Experimental investigation of air entrainment by a vertical jet plunging into a liquid pool

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Introduction

Two-phase flows, which include a liquid and a gas, occur in numerous applications of energy and process technology. The exact calculation of these flows using CFD simulations is still problematic. Bubble formation, coalescence and breakup are already complex flow phenomena that depend on many mechanisms [Biń 1993]. The bubbles interact with each other and with the continuous phase [Iguchi 1998]. For the development of CFD codes, this behavior must be precisely described in order to be able to predict more complex flow phenomena such as contact condensation, counter flow limitation or flow boiling precisely and parameter-independently. In extensive experiments, a plunging jet was analyzed, which immerses in a free fall in a liquid pool. Such a jet carries ambient air towards the free surface and entrains - under certain circumstances – a part of the gas under water. The data obtained forms a base for the validation of existing CFD codes and for the development of new ones [Zidouni et. al. 2012]. The aim of the work is the investigation of the liquid flow field induced by the jet inside the receiving pool and the simultaneous observation of the gaseous phase. The applied measurement techniques were Particle Image Velocimetry (PIV) for the analysis of liquid flow field and shadowgraph imaging, which allows a study of the dispersed air bubbles. In addition, all boundary conditions affecting the experiment were recorded.

Experimental setup

The experimental structure consists of two filled water basins arranged one above the other with a free surface (Fig. 1). The upper basin has a volume of 2.6 liters and the lower basin 95 liters. Both basins have a lateral overflow with sump, so that the levels of the basins do not change during the experiment. A pump feeds water from the overflow of the lower basin into the upper basin. Excess water in the upper basin spills over into the overflow and then back into the overflow of the lower basin. On the underside of the upper basin is a nozzle with a diameter of 6 mm through which a free jet emerges and is gravity-driven into the free surface of the lower basin. The drop height of the jet is 197 mm. When immersed in the lower basin, the jet carries ambient air with it and thus a complex flow state develops in the lower basin from a dispersed bubble field and the continuous liquid phase. The bubbles created at the immersed water jet are entrained by the liquid phase and do not rise again until they have left the zone of influence of the jet.

The investigation of the liquid flow field in the test basin is carried out using Particle Image Velocimetry (PIV). In order to eliminate parasitic reflections of the laser at the air bubbles, Rhodamin B doped PMMA tracer particles are used, which emit red light in a wavelength deviating from the green laser light by fluorescence. Using an optical bandpass filter, only the light emitted by the tracers in the light sheet is detected by the camera. The gaseous phase is investigated using shadowgraphy with subsequent image evaluation. The blue light emitted by an LED matrix is reflected and refracted at the phase boundary of the air bubbles in the water, so that their contour is perceived as a black border by the opposite camera. The use of an optical filter also makes it possible to suppress the laser light as well as the light emitted by the particles. Both measuring methods are carried out spatially and temporally synchronously, so that an image of the instantaneous velocity field of both the liquid and the gaseous phase is available at each measuring point.

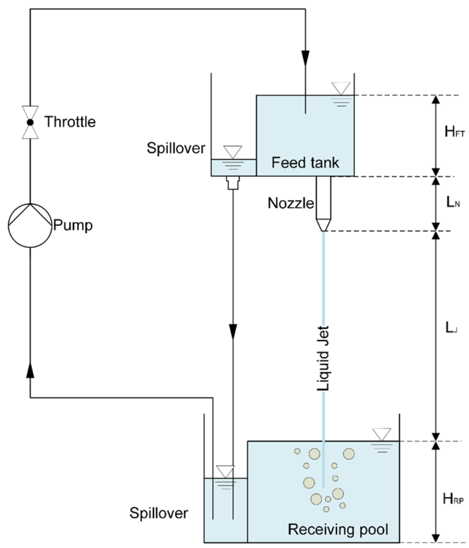

Figure 1: Scheme of experimental apparatus.

The recordings are evaluated by using the commercial software *DaVis* that detects single bubbles by recognizing light intensities that deviate from the background intensity of the field of view. A threshold value for a minimum relative intensity difference is set to exclude an intensity deviation generated by noise during bubble detection. After a bubble is detected, its size is calculated by counting the number of pixels exceeding the intensity threshold.

In order to identify the same bubble in the second double image, the algorithm checks the plausibility of the match by checking the displacement taking place and the consistency of the diameter. The velocity is calculated by dividing the displacement by the time interval between the images.

Results

In the PIV measurements, a total of 3600 double images per measurement were created and evaluated. It has been shown that a statistically significant and reproducible measurement result can be achieved with this measurement duration. The results of averaging can be seen in the diagrams in Figure 2. The diagram on the left shows the magnitude of the vertical velocity above the horizontal coordinate x. There are four curves each to the water depths 30, 90, 150 and 200 mm. It can be clearly seen that the temporally average speed decreases with increasing depth and the beam expands more and more. The velocity curve on the beam axis shows a clearly hyperbolic curve. The velocity curves parallel to the jet main axis show that the flow velocity starting from the resting water surface increasingly adapts to the flow velocity in the jet [Büttner 2018].

