Published in final edited form as:

Int J Heat Mass Transf. 2019 June ; 135: 44–51. doi:10.1016/j.ijheatmasstransfer.2019.01.101.

Forced vibration of a heated wire subjected to nucleate boiling

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Abstract

Vapor bubble nucleation during subcooled boiling on thin strip wire heaters and the resultant vibrations are studied experimentally. The results show how the subcooled boiling-induced vibrations (SBIV) are intrinsically related to the hydrodynamic flow induced near the heated wires. It is shown that the dominant force responsible for the vibrations in this case is imposed by a localized strong hydrodynamic flow rather than by the vapor recoil force. The dominant frequency of SBIV is the fundamental frequency of the wire, regardless of the individual departure frequencies of the nucleating vapor bubbles. The recorded wire vibrations are used to quantify the hydrodynamic flow. It is shown experimentally and theoretically that the flow fades exponentially with distance from the wire.

Keywords

Heat transfer; Subcooled boiling; SBIV; Vibration; Ebullition cycle; Hydrodynamics

1. Introduction

Boiling heat transfer in stagnant or flowing liquid, specifically nucleate boiling, has been a dominant means of cooling by the industry because of the corresponding high heat removal rates at the heater surface related to the high latent heat of evaporation. Accordingly, the nucleate boiling regime provides the highest heat removal rate. However, at sufficiently high heat fluxes, the spacing between the active nucleation sites diminishes because of the high surface superheat. Then, bubbles begin to coalesce, leading to film boiling. In the film boiling regime, vapor accumulation near the surface results in a drastic reduction in the heat removal rate, since the vapor layer acts as a thermal insulation. This causes a rapid increase in the surface temperature, which means that the critical heat flux (CHF) has been reached, and a “burnout” or melting and failure of a heater are possible.

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Conflict of interest

None declared.

Despite such a limitation as the CHF, the high heat removal rate provided by nucleate boiling is vital for multiple applications, such as nuclear reactor cooling, metallurgical quenching [1], and cooling microelectronics in ground and space applications [2–5], among others. To improve the output and facilitate usage of microelectronic devices, transistors are miniaturized. This leads to higher power surface densities and propensity to film boiling in pool-boiling cooling. Accordingly, control and optimization of the heat removal in relation to microelectronics are extensively studied. Recent studies have aimed at increasing the cooling rate by employing phase change materials [6], exploiting surface wettability to trigger bubble nucleation [7,8], elucidating single bubble dynamics [9,10], and employing vapor recoil force [5]. Further works were also conducted to understand the critical heat flux, such as the recent discovery of exponential vaporization fronts [11]. Efficient removal of bubbles from the heater surface and prevention of the CHF, especially in microgravity, were achieved by using the vapor recoil force [5] or ultrasonic vibrations [12–14]. For example, in [13] ultrasonic vibrations in liquid were employed to increase heat transfer under the subcooled and saturated boiling conditions. The ultrasonic vibrations affect the bubble contact line, facilitate bubble detachment [12], and delay the CHF by preventing vapor film formation [14]. Ultrasonic vibrations require spending additional energy, which diminishes the overall efficiency. The approach employing the vapor recoil force [5] uses no additional energy, but rather a part of the energy removed from the heater surface to shed the vapor film. To employ the vapor recoil force, the heater should be freely suspended, which is not the case for many practical applications such as clamped wires, suspended fuel rods, and electronic chips. These heaters are subjected to subcooled boiling induced vibration (SBIV) which may be used to increase overall heat transfer efficiency.

SBIV, which is generated by nucleating vapor bubbles, is problematic in the nuclear industry [2,15–19]. Such vibrations are detrimental to heater design, promoting fretting and wear in small confined spaces [17,19]. One example of detrimental failure due to SBIV is in nuclear power plants. Here the vibrations of fuel rods may lead to contact by surrounding walls and detrimental failure and leakage of radioactive material [19]. On the other hand, enhancement of boiling heat transfer may be possible with wire-mesh heat exchangers with self-excited vibrations of the wires. This phenomenon was already explored in the context of forced acoustical vibrations [12–14], but additional power sources were necessary. In contrast, further understanding of SBIV may lead to the ability to vibrate the heater by pulsed electric heating near the fundamental frequency, and enhance bubble departure without an extra energy source. Vibrations are related to growth and collapse of vapor bubbles [2,15,16]. Further works were related to various design aspects and the degree of sub-cooling [17,19], the applied heat flux [19], and scale-up experiments with heaters confined near walls [18]. However, because the ebullition cycle is an on-off process and the distribution of active nucleation sites is random, theoretical description of SBIV is challenging [16]. A theory of SBIV developed in [15,16] describes a vapor recoil force on the order of 10^{-4} N acting at a single active nucleation site, but has not been validated experimentally [2,15,16].

