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Oscillate Boiling from Electrical Microheaters

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Oscillate boiling offers excellent heat transfer at temperatures above the Leidenfrost temperature. Here we realize an electrical microheater with an integrated thermal probe and resolve the thermal cycle during the high-frequency bubble oscillations. A thermal rate of 10^8 K/s is found, indicating its applicability for compact and rapid heat transfer from microelectrical devices. We also report another oscillate-boiling regime occurring at lower heating power where the oscillation becomes unstable and halts after several milliseconds.

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I. INTRODUCTION

The boiling crisis is one of the most challenging problems among thermal and fluidic instabilities [1]. It occurs when the heat fed into a boiling heater overcomes a threshold and the nucleate-boiling bubbles merge into a vapor film. At that moment, the liquid loses direct contact with the heater [2] because the vapor layer has a greatly reduced heat transfer coefficient. As a result, the heater's temperature rises, which may lead to thermal-induced breakdown of the heater. Research has extended the limits of the boiling crisis by microstructuring the substrate [3–8] or adding nanoparticles to the liquid (nanofluids) [9–12].

Recently, Li *et al.* [13] reported a new boiling regime that might allow the boiling crisis to be overcome through stable localized heating (i.e., the *oscillate-boiling regime*). Their finding was that bubbles at the heater undergo stable high-frequency oscillations while remaining pinned. In particular, the bubble does not grow over time. This is achieved by the shedding of excess amount of gas and vapor by pinching off a microbubble during each oscillation. Additionally, a large-scale flow is generated that cools the substrate, thereby keeping the temperature distribution localized to the heater. The key feature to generate the oscillate-boiling regime is a miniature and localized heat source. A typical size of the heater to operate in water is about $10\ \mu\text{m}$ in diameter. Previously this was achieved by tightly focusing of a continuous-wave laser beam onto an absorbing substrate made of gold nanoparticles [13].

Yet, the use of laser light as a heat source has two drawbacks: Firstly, because of optical loss from the focusing optics and through reflections at the gold layer, only about 20% of the laser power remains available for heating. Secondly, the optical setup to generate more than one bubble becomes rather complex and rules out practical scaling up of the phenomenon. In the present work we overcome these two restrictions (efficiency and scalability) by demonstrating that oscillate boiling can be achieved with an electric heater. The additional benefit is the ability to measure the instantaneous temperature of the heater to elucidate the complex fluid mechanics in the oscillate-boiling regime.

Electrical miniature heaters have attracted much attention [14–19]. They were used to create and study the dynamics of conventional nucleate boiling, where the liquid is heated rapidly above the spinodal limit, leading to an explosive vaporization. We are not aware of reports demonstrating a stably oscillating bubble characterizing the oscillate-boiling regime.

II. MATERIALS AND METHODS

A. Electrical microheater

We design and fabricate a miniature heater to achieve the aforementioned temperatures on a sufficiently small scale. The heater consists of a 50-nm-thick platinum (Pt) layer deposited on a 200- μm -thick glass substrate. The heater is contacted with a 600-nm-thick gold layer deposited by magnetron sputtering [Fig. 1(a)]. The gold electrodes have a high electrical conductance and large cross-section area to ensure a current supply with little resistive loss. In contrast, the high resistance from

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FIG. 1. Design of the electrical microheater. (a) The fabrication process. The platinum heating layer is deposited on top of a glass substrate, followed by the gold-electrode layer. (b) The four-probe structure used to measure the heater's resistance. (c) Captured image of the microheater. The scale bar represents 20 μm .

the thin $15 \times 15 \mu\text{m}^2$ Pt heater creates a very localized heating—approaching the conditions of the laser-focus-based heater [13]. Before the experiment, a numerical simulation is performed to compare the thermal profile of an electrical heater with that of the prior laser-based heater. For the former, the electric current and Joule's equation are solved simultaneously with the heat transfer equation. In the latter, the laser-focused point is represented by a solid heat source at the gold surface and only the heat transfer equation is solved. The equations are solved with finite-element methods using the commercial software package COMSOL MULTIPHYSICS. The temperature distribution presented in Fig. 2 reveals close similarity between the two heating methods. This gives us confidence that the electrical microheater could perform very similarly to its optical counterpart.

