

Cavitation erosion - scale effect and model investigations

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Abstract: The experimental works presented in here contribute to the clarification of erosive effects of hydrodynamic cavitation. Comprehensive cavitation erosion test series were conducted for transient cloud cavitation in the shear layer of prismatic bodies. The erosion pattern and erosion rates were determined with a mineral based volume loss technique and with a metal based pit count system competitively. The results clarified the underlying scale effects and revealed a strong non-linear material dependency, which indicated significantly different damage processes for both material types. Furthermore, the size and dynamics of the cavitation clouds have been assessed by optical detection. The fluctuations of the cloud sizes showed a maximum value for those cavitation numbers related to maximum erosive aggressiveness. The finding suggests the suitability of a model approach which relates the erosion process to cavitation cloud dynamics. An enhanced experimental setup is projected to further clarify these issues.

1. Introduction

The erosive effect of hydrodynamic cavitation is so far insufficiently understood for practical prediction. Corresponding research is based on experimental investigations of erosion pattern and erosion rates. The transferability of experimental results to different facilities or conditions has to account for scale effects, foremost the size scale effect and the velocity scale effect [1]. The common experimental techniques are based on the observation of damage on material probes and employ almost exclusively metal substances. The presented results of different methods for experimental erosion assessment with metal and mineral materials suggest a high dependency of erosion rates on the employed type of probe. Such material dependencies could be caused by different damage processes for these compounds [2].

Although single bubble experiments and respective theoretical considerations could obtain outstanding information about the related microscopic damage processes [3], these findings can barely be combined with the complex conditions of large scale hydrodynamic cavitation due to immense bubble numbers, intense dynamics and unspecified interactions. A model which relates the erosive aggressiveness of transient cloud cavitation to the macroscopic cloud dynamics appears more promising for future prediction applications and could already achieve good accordance with experimental observations [4]. In detail the model postulates coherent cloud collapses which emit strong pressure waves and consequently induce the formation of micro jets in bubbles near a solid boundary which cause the actual material damage. So far the model was only implemented using time



averaged and pixel-wise greyscale fluctuations for the evaluation of the vapour fraction variations and only applied to one type of experiment, i.e. shedding cloud cavitation at hydrofoils. This paper presents a first application and assessment of the model for the conducted erosion test series.

2. Experimental Setup

The test series were conducted in the cavitation rig K26 at the hydraulic laboratory of the Technical University of Munich in Obernach. The closed circuit system contains about 12 m³ test fluid (filtered tap water) and features a 90 kW powered impeller for flow generation as well as vacuum pumps for the regulation of the system pressure. The test section had 30 cm x 30 cm cross section and 200 cm length. The approach flow velocity was controlled by LDA measurements (TSI LDA) in the center of the first third of the test section length. The system pressure was referenced at the equivalent position by piezo pressure transducers (Kistler Piezo). Furthermore the test fluid tensile strength was measured by vorto-tensimeter [5] and aeration and degassing procedures prior to the actual test assured equivalent tensile strength during the measurement campaigns. Additionally temperature and dissolved oxygen content were measured (WTW Oxi).

To create the intended cavitation phenomena a rectangular prism (height 97.5 mm) with an equilateral triangle base (side length 75 mm) was mounted in the middle of the test section with one corner pointing in opposition to the flow direction. The setup enabled the generation of minor tip vortex cavitation up to super cavitation with > 1 m length extension in the whole wake of the prism. For cavitation numbers of about 1.5 ± 0.5 transient cavitation clouds appeared in the triangle wake's shear layer vortices and resulted in cavitation erosion in the respective areas. Figure 1 illustrates the test setup and the resulting cavitation and cavitation erosion pattern. Test series were conducted for approach flow velocities between 9 m/s and 14 m/s.