As to our knowledge, no direct measurements of the force causing SBIV has been attempted. The present work aims at developing a novel method to evaluate the force determining vibrations of a clamped resistive wire (or heaters in many practical applications) in nucleate boiling.

2. Experimental

2.1 Materials

Deionized water was used as a coolant in pool boiling. Kantahl A-1 ribbon resistive wires of dimensions $0.9 \text{ mm} \times 0.1 \text{ mm}$ were used as heating elements in the custom-made immersion heaters. The density of the wire is $\rho = 7.2 \text{ g/cm}^3$ and its Young's modulus at 100°C is 210 MPa. All material properties were obtained from the manufacturer [20].

2.2. Boiling apparatus

Experiments were conducted in the pool boiling chamber shown in Fig. 1.

The pool boiling chamber was assembled from two aluminum and two borosilicate glass walls and filled with water as the working fluid. The two opposing borosilicate walls allowed observation using a high-speed camera. The other two walls were made of aluminum and had ceramic wall heaters (Omega HCS-055–120 V) attached outside to assist in sustaining a high liquid temperature in the bath. The bottom of the pool boiling chamber was also made of aluminum. The chamber was open to the atmosphere to sustain the free surface of water at atmospheric pressure. An additional immersion heater was located inside the setup (cf. Fig. 1a) to heat up the liquid to the boiling point and degas it for at least 30 min before the beginning of the experiment. Upon completion of pre-boiling, the immersion heater was switched off to ensure that the water was stagnant in the bath, and the experiment was then conducted. The water temperature was monitored by a thermocouple (Omega 5TC-TT-T-30–30).

A specially designed fixture was used to clamp the flat resistive wire heater and observe boiling-induced vibrations (Fig. 1c). Accordingly, the flat resistive wire was clamped firmly between two copper plates on opposing sides of a polycarbonate fixture, ensuring electrical contact. The length of the resistive wire was $L = 93.0 \text{ mm}$, with the 0.9 mm width being parallel to the bottom of the boiling chamber. A threaded rod pressed on the lower parts of the sides of the polycarbonate fixture, applying a preload on the flat wire to ensure that no slack was present. Using a micrometer, the change in length of the resistive wire because of the preload was measured. Then, using Hooke's law, the tension along the wire, T , due to such pre-loading was determined as $T = EA \Delta L/L$, with E being Young's modulus of the wire, A being its cross-sectional area, ΔL being the length change measured by the micrometer, and L being the original wire length.

The resistive wire was heated electrically by connecting a DC power supply (Tektronix model TDS 210) to the opposing copper plates. Due to the Joule heating of the wire, nucleating vapor bubbles formed along it. Before the beginning of the experiment, the heater was sustained at the voltage of 9.0 V applied for 10 min to degas the wire (which can possess air-filled micro-crevices) in the still boiling bath.

The voltage applied to the wire was monitored using a multimeter (Dawson Tools model DDM644) connected directly to the copper plates. The multimeter was also used to measure the electrical resistance of the wire before the beginning of the experiment, which was found to be $R = 2.4 \Omega$. The temperature coefficient of resistance is 1.0 up to the temperature of

480 °C [20], meaning the resistance would not change despite Joule heating. Thus, the heat flux released by the wire, q , was calculated as $q = V^2/SR$, where V is the voltage, S is the total surface area of the wire, and R is the resistance of the wire measured at room temperature.

2.3. Tracking the central displacement of the wire and bubble nucleation

Nucleated vapor bubbles grew and departed from the Kanthal wire, which resulted in forced vibrations. These vibrations of the clamped wire were recorded using the observation system comprised of a high-speed camera (Phantom v210) and a collimated LED light source used for illumination, as shown in Fig. 2.