To measure the instantaneous temperature of the heater, the temperature-dependent electrical resistivity of platinum is used. Besides its relatively high resistivity, platinum also has a nearly constant thermoresistance coefficient up to 500 $^\circ\text{C}$ [20]. The temperature-resistance

FIG. 2. Thermal profile of (a) an electrical heater and (b) a laser-induced heater with the same size and power.

dependency of the heater is

$$R = R_0[1 + \alpha(T - T_0)], \quad (1)$$

where R_0 and R are the initial and current resistance, respectively, T_0 and T are the initial and current temperature, respectively, and α is the temperature coefficient of resistance, which is calibrated to $1.023 \times 10^{-3} \text{ K}^{-1}$ (see Appendix A for the calibration result for the electrical heater). The resistance R to determine the temperature T is obtained from two additional probes measuring the voltage drop across the heater as shown in Fig. 1(b).

Figure 3 describes in detail the fabrication process for the electrical microheater. Initially, a 4-in.-diameter glass wafer with a thickness of 200 μm is immersed in sulfuric acid (H_2SO_4) at 120 $^\circ\text{C}$ for 30 min for cleaning. Next, the wafer is coated with hexamethyldisilazane for 2 min in a prime oven to improve photoresist adhesion onto the glass surface. Then a layer of 1.5- μm -thick photoresist 7217 (AZ Electronics Materials) is spin-coated onto the substrate at 5000 revolutions per minute for 30 s. Thereafter, the structure pattern on a prepared glass photomask is formed on the coated wafer by exposure to 365-nm-wavelength ultraviolet light for 5 s. This pattern is subsequently developed in an AZ 300MIF developer solution (AZ Electronics Materials) for 1 min (step 1). Afterward, the patterned wafer is coated with a layer of Cr(20 nm)/Pt(50 nm) by a magnetron sputter for 4 min (step 2). The wafer is then immersed in acetone for etching off the photoresist [i.e., lift-off (step 3)], which finishes the deposition of the Pt heating layer. The photolithography and sputtering processes are done one more time to deposit the heater's electrodes composed of a layer of Cr(20 nm)/Au(600 nm) (steps 4 and 5). After the last lift-off step (step 6), the device's fabrication is completed.

FIG. 3. Step-by-step fabrication process for the electrical microheater.

B. Experimental setup

The substrate with the heater is at the bottom of a rectangular acrylic container ($10 \times 10 \times 12 \text{ mm}^3$). Two of the faces of container are replaced with a microscope cover glass to ensure good imaging of the microscopic dynamics. The container is then filled with gas-saturated deionized water to a height of approximately 7 mm. This water is retained at room temperature throughout the experiment (see Appendix B).

The microheater is operated in a constant-current mode with the use of a current controller for laser diodes (Thorlabs LDC 220C). The instantaneous current is measured from the voltage drop across a $10\text{-}\Omega$ resistor connected in series with the heater. The heater's current and its resistance are recorded with a 12-bit oscilloscope (Lecroy HRO 64Zi).

The small size of the bubble and its rapid dynamics demand use of a high-speed camera. We use an SA-X2 camera (Photron), which is operated between 300,000 and 400,000 frames/s with a $20\times$ magnification lens ($20\times$ PTEM M Plan Apo, Edmund Optics). This provides a resolution of $1 \mu\text{m}$ per pixel. Additionally, a hydrophone (model HNR1000, ONDA) is placed near the heater to capture the acoustic signal emitted from the bubble oscillation. The hydrophone is connected to a third channel of the oscilloscope.

FIG. 4. (a) The experimental setup to study the oscillate-boiling heat transfer. (b) Enlarged image of the test section where the bubble is formed on top of the platinum heater.

Figure 4(a) illustrates the setup of the experiment. All electronic components (heater, power source, camera, oscilloscope, etc.) are connected to a common ground to reduce electrical noise. For the experiment, the power source, camera, and oscilloscope are simultaneously triggered with a digital pulse generator (BNC 575, Berkeley Nucleonics).

