

The floating water bridge

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Abstract

When high voltage is applied to distilled water filled in two glass beakers which are in contact, a stable water connection forms spontaneously, giving the impression of a floating water bridge. A detailed experimental analysis reveals static and dynamic structures as well as heat and mass transfer through this bridge.

1. Introduction

Water undoubtedly is the most important chemical substance in the world. Many attempts have been made to measure or calculate the structure of liquid water beyond the scale of the H₂O molecule. This is a difficult task because of the hydrogen bonding network which itself is a subject of various experimental and theoretical studies. It is being held responsible for many of water's special properties and is also the reason why water must not be treated as a simple liquid [1, 2]. The interaction of water with electric fields has been intensely explored over the last years, e.g. in context with electrospray-ionization mass spectroscopy (ESI-MS) [3], but also unusual phenomena have recently been reported, e.g. the electric field driven self-propulsion of a water droplet on a solid surface [4]. In this paper we report another unusual effect of liquid water exposed to a dc electric field: the floating water bridge. The first presentation of the water bridge was published by the ETH Zürich via the worldwide web [5].

2. Experimental details

The set-up consists of two beakers (100 mL) filled with triply deionized water. When exposed to a high dc voltage by putting electrodes into the beakers, water forms a stable, cylindrical bridge between the two beakers. For the experiments presented herein the beakers were set on an even plane, one was fixed, the other movable and controlled by a step motor, and both beakers were separated by 1 mm. The beakers were filled with triply deionized water ($R = 18 \text{ M}\Omega \text{ cm}$) such that the water surface was about 3 mm below the beaker's edge. Now one electrode was charged with 15 kV, the other was

set to ground potential. A Phywe 'Hochsp.Netzger. 25kV' (Order No 13671.93) or alternatively a high-voltage generator using a Linfinity SG3524 pulse width modulator was used with a 24 nF ceramic capacitor set parallel to the electrodes. The voltage was measured by a potential divider of 500 M Ω /500 k Ω to ground level. Since the voltage generators provide a limited current output, the electric current, which was measured with an oscilloscope, was stable at 0.5 mA. After a short electric discharge, which was build up between the two water surfaces, a water connection formed spontaneously between the two beakers; the water moved up the glass walls and built a water bridge. This effect is shown in figures 1(a) and (b).

All experiments were performed under normal laboratory atmosphere using triply distilled water.

High speed visualization was done using a colour Kodak Motion Corder SR-Series 1000 (Eastman Kodak Company, San Diego, California), including a second on-board storage and a 8–48 mm zoom objective. For direct and indirect illumination two 24 V/150 W halogen lamps were used.

For visualization of high frequency density oscillations inside the bridge a green Laser Pointer (Leadlight Technology Inc., Tao-Yuan, Taiwan, 5mW Series GLP-C0P1-05) was used.

To record the surface temperature along the water bridge, an Inframetrics Model 760 Infrared Thermal Imaging Radiometer (Inframetrics, North Billerica, Massachusetts) was used, including a 20° IR lens. Operated at a 50 Hz mode and in the 8–12 μm standard range, every 4 frames were averaged for the evaluation presented in figure 2. In order to calculate the water surface temperature from the IR emission, an emissivity value of 0.96 was assumed for the distilled water.

For Schlieren visualization a standard Schlieren set-up was used, including a 200 mW argon-ion laser (ILT 5490, Ion



Figure 1. Water bridge formation: (a) rise of water in both beakers after a high voltage was applied and a first ignition spark was observed, (b) spontaneous formation of a connection which remains stable after (c) pulling the beakers apart.

