ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-7-1

PARTICLE IMAGE VELOCIMETRY MEASUREMENTS OF THE CAVITATING FLOW IN A REAL SIZE TRANSPARENT VCO NOZZLE

Humberto Chaves*

* Technical University of Freiberg, Institute of Mechanics and Fluid Dynamics
Lampadiusstraße 4, Freiberg, D-09596, Germany
Humberto.Chaves@imfd.tu-freiberg.de

ABSTRACT
The difficulties of micro PIV measurements in high speed flow measurements in small orifices are discussed. A backlit micro PIV system was developed to measure the flow within real size transparent VCO nozzle with orifices of 150 µm in diameter. Using refractive index matching the resolution of the PIV images reaches almost the diffraction limit. Larger tracer particles than with conventional PIV are needed but a much lower light energy level of the illuminating light pulses, that have to be incoherent. A double pulse Nd-Yag laser and fluorescence medium together with a filter are used to produce the incoherent light. Both the visualization of the cavitation as well as the micro-PIV results seem to indicate that cavitation collapses or decays is a deterministic manner within the orifice of a cavitating transparent VCO nozzle.

INTRODUCTION

One basic problem that arises in gas-liquid pipe flow is that volumetric flow measurements can not be used to calculate the mean flow velocity of the liquid simply because the area occupied by the liquid does not correspond to the cross-sectional area of the pipe. It depends also on the void fraction. This is also true for the case of the cavitating flow in the orifices of injection nozzles. Here the cavitation inception occurs at the inlet of the orifice and provided the flow velocity is high enough the voids extend to the exit of the orifice. The large differences to other gas liquid flows are however, the small scale of the orifice, the typical diameter is around 150 µm and at the same time the very high velocities reaching up to 600 m/s. These facts pose stringent demands on the measurement system. If the field of view is resolved with one pixel per µm, then the pulse duration of a PIV system should be less than 1.7 ns to avoid blurring of the images. The pulse separation should give an image shift of the particle images by about 10 pixels giving a value of 17 ns.

For the experiments presented here the flow velocities are limited indirectly by the nozzle material. The nozzles are made of glass with an index of refraction close to that of diesel fuel, see Figure 1. The material strength of the nozzles only allows a pressure difference of about 3 MPa giving velocities of around 80 m/s. This relaxes the requirements on the measurement system.

An almost perfect index matching was obtained by adding α-methyl-naphthalene to the fuel. This substance is representative for the aromatics that are normally contained in the fuel. The nozzles were used in submerged conditions for cavitation imaging. The technique allows a very detailed optical access to the orifice. For extensive PIV measurements fuel was injected into atmospheric conditions to obtain longer series of images and thus to be able to average the results.

The experiments presented here are a continuation of the work presented in [1] and [2].

PROBLEMS OF USING PIV IN NOZZLE ORIFICES WITH CAVITATION

The first question that has to be answered when using PIV is how thick the light sheet should be to obtain an adequate spatial resolution and at the same time thick enough to reduce the number of out of plane motions of the tracers? The thickness of the light sheet should be much smaller than the typical scale of velocity gradients of the flow. In the present case it would mean a light sheet thickness much smaller than the orifice diameter, i.e. 150 µm. For example Fath et al. [3] performed visualization experiments using laser light sheets at the orifice exit under atmospheric conditions. The calculated sheet thickness they could produce was order of 40 µm. Walter [4] performed PIV measurements in transparent nozzles using a light sheet with 18 µm thickness. However, when using the standard PIV set-up in cavitating flows the scattered light intensity from the interface between liquid and vapour is much stronger than the light scattered by the tracers. Therefore, Walter used a fluorescent tracers and a filter to block the light scattered by the cavitation surfaces. However, the light energy per laser pulse had to be limited (3 mJ) to avoid damage to the nozzle material (Perspex). The resulting fluorescence intensity is therefore low and a camera with image intensifier is then necessary, which causes an increase of noise in the images. Elaborate evaluation is then needed to obtain the velocity from the images. Walther used a phase averaging procedure to reduce the signal to noise ratio of the correlation peak. Summarizing these results the effort needed to obtain results using a standard PIV for real size orifice flow is quite substantial.

An alternative is to use a micro-PIV technique, where all of the flow volume is illuminated by the light and the plane of observation is defined using the small depth of field of the imaging system with a large aperture (microscope objective). This however would not solve the problem caused by scattering at the surface of cavitation voids. Also here a epi-fluorescence technique is typically used.