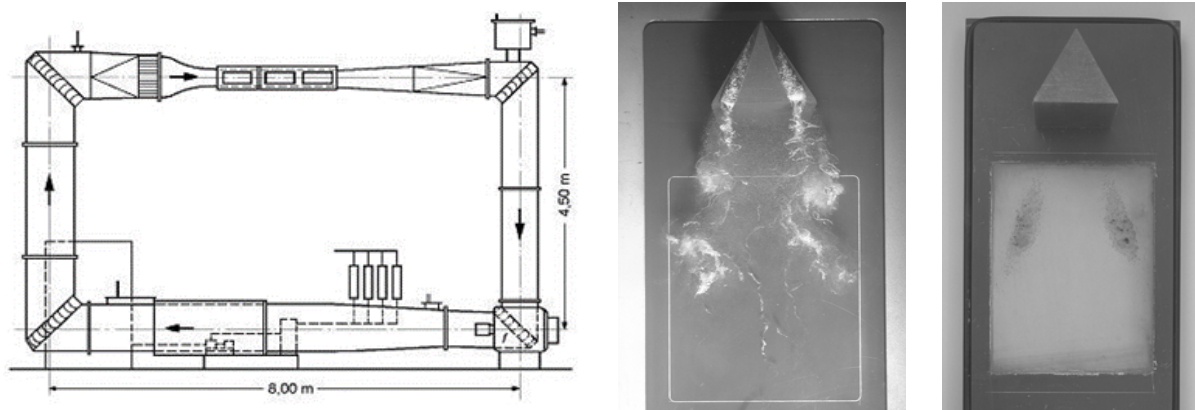


Figure 1: Schema of the test facility K26 (left), cloud cavitation behind the prismatic body in the test section (middle, flow direction top bottom) and the resulting erosion pattern on a cement probe (right)

The cavitation erosion was measured by several complementary methods. Using concrete material probes the position and size of the resulting erosion pattern was recorded by 3D laser profilometry (Micro-Epsilon measurement device and Berger-Lahr stepper motor positioning device and 0.1 mm overall accuracy). A competitive record of the eroded volumes was conducted using a volume substitution method [6], i.e. the filling of the erosion pattern by a compound of known density and the calculation of the respective volume via mass measurements (Sauter, 0.01 mg accuracy). Furthermore, a 2D pit count technique was employed [7]. The microscopic ductile deformations (“pits”) of polished stainless steel (V4A, HV10: 181) were measured by microscopic image acquisition (1.8 μ m resolution) for the whole eroded area (~ 15 cm²). Using an automated positioning (Berger-Lahr stepper motors, μ m accuracy) and image processing (LabVIEW based) the pit areas and the pit numbers could be deduced for the whole probe surface in order to identify the location of

cavitation erosion and to quantify the erosion rates in terms of the pitted area or equivalently the pit number per exposure time.

The quantification of the cavitation cloud volume and their dynamics was based on a simplified optical approach employing a CMOS digital camera (Edmund Optics, 1.3 MP, b/w) and stroboscopic illumination (DrellScop 2008). Optical access to the experiment was provided by acrylic glass in top view of the prism. The adjustment and synchronization of frame rate, exposure time and stroboscope frequency could achieve series of non-continuous but time resolved cavitation cloud images. In each tests series 1000 to 5000 images were taken. A subsequent image processing (LabVIEW based) was employed to obtain the cloud projection surface (i.e. the size of the cloud on the image) as gauge for the total cloud size.

Whereas the simplified cloud volume assessment on basis of only one perspective is in general not capable to deduce the total cloud volume because of the complex vapor structures and dynamics, the given type of cavitation cloud patterns were known from exemplary high-speed imaging [6] and the implemented approach was found suitable for an assessment of the cloud size characteristics.

3. Results

The cement based volume loss as well as metal based pit count method showed similar erosion patterns. The coordinates of the centers of erosion were constant throughout the exposure times and identical for both employed measurement techniques. In detail the exposure times were adapted to the probe material and to the respective hydraulic conditions in order to achieve erosion extents suitable for the employed measurement techniques and ranged from five minutes for high approach flow velocities up to two hours for low flow velocities. The erosion rate for volume loss of cement probes showed a magnitude from several hundred to several thousand mm³/h. The pit count method showed average pit radius of 20 μm and an exponentially decreasing relation between pit radius and pit numbers. The competitive analysis of erosion rates by pitted area and pit numbers yielded comparable results.