III. RESULTS

A. Bubble oscillations

After the power source is triggered, an initial vaporous explosion is observed, leaving behind a small bubble in contact with the microheater [Fig. 4(b)]. Within 1 ms, this bubble enters an oscillation state at a fixed frequency. During the collapsing phase of each oscillation, a microbubble is ejected from the apex of the main bubble; the microbubbles are then driven upward due to thermocapillary flow and form a stream of microbubbles. The main bubble then reexpands and a new cycle starts. Figure 5(a) shows frame-by-frame images of one oscillation period of a relatively large bubble for better visualization, while Fig. 5(b) shows a stabler and more-repeatable one. The overall dynamics can also be obtained from the acoustic emission of the bubble. Figure 6(a) depicts short-time power spectra of the acoustic emission recorded with the hydrophone signal. The spectra are plotted as a function of time (spectrogram). The amplitude of the frequency components is indicated by the color: brighter colors depict larger amplitudes. For the hydrophone signal, Fig. 6(a), the fundamental oscillation frequency is about 160 kHz and remains constant over the measurement period. Additionally, a second harmonic at 320 kHz is evident, which is well known for large-amplitude bubble oscillations. In general, the fundamental frequency varies between 90 and 300 kHz as a function of the bubble's size; it increases for smaller bubbles.

FIG. 5. Consecutive images from one period of the oscillation cycle. (a) Images of a relatively large (yet unstable) oscillating bubble to visualize the release of microbubbles in greater detail. (b) Images of a stabler and more-repeatable oscillating boiling bubble. The scale bar represents $20 \mu\text{m}$ and the frame rate is 400,000 frames per second.

FIG. 6. (a) Spectrogram from a typical bubble's emitted acoustic signal recorded with a hydrophone. It reveals a strong fundamental frequency and higher harmonics. (b) The spectrogram of the heater's resistance is recorded simultaneously and shows a very similar power spectrum. The heating power used in this experiment is 86 mW.

B. Temperature measurements

The obvious advantages of an electrical system are its simpler control of the power input and the possibility to monitor the instantaneous heater temperature during the bubble oscillation. Figure 7(a) depicts such a recording. The signal consists of a series of cycles with a fast downward spike connected with a positive-sloped signal of increasing temperatures in between. Figure 7(b) depicts an enlarged view of the thermal signal [see the dashed line in Fig. 7(a)] together with frames from a synchronous high-speed recording. The frames are recorded at the center of each interval indicated by the vertical lines (e.g., frame C showing a reexpanding bubble is taken at $t = 11.25 \mu\text{s}$). The drop of the heater temperature occurs shortly before this frame is recorded. The slope of the temperature change is remarkable: during interval C in Fig. 7(b) the heater temperature drops by 30 K within approximately 50 ns. Thus the heater experiences a cooling rate of $6 \times 10^8 \text{ K/s}$! That is also the time when the microbubble is pinched off. The temperature recovery is slower, typically within about 500 ns. After this fast recovery, the temperature continues to rise at a constant rate (i.e. from approximately 270°C to about 280°C) before the next cycle starts.

Next we compare the thermal signal with the acoustic signal as shown in Fig. 6(b). There the spectrogram of the thermal signal reveals close similarity with that of the acoustic signal. The larger noise floor of the thermal signal

FIG. 7. (a) Heater's temperature during the oscillate-boiling events for an input power of 86 mW. (b) Enlargement of the region marked with a dashed line in (a) and the corresponding bubble images. The scale bar represents $20 \mu\text{m}$.

is due to the smallness of the electric signal and some noise pickup.

In our previous work [13] it was argued that during the bubble collapse [e.g., between frame B and frame C in Fig. 7(b)], a liquid jet impinges on the substrate. During its contact with the hot surface, the heat transfer is strongly enhanced, leading to an instantaneous vaporization of a minute amount of liquid, and the subsequent vapor explosion drives the reexpansion of the bubble. During this process the heater loses energy, resulting in a drop in temperature. Soon after, the heater recovers to its initial temperature through Joule heating, and the cycle starts again.

This observation suggests that a sufficiently small electrical heater is actively cooled by the oscillate-boiling phenomenon. Applications that may profit from the cooling include integrated circuits or single high-power transistors operating above the Leidenfrost temperature. Here oscillate boiling provides a means to retain the device at a constant low temperature. It does so by utilizing the heat energy to transport cooled liquid to the device.

