Flow visualization and f-PIV of a two-phase cavitating flow through a safety relief valve at initial subcooling conditions

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Abstract The goal of this study is to characterize a challenging two-phase cavitating flow through a safety relief valve (SRV), at initial high subcooling conditions. It is known that at these conditions, the mass flux tends to be reduced due to the fluid compressibility and may cause fluttering, or chattering of the valve, and leading to potential hazardous situations. A transparent model of an API 1”½ G3” SRV has been tested mimicking different operating conditions when the valve is kept open with disk lift in the interval from 3.0 to 8.0mm. Measurements of flow rate, temperature and pressure were performed in the associated different cavitating regime. Moreover, as the transparent model made of PMMA allows optical access, precise flow diagnostics such as high speed visualization and fluorescent particle image velocimetry (f-PIV) were performed. Experimental results confirm that cavitation has major influence on the flow characteristics through a SRV in liquid service.

In a first configuration, high speed flow visualization is applied with a continuous laser, to observe qualitatively the flow pattern and the inception of liquid vaporization. Particle tracking results suggest that vapor bubbles are formed in the core of vortices detached from the shear layers attached to the valve. These rotational structures promote low pressure regions allowing the liquid to vaporize. In the second configuration, a pulsed laser with wavelength of 532nm is used together with two CCD cameras. The seeding of fluorescent particles allows separating optically both the liquid and vapor phases with a high pass and notch filter, respectively. Results of PIV post-processing confirm the existence of a submerged jet just downstream the geometrical smaller flow path cross section. This jet is characterized by two non-symmetric shear layers at its sides. Under cavitation conditions, PIV results confirm that vapor bubbles are formed preferentially inside the jet shear layers. Finally, the well-known phenomenon of mass flow limitation associated to large pressure drop through the valve is reproduced. The interaction between cavitation and flow topology is highlighted and it is believed that an understanding of the mass flow limitation driven by the cavitation is proposed for the first time. It is noticed that vapor bubbles tend to spread and accelerate the jet downstream the valve critical section. Furthermore, the vapor content is responsible for the local blockage of the flow and consequent mass flow limitation.

1. Introduction

Two-phase flows are present in daily-life and in numerous technical and industrial processes such as nuclear, chemical or mechanical engineering where different gas-liquid reactors, boilers, condensers and/or combustion systems can be found. In nuclear and thermal engineering systems the use of Safety Relief Valve (SRV) is mandatory since it is the ultimate protection against any over pressure. The complete understanding of the multi-physics taking place in the flow through a SRV is therefore important for the security of the protected process. In single phase flow such as liquid or gas discharge, reliable and well established methods are available for the SRV design. On the other hand, when the static pressure of an initially subcooled liquid falls below the saturation pressure, vapor bubbles are formed which tend to locally reduce the medium speed of sound. Similarly to a compressible flow, it is thought that this decrease of the speed of sound is linked to a limitation of the mass flow evacuated and therefore, the single phase flow methodology becomes inadequate. There are some calculation methods available in the literature, that attempt to predict the critical flow onset in SRV for two-phase systems knowing the inlet flow conditions and the outlet pressure; however none of them is acknowledged as being fully reliable in the entire domain of two-phase flow.

The goal of the present research is to improve and enrich the existent experimental database and understanding of the cavitation mechanism in a SRV by means of optical techniques. The knowledge of the
flow topology and unsteadiness characteristics in a cavitating regime is of main interest for the development and validation of numerical tools to correctly predict the physics in the entire domain of two-phase flow.

1.1 Flow visualization through photography and cinematography

Cavitating flows are normally characterized by complex three-dimensional, unsteady and turbulent effects with possible phase change. In such complex conditions, photography and cinematography are valuable tools to achieve a good insight of the physics. Two different approaches are possible. In the first case, a stroboscopic flash (very short illumination) determines the exposure time thanks to a totally dark environment [9]. The second option is to use cameras capable of extremely short shutter times such as high speed camera complementary metal-oxide-semiconductor (CMOS) and continuous illumination. If very short exposure times are required then a powerful light source has to be provided. Sugimoto and Sato [10] studied the behavior of cavitation in an orifice using 18000 fps with a metal halide light source and an argon-ion laser for a more detailed observation. Ferrari and Leutwyler [7] have also visualized the cavitation phenomenon in a globe valve at 13000 fps.

