Numerical simulation of gas-liquid flows and boiling under effect of vibrations and gravity

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Abstract. In the paper a review of investigations related to a boiling process at normal conditions of microgravity and at a vibration forcing is presented. The effect of vibrations and a bubble boiling to heat transfer in water was studied. A decrease in temperature of heated wall in both cases as compared to the cases without boiling and vibrations has been shown. The results of modeling the problem on influence of the area of a vapor film on a heat flux of heated surface at various dimensionless governing parameters are presented. It has been shown the influence of the Grashof, Marangoni numbers and the contact angle on heat flux during formatting a bubble from air film.

1. Introduction
Boiling liquid under normal conditions is a process of phase changing (vaporization) inside a liquid under intense heating. Boiling processes take place in many natural phenomena, in industrial plants and technology, and these are important for activity of human. Boiling control is essential, for example, in the cooling processes of nuclear power plants, industrial plants and electronic devices. Therefore, the study of the fundamental physical laws of the boiling process and heat transfer at boiling is very important. The boiling has been studied for a long time and many scientific works are devoted to it, for example, monographs [1-12] can be highlighted. A review of the work on the study of two-phase flows is given in [13]. An overview of the achievements of Russian scientists in the field of heat transfer at boiling was given in [14] ("- here and in after "achievements" is mean till date of publication of the review).

Studies of heat transfer at boiling are carried out, both as for normal conditions and for under special conditions. Such special conditions can be: space flight conditions, vibration effects, rotations, strict requirements for the design of liquid volumes, liquids and refrigerants with new properties, etc. It should be note that the study of the vibrational convection and vibrational effect on the stability of fluid flow were begun and carried by Permian scientists G. Z. Gershuni and E. M. Zhukhovitsky and now continues by their students and followers [15, 16].

Liquid boiling is complex physical process that depends on many parameters: liquid properties, pressure, heat exchange conditions, properties of the heated surface, etc. [1-12]. For this reason, the boiling process is not yet sufficiently well studied that to be fully mathematically formalized and that be able to find methods for effectively controlling it. Even for adiabatic conditions, two-phase flows are conventionally subdivided into the following modes according to the flow structures: stratified flow, bubble, slug (plug), annulus-dispersed flow, dispersed, superheated steam. In boiling processes, there are two different boiling regimes: bubble and film modes. These are the two main modes of
boiling: with the formation of separate steam bubbles or a continuous steam film at the heated surface. It should be noted that these can coexist together, as well as pass one into the other. More detailed information about classification of boiling modes can be found in [1-12].

Despite the fact that this classification is based on visual-optical observations and has a share of subjectivism, there are some criterion dependences of belonging of two-phase flow to this or that mode. For example, S. S. Kutateladze found dimensionless stability criterion for flows of gas-liquid systems [4-6]. Critical values of the flow transition to the annular-dispersed regime were found from experiments.

From the middle of the last century until recently, most papers on a boiling were experimental or analytical [17-33]. Advanced experimental results of distribution steam void fraction under subcooled water boiling in a vertical pipe were obtained by authors papers [17, 18]. Researchers are actively use the data of papers [17, 18] still today. Experimental data on subcooled boiling in the annular gap between coaxial tubes were presented in paper [19].

In numerical simulations of boiling processes, the difficulties related to the mathematical description of the details of the two-phase transition (the need to use some empirical data, such as determining the localization of nucleation, the frequency of separation from the wall, the size and interaction of bubbles) are arisen [7, 34-39]. For the closure of the mathematical model of the boiling process some empirical correlation dependences obtained experimentally are used. There are many papers are devoted to the definition of dependencies for boiling characteristics. For example, various correlations for convective heat transfer functions at boiling of saturated liquids were obtained in [21] on the basis of the processing of experimental data. Also in [21] it was shown that the obtained correlation dependences are valid only for nonmetallic liquids.