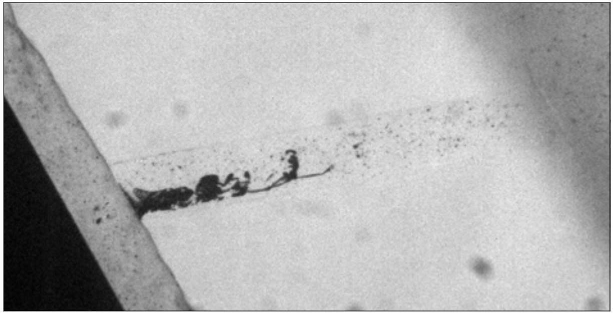
The technique adopted here is somewhat different. Usually in PIV the tracers are much smaller than the equivalent pixel size, (i.e. the object size imaged onto one pixel). Particularly for gas flows this is usually the case since the tracers have to be small enough to follow the flow. For liquid flow the tracers do not have to be as small because the density difference between the tracer and the liquid is much smaller. Neutrally buoyant tracers can actually be quite large. Therefore, in liquids tracers can be used that are large enough to obscure a pixel in backlit illumination. If the image of the tracer is smaller than a pixel, the modulation of the light collected by the pixel decreases rapidly. Therefore, for backlighting the tracers should have a size comparable to the equivalent pixel size in the object plane to obtain an adequate light modulation. Ideally the tracers should be opaque and if they are transparent their refractive index should differ strongly from that of the liquid.

In backlighting light scattered by liquid-vapour surfaces is deflected and does not reach the imaging optics. In this case no fluorescence technique is necessary to separate the tracer images from the cavitation and as a consequence no image intensifier is needed. However, an incoherent light source has to be used because a direct backlit illumination with a laser results in speckles that can not be distinguished from the images of the tracers. Due to the fact that the tracers are being imaged the amount of light needed for illumination of the images is much smaller than for conventional PIV (the factor should be in the order of the inverse of the scattering efficiency of typical tracers) and even more so for the case of the fluorescent PIV technique.

There is a further limitation that appears when using PIV for small objects. The width of the orifice measured in pixels is in the order of 100. This means that when using correlation windows of 32 x 32 pixels the spatial resolution is limited. Of course, one could shift the windows in steps that are smaller than the window size and one obtains more vectors. In a second step the size of the correlation windows can be reduced even further. However; the limitation is actually the number of tracer pairs present in the images. Eventually particle tracking is needed. When using backlighting, the number density of the tracers can not be increased indefinitely because the intensity of the light is reduced due to light extinction and at high number densities the image quality deteriorates due to multiple scattering, which is also true for standard PIV. Furthermore, at high particle concentrations the question arises whether the tracers are not affecting the flow, (mass loading). A comparison of pictures taken for the same conditions but with and without tracers clarifies this question, as can be seen on figure 1. These are close-up pictures of one of the two injection orifices of the transparent nozzle. On backlit images cavitation appears black.

The top image is an excerpt from an image with a larger field of view and has therefore a lower resolution. Not only the basic flow topology and cavitation break-up are comparable for both images, but also details are very similar. This is indeed surprising because the images were taken with different optical set-ups and from different experiments only the experimental conditions are the same. Apparently the break-up process or collapse of the cavity is reproducible to some extent in space. It seems to be a deterministic process.

without tracers, P_{inj} =28 bar; Ca=4.5



with tracers P_{inj} =29 bar; Ca=4.5

Figure 1: Comparison of the cavitating flow with and without tracers.

THE PIV SET-UP

For illumination a double pulse Nd-Yag laser at 532 nm was collimated onto a fluorescing Perspex cylinder mounted at the focus of a parabolic mirror. The incoherent fluorescence light, (595 nm) from the Perspex cylinder particles was collected by a lens and focused onto a light fiber whose other end serves then as a source for backlight illumination of the images.

The image resolution was set at 1.58 µm/pixel. The pulse duration of the laser is 5 ns. However, due to the fluorescence the pulse duration is increased to about 20 ns. The chosen laser (Minilite, Continuum) has Q-switches driven with pockels cells. This reduces the trigger uncertainty to less than a nanosecond. Previous results [1] were obtained with a different laser that had too much jitter. The PIV camera used is a PCO 1600 which allows a minimal frame separation of 180 ns. The frame separation used here was 200 ns. The PIV set-up uses the depth of field of the imaging microscope lens to define the plane of observation, see Olsen and Adrian [5], here 40 µm. Particles with a mean diameter smaller than 6 µm were obtained by sedimentation of the particles, density 1060 kg/m^3, in the test liquid, density 900 kg/m^3. Only the almost clear liquid containing the small particles after 30 minutes of sedimentation was used for the experiments.