Chern and Wang [3] adopted Particle Tracking Flow Visualization (PTFV) technique to observe the flow patterns in a ball valve. Polystyrene particles were used as seeding particles to scatter an argon-ion laser source light. This technique was also able to reveal at which conditions cavitation appears. Finally, Kim and No [8] performed an experiment to find the effects of subcooling and disk lift in a safety valve when critical conditions are established. Flow pattern visualization provided the position of vapor generation in subcooled conditions. It was also found that the critical flow rate through the safety valve is mainly governed by flow conditions such as the inlet subcooling and the inlet pressure while the effect of its geometrical section is relatively small on the critical flow rate.

1.2 Particle Image Velocimetry

During the last years, an increase of PIV measurement techniques have been developed and applied for two-phase flows. In order to suppress the intense reflections at the liquid/gas interface the standard PIV has been replaced by fluorescent Particle Image Velocimetry (f-PIV). This adaptation for two-phase flows uses fluorescence-emitting particles. The light re-emission or fluorescence occurs with a different wavelength from the light excitation source. Using the appropriate optical filter, liquid and vapor phase can be separated without any disturbance as the vapor interface is illuminated by the light source and the seeding particles trapped in the liquid illumination with the fluorescent wavelength. Dias and Rietzhmüller [5] compared both PIV and f-PIV, by measuring the flow field induced by a single bubble in a water tank. It was shown that a considerable reduction of the error was obtained by adopting the novel technique.

A further improvement was performed by Friederichs and Kosyna [6] in the characterization of a cavitating flow through a radial impeller pump. In their experiments, simultaneous velocity measurements and cavitation observations were performed by using two cameras: one equipped with a low-pass filter to record the fluorescence images, the other equipped with a band-pass filter, enabling the recording of vapor structures. Both cameras were focused on the same field of view thanks to an optical mirror system. Their approach has been recently also used by Iliescu [4] for the analysis of a cavitating draft tube vortex in a francis turbine, where two cameras were also used simultaneously. The first camera had an antireflection-coated filter, focused on the laser wavelength, to record the reflections in the laser light from the cavitation rope/water interface; while the second camera had a cut-off filter on the emission wavelength of fluorescent particles. The vortex core boundary was extracted by image processing of the first camera images and the velocity field was extracted from the second camera images.

2. Experimental setup

Following similar approaches as described in the previous section, an experimental campaign is carried out to characterize a challenging flow experiencing cavitation in a SRV. Instead of using a spring, as illustrated on the left side of Fig 1, the design of the valve was modified to allow the adjustment of the disk at any
desired lift. On the right side of the same figure, a sketch of the experimental facility is presented: water is pumped from a 750L reservoir in a closed loop. The backpressure can be adjusted either by the control valve situated downstream the tested SRV, or by the vacuum pump which is located on the top of the reservoir. The flow rate and operating pressure are controlled with a variable speed motor connected to the pump.

![Diagram of the experimental setup](image)

**Fig 1** Transparent model of API 1 ½ G3” SRV (left). Experimental facility (right).

Measurements of flow rate and pressure upstream and downstream the SRV test element were performed at different openings of the valve (3, 4, 5 and 8) and cavitation conditions (a→f). Each experimental point is defined accordingly, as shown in the following table:

<table>
<thead>
<tr>
<th>Disk lift of the SRV</th>
<th>Pressure conditions: Upstream SRV</th>
<th>Pressure conditions: Downstream SRV</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 mm</td>
<td>( P_1 ) 2.5 barg</td>
<td>( P_2 ) [1.0, 0.8, 0.5, 0.2, 0.0, -0.2, -0.5] barg</td>
<td>3 a,b,...g</td>
</tr>
<tr>
<td>4.0 mm</td>
<td></td>
<td></td>
<td>4 a,b,...g</td>
</tr>
<tr>
<td>5.0 mm</td>
<td></td>
<td></td>
<td>5 a,b,...g</td>
</tr>
<tr>
<td>8.0 mm</td>
<td></td>
<td></td>
<td>8 a,b,...g</td>
</tr>
</tbody>
</table>

**Table 1** Experimental test matrix.

The transparent model made of polymethylmethacrylate (PMMA) allows optical access to perform precise flow diagnostics. Two independent visualization systems are used and summarized in Table 2. In both configurations, a laser sheet with thickness of 1mm is adjusted by passing the light through a cylindrical and spherical lens. The field of view is kept identical for all conditions.

