UNDERSTANDING OF DYNAMICS OF A TWO-PHASE FLASHING JET USING MULTI-INTENSITY-LAYER PIV AND PDA

D. Yildiz, R. Theunissen, J.P.A.J. van Beeck, M.L. Riethmuller

von Karman Institute for Fluid Dynamics
Chaussée de Waterloo 72, B-1640 Rhode-Saint-Genèse, Belgium
(32) 2-359.96.11 (Phone) ; (32) 2-359.96.00 (Fax) ; yildiz@vki.ac.be

ABSTRACT
Two-phase flows hold an interest in many areas of science and engineering. In the safety field, one such topic is the accidental release of flammable and toxic pressure-liquefied gases. In case of such a release, a flashing vapor explosion takes place resulting in a very dense two-phase cloud. In particular, if the released substance is flammable, this cloud can be combustible and can lead to deflagration or detonation. For understanding the source processes of flashing and risk assessment, data related to cloud characteristics (i.e. droplet size, velocity, temperature) is needed especially in the near region of the release. Due to the non-equilibrium nature of the near field regions accurate data measurement is not possible with intrusive techniques. Therefore, laser-based optical techniques like Particle Image Velocimetry (PIV), Particle Tracking Velocimetry and Sizing (PTVS), Phase Doppler Anemometry (PDA) present the only possibility to obtain information for particle diameter and velocity evolution in this harsh environment. The main object of the present work is to assess the velocity field distribution in a two-phase flashing jet of R-134A by using PDA and PIV. An attempt was made to measure the velocity of different droplets classes using Multi-intensity-layer PIV. In terms of velocity field, the comparison between PIV and PDA is good, even in very dense regions. In these regions, Multi-intensity-layer PIV does not increase the accuracy due to the speckle like particle pattern.

1. INTRODUCTION
Two-phase flows hold an interest in many areas of science and engineering. In the safety field, one such topic is the accidental release of flammable and toxic pressure-liquefied gases; the failure of a vessel or pipe in the form of a small hole results in the formation of a two-phase jet containing a mixture of liquid droplets and vapor. These droplets are generated by flash boiling (boiling violently because a droplet is above the boiling point in ambient pressure) and aerodynamic fragmentation. Of specific interest in this area are the mathematical models and predictive computer codes, which may be applied to such releases. It is hoped that these models will embody the adequate understanding of the processes involved, and may be used in designing and assessment to improve transport and storage design, site location, layout and other safety features. Experimental data on size and velocity distribution of the droplets are required to make an accurate prediction of the likely consequences of any given two-phase release from known initial storage conditions. Due to the non-equilibrium nature of the near field regions accurate data measurement is not possible with intrusive techniques. Therefore, laser-based optical techniques like Particle Image Velocimetry (PIV), Particle Tracking Velocimetry and Sizing (PTVS), Phase Doppler Anemometry (PDA) present the only possibility to obtain information for particle diameter and velocity evolution in this harsh environment.

2. FLASHING MECHANISM
When a liquid is at a temperature above the saturation temperature for its pressure, it is superheated and is out of thermodynamic equilibrium. In a static situation and under carefully controlled conditions (pure substance, perfectly clean and smooth vessel and no physical disturbances) it is possible for a liquid to be maintained in this meta-stable state. Under most practical circumstances, however, the ideal conditions cannot be met and the meta-stable liquid will return to its equilibrium condition through evaporation, thus releasing its superheat as latent heat.

Thermal non-equilibrium is necessarily present in flashing situations. Under adiabatic conditions, the vapor formed can obtain its latent heat of vaporization only at the expense of the sensible heat of the remaining liquid. A liquid at its saturation temperature and pressure can gain superheat in one of two ways: it can be heated to a higher temperature while its pressure is maintained, or it can be depressurized rapidly so that its thermal inertia ensures the internal temperature remains nearly constant and above its new saturation temperature. In the former case, the higher temperature will be at the interface of the liquid and its
surroundings, and evaporation, when it occurs, will be at the interface. In the latter case, the highest
temperature will be inside the liquid and evaporation will tend to be from within.

As stated by (Owen and Jalil 1991), 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 within the liquid through bubble
growth. This process can be extremely violent and explosive. Because of the relatively large vapor pressure
of the material, a combination of fluid dynamics and thermodynamics instabilities will then lead to break-up
into small droplets. Figure 1 shows a general view of a two-phase flashing jet. Equilibrium will be reached
when the fraction of the liquid converted to vapor has extracted enough energy from the residual liquid.