The LED light source in Fig. 2 was collimated using a plano-convex lens. For the high-speed camera, spacer rings and a Nikon AF NIKKOR 50 mm lens at a f-stop of 1.8 were used for the observation. The exposure of the high-speed camera was set to 12 μ s. These parameters allowed for a high magnification and resolution of 202.16 pixels/mm to observe the vibration of the resistive wire along a 6.2 mm span. Under such conditions, a low depth of field along with good illumination of the wire were obtained. All the conditions for the camera were chosen to optimize high-resolution recording of the vibrating Kanthal wire. Still-frame images were extracted from the high-speed video and converted into black and white images. A specially developed code was programmed in MATLAB R2016 to track the central displacement of the Kanthal wire. The code measured the pixel location of the wire centerline over the entire visible span, skipping over the locations where nucleated bubbles were present. The flow chart of the MATLAB code's logic for processing of the extracted still-frame images is shown in Fig. 3a. In addition, an example of the extracted image of the central part of the wire processed using the MATLAB code is shown in Fig. 3b.

The vertical displacement of the centerline for the observed 6.2 mm span of the wire (6.7% of the 93 mm length) was averaged and the value was recorded as a function of time. Because the wire displacements are relatively small, the mean displacement of the central span of wire reflects the true central displacement. Using the MATLAB library, a Fast Fourier Transform (FFT) of the signal (the displacement versus time) was also obtained.

Observations of the 50 μ m polystyrene tracer spheres (Cosphe-ric part number CPMS-0.96 45–53 μ m) were suspended in water and used as tracers. This allowed recording of fluid flow near the nucleating and growing vapor bubbles. The tracer buoyancy was negligible since the density of the microspheres is approximately 0.96 g/cm³, which closely matches the density of water at 100 °C, $\rho_L = 0.958$ g/cm³ [21].

3. Theoretical description of vibrations of clamped wire

Consider forced vibrations of a clamped wire of length L , width w , and thickness b driven by a hydrodynamic flow induced by nucleate boiling, as sketched in Fig. 4. The equation of the dynamic bar bending in the case of relatively small vibration amplitudes reads [22]:

$$m' \frac{\partial^2 y}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} - T \frac{\partial^2 y}{\partial x^2} = \frac{1}{2} \rho_L C_D w \left| U_L(t) - \frac{\partial y}{\partial t} \right| \left(U_L(t) - \frac{\partial y}{\partial t} \right) \quad (1)$$

Here y is the vertical coordinate perpendicular to the unperturbed wire, x is the longitudinal coordinate reckoned along the unperturbed wire (cf. Fig. 4), E is Young's modulus of the wire material, I is the cross-sectional moment of inertia of the wire, T is the force acting along the stretched wire, m' is the mass per unit length of the wire, which includes the added mass of the surrounding liquid, C_D the drag coefficient, ρ_L the liquid density, and $U_L(t)$ the local flow velocity generated by the growth and collapse of the vapor bubbles, which is implied to be normal to the wire direction.

The term on the right-hand side in (Eq. 1) is the viscous drag imposed on it because of the flow with velocity $V_R = U_L(t) - \partial y / \partial t$ relative to the wire. Viscous drag on a cylindrical wire was used as an estimate of the drag coefficient because relationships for the flat wire are unavailable, as to our knowledge. The drag coefficient is determined from the data of [23] as $C_D = 10.99 \text{Re}^{-0.58}$, with the Reynolds number $\text{Re} = \rho_L |U_L(t) - \partial y / \partial t| w / \mu_L$, and μ_L being the liquid viscosity. The fitting equation to the data from [23] is shown in Fig. 5.

In the present case approximately, $m' = \rho_m S - \rho_L S + 0.289 \rho_L \pi w^2$, where $S = w \times b$ is the cross-sectional area of the wire, ρ_m is the density of the Kanthal wire, and $0.289 \rho_L \pi w^2$ is the added mass of a plate [24].

For a thin wire, as in the present case, the effect of the bending stiffness is negligibly small compared to the effect of the wire stretching: $Ewb^3/12TL^2 = 0.0005 \ll 1$, where $T = 4.06 \text{ N}$. Note that the wire stretching is pre-determined by its installation in the setup and thus, known. Then, Eq. (1) is reduced to the following wave-like equation:

$$m' \frac{\partial^2 y}{\partial t^2} - T \frac{\partial^2 y}{\partial x^2} = \frac{1}{2} \rho_L C_D w \left| U_L(t) - \frac{\partial y}{\partial t} \right| \left(U_L(t) - \frac{\partial y}{\partial t} \right) \quad (2)$$

Using the experimental time series for the central deflection of the wire measured by the method described in Section 2.3, one can determine the derivatives