EXPERIMENTAL SET-UP

To visualize the flow in the nozzles the tip of a standard VCO nozzle was replaced by a glass prism which has a conical recess for the needle tip and two angled holes of about 1 mm in length and 0.15 mm diameter, Fig. 2 is a picture of this nozzle. One orifice is tilted backwards relative to the injector axis. A mixture of diesel fuel and α-methyl-naphthalene was chosen to match the index of refraction of the glass of the prism. This permits the observation of the flow within the nozzle hole and at the needle seat for real size injector geometry. The work is the continuation of previous experiments where the holes had a larger diameter, see [2]. By submerging the injector into diesel fuel all distortions caused by the mismatch of the glass or fuel to the surrounding fluid can be eliminated allowing observation from any view direction. The only disadvantage of the technique is that when the back pressure is low the cavitation bubbles that exit the nozzle do not collapse immediately thus obscuring the view. Above a typical pressure of 0.3 MPa the bubbles collapse near the nozzle exit in a rapid manner.

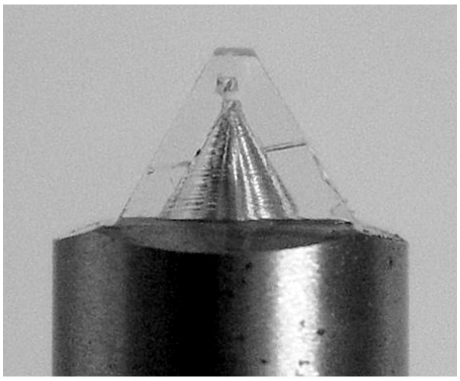


Figure 2: Image of the transparent VCO nozzle. The orifices are 150 µm in diameter.

The needle has to be fixed at a pre-set lift because the closing impact of the needle would destroy the glass prism. The lift value was set at a large value to exclude the effects at low lift. Therefore, the experiment is controlled by an electromagnetic valve in the line. Furthermore, the range of pressure difference that can be applied to the glass nozzle is limited, the authors do not know the limit yet, but the policy is to obtain as much information from the nozzle before it is pushed to the limit. The fabrication of such nozzles is a tedious task.

The limitation in the pressure range appears at first to be unrealistic, since real injection systems are now reaching 200 MPa rail pressure. However, the back pressure in an engine ranges between 4-6 MPa. Then the cavitation number for such systems would be in the order of 33. For standard common rail systems the cavitation number is in the range covered by the present experiments. The influence of the Reynolds number on the flow is small for short axial orifices; see Chaves and Ludwig [6]. The reason is that the viscous pressure losses in short tubes ($L/D \approx 6$) are negligible. The pressure losses are mainly due to Carnot losses downstream of the vena contracta. Boundary layers only start to develop after cavitation separates from the orifice wall. Also turbulence is transitional although the nominal Reynolds number ranges around 30,000 for engine injection conditions. For this reason, the orifice flow is inherently unstable and very sensitive to perturbations.

The present experiments can not reproduce the Reynolds numbers for engine conditions.

For the variation of the main process parameter i.e. the cavitation number a quasi-steady variation of the backpressure for constant injection pressure was performed. The cavitation number here is defined here as the ratio of pressure difference between injection and back pressure divided by the back pressure and assumes that the vapour pressure of the fuel is relatively small, $Ca = (Pinj-Pch)/Pch$. A small chamber containing fuel vapour and air was connected to the injection chamber. During the injection period of the order of tens of seconds the total amount of fuel in both chamber increases thus compressing the vapour and the air. Thus, the backpressure increases with a speed which depends on the initial ratio of fuel volume to the total volume of the chambers and on the volume flux through the nozzle. Finally the pressure difference between injection and backpressure is zero. We call this a “blow-up” type of set-up; see also Chaves and Ludwig [6]. Both the injection pressure and the backpressure are measured by Kistler pressure transducers that were recalibrated with a pressure balance. Figure 3 is a schematic drawing of the set-up.