<table>
<thead>
<tr>
<th>Configuration / System</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Continuous 20W</td>
<td>Double Pulsed 15Hz / 100mJ</td>
</tr>
<tr>
<td>Cameras</td>
<td>Phantom v7.0 CMOS</td>
<td>2 CCD ImagerProSX</td>
</tr>
<tr>
<td>Separation Time</td>
<td>-</td>
<td>18 μs</td>
</tr>
<tr>
<td>Optical Filters</td>
<td>No filter</td>
<td>Stop-band + Pass-band filters</td>
</tr>
<tr>
<td>Technique</td>
<td>Flow visualization</td>
<td>f-PIV</td>
</tr>
</tbody>
</table>

**Table 2** Characteristics of the optical systems.

In the first configuration, high speed visualization is applied with a continuous laser, to observe qualitatively the flow pattern and the inception of liquid vaporization. A large exposure time of 117 μs with sampling frequency of 8 kHz is set to highlight the streamlines of the flow obtained straight fully thanks to the seeding particles acting as tracers. Both single phase and cavitating flow experiments are performed without any optical filter. In the second configuration, illustrated in Fig 2, a pulsed laser with wavelength centered at 532nm is used together with two charge couple device (CCD) cameras to visualize the illuminated zone and
separate both liquid and vapor phases, with a series of 300 paired images acquired at a frequency of 15Hz. Both cameras resolution are 2500x1700 pixels for a 60x40 mm² spatial domain. To focus both cameras on the same area, a beam splitter is used. The first camera uses a 532 ± 10 nm pass-band filter, selecting on the laser wavelength, and a polarizer to attenuate the light intensity. The second camera has a stop-band filter (532±5nm) allowing separating the fluorescent seeding particles emission. The two cameras are synchronized (PTU - Fig 2) with the luminous flashes and then simultaneously exposed.

![Fig 2 Optical setup for f-PIV measurements (configuration 2). Field of view is kept identical in both configurations.](image)

The vector processing is performed with LaVision DaVis 8 commercial software, based on the cross-correlation technique. The shape of the cavitation bubbles is determined through image processing from the first camera, while unsteady velocity fields are obtained from the second one.

### 2.1. Optical Calibration

For the proper evaluation of the 2D displacement of the particles, and a correct overlapping of images taken from the cameras (particularly in the case of configuration 2); a calibration of the two fields of view is necessary. The camera calibration consists in defining the coefficients of a third order polynomial function that relates the real spatial locations in the measurement plane to the corresponding positions in the recording one. This function includes the geometrical and optical characteristics of the cameras setup, taking into account optical distortions, lens aberrations and interposed media with different refractive indices (water, PMMA, and air). By acquiring images of a target with well specified spatial markers, their corresponding positions in the image plane are known, and thus the polynomial coefficients can be determined. The calibration is performed by placing a 2D metallic target 120x120mm² with 28x29 equidistant holes (2mm diameter), in the measurement plane position. The test section is then filled with water for reproducing the optical configuration during measurements. Both cameras are focused on the target and the calibration images are acquired. The laser sheet is then aligned with the target surface and finally the valve disk is placed without modifying the optical arrangement. Fig 3 shows the sum of both images acquired, after the calibration correction has been applied.

![Fig 3 Sum of corrected images taken by both cameras (configuration 2).](image)

The maximum deviation of the calibration was found to be 1.84 pixel and 2.00 pixel for the first and second camera, respectively. These values are in agreement with the ones recommended in the literature [1].
2.2. Seeding Intrusiveness

Fluorescent red polyethylene microspheres are used as seeding particles, with an emission peak at 605nm. The concentration of particles inside the facility is around 20g per 1000 liter of water. The relative density of 0.995 against the water one and the range size of 53-63 μm allow these particles to accurately follow the flow. In order to evaluate the particles intrusiveness against the cavitation occurring in the test section, two different criteria are defined and reported in Fig 4: the flow rate and the noise produced by the flow passing through the valve.

![Flow rate and noise level](image)

**Fig 4** Analysis on the particles seeding intrusiveness: flow rate (left) and noise level (right).

Both criteria are measured before and after the particles seeding, at different valve openings and cavitation conditions. It is shown that particles do not have a significant influence on the cavitation phenomenon. Both the flow rate and unsteady pressure measurements, presented in Fig 4 confirm this independence for the different valve openings and cavitation conditions. This can be explained by the low particle concentration used in the present experiments, which does not increase significantly the number of cavitation nucleation sites. Furthermore, the seeding particles range size of 53-63 μm is well above experimental data reported in the literature [2], that promotes significantly the cavitation inception (less than 10 μm). Another important remark concerning the seeding intrusiveness is the spatial location of both particles and vapor bubbles. In certain experiments performed in configuration 2, it is found that both bubbles and particles (captured by two different cameras) are visible in the same region, as enhanced in Fig 5.