Compared with the estimated Leidenfrost temperature of 227°C from Baumeister and Simon [21] for water as the fluid and platinum as the substrate, the heater's temperatures shown in Fig. 7 are higher. This result shows that oscillate boiling remains operational above the Leidenfrost temperature, which is in stark contrast to nucleate boiling. Thus, oscillate boiling may offer a route to overcome the boiling crisis.

There have been reports where electrical heaters are used to study the thermal profile of a boiling bubble [16,19]. Romera-Guereca *et al.* [19] also reported temperature oscillation from an electrical microheater following the nucleate-boiling event. They explained the bubble

oscillation cycles with vaporization and condensation due to the thermal gradient in the surrounding subcooled liquid. We, in contrast, explain the cooling with liquid jetting; the bubble oscillation is essentially inertial cavitation (for a model see Ref. [13]). The most-striking difference is that Romera-Guereca *et al.* observed a few tens of thermal oscillations before they died out and the heater temperature rose. In contrast, we see oscillations lasting for millions of cycles. This difference is because their heater is a thin strip that may allow the bubble to grow in the less-confined direction, destabilizing the oscillations.

C. The stable and unstable regimes

The key advantage of an electrical heater over the previous laser heat source is the ability to have good control of the heating power by adjustment of the electric current into the heater. Figure 8(a) shows the maximum bubble radius and the mean temperature of a square heater (15- μm width) as a function of the electrical power. Here the bubble's effective radius is defined as the radius of a hemisphere with equivalent volume. The error bar is derived by our combining the relative error from multiple measurements and the absolute error coming from the resolution of the camera. With increasing power, three distinct parameter regimes are identified: For electrical power below 35 mW, the vapor bubble explosion is absent and convective heating prevails. Once the electrical power is above 35 mW, a vapor explosion occurs, followed by a small bubble undergoing volume oscillation (phase 1). However, unlike the one shown in Fig. 7, this oscillation shows neither the periodic microbubble pinch-off nor the temperature spikes from the liquid-jet impact (phase 2). It lasts several milliseconds and then decays as the bubble's size increases (phase 3). The oscillation eventually stops, and the bubble continues to grow due to heating (phase 4). The recordings of this process are presented in Appendix C. During this transition, the heater's temperature increases from about 120 °C to more than 200 °C. Figures 8(b)–8(d) depict the acoustic signal, the heater's temperature, and the effective radius of the bubble, respectively, during the course of phases 2–4. We term this regime the “unstable-oscillate-boiling regime” to distinguish it from the stable-oscillate-boiling regime (shown in Figs. 5–7) where the oscillation has a constant frequency and lasts for hundreds of milliseconds. Likely this unstable behavior is the result of gas accumulation from the liquid (i.e., through rectified diffusion [22]) and from residual gas of the vaporized water. We speculate that the smaller bubble in this regime does not collapse as violently. Then the jet does not reach the hot substrate, which stabilizes the bubble shape during reexpansion and avoids the microbubble pinch-off. This hypothesis is supported by the absence of thermal spikes in the heater's temperatures; see the inset in Fig. 8(c). We believe that the observation

FIG. 8. (a) Properties of oscillate-boiling bubbles with different input power. In the unstable regime, the data are captured during the oscillations before the bubble grows thermally. (b) Spectrogram of the acoustic signal emitted from an unstable-oscillate-boiling bubble. (c) Heater's temperature during the transition from oscillate boiling to the growth mode. The inset shows an enlargement of the dashed red rectangle. (d) Bubble's effective radius derived from the captured recording. The inset shows an enlargement of the dashed red rectangle.

of Romera-Guereca *et al.* [19] belong to this unstable regime.

