OPEN ACCESS

Optical diagnostics for high power pulsed underwater electrical discharge characterization

To cite this article: J Deroy et al 2014 J. Phys.: Conf. Ser. 500 142010

View the article online for updates and enhancements.

You may also like

- Streamer propagation and pressure waves produced by a nanosecond pulsed surface sliding discharge: effect of the high-voltage electrode shape E Moreau, K Bayoda and N Benard
- Numerical simulation of streamer, pressure wave, and vortex induced by nanosecond pulsed surface dielectric barrier discharges Jiao Zhang, Weiwei Tang, Yanhui Wang et al.
- <u>Performance of a cryogenic system</u> prototype for the XENON1T detector E Aprile, R Budnik, B Choi et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 18.216.190.167 on 03/05/2024 at 16:29

Optical diagnostics for high power pulsed underwater electrical discharge characterization

J Deroy¹, A Claverie², G Avrillaud¹, M Boustie², E Mazanchenko², D Assous³ and A Chuvatin⁴

¹Bmax, 30 bd de Thibaud, 31104, Toulouse, France,

² Institut PPRIME, UPR 3346, CNRS-ENSMA-University of Poitiers, B.P.40109, 86960, Futuroscope, France

³ IDIL, Rue Claude Chappe, 22300, Lannion, France,

⁴ LPP, UMR 7648, CNRS-Ecole Polytechnique, Route de Saclay, 91128, Palaiseau CEDEX, France

E-mail: Julien.D@bmax.com

Abstract. In order to evaluate the behavior of a high power pulsed underwater electrical discharge, and especially characterize the pressure generated by such a discharge, we implemented several optical diagnostics. We first observed directly the expansion of the plasma produced by the dielectric breakdown of the water between the electrodes and the resulting gaseous pulsating bubble. This observation led to an estimate of the pressure inside the bubble with respect to time. We then visualized the propagation of the pressure wave generated by the discharge with shadowgraph and Schlieren setup. The obtained velocity was then used to evaluate the theoretical maximum pressure at the pressure front. Finally, we measured the velocity induced by the pressure wave on a thin aluminum disk with a heterodyne velocimeter and used numerical simulation to obtain a temporal form of pressure. These methods and results can be used to develop and assess performances of processes using underwater electrical discharges to generate pressure waves such as electrohydraulic forming.

1. Introduction

High pulsed power systems have been used in a variety of scientific and industrial applications for many years. One of these consists in the generation of an electrical discharge in water in order to produce a strong dynamic pressure wave. This technique has especially been used in the manufacturing industry [1], enabling the forming of complex shapes at high speeds since the 1950-1960, following the work of Yutkin [2]. Processes optimization is still needed and is related to a better understanding of the dynamic behavior of materials but also to the generated pressure characterization. One of the characterization methods uses post experiment deformation measurement to assess process efficiency but it inherently lacks in useful information about the pressure wave dynamic. Therefore, pressure sensors, which are acoustic to electrical signal transducers, are used to measure the pressure wave temporal shape. However, the use of pressure sensor is not straightforward as most of them are sensitive to the strong electromagnetic field generated by the discharge and their bandwidth is not adapted to the pressure rise time or their structural response quickly prevents a correct readout, precluding a proper recording of the pressure decaying phase.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution $(\mathbf{\hat{H}})$ (cc) of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1

The aim of our study was to address some of the processes associated with the electrical to mechanical energy conversion. To do so, we first used a set of three cameras to observe the evolution of the conductive channel radius during the energy deposition phase, the following bubble expansion/compression phase and also the propagation of the pressure wave generated by the discharge. We then used an indirect pressure measurement by coupling a heterodyne velocimeter to the numerical simulation of the process.

2. Experimental setup

To induce electrical discharge in water, we used an electrical generator with a capacitive storage of up to 16.65 μ F that can be charged up to 40 kV. During the charging phase, the generator is isolated from the discharge electrodes by a pressurized air switch. Then, the switch closure brings a high enough voltage to the two electrodes immerged in water so that a dielectric breakdown occurs. This breakdown creates plasma in which the stored electrical energy is quickly deposited, typically on the order of tens of microseconds. This rapidly expanding plasma vaporizes the surrounding liquid water and those two phenomena generate a strong propagating pressure wave in water due to its low compressibility.

The electrical energy deposition is monitored by a Northstar VD-120B-10 voltage divider with a ratio of 1:10000 V/V, a 15 MHz bandwidth and a maximum tension of 120 kV AC/DC. This probe is coupled with a pulsed current transformer 3-0.002 from Stangenes with a 500 A/V ratio, a 100 ns rise time and a maximum peak current of 200 kA.