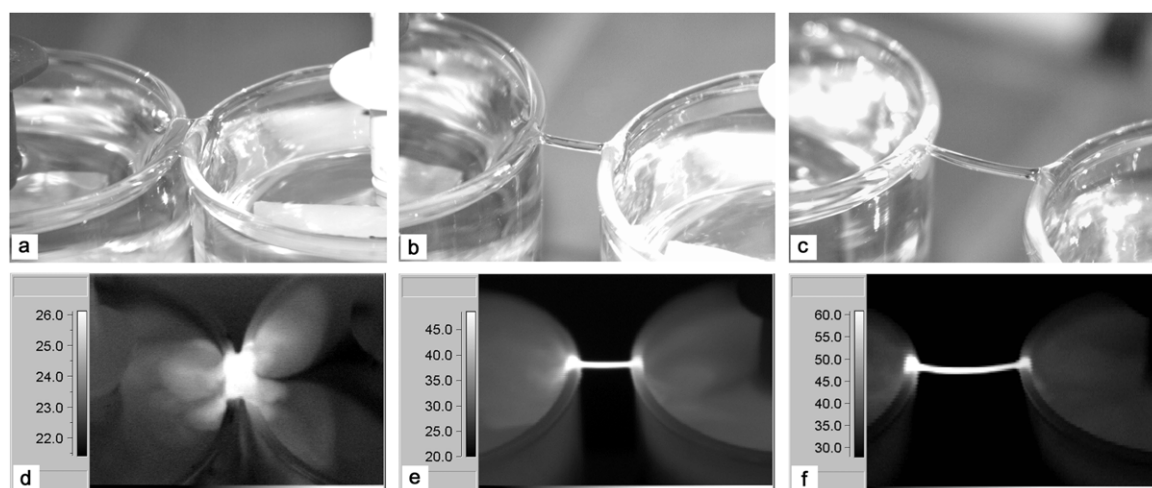


Figure 2. Thermographic visualization of the water bridge. Immediately after the formation of the bridge (a) a slightly raised temperature (26 °C) was observed (d), after 15 min of operation and a length of 10 mm (b) a higher temperature (46 °C) was measured (e). With a longer, but thinner bridge ((c), 15 mm length) the local surface temperature increases up to 60 °C with ‘hot spots’ at thinner diameters (f).

Laser Technology, Salt Lake City, Utah) operated in the multiline mode and a 20 \times microscope objective together with a 12.5 μ m pinhole as the light source. The optical path was formed by two folding mirrors (plane, $\lambda/1$ surface, 80 mm diameter) and two spherical mirrors (focal length 1524 mm, $\lambda/1$ surface, 150 mm diameter) in a symmetric optical arrangement, with a parallel beam in the test section. The recordings in figure 3 were done using no Schlieren stop, the Kodak Motion Corder described above and an additional cylindrical lens (focal length 150 mm, 50 mm diameter) placed in the optical path right after the water bridge. This additional lens was used to compensate for the diffraction by the cylindrical geometry of the water bridge and enabled a visualization of inner structures deflecting light in the lateral direction.

3. Results and discussion

Almost no electrolysis was observed and the bridge did not form, respectively; it was destroyed when ions were added to the water or if water of higher conductivity was used. With glass beakers of 6 cm diameter, the bridge had a cylindrical form with a diameter of 1–3 mm. If the movable beaker was pushed away from the fixed one, the bridge remained intact up to an extension of 25 mm if the voltage was raised to 25 kV (figure 1(c)).

When the voltage is shut off instantaneously, the surface tension turns the bridge into a series of falling droplets.

The bridge is also highly sensitive to additional external electric fields. When an electrostatically charged glass rod was brought close to the bridge, the polar water molecules were aligned due to the inhomogeneous electrostatic field of the surface charges on the rod, resulting in an attractive force between the rod and the bridge. This caused the bridge to bend towards the glass rod forming a water arc.

Independent of the length of the bridge, an effective transport of water from one vessel to the other was observed, usually from the anode to the cathode beaker. Generally the direction of mass transport cannot be predicted. The bridge was stable up to 45 min but eventually broke down. This is probably due to the heating of the water within the bridge. Using a thermographic camera system a heat and mass transfer between the two beakers was visible. The surface temperature of the water was about 20 °C in the beginning (figures 2(a) and (d)) and rose above 60 °C after 30 min of operation and extended the bridge length (figures 2(b), (c), (e) and (f)). Note the different temperature scales in figures 2(d)–(f)). The highest temperature was reached at the smallest bridge diameter. Low frequency oscillations of the heat and mass transfer were observed along the bridge.

While low frequency oscillations were observed using a high speed camera system and turned out to be surface waves, a laser illuminated Schlieren visualization revealed additional inner structures oscillating inside the bridge at frequencies above 3 kHz. These high frequency oscillations were also affirmed by a green Laser Pointer focused by the cylindrical bridge forming a light sheet which oscillated in the lateral