With the increasing performance of computers and the development numerical methods, papers related to the numerical modeling of the hydrodynamics of gas-liquid flows, both to isothermal two-phase systems and to boiling, began to arise [32-45]. Papers on the study of the boiling process based on numerical solutions of the Navier-Stokes equations began to appear after the proposed N. Kurul and M. Z. Podowski RPI model subcooled boiling (Rensselaer Polytechnic Institute-RPI) [34]. The RPI model [34-36] is based on the assumption that the total heat flux $q_r$ at the heated wall can be represented as the sum of three components: $q_r = q_l + q_e + q_g$, where $q_l$ - is the heat flux applies to single-phase fluid turbulent convection, $q_e$ - is the evaporation heat flux, $q_g$ - is the heat flux from the cold liquid, due to the filling of vacancies of the vapor bubbles departing from the wall (quenching heat flux). Such representation of the total heat flow at the wall helps to the numerical simulation of nucleate boiling subcooled liquid at heated wall. RPI model is widely used by various CFD software developers. The review [37] provides a comparative description of the capabilities of various CFD codes for modeling two-phase flows. The paper [42] presents numerous results of modeling of isothermal flows and comparison with experimental data on the distribution of velocities and steam and water fractions. In [37, 38] the results of simulation the boiling of subcooled liquid in comparison with experimental data on the distribution of steam [18, 19] are presented.

In papers [43-46] provide surveys of CFD simulations of boiling under normal conditions (for normal earth gravity and without vibration effects). The review [43] discusses the state of researches on heat transfer with boiling. Basic experimental facts, physical models and correlations of experimental data on heat transfer coefficient (HTC) are reconsidered Universal based correlation of boiling HTC of various liquids is presented. The ways of further researches of the boiling problems are discussed. In [44] is review the state-of-the-art of CFD modeling of complex multiphase flows and discusses about further progress for improving that. Authors [63] description of direct numerical simulations of multiphase flows on bases of the ‘one-fluid’ formulation where a single set of equations is used to describe the entire flow field and interface terms are included as singularity distributions. The results of the improved approximation of the liquid-gas interface are presented. The results of CFD modeling based on RPI model [34] are presented in [45, 46]. The results were compared with DEBORA's French experimental test data. The results of comparisons showed good accuracy after
additional settings up empirical dependencies for DEBORA experiments. In [45] this was done using the commercial code Ansys CFX, and in [46] RPI model was incorporated into the open code OpenFOAM. The authors of both papers discuss the applicability of these implementations for the simulation of industrial problems with the boiling processes.

The flow of liquid at boiling is turbulent. For numerical simulations of boiling, the need of correct description of a turbulent two-phase flow (with a variable liquid-gas interface) gives additional difficulties [14, 37, 38]. In the papers [47-49] was extended the baseline model for the CFD-simulation of turbulent bubbly flows in the Euler-Euler framework by improving the modelling of bubble-induced turbulence. The closure terms in the transport equations of the k-\omega SST model are revisited and replaced with the model recently proposed by Ma et al. [49] which is based on an analysis of the turbulent kinetic energy budget obtained from direct numerical simulation data. In case of vertical pipe flow significant improvements in the predicted gas volume fraction and velocity profiles are obtained, especially in high gas volume fraction cases where bubble-induced turbulence is dominant.