$\partial y / \partial t \Big|_{x=L/2}$, $\partial^2 y / \partial t^2 \Big|_{x=L/2}$, and $\partial^2 y / \partial x^2 \Big|_{x=L/2}$, and obtain from Eq. (2) the following equation which determines the fluid velocity $U_L(t)$

$$\frac{1}{2} \rho_L C_D w \left| U_L(t) - \frac{\partial y}{\partial t} \Big|_{x=L/2} \right| \left(U_L(t) - \frac{\partial y}{\partial t} \Big|_{x=L/2} \right) = m' \frac{\partial^2 y}{\partial t^2} \Big|_{x=L/2} - T \frac{\partial^2 y}{\partial x^2} \Big|_{x=L/2} \quad (3)$$

Because of the difficulty in resolving the entire wire and still achieving a high-resolution of its vibrations, the finite difference approximation accounting for clamped ends of the wire $\partial^2 y / \partial x^2|_{x=L/2} = -8y|_{x=L/2} / L^2$ was used.

4. Results and discussion

During the entire experiment, water was sustained at the temperature of 95 °C. The submerged Kanthal resistive wire was heated by Joule heating with the released power corresponding to the heat flux of $q = 18.18 \text{ W/cm}^2$. Accordingly, nucleate boiling occurred along the wire and the corresponding surface superheat was $\Delta T = T_w - T_{\text{sat}} = 6.33 \text{ K}$, found from the boiling curve for water on a nichrome wire at atmospheric pressure [25].

4.1. Vibrations of the clamped wire

The 6.2 mm span in the middle of the clamped wire vibrating because of the nucleate boiling was recorded at the frame rate of 2,000 fps. The resolution of the recording was 202.16 pixels/mm and the recording time was 8.582 s. An additional recording of the Kanthal wire without applied voltage was also conducted to determine the effect of the environmental noise on the wire. This environmental noise was due to the natural noise pollution in the laboratory. Such noise was mitigated by dampening foam pads, and eliminated using spectral subtraction. Both recordings were processed using a MATLAB code described in Section 2.3 and the data for the displacement of the middle span of the wire in time, as well as the FFT (Fast Fourier Transform) of the signals, are shown in Fig. 6a and 6b.

Fig. 6a shows that vibrations of the heated wire are similar to the SBIV observed in [15–19]. In those experiments, SBIV was analyzed on heater rods. It was observed that they vibrated due to the nucleation and departure of vapor bubbles. However, these works focused primarily on the resulting accelerations measured by an accelerometer and the degrees of subcooling. Note that the amplitude of the wire vibrations with applied voltage is typically four times higher than without applied voltage (the noise, cf. Fig. 6a1 and 6c1 with 6b1). The accuracy of the experimental signal corresponding to the displacement with the applied voltage can be improved by using spectral subtraction following the methodology ascertained by the arrows in Fig. 6. Specifically, it was done by first taking the FFT of the experimental signal and the noise signal for the central displacement. Then, the FFT corresponding to the noise signal was subtracted from the one for the experimental signal, and the inverse Fourier Transform (IFFT) was used to obtain the filtered signal for the central displacement. The resulting filtered signal for the central displacement as a function of time and its FFT are shown in Fig. 6c.

Fig. 6c shows that the force generated by nucleating bubbles induces wire vibrations at the frequency of $\sim f = 362.56 \text{ Hz}$ (cf. Fig. 6c3). For an $\sim 1 \text{ mm}$ bubble, the growth and departure frequency estimated using the correlations from [26,27] is $\sim 135.9 \text{ Hz}$, i.e., significantly lower than the observed wire vibration frequency. In a separate set of experiments, the bubble departure frequencies for the present Kanthal wire in the setup in Fig. 1 was $\sim 93 \pm 65 \text{ Hz}$. These frequencies are not recorded in the wire vibrations in Fig. 6. Therefore, one would expect that the measured frequency in Fig. 6a3 is the fundamental frequency of the wire

which is not associated with a distinct growth and departure frequency of the nucleating bubbles.

