Simulating self-oscillations in a boiling flow of subcooled liquid in the channel

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Abstract. Results of experimental and theoretical research of dynamics of boiling of highly subcooled ethanol in the ring channel under the conditions of pulsing heating of the interior wall are presented. In experiments with the vertical channel, pulsations of a vapor film on a heater wall, accompanied by pressure oscillations with growing amplitude (the self-oscillatory mode), were observed. The mathematical model, which describes the non stationary process of boiling of ethanol in the channel, is presented. Model takes into account pulsations of a vapor film, evaporation of overheated liquid on a heater wall and vapor condensation owing to a flow of highly subcooled liquid. In numerical calculations the conditions of development of self-oscillations owing to evaporation of the liquid getting on a hot wall in the course of pulsations of a vapor film are revealed. Results of calculations well agree with experimental data.

1. Introduction

Studying the non-stationary thermohydraulics processes with the phase transitions, occurring during contact of a highly heated solid body with a cooling liquid, is of interest for many technical applications. A number of researches [1-6] are devoted to the boiling of subcooled liquids under the conditions of pulsing heating of a wall. In these experiments, the pressure oscillations with amplitudes, which represent danger to steady operation of the power equipment, are detected. In experiments [6] the self-oscillatory mode for the first time has been detected at boiling of highly subcooled ethanol, flowing in the ring channel. Conditions of cooling of a heater at which pulsation of a vapor film on a heater surface leads to intensive heat transfer are revealed. The similar phenomenon was revealed in experiments [7, 8], where the behavior of a vapor film on the high-temperature solid surface entrained in the large volume of liquid subcooled to the temperature of saturation was studied. It was revealed that at certain combinations of the values of temperatures of a hot surface and cold liquid the collapse of a vapor film occurs, accompanied by pressure oscillations having amplitude of tens of kilopascals and frequency from several units to hundred of hertz. Thus, on a vapor-liquid interface the disturbance, looking like standing or traveling waves with the amplitude of 100-200 micrometers approximately equal to a vapor film thickness, was observed. The present study is aimed at revealing the physical mechanisms responsible for development of self-oscillations in the channel, observed in experiments [6]. The simplified mathematical model of this process is developed and results of numerical modelling are compared to available experimental data.
2. Experiments with ethanol

In [6] the detailed description of realization of a self-oscillatory mode in the course of cooling of a metal wall heated to temperature \( T_w = 513 \pm 5 \) K by a flow of ethanol subcooled with respect to saturation temperature is presented. Experiments were carried out in vertically oriented channel, which is a part of a closed loop, where the fluid circulates. The loop is equipped by the capacitor with water cooling, centrifugal pump and intermediate heat exchanger for maintenance of the preset temperature of a liquid flow. The working channel (figure 1) having section in the form of a quadrate of 18×18 mm\(^2\) and length of 450 mm is equipped with optically transparent windows and sensors for measuring temperature, pressure and flow rate. Central tube subjected to heating (heater) is made of 321H stainless steel and has the diameter of 12 mm and wall thickness of 1 mm. Heat release in the heater resulted from passing the controlled three-phase rectified electric current with a pulse duration from 60 to 300 ms and with a rate of the wall heating of 600−2000 K/s. Under the experimental conditions the main quantity of heat is spent on wall heating. The process was visualized with a digital system VS-FAST with shooting speed of 2000 frames/s. Measurement of pressure dynamics was performed with inductive pressure sensors DD-10, placed in the upper and lower sections of the channel. Signals from the sensors with a frequency of 10 kHz were supplied to high-speed ADC L-761, coupled with industrial computers. Temperatures of the flow and wall of the heating element were measured by submerged chromel-copel thermocouples and chromel-aluminum thermocouples, attached to the inner wall surface. Decomposition of the signal on modal basic functions was applied to the time-frequency analysis of signals of pressure with the subsequent application of Hilbert-Huang Transformation. Such processing has allowed the selection of the amplitude and frequency components of a signal, which depend on time. The initial pressure in the channel was 0.3 MPa. The value of liquid subcooling to saturation temperature was varied in the experiments from 10 to 135 K. The initial velocity of ethanol \( u_0 \) was varied in the range from 0 to 1.1 m/s.