The cameras we used were chosen to best render each of the phases we needed to observe. During the first tens of microseconds, corresponding to the energy deposition phase, we used an intensified CCD camera Princeton PiMax 1K, with intensifier Gen2 to directly visualize the discharge channel expansion. This camera has 1024×1024 imaging pixels and a 16 bits depth for intensity sampling. These features come with a limited sampling frequency (1 Hz) allowing us to record only one frame per discharge. We therefore made sure that the energy deposition was repeatable so that we could reasonably expect to get the same behavior from multiple discharges. The strong initial brightness enabled us to avoid the use of a backlighting source and the exposure time was reduced to 2 ns to avoid saturation and make use of the 16 bits sensor depth.

For the expansion/compression phase of the generated gas bubble, which takes place in a few milliseconds, we chose a high speed Photron APX RS3000 with a sampling frequency ranging from 3-250 k frame/s depending on the chosen resolution. This camera was coupled to a backlighting in order to observe the whole bubble because only the central part of it emits light.

The last camera we chose was an ultra high speed Shimadzu HPV-2, with a 312 x 260 imaging pixels CCD sensor and up to one million frames per second acquisition rate coupled to a Schlieren or shadowgraph setup to study pressure wave propagation, the arrangement of which is shown figure 1.



Figure 1. Optical arrangement of a Schlieren setup.

Lastly, a heterodyne velocimeter from IDIL was used to indirectly retrieve the pressure generated by an electrical discharge as we measured the speed of a thin aluminum flyer put in motion by an incoming pressure wave in water. This flyer was chosen very thin, 50 μ m, so as to minimize response time and large, 50 mm of diameter, so as to free the measurement from 2D effects for several microseconds, which is enough in our case to determine the pressure wave decay time constant.

3. Results and discussion

3.1. Conductive channel expansion phase

The pictures shown in figure 2 were acquired after a 1.5 kJ discharge in a point-point electrodes configuration with a 10 mm gap. They showed that the cylindrical geometry chosen for the simulation of the conductive channel phase is justified. This hypothesis allowed simplification in the expression of the electrical resistance calculation. Moreover, Timoshkin and al. [3] referring to the work of Hammond [4], stated that a spherical bubble of the same volume can be used for the expansion phase because the two shapes are equivalent in terms of maximum pressure if the measurement is made at least at half the cylindrical charge height. In our case it corresponded to a 5mm stand-off from the discharge channel, condition that was met because we measured the pressure several centimeters away from the discharge.



Figure 2. Conductive channel expansion observed with the ICCD.

The model we used to correlate the measured energy deposition E to the discharge channel radius R was the one presented by Timoshkin [3], where they considered the plasma as a perfect gas, the expansion rate of which is slow compared to the sound speed in water. They also neglected radiative and conductive heat transfer as well as the influence of hydrostatic pressure and other negligible terms. From these hypotheses and the equations of conservation of mass, energy and momentum, one gets equation (1): $R^3 \left(\frac{3\gamma}{2}\dot{R}^2 + R\ddot{R}\right) = \frac{3(\gamma-1)}{4\pi\rho_0}E$; where γ is the heat capacity ratio and ρ_0 is the standard liquid water density.

As depicted in figure 3, the measured radius was smaller than the simulated one from equation (1) by 20 to 40 %. This discrepancy can be explained by the fact that we only saw the channel part that was hot enough to emit light when the energy was used to expand the whole system, comprising the conductive channel and the surrounding cooler gas bubble that grew bigger with respect to time.



Figure 3. Comparison between the measured channel radius with ICCD and the calculated one.

3.2. Bubble phase expansion after energy deposition

As we just shown, the accurate measurement of the expansion of a bubble containing a mixture of plasma, atomic gas and water vapor was rather difficult based solely on the light that was emitted by

the bubble hottest part. In the following, a backlighting source was used to overcome this issue. By increasing the camera exposure time due to the overall lower brightness we could therefore capture the whole bubble at later time. As can be seen in figure 4, the volume occupied by the non luminous bubble part prevails once the energy deposition phase has ended.



Figure 4. Bubble expansion after the energy deposition as observed by the high speed camera.

For each experiment, we analyzed the pictures and extracted the bubble radius assuming a spherical symmetry. An example of the results is shown in figure 5, with a polynomial fit extrapolating the missing data where the only additional constraint was a null initial radius.



Figure 5. Comparison between measured and simulated bubble radius and simulated pressure.

From the bubble estimated period τ , the bubble energy was determined with equation (2) given by Willis [5]: $E = \frac{\tau^3 P_0^{2.5}}{1.14^3 \rho_0^{1.5}}$ where P_0 is the atmospheric pressure in normal conditions. This formula led to the underestimation of the bubble energy (E=52.7 J) whereas the measured one with our electrical diagnostics was E=111.6 J. This discrepancy is most likely due to the fact that this formula is relevant to a bubble generated far from any interface, whereas the free surface and walls stood at 23cm from the bubble center. These interfaces modified the flows due to the reflection of the generated pressure wave. A simulated radius from equation (1) is shown in figure 5 where the energy deposition was cut once the estimated bubble energy from the camera was reached. Given the fact that the simulated radius agrees well in terms of maximum radius and period with the measured one, this cut-off criterion is an appropriate way of taking into account the discharge chamber finite size. A simulated internal pressure from equation (3): $P = P_0 + \rho_0 \left(\frac{3}{2} \dot{R}^2 + R\ddot{R}\right)$ is shown in figure 5 on the secondary axis on a logarithmic scale.