An effect of controlled vibrations on the liquid to intensify the processes of heat and mass transfer can be very effective, similarly like the efficiency of mixing impurities in the liquid by means of vibrations (translational or rotational), which is known to everybody from life experience. The influences of vibrations on convective heat transfer in liquid volumes were studied in [22-31, 51-58]. In experimental paper [22] declared that due to vibrations, the heat transfer coefficient could be increased by 50%, and by 200% in [23]. In [54] the decrease in the thickness of thermal and dynamic boundary layers was numerically shown, which also indicates the possibility of significant intensification of heat transfer. In [54, 55] the influence of vibrations on the thickness of temperature boundary layers (on heat flow) during the growing of single crystals was presented. In [55] the results for decrease of the thickness of boundary layers during vibrations for the model of the Czochralski crystal growth method with a submerged vibrator, for various properties of liquids with and without convective flows, which confirms the general character of this fact [54], was shown. This effect is enhanced by increasing the value of the Prandtl number for certain parameters of vibrations. The conditions of selection parameters of vibrations for the effective action of vibrations to decrease thickness of the temperature layers indicated in [55]. Also in the paper [55], the influence of rotational oscillations of the submerged plate on the mixing of the melt and on the average temperature was shown. The influence of controlled oscillations of wall on the heat flow (temperature at the heated wall) in the two-phase (water-gas) system presented in [56]. An experimental investigation carried out in [57] to determine the effects of heat transfer surface vibration on nucleate pool boiling heat transfer coefficient of saturated water at atmospheric pressure. Visualization of boiling phenomenon showed that frequency of bubble formation increased with decreased bubble departure diameter when surface vibration was induced. In [58, 59] heat transfer was studied in order to intensify it in vibrating heat pipes. In paper [59] discusses the heat transfer enhancement of micro oscillating heat pipes using self rewetting fluid. To clarify the heat transfer enhancement mechanism, the thermo physical properties (including surface tensions and contact angles) of fluids have been comparatively analyzed. Furthermore, to find out the strengthening effect, experimental studies were performed on micro oscillating heat pipes were operated in vertical and horizontal orientation. In [59] in order to choose suitable geometry and cooling methods of oscillating heat pipes for enhancing heat transfer in the machining processes, a novel heat transfer prediction model of oscillating heat pipes was proposed. The prediction model is expected to provide guidance for designing oscillating heat pipes for enhancing heat transfer.

Early experimental studies of influence vibrations on boiling process were papers [24, 25]. Results of experimental investigation to determine the effect of relatively high amplitude and low frequency harmonic oscillations of a sphere on nucleate pool boiling of liquid nitrogen at atmospheric pressure presented in paper [24]. The authors [25] argue that vibrations do not affect the first critical heat flow at the saturation temperature of the liquid but effect on the subcooling of the liquid. In many boiling studies, the effect of oscillations of heated wires on the intensification of heat exchange up to several times has been shown. But in the review [26] it is indicated that works devoted to the study of the
boiling process under the influence of vibrating heating surfaces in the form of thin wires is less
promising than investigation of the vibrations of the entire liquid volume to transfer the results of
research to real installations. In [26] it was indicated that volume fluctuations can intensify heat
transfer up to 50% and only at the initial and final sections of the boiling curve. The time-mean heat
transfer of the incompressible laminar boundary layer on a flat plate under the influence of oscillation
was studied analytically in [27]. These results were shown the time-mean heat flux at the wall can be
several times as more with high frequency oscillation as that without vibration. For the first time study
of work of heat pipes on the vibration modes in a wide frequency range was carry out by the authors of
[28]. It was indicated that the resonance effects that occur when the heat pipe under conditions of
vibration effects. In paper [29] the unsteady effects of the crisis of boiling was experimentally studied
for ball and cylinder. The reduction time of the onset of the crisis the heat flux was found in a
definition range of vibration frequencies. This can reduce the duration of decrease the intensity of
boiling heat transfer.

In the review papers [30, 31] the prospects using of vibration effects to the intensification of heat
and mass transfer processes was indicated. In [30] it is also shown that the effects of vibration action
can have a resonant and hysteresis character, and can both improve and worsen the heat transfer.
Therefore, additional more detailed studies of the effect of vibrations on the boiling process are
needed. In [31] it is concluded that the main directions of research should include the definition of
optimal modes of operation and the creation of special vibration devices.