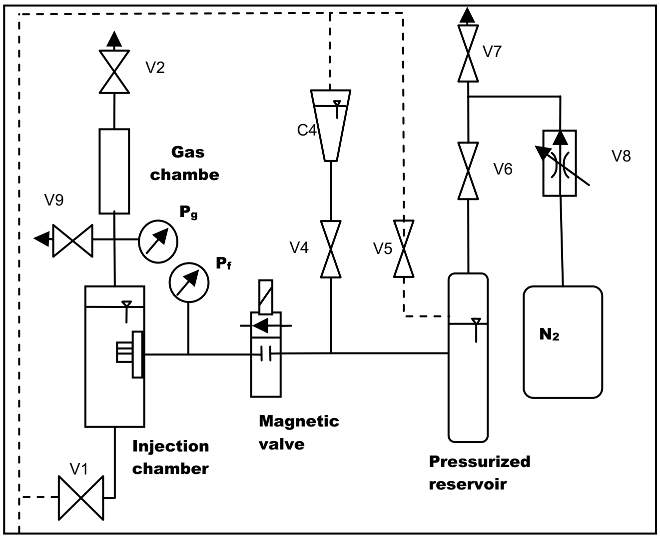
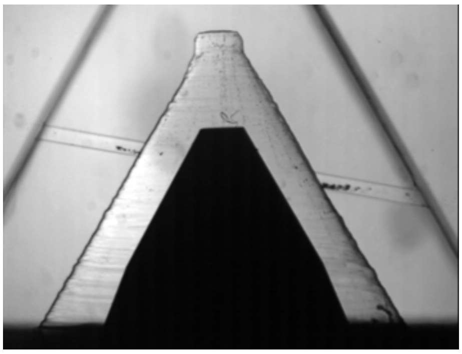


Figure 3: Schematic drawing of the experimental set-up

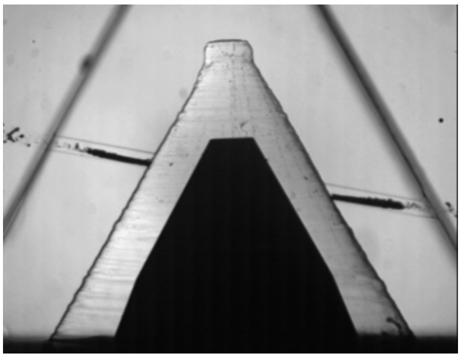
CAVITATION IMAGING

Initial experiments to visualize the cavitation phenomena in the nozzles and at their outlet were performed. The flow region is imaged with a long distance microscope onto a CCD-camera recording pictures at a framing rate of 25 frames/s. One obtains in the order of 250 frames per run. The illumination is backlight with a short light flash of 20ns duration, which is short enough to avoid blur of the images.

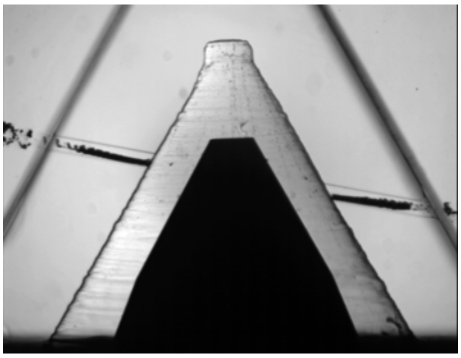
As one can see on the images of Figure 4 cavitation inception occurs for a cavitation number below 4 for this type of nozzle at the inlet and more precisely at the corner with the highest flow deflection. Cavitation regions appear as black patches on backlit images because the light is refracted by the liquid-vapor interface and does not reach the imaging lens. The uppermost part of the orifices remains free of voids. The timing pulses for illumination are recorded simultaneously with the pressure traces. In this manner the injection and back pressures at the instant of acquisition of each image are known, so that the cavitation number can be calculated for each frame. The main advantage of this “blow-up” technique is that with one experimental run a large range of cavitation numbers are achieved within a short time. By changing the injection pressure a variation of the Reynolds number for a similar cavitation number range is achieved.



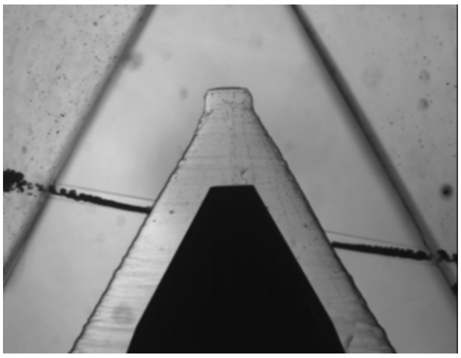
Ca≈4, Re=2935 (Run 4, Pict. 31)



Ca=6.1, Re=3606 (Run 8, Pict. 20)



Ca≈7.4, Re=3674 (Run 8, Pict. 3)



Ca=17.8, Re=3606 (Run 7, Pict. 3)

Figure 4: Backlit images of the cavitating flow at high needle lift

For PIV measurements the "blow up" technique is not quite as attractive although it was used in [1]. The reason is that although one image pair can give an idea of the flow the seeding can not be high enough to fully resolve it. Therefore, a large number of image pairs for the same conditions allows a better resolution and furthermore the calculation of fluctuations.