Data of high-speed video recording has shown that in the course of boiling up on the tubular heater, the vapor film, which pulsates with frequency of 47−53 Hz, is formed. Vapor film pulsations proceed during, approximately, 1 s, and are accompanied by growing pressure oscillations, thus the amplitude of oscillation attains the maximum value in 1.35 MPa (see figure 2). Further pressure oscillations decrease owing to considerable cooling of a heater wall by a flow of subcooled liquid.

![Figure 1](image1.png)  
**Figure 1.** Scheme of the channel with a vapor film having thickness \( h \).

![Figure 2](image2.png)  
**Figure 2.** Dynamics of pressure in ethanol in a self-oscillation regime. Experimental conditions are: \( u_0 = 0.4 \) m/s \( \Delta T_{sub} = 86 \) K, \( dT_u/dt = 830 \) K/s.
3. Theoretical model

3.1. Initial suppositions of model
Let's accept the following simplifying assumptions: 1) Development of self-oscillations as a whole is determined only by geometrical parameters of the channel, physical parameters of liquid and conditions of heating. 2) Liquid is considered as incompressible, properties of liquid are considered as constants. Vapor is considered as saturated; dependence of vapor pressure \( p_v \) on its temperature \( T_v \) is described by Clausius–Clapeyron relation \( \frac{dp_v}{dT_v} = \frac{\rho L}{T_v^2} \). Vapor is considered as ideal gas with equation of state \( p_v = R_g \rho_v T_v \). 3) We suppose the channel section has the ring shape. Gap \( \Delta_h \) between an interior and exterior wall is counted through the value of a flow area of the real channel. 4) When boil begins, the heater in length \( b = 150 \text{ mm} \) becomes covered by a vapor film of thickness \( h \) which depends only on time. 5) On all length \( b \) of a heated section the pressure in channel is considered as uniform and equal to vapor pressure \( p_v(t) \). 6) Two liquid columns of identical length \( l = 150 \text{ mm} \) are located below and above the heater. 7) Pressure at the channel inlet \( p_1 \) and pressure at the channel outlet \( p_2 \) are supposed be constants. Values \( p_1 \) and \( p_2 \) differ from initial pressure in the channel \( p_s \) only owing to hydraulic resistance of branch pipes \( \zeta \).

3.2. The model equations
At the initial stage of process, when there is still no vapor phase, distribution of temperature in liquid \( T(y, t) \) near the heater wall is described by the equation

\[
\frac{\partial T}{\partial t} = a_1 \frac{\partial^2 T}{\partial y^2},
\]

with boundary conditions \( T|_{y=0} = T_w(t) \), \( T|_{y=\infty} = T_i \) and initial condition \( T(y, 0) = T_i \). Here \( y \) is distance from a wall, \( T_i \) is temperature of subcooled liquid in the channel, \( T_w(t) \) is temperature of a heater wall, which grows with time according to a relationship \( T_w = T_i + B_w t \). In the course of heating of a wall its overheating attains critical value \( \Delta T_{cr} \) and at this moment of time, a vapor film appears instantly in the layer of the overheated ethanol. Where the temperature of liquid is equal to temperature of saturation \( T_s \) at the preset initial pressure \( p_{iw} \), a thin vapor film having two interface appears. External surface of the vapor film adjoins to a stream of subcooled ethanol in the ring channel. The microlayer of overheated liquid on a heater wall adjoins the internal surface of a vapor film. The vapor pressure at the moment of vapor film formation, accordingly, is equal to pressure in system \( p_s \). On an internal surface of a vapor film, evaporation of a liquid microlayer occurs, but condensation occurs on its external surface because of a contact with a stream of subcooled liquid. Note that a characteristic thickness of the heated liquid layer at the moment of boiling has the value of an order of 0.1 mm. Distance from a wall, where the vapor film appears (i.e. an initial thickness of a microlayer \( \delta_0 \)), and initial thickness of a vapor film \( h_0 \) have the values of an order of 0.01 mm also.