For tests with identical flow velocities both measurement techniques, cement based as well as metal based one, showed maximum erosion rates in the area of a cavitation number $\sigma = 1.5 \pm 0.1$ and monotonously decreasing values for higher or lower cavitation numbers. Considering the velocity scale effect both techniques confirmed a high increase of the erosion rate with increasing approach flow velocity. Figure 2 shows a 3D visualization (surface and contour lines) of the dependency of the erosion rate on flow velocity and cavitation number for the volume loss method. Considering the velocity scale effect the erosion rate of cement probes, i.e. the eroded volume per exposure time yielded best fits for the ninth power of the velocity. The equivalent relation for metal probes revealed best fits for the sixth power of the velocity.

The analysis of the cloud size was based on the average value of the cloud projection size. The standard deviation of the cloud projection for all clouds of one experimental setup was used to quantify the cloud size fluctuations. The average cloud projection size decreased with increasing cavitation number which is coherent with the cavitation number definition. The standard deviation of the cloud sizes i.e. the cloud fluctuations showed a local maximum in the vicinity of $\sigma = 1.4$ to $\sigma = 1.5$. Both relations are illustrated in figure 2 for an exemplary approach flow velocity of $v = 9.2$ m/s.

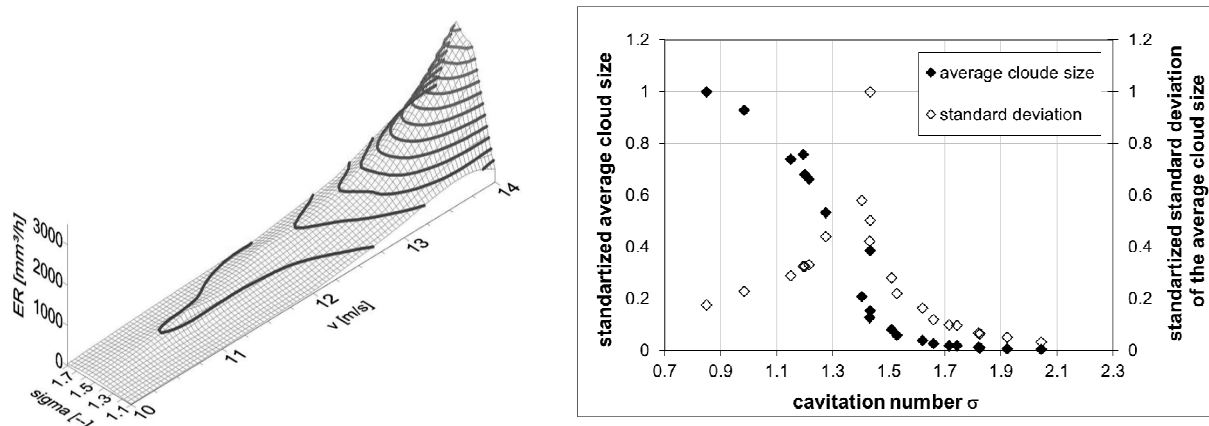


Figure 2: Dependency of erosion rate ER on flow velocity v and cavitation number σ (left) and dependency of average cloud size and its fluctuations on the cavitation number for $v = 9.2$ m/s (right)

4. Conclusion

The obtained erosion data quantifies the velocity scale effect for the underlying cavitation type for both employed measurement techniques. The pit count results are coherent with literature references [2]. The diverging scale effect for the cement material indicates a significantly different damage process for this type of compounds and their higher vulnerability face to hydrodynamic cavitation load, similar to recent finding about damage process material dependencies for further materials [8]. The investigation of the cavitation cloud size and its fluctuations revealed maximum cavitation cloud fluctuations for those hydrodynamic conditions which were also related to the highest erosion rates. This finding corresponds to the cavitation cloud erosion model hypothesis [4] and thus suggests its suitability for the given cavitation phenomenon.

In following research projects the cavitation cloud size will be recorded time resolved and volumetric by use of several high speed cameras to verify the suitability of the erosion model in detail. The time resolved investigation will also gain insight to the underlying processes of the velocity scale effect. Furthermore a simultaneous microscopic observation of the cavitation load on the surface is intended to obtain information about the actual damage process.

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