Inception depends to a certain extent on the Reynolds number (defined with the Bernoulli velocity and the nozzle diameter). However, for higher cavitations numbers the effect of the Reynolds number decreases and the length of the cavitation region divided by the nozzle length for different injection pressures collapse more or less onto one curve, see Figure 5.

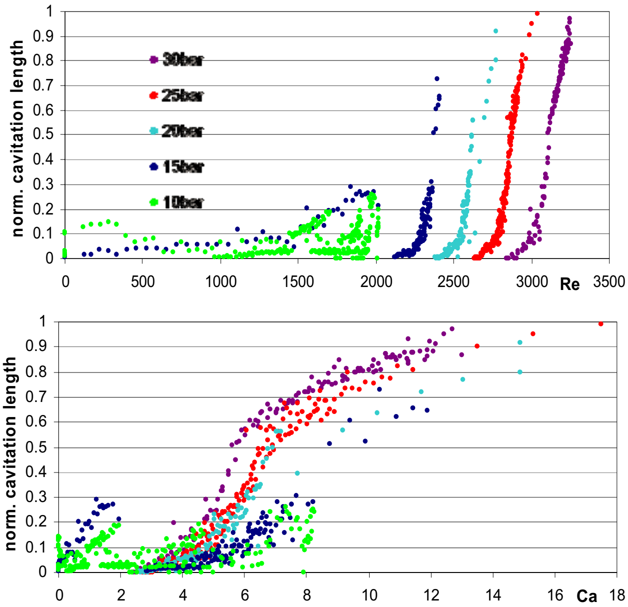


Figure 5: mean length of the cavitation normalized with the orifice length vs. Reynolds number and cavitation number for intermediate needle lift (270 µm)

There are various phenomena that can be observed on these pictures. The first is the increase in length of the cavitation. For a cavitation number above 6 the vapor pockets reach the exit of the nozzle, this is called supercavitation because the collapse of the cavities occurs downstream of the orifice. This terminology is used for example in the case of hydrofoils. For cavitation numbers above 12 also the bulk of the cavitation reaches to the exit. Secondly, cavitation is produced also downstream of the orifice in the core of vortices and at higher flow velocities due to turbulent pressure fluctuations. The cavitation topology is that of a continuous void that breaks up into smaller voids at its tip is a more or less regular manner. Lastly a pronounced helical shape of the cavitation void can be observed at high cavitation numbers and high lift of the needle. This is due to the asymmetrical inflow conditions to the orifice.

In order to understand these phenomena the aim of the present paper is to have a closer look at the flow and to measure planar velocity distributions to gain some more insight into the mechanisms of the interface dynamics.

MICRO-PIV RESULTS

Figure 6 is one of the original PIV image pairs. One can observe that the interface between the liquid and the gas shows small undulations near the orifice inlet that are quickly amplified and finally lead to break-up of the cavitation void. Also the tracers can be seen as small black dots on this image. As a matter of fact this image pair was chosen because there are two tracer particles between the cavitation zone and the orifice wall adding proof to the fact that the void separates from the wall. In this case the vortical motion is not as pronounced due to the lower needle lift. The inflow to the orifice is much more symmetric than at high lift values.

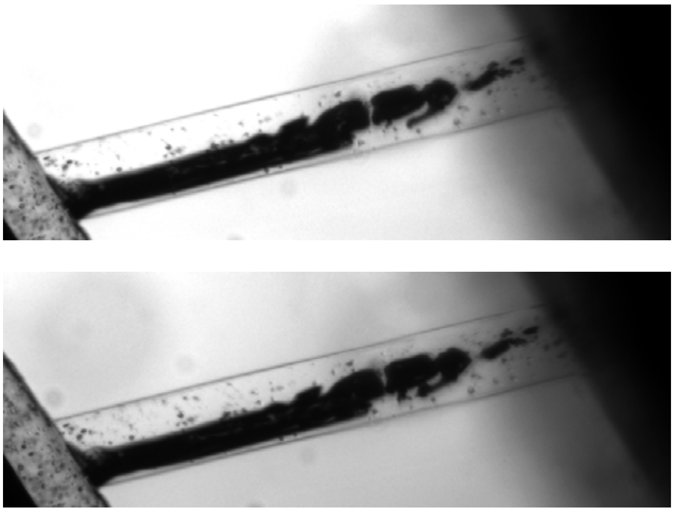


Figure 6: An excerpt of one of the original PIV image pairs of the left orifice of the VCO nozzle for cavitating flow at an injection pressure of 1.7 MPa into the atmosphere.