![Figure 1 A general view of the two-phase flashing jet](image)

The initial, flashing stage of the jet, where the system is furthest from an equilibrium is least understood and
there is a need for accurate and reliable data in order to generate and/or refine useful mathematical models
and computer codes. Due to the non-equilibrium nature of the near-field regions accurate data measurement
is not possible with intrusive techniques such as thermocouples. Non-intrusive methods, such as laser-based
techniques present the only possibility for obtaining accurate data measurements in this environment.

This paper represents experimental work undertaken in order to obtain an indication of the velocity in a two-
phase flashing jet using PIV and PDA. The use of multi-layer PIV was tested and compared to data obtained
by PDA. A pressurised bottle of R-134A was used to do the measurements at different distances from the
nozzle.

3. EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUES

3.1 Facility of PDA measurements

The experimental investigation consists in the study of a horizontal flashing two-phase R134a jet. The flow
was generated by a pressurised bottle under 6.63 bars at 25°C containing liquid R-134a (1,1,1,2 –
Tetrafluoroethane: CF₃-CH₂F). In order to be able to repeat the experiments the nozzle of the bottle was
connected to a pressure transducer, calibrated with a water manometer. The preliminary measurements of
the spray characterization were performed by using Phase Doppler Anemometry (PDA). This technique
allows the simultaneous measurements of the velocity and the size of the particles, in present case of the
droplets.

The operational principle of this non-intrusive technique is measuring the scattered light by a particle. The
PDA consists of a laser beam emitter and receiver optics. The probe volume is the crossing of the laser beam
of the emitter. The intersection of the two beams produces a fringe pattern. The scattered light of the particle,
crossing the probe volume is originating from the far field interference produced by the laser beams. The
light emitted by the droplet is detected by a photo-multiplier. The signal is a Doppler signal for which the
period between two peaks corresponds to the time necessary for a particle to move from one fringe to the
next. The knowledge of this distance, which is a function of the wavelength of the beams, allows the
computation of the component of the velocity perpendicular to the fringe pattern. The particle diameter is
deduced from the curvature of the beam which is the function of the phase between two signals recorded
along two different positions. This measurement technique considers the droplet to be spherical. The relation
linking the curvature of the beams (thus the diameter) of the particle with the phase shift of the signals is an
analytical expression (geometrical optics) which is used for the data acquisition and processing software.
This relation depends upon the angular position of the photo multiplier and the diffusion mode chosen: light
reflected by the surface of the particle or scattered, coming from the inside of the particle if it is semi-
transparent, as it is the case for the droplet in air. These input parameters have to be considered and adjusted
before data acquisition.
Figure 2 shows the view of the set-up used for the PDA droplet size and velocity measurements. The measurements were taken in the centerline along the jet axis. The measurements were performed at 30° forward scattering mode placing the emitter and receiver optics as shown in Figure 2.

![Figure 2 The R134a reservoir and PDA instruments](image)

3.2 Facility used for the PIV measurements

The PIV measurement chain is composed of

- A double pulse YAG laser (wavelength 532nm and pulse duration of 5 ns) firing up to 200 mJ per pulse at a frequency $f_{\text{YAG}} = 8.2$ Hz for our experiments; the laser sheet illuminates a meridian (vertical) plane of the flow;
- A signal generator “Agilent” which was used as a ‘master’ to generate signals,
- A multi-channel delay generator of Stanford type which was triggered externally,
- A PCO fan-cooled 12-bit (4096 gray levels) digital camera, having a full field resolution of $(1280 \times 1024) \text{px}^2$ acquiring images from an angle of 90° with the laser
- A PC with frame grabber and acquisition program Sensicam allowing to acquire series of 25 pairs of images at a frequency equal to the half of the frequency of the YAG laser: $f_{\text{acq}} = 4.12$Hz
- Seeding for the measurement was provided by the liquid R134a droplets in the jet, and/or the presence of water vapor droplets created by the cooling effect of the jet on the co-flowing ambient air.

The measurements are taken along the jet axis. The droplets of the two-phase jet are illuminated by the doubled cavity pulsed Nd: Yag laser. The laser beam is formed in a laser sheet of about 0.27mm thickness in the test section. The pulse separation is adjusted according to the measured velocities varying from 0.5 µs to 30µs. Figure 3 gives a view of the synchronization-data acquisition system (a), R134a reservoir and optics (b) used for the PIV measurement campaign.