The left-hand side of (Eq. 2) reveals the fundamental angular frequency of $\omega = k\sqrt{T/m'}$, where k is the wavenumber, $k = 2\pi/(2L)$, because the vibrations shown in Fig. 4 correspond to one half of the wavelength (the latter is equal to $2L$). Therefore, the frequency of the wire is $f = \omega / 2\pi = \sqrt{T/m'}/(2L)$, which yields $f = 305$ Hz for the measured longitudinal tensile force in the wire of $T = 4.06$ N. This frequency is close to the measured dominant frequency in Fig. 6c. The measurement of the tensile force was based on the measured length change of the wire during preloading using a micrometer and Hooke's law, as discussed in Section 2.2. The resolution of the micrometer was 0.01 mm, which corresponds to the standard deviation of ± 2.03 N in the measured force. Accordingly, $T = 4.06 \pm 2.03$ N and the fundamental frequency $f = 216.30$ to 374.40 Hz, which incorporates the measured dominant vibration frequency of $f = 362.56$ Hz, but still excludes the boiling frequencies observed.

In the results in Fig. 6, the phenomena of SBIV of the heated wires are recorded, which show that such frequencies cannot be triggered by growth and departure of individual bubbles. The origin of the wire vibrations is elucidated in the following section.

4.2. Bubble-generated flow velocity

The flow field found as described in Section 3 affects the wire and induces the SBIV. Using Eq. (3) and the processed filtered signal for the central displacement of the wire from Fig. 6c, the corresponding velocity of liquid $U_L(t)$ is found and shown in Fig. 7.

In Fig. 7, the root-mean-square velocity is $U_{L, RMS} = 0.75$ m/s. Flow with such velocities can be observed by the motion of tracer spheres near the Kanthal wire. The corresponding sequence of images of the motion are shown in Fig. 8. Note that the camera settings ensured a low depth of field, thus the particle tracked was in the same focal plane as the Kanthal wire.

The velocity of the tracer particle in the y-direction located close to the bubble in Fig. 8a is shown in Fig. 9. It reaches the maximum value of $U = 0.90$ m/s near the wire, and is of the order of $U_{L, RMS}$ measured from wire vibrations. Far from the wire, the velocity of the particle is zero and it ractically does not move (Fig. 8b).

In Figs. 8b and 9 the particle practically does not experience the flow at the distance of approximately 1.05 mm from the nucleating bubble. Thus, it is observed that nucleating bubbles on the wire displace and entrain liquid during their growth and departure. Such a liquid flow means that the wire with nucleating bubbles essentially acts as a wave generator. The recorded flow field is associated with this wave generator, and thus expected to exponentially fade [28]. The present generator is slightly different from the free surface waves of [28] because here the wave is generated by a vibrating 'bottom' in the liquid bulk at some distance below the free surface. The detailed calculations shown in the Appendix are summarized in Fig. 10 in the contour plot for they-component of liquid velocity, v , with the vibrating bottom at the depth of $y = -85$ mm.

Fig. 10 shows that the flow field generated by nucleating vapor bubbles on the Kanthal wire would be localized. According to the two-dimensional predictions, illustrated in Fig. 10, the velocity decreases to the level of 10% of the velocity at the wave generator approximately at a distance of 17 mm from it. In three-dimensions, as in the experiments, the velocity decay should be even more abrupt than in the 2D case. Indeed, the flow is confined in the layer of 1.05 mm in Figs. 8b.

5. Conclusion

The novel method of measurements of vibrations of a wire with nucleating bubbles in boiling is proposed. It is shown that the dominant vibration frequency of the wire is its fundamental frequency and is not associated with the frequency of growth and departure of individual bubbles. The velocity magnitude of wire vibration was measured. Also, the liquid velocity generated by nucleating and growing bubbles acting as a piston was measured using tracer particles. These two velocities were of the same order, approximately 0.8–0.9 m/s. Therefore, wire vibrations were attributed to the surrounding liquid flow-imposed drag. Moreover, the surrounding liquid flow was found to be localized close to the wire, and abruptly fading at locations as far as about 2 mm from it. This finding is corroborated by a model solution for a 2D wave generator submerged in the liquid bulk, corresponding to the wire with growing and nucleating bubbles. The phenomena studied in the present work are relevant to subcooled boiling-induced vibrations (SBIV). The results can be used in practical SBIV cases to determine and control the spacing between fuel rods or heated element sufficient to prevent their hydrodynamic interactions.

Acknowledgement

The authors are grateful to NASA for the support of this work through the Grant No. NNX17AF33G.

Appendix A

Consider a 2D problem on a wave generator submerged in ideal liquid at a depth h below the free surface (Fig. A1). The Cartesian coordinates x and y are associated with the unperturbed free surface at $y = 0$.