![Interaction between seeding particles and vapor bubbles](image)

**Fig 5** Interaction between seeding particles and vapor bubbles. Left: Cavitation structure taken from CCD 1. Right: Particle image taken from CCD 2, enhancing vapor regions reconstructed from CCD 1. (configuration 2)
Physically, the existence of seeding particles inside the bubble is not possible for two main reasons: 1) The nucleation site is much smaller than the particles size; 2) The bubble inception tends to expel its surroundings so the particle is more probably pushed by the bubble rather than it is captured inside of it. The most suitable explanation for the images presented above is interpreted as light reflection on bubbles interfaces registered by camera 1 (left side of Fig 5) that are located between the laser sheet and the camera, while the particles taken by camera 2 (right side of Fig 5) are mainly those inside of the laser sheet. This supports why such behavior is not evidenced in all the experiments. Due to the highly unsteadiness of the cavitation inception, bubbles can be formed outside the laser region and be illuminated by the light reflection coming from particles or even from other bubbles present in the flow.

3. High speed visualization results

High speed visualizations of the flow are presented in this section, for a valve opening of 8.0 mm. For the sake of comparison, two experimental points and presented in single phase and cavitating flow conditions.

3.1. Instantaneous flow topology

Visualizations shown on the left side of Fig 6 correspond to a single phase flow condition. The flow is entering the chamber from the nozzle located in the bottom right corner. As the flow trajectory is changed due to the presence of the valve disk, a submerged jet is formed with counter rotating vortices at its sides. These vortices are typical characteristics of coherent structures, which are formed in periodic mode and develop in amplitude following the jet. Spatial and temporal evolutions of the vortices are identified in the same figure.

Fig 6 High speed visualization in a SRV at 8.0 mm. Left: single phase (test 8a). Right: cavitating flow (test 8c).
As the pressure drop though the valve increases, the flow starts to experience cavitation. On the right side of Fig 6, high speed visualizations are presented for a cavitation case. Results show that cavitation bubbles, which are visible in regions of higher intensity, are formed in the core of coherent structures downstream the geometrical section of the valve. These rotational structures promote low pressure regions allowing the liquid to vaporize. This cavitation mechanism is generally referred as vortex cavitation.

3.2. Averaged flow topology

Images recorded from the high speed visualization are post processed. Namely, the intensity gray scale of each pixel is averaged for the ensemble of 2000 images. Results are presented in Fig 7 for different cavitation regimes. Please note that by averaging the ensemble of images, the seeding particles visible in the instantaneous fields are filtered out, and the contrast between liquid and vapor becomes more evident.

![Fig 7 Average of high speed visualizations at different cavitation regimes.](image)

From the above results, it is well evidenced that the vapor content increases significantly with the pressure drop of the valve (see Table 1 for identification of the test cases). In fact, as the velocity increases (higher pressure drop), the vortices promoting low pressure regions become more intense and therefore vaporization of the liquid is more likely to occur. Another important remark is the location of vapor region which is limited to both sides of the liquid jet for different cavitation regimes. As it will be shown from the f-PIV results this regions are characterized by a high content of vorticity.

4. f-PIV results

In this section, f-PIV results using configuration 2 are presented. The two cameras images are processed separately. The distortion correction is performed to both cameras images with the calibration transform prior to processing. The camera 1 images are processed to extract the vapor phase, by averaging the intensity levels of all the images taken at a given experimental point. Then, the contrast is amplified by histogram analysis and finally the image is rendered binary through the definition of a threshold value. On the other hand, camera 2 images are processed to extract the liquid velocity. The instantaneous velocity field is retrieved by cross correlation of the two frames, properly masked in the regions of the nozzle and disk of the valve. Results are filtered by local mean value and peak validation criteria (the relative height of the highest cross correlation peak compared to the second highest is selected at a value of 1.5 i.e. SN > 1.5).

4.1. Instantaneous velocity fields

An example of instantaneous velocity field is presented in Fig 8 for the case of single phase flow at 8mm opening of the valve for two different time instants.
It is noticed from the above results, that the flow presents significant instabilities downstream the geometrical section. This has been shown for both the liquid and cavitation experiments for all the valve openings investigated. The characterization of such instabilities in the frequency domain is not possible at the moment, due to the limitation on the maximum acquisition frequency of the PIV system (15 Hz). This feature will be addressed in the future when time-resolved data will be available. Therefore, post processed results presented in the following section 4.2 are based on statistical analysis of the instantaneous data.