Bubbles in the unstable-oscillate-boiling regime have four phases in common: They start through an explosive nucleation (phase 1), followed by an initial oscillation (phase 2). The frequency may or may not be constant. Phase 2 is followed by a decrease in oscillation amplitude and frequency while the bubble increases in size (phase 3). The oscillation then ceases and the bubble grows thermally (phase 4). The duration of each phase differs greatly, and it is not possible to attribute reproducible trends. For example, Fig. 9 shows a second example of an unstable-oscillate-boiling bubble. Again the bubble reveals the four phases. However, here the oscillation phase (phase 2) lasts approximately 2 ms—a relatively short time as compared with the decay phase (phase 3),

FIG. 9. Unstable oscillate boiling revealing only a short interval of oscillate boiling. (a) The spectrogram. (b) The bubble's effective radius taken from individual frames from the high-speed recording. The inset shows an enlargement of the marked region. (c) Captured images of the bubble. The time between two consecutive frames is $3.33 \mu\text{s}$. The scale bar represents $20 \mu\text{m}$.

which lasts approximately 8 ms. This is different from the case presented in Figs. 8(b)–(d). Overall, we do not find a simple relation between the heating power and the duration of each phase nor the frequency of the unstable oscillation. The stable and unstable modes can be easily distinguished, and a summary of their features is presented in Table I. Yet, we acknowledge the lack of a quantitative description of the unstable regime, which will be overcome in future work.

The regime of *stable oscillate boiling* can be reached only if the gas uptake of the bubble is balanced by the gas release through microbubble pinch-off. For the present geometry, the electrical power must be above 50 mW

to achieve stable oscillate boiling. As the bubble enters this regime, its maximum effective radius increases [see Fig. 8(a)], leading to a stronger bubble collapse, which favors liquid-jet impact. The size of the bubble increases and the oscillation frequency decreases with increasing power. The maximum power of this electrical design is 90 mW. Above this value the platinum thin-film resistor is destroyed, likely due to melting.

Figure 8(c) reveals another thermal effect of oscillate boiling. While the bubble oscillations decay (phase 3) and the thermal growth sets in (phase 4), the heater's temperature increases by about 100 K. We explain this temperature rise by the absence of advective cooling of the heater once the flow generated by the bubble oscillations ceases. The oscillate-boiling regime provides a means to sustain the heater at a lower operating temperature by advective cooling.

IV. DISCUSSION

A. Different sizes of the electrical microheater

Experiments are performed with square heaters of different sizes (i.e., side length of 10, 15, and $20 \mu\text{m}$). The 10- and $15\text{-}\mu\text{m}$ -sized heaters show similar behaviors; namely, with increasing electrical power a transition from convective heating to unstable oscillate boiling and then to stable oscillate boiling. As expected, the electrical power thresholds are lower for the $10\text{-}\mu\text{m}$ -sized heater as compared with the $15\text{-}\mu\text{m}$ -sized heater. These properties are presented in Fig. 10. The $20\text{-}\mu\text{m}$ -sized heater cannot produce stable oscillate boiling. Up to the point of electrical failure, only unstable oscillate boiling is found. This regime quickly transits to the thermal-growth phase (phase 4). Again, this observation agrees with previously reported results obtained with laser heating. There the focus had to be sufficiently small to obtain stable oscillate boiling.

B. Comparison between electrical heating and laser-based heating

Oscillate-boiling bubbles generated by the electrical heater show oscillation frequencies in the stable regime

TABLE I. Distinguishing the stable-oscillate-boiling regime from the unstable-oscillate-boiling regime with a $15 \times 15 \mu\text{m}^2$ heater.

	Unstable oscillate boiling	Stable oscillate boiling
Heating power range	35–50 mW	50–90 mW
Periodic microbubble pinch-off	No	Yes
Rapid cooling during each cycle	No	Yes
Phase 1	Explosive nucleation results in a small oscillating bubble.	
Phase 2	Either varying oscillation frequency or adjusts to a fixed frequency.	The bubble quickly adjusts to a fixed size and frequency.
Phase 3	Bubble increases in size while frequency drops.	Not applicable
Phase 4	Oscillations decays and bubble grows thermally.	Not applicable

FIG. 10. Parameter study of oscillate-boiling bubbles with different input power where the size of the heater is $10 \times 10 \mu\text{m}^2$. Here the bubble's radius is defined as the radius of a hemisphere having the same volume.

qualitatively and even quantitatively similar to the ones obtained from a laser-based heat source [13] (see Fig. 11). Yet, one needs to take into account that the two approaches lead to rather distinct thermal distributions. The electrical heater has a mostly constant temperature over the surface, which also restricts the size of the bubble. The laser heater, on the other hand, provides a Gaussian intensity distribution, which allows the bubble to choose its size. The previously proposed model, which assumes that the bubble's size can be independently adjusted, is therefore less accurate in the case of an electrical heater.