After heat release is terminated, the heater wall cools down because of evaporating liquid microlayer. Thus, evolution of the wall temperature is presented by the equation

\[
\frac{dT_w}{dt} = \frac{\rho \alpha_c A_w}{\rho_c c_v \Delta_w} \frac{(T_s - T_w)}{\delta},
\]

and evolution of microlayer thickness \( \delta(t) \) is presented by the equation

\[
\frac{d\delta}{dt} = \frac{c_v \alpha_l (T_s - T_w)}{L},
\]

where \( \rho, \rho_c, \rho_v, \alpha_c, c_v, \alpha_l, c_l, \Delta_w, \Delta_v \) are density, thermal capacity, thermal conductivity, heat conduction coefficient, density of vapor, liquid, wall, thermal conductivity respectively.
Since the moment of its formation, the vapor film influences dynamics of a fluid flow in the channel. Vapor pressure change leads to a change in velocities of liquid columns $u_1$ and $u_2$ according to the equations

$$\rho_1 \cdot \frac{du_1}{dt} = p_1 - p_v - \frac{\rho_1 u_1}{2},$$

$$\rho_2 \cdot \frac{du_2}{dt} = p_v - p_2 - \frac{\rho_2 u_2}{2}.$$  \hspace{1cm} (4)

(5)

In turn, values of velocity $u_1$ and $u_2$ are related to changing thickness of the vapor film by the equation

$$\frac{dh}{dt} = \frac{\Delta_h}{b} (u_2 - u_1),$$

which represents a condition of incompressibility of liquid in the channel. The vapor pressure varying owing to both phase transformation and change in vapor film volume $V = h \pi d b$ can be defined from the equation of balance of a vapor mass

$$\frac{d(p, V)}{dt} = V \left( q_v + q_i \right).$$

Here $q_2 = \frac{\lambda_v}{L} \frac{\partial T}{\partial z}|_{z=0}$ and $q_1 = \frac{\lambda_l}{L} \frac{T_v}{\delta}$ are mass fluxes on exterior surface of a vapor film, where condensation occurs ($q_2 < 0$) and on an interior surface of a vapor film, where evaporation occurs ($q_1 > 0$). Using vapor equation of state, Clausius-Clapeyron relation and equation (6), the equation for vapor mass can be transformed as

$$\frac{dT_v}{T_v dt} = \frac{\kappa}{h} \left( \frac{\Delta_h}{b} (u_1 - u_2) + \frac{\rho_1 c_i a_i}{\rho_1 L} J \right).$$  \hspace{1cm} (7)

Here $\kappa = \left( \frac{L}{R_x T_v} - 1 \right)^{-1}, \ J = \frac{\partial T}{\partial z} \bigg|_{z=0} + \frac{T_v - T_i}{\delta}.$

The equation (7) relates to a change in the temperature of vapor and motion of liquid columns, and also intensity of evaporation and condensation. Vapor pressure is calculated from a relation which is an output from Clausius-Clapeyron relation and vapor equation of state: $p_v = p_v \exp \left( \frac{L}{R_x T_v} - \frac{L}{R_x T_i} \right).$ The mass flux $q_2$, caused by condensation, is calculated on the basis of the following classical problem of a convective heat exchange to a fluid flow.

Let the fluid, whose temperature is equal to $T_i$ moves with velocity $u$ along the flat surface, whose temperature is equal to $T_v$. The temperature field in fluid $T(x, z)$ is described by the equation

$$u \frac{\partial T}{\partial x} = a_i \frac{\partial^2 T}{\partial z^2}$$

(8)

with boundary conditions $T(0, z) = T_v$, $T|_{z=0} = T_v$, $T|_{z=\infty} = T_i$. This problem has an analytical solution [9] from which the local gradient of temperature $\partial T/\partial z$ on a surface $z = 0$ is calculated. Thus, value of a mass flux averaged on length of a heater is equal

$$q_2 = \frac{\lambda_v}{L} \frac{1}{b} \int_0^b \frac{\partial T}{\partial z} dx = \frac{\lambda_v}{b L} \frac{2}{\sqrt{\pi}} \sqrt{u/a_i b}.$$  \hspace{1cm} (9)
As velocities of liquid columns \( u_1 \) and \( u_2 \) are different, the average velocity \( \langle u \rangle \) is used in (9).