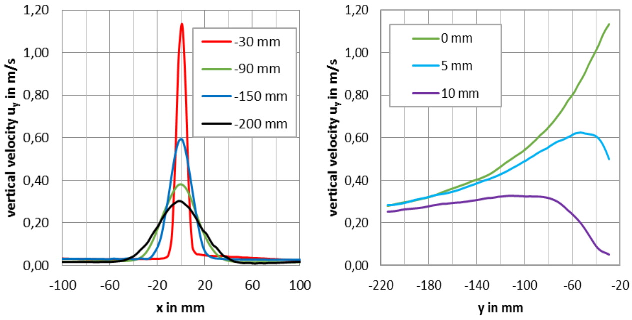

Figure 2: Vertical flow velocity of the liquid phase along the horizontal coordinate (left) and parallel to the vertical jet axis (right).

As the qualitative observations show an intermitting behavior of the flow with a time scale of several minutes, the recording time is set to 60 min, analogous to PIV measurements. The sampling rate was set to 1 Hz as results showed that a higher frequency increases the amount of data, though not delivering more information. This resulted in 18 sequences, each consisting of 200 calculations of the instantaneous velocity field. The trends of the moving average of the absolute fluid velocity as well as the trend of the standard deviation are converging. After a total of 18 measurement sequences, the variation of the moving average velocity from sequence 17 to 18 is less than 0,5 % in each range studied. Thus, the averaged flow field formed from 3,600 immediate images over a period of 60 minutes can be described as statistically significant.

A total of 173,000 bubbles were recorded during the first measurement. By repeating the experiment under identical conditions as a comparative measurement, only 29,000 bubbles were count. The evaluated data showed that the number of bubbles is subject to strong fluctuations. In order to be able to compare the measurements, the values were normalized and the accumulated frequency compared. Figure 3 shows the number of different bubble diameters and the accumulated frequency of measurements. However, the distribution of the bubble sizes always matches well. The different number of bubbles could be due to inaccurate boundary conditions. Special attention should be paid to water quality. To further investigate this influence, surface tension, oxygen content and conductivity will be exactly measured in order to be able to better compare future results.

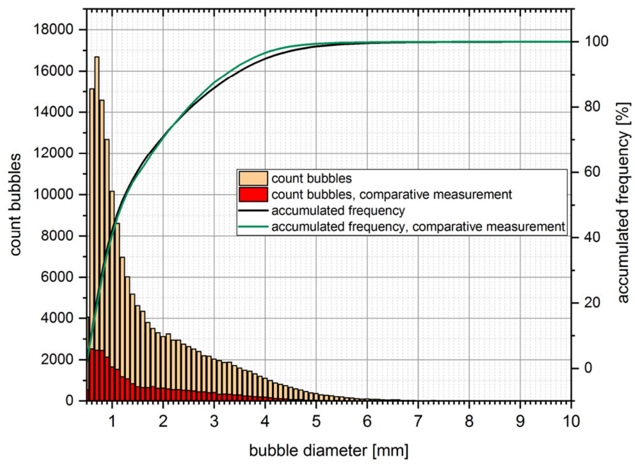

Figure 3: Histogram and accumulated frequency of measurement and comparative measurement [Büttner 2018].

The evaluation of the bubble velocities can be seen in Figure 4. The bubble velocity is plotted along the horizontal coordinate for a pool height between -90 mm and -95 mm. Each mark represents a bubble. The bubble size is proportional to the mark size in the diagram.

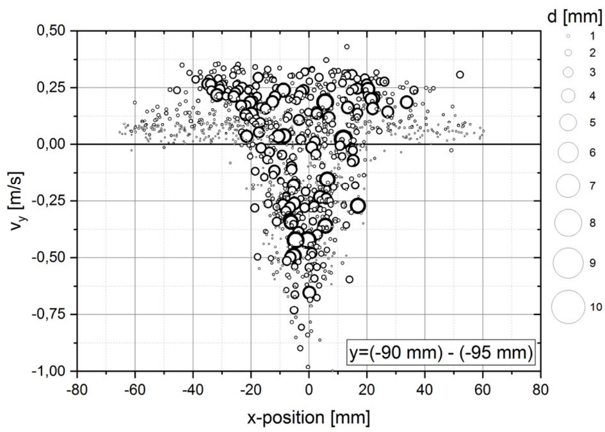

Figure 4: Vertical bubble velocity along the horizontal coordinate for a water depth of -90 mm to -95 mm [Büttner 2018].

In the negative region of the velocity scale, the bubbles move downwards and are attracted to the immersing jet. In the positive region of the velocity the bubbles rise upwards.

Further measurements at other water depths show that the bubble velocity decreases as the depth increases, until the penetration depth of the bubble swarm is finally reached. However, the ascent speed remains almost independent of the water depth. It can also be said that large bubbles tend to rise closer to the immersing water jet, whereas small bubbles are sometimes carried far into the width.

Conclusions

The results of the experiments show that both the liquid field and the entrained air bubbles have transient properties. A time scale was determined in which the time-averaged flow field of the liquid phase and the amount of air bubbles present in the basin can be regarded as statistically significant. The reproducibility of the averaged liquid flow field could be demonstrated.

Thus, in addition to statements about the velocities, statements could also be made about the mean turbulent kinetic energy, the mean turbulence degree and the mean Reynolds stresses as a function of the location.

In spite of strongly differing total numbers of bubbles recorded in the comparative measurement, the same tendencies in the frequency of bubble diameters were found.

Further experiments will quantify the influence of water quality on the results. In addition, 3D measurements of the relevant quantities are planned to improve the information content and accuracy of the data.

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