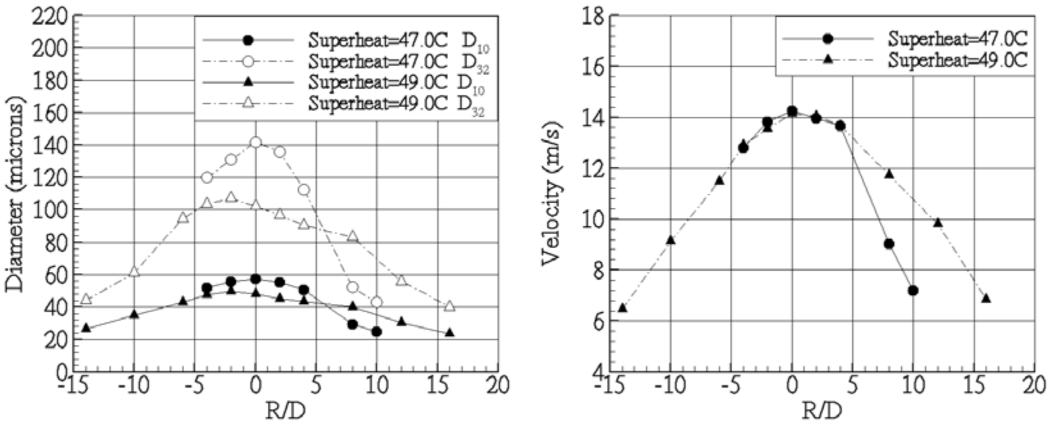

Fig. 6 The effect of superheat on droplet size and velocity evolution for 1 mm nozzle (Backpressure=7.0-7.5bars, x/D=187) in horizontal direction, z/D=-4

3.3) Effect of the pressure on distributions

To understand the effect of pressure on the flow characteristics, radial profiles for the jet initiated from a 1 mm nozzle has been provided for far field measurements. Three different pressures such as 7.10 bar, 10.15 bars and 12.20 bars were used. To increase pressure without changing the superheat (47.0ºC-47.7ºC), N_2 was injected. Measurements were conducted at x/D=187 downstream the nozzle. In Fig. 7, the evolution of the averaged droplet diameters (D_{10} ad D_{32}) (left) and the mean velocity (right) with increasing pressure was displayed. The droplet sizes decreases with pressure increment and this effect may have a bigger effect on the centreline than towards the periphery. Brown & York [1] and Hervieu & Veneau [10] reported a decrease in droplet diameter with increasing pressure, as well. The velocity profile shows a shift towards higher values, as expected, without changing the distribution pattern. At the periphery, the pressure does not influence the droplet sizes. The velocity shows a shift towards higher values with pressure increase, as expected.

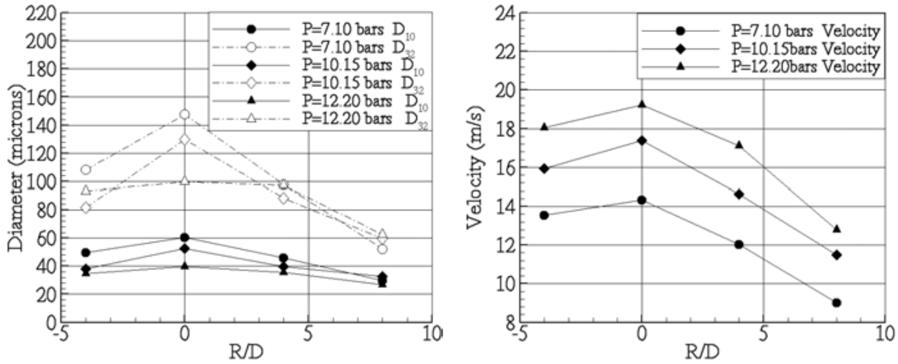

Fig. 7 The droplet size and velocity evolution for 1 mm nozzle in the horizontal radial direction with increasing pressure, z/D=-4

4) CONCLUSIONS

The effect of different initial pressures, temperatures and orifice diameters on the droplet size and velocity distributions of a flashing R134A jet along the radial and axial directions are studied by means of high speed imaging and Phase Doppler Anemometry (PDA). It is shown that, the droplet sizes and velocities are larger in the centre and they decrease towards the sides. The droplet sizes and velocity mean values decrease going further from the nozzle due to evaporation and the jet becomes wider. It seems that the larger nozzle leads to slightly bigger mean diameters (D_{10} and D_{32}) in the far field without influencing the velocities. PDA measurements taken in the far field indicate that the droplet diameters are decreasing with increasing superheat at the centreline for the same driving pressure. The envelope of the spray at this axial position presents a wider radial distribution for higher superheat. On the contrary, velocity does not seem to change significantly with the superheat if the driving pressure is kept constant. When the measurements are done with the same superheat but different pressures, it is observed that the droplet sizes decreases with increasing pressure with a more important influence on the centreline than towards the periphery.

5) ACKNOWLEDGEMENTS

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