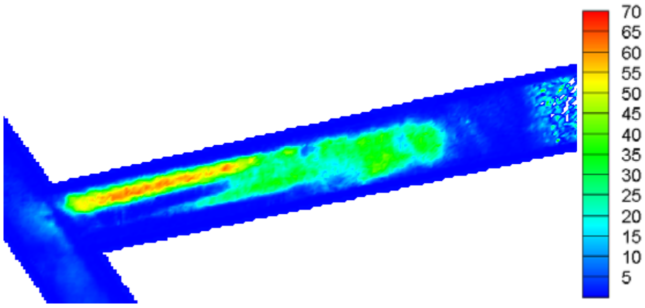


Figure 7: Example of the velocity magnitude in m/s using adaptive correlation windows of 16 x 16 pixels and a shift of 4 pixels.

Figure 7 is a resulting velocity magnitude plot for the same conditions as in figure 6. A total of 60 image pair was used for this evaluation. The cross-correlation algorithm does not distinguish between tracers and cavitation structures, so that even in areas where the cavitation obscures the flow some data is obtained because the interface at some points allows some light to reach the camera, i.e. when it is almost perpendicular to the light beams. This fact has been used for two point correlation measurements before, see [7].

If one compares the original image with the velocity results one can first observe that the flow velocity is much higher in the translucent part of the image above the cavitation area near the inlet. This can be interpreted as a change of the flow area available for the liquid. This area will correspond to almost the whole cross-section of the orifice at its exit. Therefore, the results are physically sound. The maximal velocity attained is close to the value one expects from a simple Bernoulli calculation : 60 m/s. Surprising is however that there is a certain periodicity in the velocity magnitude further downstream. The length scale of this periodicity is comparable to the wavelength of the disturbances of the interface in the direct image. One would expect due to the averaging process that there would be a smooth transition in the velocity distribution. Could it be that although the cavitation does not have a spherical shape that this is an indication of a rebound process known from the collapse of cavitation bubbles that contain some air? Apparently the changes in velocity are localized.

CONCLUSIONS

The backlighting micro-PIV technique has been proven to function under conditions not exactly but closer to real diesel fuel injection conditions as was possible up to now. The limitations are not of the technique itself, but due to the limits imposed by the material of the nozzles. In principle provided a nozzle is available the method would also work for very high injection pressures. The lasers needed for illumination can be triggered at any time and there are lasers with pulses short enough to avoid blurring. There is a limit to the minimal frame separation of double frame cameras.

The most important new result of these experiments is that cavitation appears to collapse in a very deterministic and localized manner.

REFERENCES

[1] H. Chaves, R. Miranda and R. Knake, Particle Image Velocimetry Measurements of the Cavitating Flow in a Real Size Transparent VCO Nozzle, *Proc. 6th International Conference on Multiphase Flow, ICMF 2007*, Paper No S4_Mon_C_6

[2] R. Miranda, H. Chaves, U. Martin, and F. Obermeier, Cavitation in a Transparent Real Size VCO Injection Nozzle. Proc. ICLASS 2003 Sorrento , 2003

[3] A. Fath, A., K.-U. Münch, and A. Leipertz, Spray Break-up Process of Diesel Fuel Investigated Close to the Nozzle. *Proc. ICLASS-´97*, 513-520, 1997.

[4] Walther, J. PhD Thesis Tech. Univ. Darmstadt, Germany, 2002

[5] M.G. Olsen and R.J. Adrian, Out of focus effects on particle image visibility and correlation in microscopic particle image velocimetry. *Exp. in Fluids*, Suppl., 166-174, 2000.

[6] H. Chaves, and Ch. Ludwig, Characterization of cavitation in transparent nozzles depending on the nozzle geometry. Proc. ILASS 2005 Nottingham, 2005

[7] H. Chaves, and F. Obermeier, Correlation between light absorption signals of cavitating nozzle flow within and outside of the hole of a transparent diesel injection nozzle, *Proc. ILASS-Europe'98*, 1998