The level of the gravity force is another one reason which influence on heat and mass transfer
during the boiling. The boiling at weightlessness is fundamentally different from the boiling on
terrestrial conditions. Microgravity suppresses the convection and gravitational buoyancy of the
bubbles in the boiling process. When the bubble is on a heated surface in weightlessness, it effectively
isolates the surface from the surrounding liquid, causing a further increase of temperature. As the
vapor bubbles formation, they do not go upwards from heating surface, but these grows and unite into
a big bubble that can oscillates in the liquid. Near the heating element, a layer of steam is formed, that
not allows the good transfer of heat to the entire volume of the liquid. The liquid that are at some
distance from the heat source stays relatively cold.

The first Space experiments on the study of the boiling were performed in the 90s of the last
century by American scientists during the flights of the Space Shuttle [32]. They found that when the
boiling in microgravity, the liquid produces several bubbles and one large bubble absorbing smaller
ones. Studies of the boiling process in Space are important, for example, for understood how liquid
boils in Space and it is possible to create a better cooling system, fuel storage and system life support
of a spacecraft.

In microgravity, boiling becomes a much slower process. However, as French physicists
discovered [32], the vibration of the liquid can lead to its sudden boiling. This result has important for
the Space industry. The article [32] describes the results of an experimental study of the influence of
high-frequency oscillations on the boiling rate of liquid hydrogen. The major result of the experiments
of French physicists is that in weightlessness conditions vibration accelerates the phase transition of
liquid into steam. In experiments [33], complex hydrodynamic flows accompanying the evolution of
the bubble network passing parallel to the phase transition itself were observed. Both these phenomena
support and reinforce each other, leading to extreme instability of the liquid even in weightlessness.
The authors of the paper [33] emphasize that the phenomenon discovered by them has not only
applied, but also fundamental scientific interest.

A review of the papers on the studding of the boiling process in microgravity was presented in [50].
The paper describes and analyzes all known Space experiments on boiling and concludes that the
quality of the experiments is unsatisfactory and from the results of these experiments it is impossible
to tell a quantitative conclusion about the influence of microgravity on the boiling characteristics (the
probabilistic presence of thermo-capillary convection is indicated). In the review [50] it was told that
there are no unambiguous conclusions from the analysis of the results of Space experiments.
The review of papers on the investigation of the crisis of heat flow at boiling was devoted in the paper [51]. In [52] experimental finding that in identical flow conditions different superheats required for incipience of boiling at an artificial nucleation site in microgravity and on terrestrial conditions. In microgravity, bubbles start sliding but are probably fully detached, whereas in terrestrial experiments bubbles directly lift off from the artificial nucleation site. In [53] the results of the nuclear boiling experiment on spacecraft were presented. The main conclusion from this experiment is that a bubble can be ejected from a heated wire in the absence of gravity, instead of creating one large steam bubble. The authors [53] reported that bubble could be ejected from a heated wire in the absence of gravity force, due to the momentum in the growth of the bubble exceeding the surface tension force that holds the bubble on the wire. In papers [56] the problem of the influence of the vibrations on force convective flow of water and heat transfer in channel with and without the subcooled bubble boiling was considered by numerically. An experimental investigation was carried out in paper [57] to determine the effects of heat transfer surface vibration on nucleate pool boiling heat transfer coefficient of saturated water at atmospheric pressure. The circular copper test surface of 19mm diameter was electrically heated and vibrated vertically using a mechanical vibrator at frequencies ranging from 0 to 25Hz and amplitude from 0 to 5mm. An improvement in heat transfer coefficient up to a maximum of 123% was observed with the highest amplitude and frequency of vibration in the investigated range.

It should be noted that in addition to vibrations and gravity, there are other ways to intensify heat and mass transfer, which in this paper will not be considered, for example, rotation. Rotations can be of various types, for example, uniform or periodic (accelerated-delayed), total volume or submerged impellers, rotations with different axes of rotation and frequencies, etc. For example, the results of numerical simulation [60], showed the ability to control heat and mass transfer using rotations of the melt during crystal growth.