The flow is sought as the solution of the 2D Laplace equation for the potential φ . The boundary condition at the wave generator reads

$$v|_{y=-h} = \frac{\partial \varphi}{\partial y} \Big|_{y=-h} = V_0 \exp[i(\omega t + Kx)] \quad (4)$$

Here v is the y -velocity component, V_0 is the amplitude of small perturbations of the wave generator, K is its wavenumber, and ω is the frequency of its oscillations, t is time, and i is the imaginary unit.

In the linear approximation, and accounting for the fact that pressure at the free surface is immaterial and can be posed as $p = 0$, the boundary condition at the free surface is found from the non-stationary Bernoulli equation as

$$\left. \frac{\partial \varphi}{\partial t} \right|_{y=0} = -g\eta \quad (5)$$

where g is the gravitational acceleration, and $\eta = \eta_0 \exp[i(\omega t + Kx)]$ is the amplitude of the resulting waves at the free surface.

The linearized kinematic boundary condition at the free surface reads:

$$\left. \frac{\partial \eta}{\partial t} \right|_{y=0} = \left. \frac{\partial \varphi}{\partial y} \right|_{y=0} \quad (6)$$

The solution of the Laplace equation yields the potential in the following form

$$\varphi = \exp[i(\omega t + Kx)](A \cosh ky + B \sinh ky) \quad (7)$$

where A and B are the constants of integration. They are found together with the amplitude η_0 from the conditions (4)-(6). After that the expression for the y -component of the flow velocity $v = \partial \varphi / \partial y$ takes the following form

$$v = V_0 \exp[i(\omega t + Kx)] \frac{(gK \sinh Ky + \omega^2 \cosh Ky)}{(\omega^2 \cosh Kh - gK \sinh Kh)} \quad (8)$$

The short-wave limit of Eq. (8), appropriate in this case of nucleate boiling on a submerged wire, yields

$$v = V_0 \exp[i(\omega t + Kx)] \exp[-K(h - |y|)] \quad (9)$$

which reveals the exponential decay of v at a distance y as $\exp[-K(h - |y|)]$.

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Fig. 1. Setup used for pool boiling. (a) Schematic of the setup. (b) Specially designed clamped resistive wire heater. (c) Photographic image of the setup.

Fig. 2.
Schematic of the observation system used for tracking vibrations of the clamped resistive wire.

Fig. 3.

(a) Flow chart of the MATLAB code used to extract the central displacement of the Kanthal wire. (b) A processed image of the central 6.2 mm-long wire span. The green line corresponds to the centerline of the wire (the middle plane in its thickness) used to measure the displacement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Forced vibrations of clamped wire (shown in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5.
Comparison of the fitting equation $C_D = 10.99Re^{-0.58}$ (line) with the experimental data (symbols)[23]

Fig. 6.

(a1) Central displacement of the clamped wire versus time for the voltage applied resulting in the heat flux of $q = 18.18 \text{ W/cm}^2$ released by the wire; (a2) the first 0.25 s of the signal; (a3) FFT of the signal. (b1) Central displacement of the clamped wire in time without voltage applied; (b2) the first 0.25 s of the signal; (b3) FFT of the signal. (c1) The filtered signal for the central displacement of the clamped wire in time with the applied voltage and the released heat flux of $q = 18.18 \text{ W/cm}^2$; (c2) the first 0.25 s of the signal; (c3) FFT of the signal

Fig. 7.

Flow velocity $U_L(t)$. (a) The signal corresponding to the first 0.5 s of vibrations, whereas (b) shows the entire recorded signal.

Fig. 8.

Images of the motion of a 50 μm polystyrene tracer particle located near the wire. (a) A 50 μm polystyrene tracer sphere near a nucleating vapor bubble. (b) A tracer sphere at some distance from the nucleating bubble. The time between the frames is 0.37 ms and the red circle encompasses the tracer sphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9.

Velocity of the 50 μm tracer particles from Fig. 8a in the y-direction. The blue line corresponds to the velocity of the 50 μm tracer sphere near a nucleating vapor bubble (cf. Fig. 8a), whereas the red one – to the velocity of the tracer sphere at some distance from the nucleating bubble (cf. Fig. 8b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 10.

Contour plot of the predicted 2D field of the y-component of velocity v generated by a wave generator submerged at $y = -85$ mm in a boiling bath of liquid. The red-dashed line shows the location of the 10% of the amplitude of the velocity at the wave generator (taken as U_L , $RMS = 0.75$ m/s, the location of the blue-dashed line $x = \text{const}$ along which the inset plot for $v(y)$ is predicted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. A1.
Wave motion originating from a submerged wave generator.