C. Effect of gas concentration in the liquid

Additional experiments are conducted using degassed water. The water is placed within a vacuum chamber at 3-mbar residual pressure for 60 min. A comparison of the bubble dynamics in saturated and degassed water is shown in Fig. 12. We find stable oscillate boiling in the degassed water too. The bubbles demonstrate at the same heating power very similar sizes and oscillation frequencies. Bubbles in standard and degassed water emit a stream of microbubbles. At first thought one may argue that the bubbles therefore consist mostly of vapor.

FIG. 11. The relationship between the bubble's maximum effective radius and its resonance frequency. Results from laser-based heating are also shown.

FIG. 12. Captured images and spectrogram of the emitted acoustic signal of an oscillate-boiling bubble in (a) normal deionized water and (b) degassed water. The scale bar represents $20 \mu\text{m}$. The power used for both cases is 50 mW.

However, close to the bubble the liquid, due to the high temperatures, even at low absolute concentrations from the degassing procedure may still be oversaturated and therefore available for diffusion into the bubble. While the overall gas concentration does not have a strong effect on the bubble dynamics, we cannot rule out the contributions from noncondensable gas within the bubble. More-careful experiments are necessary to answer the question of what constitutes the bubble.

V. CONCLUSION

In conclusion, the oscillate-boiling regime can be achieved not only through optical energy as shown previously but also with electrical Joule heating. We demonstrate a suitable design to achieve precise and simple electrical control with the advantage that the heater's temperature can be monitored. The fast temporal response of the thermal sensors reveals an enormous cooling rate of $6 \times 10^8 \text{ K/s}$ during a brief moment when the jet impacts. Temperature recordings of the heater for the three identified regimes of convective heating, unstable oscillate boiling,

and stable oscillate boiling are reported. In general, at lower electrical power, oscillate boiling is unstable; the average bubble volume increases over time due to accumulation of gas inside the bubble. At higher power, stable oscillate boiling is obtained. In this regime the heater's temperature is controlled and limited by the effective heat transfer of jet impact caused by the collapse of the non-spherical bubble. Thus, the oscillate-boiling phenomenon may not only be a promising candidate for heating applications but may also allow the effective removal of heat from electrical devices plagued by Ohmic heating.

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APPENDIX A: CALIBRATION OF THE MICROHEATER

The relationship between the microheater's resistance and its temperature is

$$R = R_0[1 + \alpha(T - T_0)], \quad (\text{A1})$$

where R_0 and R are the initial and current resistance, respectively, T_0 and T are the initial and current temperature, respectively, and α is the temperature coefficient of resistance. Throughout the experiment, the heater's resistance is monitored by use of the four-probe structure. To convert this value into temperature, we use a calibration procedure to find α .

In this calibration, the test section with the microheater at its bottom is filled with externally preboiled water. Then as the water cools down, we measure the heater's resistance as a function of temperature obtained with a type-K thermocouple submerged in the water. The data are then fitted to a straight line to obtain α . The results of the calibration are presented in Fig. 13.

FIG. 13. Calibration curve of the heater's resistance as a function of temperature.

APPENDIX B: TEMPERATURE OF BULK WATER

Throughout the experiment, a type-K thermocouple is placed 500 μm above the heating spot to monitor the temperature of the bulk liquid; no change is observed. This result is not surprising since simple calculation shows that heating 1 cm^3 of water (maximum capacity of our water container) with 100-mW input power (maximum input power before the heater breaks down) in 1 s (duration of the experiment) will increase the bulk temperature by less than 0.1 K.

APPENDIX C: VIDEOS

The fast dynamics of the oscillate-boiling bubble is captured with high speed imaging. Here we presents the representative results of two cases: stable oscillate boiling and unstable oscillate boiling.

VIDEO 1. Recording of an electrically generated oscillate-boiling bubble at 400,000 frames/s. The scale bar represents 20 μm .

VIDEO 2. Recording of the transition from oscillate boiling to the growth mode. The time interval between consecutive frames is 50 μs and the scale bar represents 20 μm .

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