Thus, from the review of the considered papers, it can be concluded that today for more full understanding of the boiling processes necessary to carry out complete research (theoretical, numerical and experimental) both for earth and Space conditions with and without vibration action. It should be noted that the authors of the experimental paper [20] have the same independent opinion about that.

2. Results of numerical simulation

This paper presents the results of numerical modeling of two tasks:

- task-1 - it is problem of the influence of the wetting angle and air spot contact area on heat transfer during the forming of a gas bubble(s) on a horizontal heated plate in terrestrial and in weightlessness conditions;
- task-2 - it is problem of the effect of vibrations and boiling on the heat exchange of flow water between two vertical heated plates.

In this paper, the VOF (Volume Of Fluid) method was used in the mathematical model to determine the liquid-gas interface [63]. For simulation of nucleate boiling liquid, the RPI model of boiling subcooled liquid was used [34, 56, 57, 62, 63].

2.1. Task-1. Effect of air spot contact area and wetting angle on heat exchange at the wall

Capillary forces and wetting angle plays an important role in the formation of steam bubbles and film boiling on the heated surface to the dynamics of the heat-mass transfer processes. Experimental results of paper [61] confirm that the characteristics fluid flows are greatly affect the contact angle and capillary forces occurring on the walls of the container.

A simplified model problem of the initial stage of bubble formation in liquid on horizontal heated flat wall is considered. Several parameters of task-1 are considered: three values of the wetting angle of the heated wall ($\gamma = 0^\circ, 90^\circ, 180^\circ$) and two cases of covering heated wall by air film with the form of 1 or 2 bubbles (the segment(s) of oval shape was covered 75% of the wall). In the cases of the formation of one or two bubbles, all the properties and conditions were the same. The initial total spot contact area at wall of two air films (2 bubbles) was equal to the spot contact area with one air film (1
bubble). The initial total volume of the two bubbles was approximately equal to the volume of gas occupied by one bubble. It assumed that the geometry of the air film on heated wall at the initial moment is given. For following beginning time moments, the changing of shape and dynamic of heat transfer are studying for different wetting angles, areas of films and properties of liquids.

To solve task - 1 we use a mathematical model based on the numerical solution of the Navier-Stokes equations for a two-component (liquid-gas) system. The Navier-Stokes equations with the energy transfer equation can write as follows:

\[ \text{div} \ u = 0 \]

\[ \frac{\partial}{\partial t} (\rho u_j) + \frac{\partial}{\partial x_i} \left( \rho u_j u_i \right) = - \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i} \left( \mu \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \right) + \rho g_j + F_j \]

\[ \frac{\partial \rho c_{\rho a} T_a}{\partial t} + \nabla \cdot \left( \rho c_{\rho a} u_a T_a \right) = \text{div} \left( e_a \alpha \nabla T \right) + F_a \]

\[ \frac{\partial e_a}{\partial t} + u_j \frac{\partial e_a}{\partial x_j} = F_{e_a}, \quad u = \sum_a e_a u_a, \quad \mu = \sum_a e_a \mu_a, \quad \sum_a e_a = 1 \quad (p_1 - p_2 + \sigma k) n_i = (\tau_{1i} - \tau_{2i}) n_i + \partial \sigma / \partial x_i \]

where \( u \) is the velocity vector with components \( u_j \), \( F \) is the force vector with components force \( F_j \) acting on the interface of "water-air" and is given from the equilibrium condition of surface forces and pressure, \( j \) is the index of the coordinate component \((j=1,2\text{ for } 2D \text{ and } j=1,2,3 \text{ for } 3D)\), \( n_a \) - the unit normal vector, \( k=-\nabla n_i = I/R_1+I/R_2 \) - curvature, \( R_1, R_2 \) - radius of curvature for the interface of "water-air", \( \tau_{\text{out}} \) - viscous stress tensor, \( e_a \) - volume fraction \((0 \leq e_a \leq 1)\), where \( \alpha \) - fraction index: \( \alpha = 1 \) - air, \( \alpha = 2 \) - water.