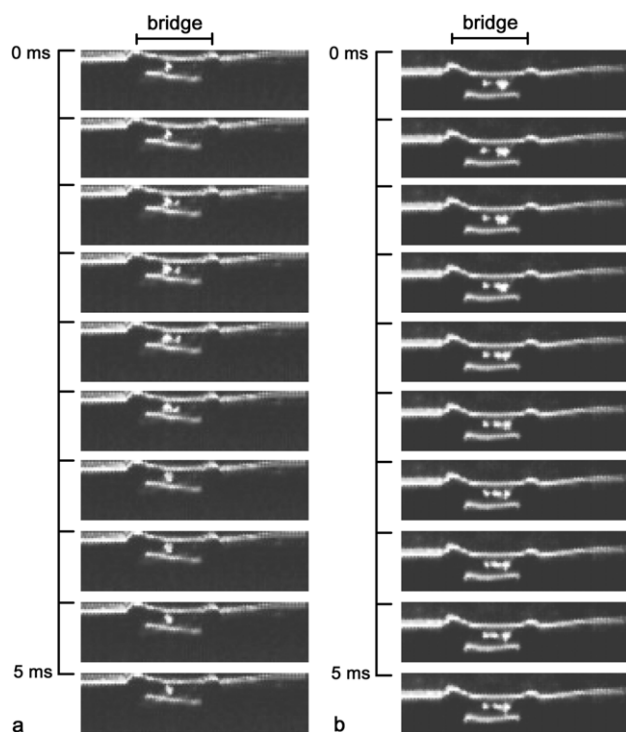


Figure 3. Density gradients within the water bridge, recorded with a high speed camera at a 10 kHz frame rate (1/20 000 s exposure time), every 5th image is depicted. (a) shows a single structure typical for a ‘young’ bridge (5 min operation time). (b) shows multiple structures (after 30 min operation time). In these images, the length of the bridge was approximately 10 mm.

direction at high frequencies. In combination with a high speed camera system the Schlieren visualization showed these inner structures in detail (figures 3(a) and (b)).

These structures were recorded with a 10 kHz frame rate (1/20 000 s exposure time), and every 5th image is depicted in figure 3. In this type of visualization density gradients deflecting a parallel light beam in the horizontal direction became visible. The light refraction by the cylindrical geometry of the water bridge was compensated for by an additional external cylindrical lens. The lateral gradients deflected the parallel light beam, forming focal spots in front of the bridge. These spots are visible in figures 3(a) and (b) for two different operation times after the start-up of the bridge. Obviously, the surface waves which are likely to be caused by the surface tension were much slower than these moving inner structures. The high frequency oscillation of these inner structures were probably triggered by the waviness of the voltage supply, which is caused by the pulse width modulator, but smoothed by the capacitor. In every experiment, first a single inner structure can be observed, then additional structures appear after a few minutes of operation. This decay might be caused by the increasing temperature of the bridge or by dust particles contaminating the water during operation. Adding a watery solution of soap enforced this structural decay and besides the bridge became substantially thinner and disrupted in due course forming small droplets. From a stereoscopic observation the focal point formed in a parallel light beam by the lateral structure in figure 3(a) was located in space and the gradient in the refractive index

estimated using the approximate focal length assuming a cylindrical symmetry. Together with the Gladstone Dale constant for water ($2060 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$) and the Clausius–Mosotti equation, a density change from the beaker edges towards the centre of the bridge in the range of 7% was found, in relation to the density of water at room temperature (998 kg m^{-3}). A possible explanation for this density change is an arrangement of the water molecules to form a highly ordered microstructure.

4. Conclusions

It is reasonable to presume that the bridge forms between the two beakers due to the electrostatic charges on the water surface [6] producing a ‘cone-jet’ as described by Hartman and co-workers [7–9]. Using a high starting voltage and due to the high dielectric constant of water, the electric field concentrates inside the water arranging the water molecules to form a highly ordered microstructure. This microstructure remains stable after the connections forms. Wider bridges therefore need higher voltages to obtain a stable equilibrium between the surface tension and the ordered dipole–dipole bonding force caused by the high electric field. Assuming microstructures in liquid water as proposed by Head-Gordon and Johnson [10], the high electric field could enforce smaller intermolecular distances leading to the density change observed in the experiments presented.

An addition of ions distorts the structure due to the attraction between ions and water molecules. So, the build-up of hydrospheres around the dissolved ions is responsible for the instabilities or the break-up of the bridge in that case. Thus, adding a surfactant leads to an enforced structural decay and a lower surface tension. Both effects result in instability and disruption as described above.

Due to the small-scale auto-protolysis there is a small conductivity ($R = 18 \text{ M}\Omega \text{ cm}$) and an electric current flows through the bridge which in this case acts as a resistor and slowly heats up, with the thermal excitation disturbing the hydrogen bonding and enforcing decay.

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