![Figure 3 Set-up used for PIV measurements](image)
The minimum $\Delta t$, between two frames of the PCO camera is 290ns. The integration time of frame 1 is $155\mu s$ (time for the charging of the pockel cells of the laser), while the integration time for the frame2 is fixed. With a Stanford type delay generator, it was observed that the minimum pulse separation was $2\mu s$. To go below that, it was decided to use an “Agilent” type of signal generator to have a proper synchronization. This equipment was used as master and produced a signal that was sent to both the camera and the “Stanford”. To check the conditions in which both equipment should work, the output signals coming from the signal generator and the “Stanford” were firstly connected to an oscilloscope. Figure 4 show the sketch of the synchronization system and Table 1 gives the settings of the signal generator and Stanford box.

![Figure 4 The synchronization mechanism](image)

**Table 1 Settings of the “Stanford” and the “Agilent” Signal Generator**

<table>
<thead>
<tr>
<th>“Agilent” Signal Generator</th>
<th>“Stanford”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier wave: squared</td>
<td>Trigger: external</td>
</tr>
<tr>
<td>Carrier frequency: 3.00 kHz</td>
<td>$A = T+0.0000181$ sec</td>
</tr>
<tr>
<td>Amplitude: 2 Volts peak to peak</td>
<td>$B = A+0.000155$ sec</td>
</tr>
<tr>
<td>Offset : 1V</td>
<td>$C = A+\Delta t$</td>
</tr>
<tr>
<td>Burst rate : 8.2 Hz</td>
<td>$D = C+0.000155$ sec</td>
</tr>
<tr>
<td>Burst count: 1 cycle</td>
<td></td>
</tr>
<tr>
<td>Burst phase: 0</td>
<td></td>
</tr>
</tbody>
</table>

The PCO camera was working in double short mode, with a frequency of 4.12 Hz. The measurement area in pixels was 1280 pixels in the horizontal direction and 1024 pixels in the vertical direction, using the full resolution. A 20mm ring and 35mm objective were added to the camera.

PIV measurements are performed at different positions covering the area close to the nozzle where the information related to the source processes of flashing phenomena is more crucial. The digital PIV images are processed using the cross-correlation algorithm WIDIM (Window Displacement Iterative Multigrid) developed at VKI by (Scarano and Riethmüller, 1999). This algorithm is based on an iterative multigrid predictor-corrector approach, where the displacement field obtained on a coarse grid at the step $i$ is used as a predictor for the computation of the corrected displacement field on a finer grid at the step $i+1$. This allows to partially get rid of the coupling resolution/accuracy that would otherwise limit the spatial resolution of the measurement. Furthermore, the sub-pixel displacement of the interrogation window allows to avoid the peak-locking phenomena. Finally, the interrogation windows are deformed to account for the velocity gradient. In our measurements, the initial image has 1280(H)x1024(V) pixels and the initial windows size is 128x128 pixels. The number of refinement steps and therefore, the size of final window and the number of vectors determined, depend on the seeding density. The velocity uncertainty is mainly associated with the uncertainty in determining the particle image displacement, which is less than a tenth of a pixel.
4. EXPERIMENTAL RESULTS

4.1 PDA Results

It was observed from PDA measurements that there is a wide range of droplet size distribution and these droplets receive different light intensities. Figure 5 shows the velocity profile at the centerline along the jet axis. It shows that the velocity increases going further away from the nozzle, due to the explosive character of the flashing jet. From a certain distance on, the velocity decreases as in an ordinary spray, due to air entrainment.

Figure 6 shows the droplet size evolution in comparison of $D_{32}$ (average droplet diameter computed by the ratio of the total volume to total surface area of the total droplets at that measurement point) to $D_{10}$ (the arithmetic mean value of the droplet diameters). It can be seen that close to the nozzle the values of $D_{32}$ and $D_{10}$ differ from each other, whereas they approach to each other moving further away from the nozzle. This different behavior can be explained as the flow shows a poly-dispersed character close to the nozzle and becomes mono-dispersed further away. Near the nozzle, there are liquid ligaments and large droplets, which are superheated. They continue to break up and/or evaporate going further from the nozzle creating an expansion region. At about 10 cm from the nozzle, they slow down with distance due to the entrainment of air.