To determine the change of the interface shape in time, the equation of transfer of the phase fraction function \( e_a \) is included in the system of equations. The numerical solution was carried out by two methods: the finite element method and the control volume method. The scheme of the mathematical model is show in figure 1 (a) – it is one spot of air film “1-bub”, b) – it is two spot of air film “2-bub”). The details of the problem statement, the mathematical model used here and the results of verification calculations can find in [56, 62].

![Figure 1](image1.png)

**Figure 1.** The scheme of the mathematical model.

a) One spot of film “1-bub”  b) Two spot of film “2-bub”

The dimensionless heat flux on the wall (Nusselt number \( \text{Nu}=\chi h / \lambda \)) depends on: Prandtl number \( (\text{Pr}=\nu / \alpha) \), Grashof number \( (\text{Gr}=g \beta \Delta T h^3 / \nu^2) \), Marangoni number \( (\text{Ma}=\beta_a \Delta T h / \nu a) \), the value of the wall overheating, the relative area occupied by the air film, the contact angle and the surface tension \( \sigma \). Here are denoted: \( g \) - acceleration of free fall; factors: \( \chi \) - heat transfer, \( \lambda \) - heat transfer, \( \nu \) - kinematic viscosity, \( \alpha \) - temperature transfer, \( \beta \) - temperature expansion, \( \beta_a = -1 / \sigma, \partial \sigma / \partial T \);

![Figure 2](image2.png)

**Figure 2.** Wetting angle \( \gamma \) and surface tension forces.
scales: \( h \) - length and \( \Delta T \) - temperature. Liquids and conditions with the following ranges of dimensionless parameters were considered: \( 1 \leq Pr \leq 7, \ 0 \leq Gr \leq 10^8, \ 0 \leq Ma \leq 10^3 \).

Definition of wetting angle \( \gamma \) presented in figure 2. The wetting angle \( \gamma \) is determined from the Young-Dupré equation of the equilibrium of forces in phase contact point on the wall: 
\[
\sigma_s = \sigma_{sl} + \sigma_L \cos \gamma,
\]
where \( \sigma_s \) is the surface tension forces \( \sigma_s \) and \( \sigma_L \), and \( \sigma_{sl} \), the contact angle. From the last expression, it can be received for work depending on the area and the contact angle follow expression
\[
A = \frac{\sigma_{sl} + \sigma_s \cos \gamma }{S \gamma}.
\]
From the last expression, it can be determined that in general with \( \sigma_{sl} + \sigma_s \) the work of the steam bubble formation depends on the ratio of \( S_{sl} / S \) areas and on the wetting angle \( \gamma \). It should note that the changing of wetting angle could also change the ratio of areas \( S_{sl} / S \).

The results of numerical simulation of task-1 are present in figures 3, 4. In figure 3 the dependences of the Nusselt number on time for water and three values of contact angle \( \gamma = 0^\circ, 90^\circ, 180^\circ \) (figure 3(a), (b), (c), respectively) are shown. These results obtained for two cases of the initial arrangement of spots of air films (bubbles): for one spot of air film (form of one segment of ellipsoid (oval) - it is "1 bub" (figure 1(a)) and for the case of two spot of air films (form of two segments of ellipsoid - it is "2 bub") (figure 1(b)).

![Figure 3](image-url)

**Figure 3.** Time dependence of the Nusselt number for three values of the contact angle
(\( \gamma = 0^\circ, 90^\circ, 180^\circ \)) (line 1 - “1 bub”, line 2 - “2 bub”) for \( Pr = 5, Gr = 1.3 \times 10^8, Ma = 0 \).

These results show the effect of the wetting angle on the Nusselt number as versus time. The average Nusselt number increase faster in time for a wall with a wetting angle \( \gamma = 0^\circ \) and \( \gamma = 180^\circ \) for the case of one air spot bubble at the wall ("1 bab") than for the case "2 bab" figure 3(a,c). For a wall with a wetting angle \( \gamma = 90^\circ \), the Nusselt number grows faster as versus time in the case of two air spot bubbles at the wall ("2 bab") figure 3(b).