Thus, system the ODE (2)–(7) together with a partial equation (1) and closing relations represent the mathematical model of thermo-hydraulic processes with the phase transitions, occurring at boiling up of subcooled liquids in the ring channel under the conditions of pulsing heating.

4. Results of numerical simulating

Set of equations (2) – (7) are solved numerically by the implicit finite difference method with iterations, equation (1) is solved by a sweep method by means of the implicit scheme. A series of calculations for the conditions of experiments [6] with variation of arbitrary parameters of model (critical value of wall overheating \( \Delta T_{cr} \) and initial thickness of a vapor film \( h_0 \)) have been fulfilled. Calculations have shown that in all cases the initial microlayer on a heater wall completely evaporates during \( 0.1 \) s approximately. After that during \( 0.2–0.3 \) s the full condensation of vapor film occurs, which is accompanied by damping pressure oscillations with amplitude of \( 0.1–0.15\)MPa. This result well agrees with experimental data for those conditions, when the self-oscillatory mode does not occur. Apparently, development of self-oscillations is possible only under the condition of vapor mass feed owing to the renewal of an evaporating liquid microlayer on the heater wall. Liquid supply to a hot wall has been considered in model on the basis of following reasoning. While the thickness of a vapor film attains a minimum (in each cycle of oscillations), a liquid microlayer of the preset thickness \( \delta \) appears instantly on a heater wall. The foundation for such supposition consists of the following. The interface of vapor–subcooled liquid is covered by the waves, whose amplitude can be comparable with the minimum thickness of vapor film [7, 8]. At those instants, when the thickness of vapor film is close to minimum, the crests of waves adjoin a hot wall leaving a liquid layer on a wall. Besides, at the closing stage of compression the acceleration of external surface of vapor film is directed towards a liquid. Large enough magnitude of this acceleration provides the development of Rayleigh–Taylor instability at interface. As a result of interface instability, droplets, broken from an interface, appear on a wall. In figures 3 and 4, the results of calculations of self-oscillations for the experimental conditions specified in figure 2 are shown at \( \Delta T_{cr} = 25 \) K, \( h_0 = 0.1 \) mm, \( \delta_* = 6 \) \( \mu \)m. In figure 3 where dynamics of pressure in the channel is shown, it is visible that cyclic renewal of a liquid microlayer leads to a growth of oscillations. The pressure amplitude of oscillation during \( 0.4 \) s grows and attains the maximum value of \( 1.35 \) MPa and then gradually decreases because of slow cooling of a heater wall. The amplitude gained in calculation and oscillation frequency \( (45–50\) Hz) agrees well with the experimental data shown in figure 2. Figure 4 shows in details a stage of development of oscillations. In a figure it is visible that after evaporation of an initial microlayer by thickness of \( 20 \) \( \mu \)m in each

**Figure 3.** Pressure evolution in self-oscillations. Calculation for conditions presented in figure 2.

**Figure 4.** Initial stage of self-oscillations.
cycle of compression, the short "surge" caused by inflow of vapor from the evaporating liquid microlayer appears on the pressure peak. The renewed microlayer with the thickness of \(6 \mu m\), appearing during the moments of the minimum thickness of vapor film, completely evaporates in time essentially smaller, than the period of oscillations. As a result of action of such "surges" of pressure, the amplitude of oscillations grows and reaches the stationary level close to observed in experiments.

5. Conclusions
The simplified mathematical model, which describes the liquid flow boiling under the conditions of pulsing heating of a channel wall, is developed. The model describes an appearance of a thin vapor film and its subsequent pulsations owing to intensive condensation in a flow of highly subcooled liquid. The model describes the self-oscillatory mode, which has been detected in experiments [6], and predicts an amplitude and frequency of nonlinear oscillations well. Development of self-oscillations is provided with supply of liquid on a hot heater wall during oscillations of a vapor film. The high amplitude of nonlinear oscillations is supported as a result of balance of processes of condensation and evaporation during one period of oscillations.

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