![Figure 5 Axial centerline velocity profile along the jet.](image1)

![Figure 6 Centerline droplet size evolution along the jet axis](image2)

4.2 PIV Results

The PIV measurements were taken along the jet axis, the laser beam aligned with the centerline. The flow was investigated at a position near the nozzle, 5 cm further from the nozzle and 7 cm far from the nozzle. Figure 7 shows the camera positions at different axial distances.

![Figure 7 Camera positions at different axial distances.](image3)
It should be noted that two-phase flashing jets, as studied here and in the literature (Hervieu and Veneau, 1996), (Allen 1998a), (Allen 1998b) present an optically harsh environment. The density of the jet is very high and steep density, velocity and temperature gradients exist within it. This poses many problems including high beam attenuation, strong ambient backscatter and potential beam path distortion. Even for the most sophisticated optical technique this can lead to inaccurate measurement or, at the extreme, an inability to acquire any data at all in certain regions.

Figure 8 shows PIV images at different camera positions: at the nozzle (8a), at a position where the axial position 5-7cm from the nozzle could be measured (8b), and at an axial position where the camera sees the field between 7-9 cm from the nozzle (8c). Close to the nozzle, there are a high amount of liquid ligaments, large droplets and speckle patterns observed. As seen in the image, the seeding is very high. Looking at the image corresponding to the region situated from x=5cm to x=7cm downstream of the nozzle, it can be said that there are smaller droplets. Moving to the measurement location situated from x=7cm to x=9cm downstream the nozzle provides an optically easy environment, where the seeding is moderate, the droplets can be easily observed and speckle behavior almost disappears.

Processing was done using an initial-window-size of 128 by 128 pixels and 1 refinement (final window size 64(H)x64(V)). The instantaneous vector field shows very complex behavior whereas averaging over 25 images smoothen the results, as expected. Applying smaller window-sizes than 128 by 128 pixels do not lead to better results, on the contrary. The effects are visible especially when the vector-field is depicted. Close to the nozzle, PIV gave good results measuring only the velocity of ensembles of droplets that optically could not be separated from each other. Secondly, a flashing jet is a two-phase flow, meaning that both vapour, i.e. gas, and droplets of liquid appear in the same frame and in the same image regions with high and low particle density. Correlation of smaller and bigger particles in high and low density regions together may also lead to lower values of the Signal-to-Noise-Ratio (SNR). Figure 9 shows the averaged Signal-to-Noise-Ratio distributions on these three positions. Close to the nozzle (Figure 9), there is low Signal-to-Noise-Ratio (majority between 1.4 to 1.60). Despite the speckle type image, the results are quite promising. At the location from x=5cm to x=7cm downstream the nozzle (Figure 9), the major value increased to a range 1.80-2.4. Finally at the last case, which is the x=7cm to x=9cm downstream the nozzle (Figure 9), the averaged Signal-to-Noise-Ratio is higher that 2.4 in most of the regions. Figure 10 gives the averaged velocity fields at the three observation frames. The vector fields show expected flow patterns.
4.3 Comparison of PDA and Standard PIV

Figure 11 gives the axial velocity profile compared for the two techniques (PIV and PDA) in the first 9 cm downstream the nozzle. As seen from the graph, the flow starts with low velocity, having an increase further away from the nozzle. This can correspond to the flashing mechanism that the large droplets and liquid ligaments experience. PDA results are higher close to the nozzle since only the spherical droplets are validated whereas PIV does not take the shape into consideration.

4.4 Comparison of PDA and Multi-intensity layer PIV

It was explained in previous sections that PDA measurements showed a wide range of droplet size distribution and these droplets receive different light intensities. This observation lead us to attempt a Multi-intensity-layer PIV approach, which was initialized and published by (Yamada et al. 1998) and (Palero et al.,
In this technique, the original source image is divided into different layers of images made of different ranges of intensities and it is expected that different ranges of intensities correspond to different ranges of droplet sizes.