4.2. Averaged velocity and vorticity fields

By averaging the ensemble of instantaneous velocity fields, statistical convergence is reached for 200 velocity fields with 5% of uncertainty. Results presented in Fig 9 refer to the averaged light intensity captured from camera 1 and mean velocity processed from camera 2 measured at 5.0mm disk lift opening of the valve, for single phase and cavitating flow conditions.

Results reveal the flow topology through the valve for a single phase and cavitating flow condition.
Regarding the averaged light intensity displayed on the top figures, the vapor cloud forming just downstream the critical section is well visible for test 5f. These results confirm that critical flow conditions are obtained with the geometric section partially filled by vapor. On the other hand, in the single phase case of test 5a, there is no significant light intensity registered which is interpreted as a purely liquid flow. The existence of a liquid jet downstream the critical section is well evident from the chart of the velocity magnitude in both cases. It can be seen that the maximum velocity increases considerably between the two operative conditions (5a→5f). Furthermore, the location of the maximum velocity is shifted upstream towards the critical section. As a consequence, the liquid jet downstream the valve tends to be slightly larger due to mass conservation that has to be respected along the flow path, with higher recirculation regions. Velocity profiles were integrated through the axisymmetric domain to check the measurement uncertainty on the mass flux. Results are in agreement with the flux measured by the flow meter located upstream of the test section.

Then, to evaluate the evolution of the flow downstream the critical section, it was decided to plot the velocity data over two sections perpendicular to the jet direction at 1.5D and 1.7D, respectively, from the axisymmetric axis of the valve (being D the nozzle internal diameter). Both sections are identified in the velocity maps of Fig 9. The extracted data is then presented in Fig 10 for both sections, including all the experiments performed at 5.0mm.

![Fig 10 Velocity measurements at sections 1.5D and 1.7D (valve opening 5.0mm).](image)

First of all it can be seen from the above curves that the jet tends to enlarge significantly from the first to the second section investigated. Then, it is possible to verify that the jet is not entirely symmetric. Regions at x<0.5 correspond to larger recirculation areas in the valve body, in which the entrainment of the flow becomes higher at larger cavitation regimes (a→f). On the other hand, all the x>+0.5 correspond to the region between the jet and the nozzle, in which the velocity slightly decreases with the pressure drop (a→f). Concerning the maximum velocity of the jet, it is noticed in both sections an important decrease occurring at higher cavitation regimes (e and f). This decrease of velocity is compensated by the increase of entrained flow at x<0.5 resulting in a higher mass flux in agreement with the data measured by the flow meter placed upstream the test section.

After changing direction due to the presence of the disk, the flow enters the chamber with large recirculation areas from both sides and consequent vortices generation. In order to detect the location of the shear layers the absolute value of the vorticity is computed. Results of vorticity fields are shown in Fig 11, as well the standard deviation (rms) of the velocity measurements for single phase and cavitating flow conditions. It is shown the presence of two non-symmetric shear layers located downstream the valve. Under cavitation conditions, it is confirmed that vapor bubbles are formed in the shear layers, characterized by a high vorticity.
Fig 11 Vorticity fields and standard deviation for single phase and cavitating flow conditions (valve opening 5.0 mm).

Regarding the rms-value, it is noticed from the above results that instability of the flow tends to amplify as the velocity augments. The region of the liquid jet is characterized by high rms-values corresponding to turbulence intensities up to 50%. It is concluded that such high levels cannot be consequence of turbulence but is rather due to the combined perturbations from the liquid phase and from the vapor phase (bubbles) that are present on the flow downstream the critical section, which were already discussed in the instantaneous velocity field given in Fig 8. The characterization of such perturbations is planned in the future with time-resolved PIV data.

5. Conclusions

Two independent optical measurement techniques are described and successfully applied in a challenging cavitating flow through a SRV. The results enrich experimental database available in the literature for the characterization of such devices. The use of fluorescent particles has proved their effectiveness in the results obtained, with minimum interferences to the cavitation phenomenon.

In a first configuration, high speed flow visualization allows the description of the flow passing through a SRV. The existence of vortices downstream the critical section is detected and linked to the cavitation inception. As the velocity increases, these vortical structures promote low pressure regions allowing the liquid to vaporize. Then in the second configuration, f-PIV results confirm a flow topology similar to a jet, characterized by a high velocity in the center and shear layers on both sides. The phenomenon of mass limitation is reproduced and interaction between cavitation and flow topology is highlighted and understood for the first time. It is noticed that vapor bubbles tend to spread and accelerate the liquid jet, shifting the location of the maximum velocity upstream towards the critical section. The vapor content is then responsible for the local blockage of the flow and consequent mass limitation.
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References