3.3. Visualization of pressure wave propagation

The pressure wave generated by the electrical discharge in water modifies the density of water during its propagation, therefore changing its optical index as stated by the Gladstone-Dale law. Those changes in optical index were observed thanks to the Schlieren [6] or shadowgraph [6] technique. An example of pictures obtained in Schlieren configuration is shown in figure 6.

Journal of Physics: Conference Series 500 (2014) 142010



Figure 6. Visualization of pressure wave propagation with Schlieren configuration from figure 1.

Depending on the measured propagation speed D, the maximum pressure is obtained using an approximation of the Rankine-Hugoniot relationships, giving equation (4): $P \approx \rho_0 \frac{D(D-c_0)}{s}$, where c_0 is the sound speed of water at rest and s is the shock Hugoniot slope and $D = c_0 + su$, where u is the material speed. This method allowed us to estimate pressure comprised between 228 bars and 1898 bars depending on the initial energy stored, at a distance of 8 to 15 cm. The main drawback of this method was a quite high uncertainty, between 27 and 83 % depending on the configuration, mostly due to the limited "spatial resolution/acquisition frequency" trade-off. Those uncertainties were too high to characterize the phenomenon so this diagnostic was mostly used as an "order of magnitude" pressure estimate rather than a qualitative one. Nevertheless, these pictures helped us understand how the pressure wave interacted with surrounding objects, such as the structure of the pressure sensors we used, which was useful during the obtained signals post processing.

3.4. Indirect pressure measurement with heterodyne velocimetry

The indirect measurement of pressure presented in the second part has the advantage of having a shorter response time than most piezoelectric transducers, whose drawbacks were studied by Grinenko and al. [7] or Sayapin and al. [8]. However, it required a numerical simulation in order to obtain the pressure. This task was performed using LS-DYNA[®] where the system was modeled with a 2D axisymmetric approach. The applied pressure was constrained to a temporal evolution in the form of equation (5): $P = P_{max} exp(-t/\tau)$, where P_{max} and τ were adjusted to fit the resulting measured speed at the flyer center.



Figure 7. Comparison between measured and simulated velocity at the flyer center, time reference at the maximum speed.

In figure 7, matching between the measured and simulated velocities can be seen for the maximum speed and decay time for a maximum input pressure of 100 bars and a pressure decay time of 6 μ s. The two other features that were not well rendered were the measured velocity rise time and the secondary peak around 7 μ s. The rise time in the simulation was only slower due to the mesh size chosen to model water in order to have a reasonable computation time. A mesh convergence showed that sufficiently dense mesh rendered the actual rise time but ours does not affect maximum pressure

or decay time. The secondary peak was only a reflection on the structure holding the flyer in water and did not represent a feature of the pressure wave itself so it was not relevant to try fitting it better to the experiment. As simple geometrical calculation showed, considering a spherical propagating wave, an angle of only 10° compared to a flyer perfectly perpendicular to the discharge center axis explained the time delay between the simulated and measured secondary peak.

4. Conclusions

We described and analyzed a variety of optical diagnostics used to characterize pressure waves generated by pulsed electrical discharge in water. Those diagnostics were separated between the imaging and indirect pressure measurement techniques. Imaging diagnostics gave rough estimates on quantity of interest, due to rather high uncertainties. Indirect pressure measurement technique, using a heterodyne velocimeter, displayed interesting features: a short rise time, an immunity to electrical charges generated by the discharge and a higher maximum pressure levels as the flyer was the only deformed part. This last feature was also its main drawback as a new flyer was needed each time we made a new experiment.

Acknowledgments

We would like to thanks the PPRIME Institute and IDIL for valuable advice and for helping us by providing the optical diagnostics shown in this study.

References

- [1] http://www.bmax.com/technology/electro-hydraulic-forming/
- [2] Yutkin L A 1961 *Electrohydraulic effect* Foreign Technology Div Wright-Patterson Afb Ohio (No. MCL 1207)
- [3] Timoshkin I V, Fouracre R A, Given M J and MacGregor S J 2006 J. Phys. D. Appl. Phys. 39 4808
- [4] Hammond L 1995 Aeronautical and Maritime Research Laboratory Report DSTO-GD-0029 (Melbourne, Australia)
- [5] Willis H F 1941 British Report WA-42-21
- [6] Prenel J-P and Smigielski P 1999 *Techniques de l'ingenieur CND: methodes surfaciques* Editions T.I. af3332
- [7] Grinenko A, Gurovich V T, Krasik Y E, Sayapin A, Efimov S and Felsteiner J 2004 Rev. Sci. Instrum. 75 240-244
- [8] Sayapin A, Grinenko A, Efimov S and Krasik Y E 2006 *Shock Waves* **15** 73-80