It was stated in the previous sections that close to the nozzle, PIV gave good results with 1 window refinement (final window size 64(H)x64(V)). It was possible to measure only the velocity of ensembles of droplets that optically could not be separated from each other, due to the speckle like pattern. This explains why the multi-layer approach is not likely to give any additional information more than Standard PIV. But further downstream, more window refinement could be applied because single droplets can be identified. Therefore, multi-intensity-layer PIV is attempted on the images taken at a location from x=7cm to x=9cm downstream the nozzle. Figure 12 presents an original 12-bits PIV image, where the intensity range is between 0 to 4095. PDA results showed that the droplet range changes from nearly 0µm to 800µm in the flow field. Supposing the background intensity is zero, the 0µm droplet size was assumed to have 0 light intensity whereas the largest observed droplets (800µm) correspond to intensity level 4095. Three different layers were defined with intensity ranges 0-300 (Figure 13a), 300-600 (Figure 13b) and 600-4095 (Figure 13c). Table 2 shows the corresponding diameter ranges found from PDA measurements for three intensity ranges. From Figure 13, it can be seen that large droplets tend to be near the jet axis and the droplets occupy more than 1 pixel to eliminate peak-locking, differently than the measurements of (Yamada et al. 1998). Because of the Gaussian beam intensity distribution of the laser beam, a higher range of intensity levels is related to a narrower range of larger droplet sizes. Also, when the particle’s diffraction peak extends over more than 1 pixel, the same particles can contribute to various intensity levels. Therefore, having a careful look on Figure 13 shows that Figure 13a, Figure 13b and Figure 13c provide more often the information belonging to the same particles. In such conditions, processing the original image with different light intensity layers does not guarantee that different light intensities will correspond to different droplet sizes.

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Diameter range (µm)</th>
<th>Intensity range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-216</td>
<td>0-300</td>
</tr>
<tr>
<td>2</td>
<td>216-306</td>
<td>300-600</td>
</tr>
<tr>
<td>3</td>
<td>306-800</td>
<td>600-4095</td>
</tr>
</tbody>
</table>
It was observed that Multi-intensity-layer PIV approach has not improved the Signal-to-Noise Ratio. It was mentioned in the previous sections that the original image has a SNR of around 2.4 in the centreline whereas this value is 1.7 for “Layer 1”, 1.9 for “Layer 2” and 2 for the “Layer 3”.

Figure 14 presents the velocity profiles for the different light intensity ranges. The results belonging to “Layer 1” show discrepancies from the velocity profile for the complete 0-4095 light intensity range, all over the measurement section, whereas the other two cases show differences only on the parts where the SNR is low. It was observed that the velocity discrepancy increases where the SNR decreases, but in the regions where SNR is high, there is no significant change.

![Figure 14 The velocity profile of the flashing jet using different intensity levels](image)

As can be seen from Table 3, the PDA measurements do not show different velocities for different diameter ranges, which is in agreement with the Multi-intensity-layer PIV measurements for the high SNR regions. However, the treatment per intensity layer did not lead to a higher SNR comparing to Standard PIV and was therefore, really more useful for the present case than just indicating that the bigger droplets were encountered near the jet’s centreline.

<table>
<thead>
<tr>
<th>Diameter Range</th>
<th>X= 0.07m far from the nozzle</th>
<th>X=0.09m far from the nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>D &lt; 216µm</td>
<td>32.4 m/s</td>
<td>32.8 m/s</td>
</tr>
<tr>
<td>216µm&lt;D&lt;306µm</td>
<td>32.2 m/s</td>
<td>32.4 m/s</td>
</tr>
<tr>
<td>306µm&lt;D&lt;800µm</td>
<td>29.1 m/s</td>
<td>32.9 m/s</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Dynamics of two phase flashing R134A jet has been studied using Standard PIV, PDA and Multi intensity layer PIV. Standard PIV works well in the far field from nozzle whereas the speckle-type image pattern results in low signal-to-noise ratio near the nozzle. PDA and PIV results show similar patterns in the velocity measurements. It can be observed that there is an increase of velocity further away from the nozzle due to the flashing evaporation of the droplets. Considering the droplet size evolution, close to the nozzle the values of $D_{32}$ and $D_{10}$ differ from each other, whereas they approach to each other moving further away from the nozzle. This different behavior can be explained as the flow shows a poly-dispersed character close to the nozzle and it becomes mono-dispersed in the downstream. PDA measurements show that different diameter ranges do not have different velocities, which is in agreement with Multi-intensity-layer PIV on the regions where the SNR is high. However, Multi-intensity-layer PIV treatment does not increase the SNR comparing to Standard PIV and does, therefore, not seem to improve the velocity measurements. This is due to the
speckle type scattering pattern in very highly dense pattern regions, the Gaussian beam intensity profile of
the laser beam and the extension of the particle diffraction pattern over more than one pixel.

6. REFERENCES


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