The dependences of the heat flux (Nusselt numbers) as versus time in the absence of natural convection (\( Gr=0 \)) for different Marangoni numbers are shown in figure 4(a). The dependences of the heat flux (Nusselt number) as versus time in the absence of capillary convection (\( Ma=0 \)) and in the presence of natural convection for different Grashof numbers are shown in figure 4(b). The wetting angle was coincided in both cases. It should be noted that in case of an absence of natural and thermocapillary convective flows (\( Gr=0, Ma=0 \)) there may be a weak fluid flow. This flow can be caused by surface tension forces and a changing in the initial shape of the spot of air film (bubble(s)), which
affects to the value of the Nusselt number (figure 4b). At thermo-capillary convection \((Ma \leq 10^3, Gr = 0)\), for the same Marangoni number, the average Nusselt number changes in time more and faster in the presence of one spot of air film (“1 bub”) on the heated wall than in the presence of two spots of air films (“2 bub”) (figure 4(a)).

![Figure 4](image)

**Figure 4.** Nusselt number (Nu) as versus time
(a) - thermo-capillary convection \((Gr = 0, Ma \neq 0)\), (b) - natural convection \((Gr \neq 0, Ma = 0)\).

For the examined parameters \((10^7 \leq Gr \leq 10^8, Ma \leq 10^5)\), natural convection has a stronger effect on the Nusselt number than thermo-capillary convection (figure 4). These results qualitatively correspond to the results of the paper [65].

2.2. Task-2. Heat transfer in the channel with vibration or boiling and without vibration and boiling

In the given paper the problem of the influence of the vibrations on force convective flow of water and heat transfer in channel with and without the subcooled bubble boiling are considered. The water flow is carried out from below upwards in the flat channel between two heated up steel plates. A flat vertical channel with height 2m, width 1m and a thickness 5mm, internally between plates distance equal 15.4mm is considered (figure 5).

![Figure 5](image)

**Figure 5.** The scheme of the modeling region.

The plates outside were uniformly heating with a constant heat flux \(q\) (\(q\) values were 345.6 kW / m²). At the entrance to the channel, the pressure was \(P = 45\) atm and the water was directed from the bottom up at a velocity of \(V = 1\) m/s and a temperature of 473.15 K, which was below the boiling point for the given pressure. Both cases with constant and variable water properties were considered in the simulation. When simulation of the boiling the properties of water were variable.

Modeling is carried out on the basis of the numerical solutions of 2D Navier-Stokes equations for two-phase a turbulent flow and the equation of energy which were written in Euler approach for each phase. The \(k-\varepsilon\) turbulence model was used to simulate this problem. It was used \(k-\varepsilon\) model with additional terms in equations for case of presence of bubble boiling [62]. In work influence of
harmonious vibrations of vertical walls (as \( x = Asin(2\pi ft) \)) on heat transfer is considered. For simulation of flow in the region with changeable geometry dynamic grids are used. The time step got out from conditions of numerical stability and that for one period of fluctuations it was necessary not less than ten time steps for any frequency of fluctuations. For modelling of process of subcooled bubble boiling it is used RPI model of [34], with analytical correlations for frequency and for the sizes of generated and condensed bubbles, and also with analytical dependences for lift and drag forces acting on steam bubbles. Validation of model of saturated bubble boiling and comparison numerical results have been done for similar conditions for a tube and have given the good agreement with experimental data of [17-18]. Influence of drag and lift forces on moving of bubbles were investigated and comparison with experimental data [42].

For the given problem results of heat transfer and steam phase distribution, as taking into account boiling process, and without taking into account boiling for vibrations of walls with amplitudes from \( 10^{-3} \) to \( 10^{-4} \)m and with frequencies from 0 to 50Hz are resulted. In figure 6 show the distributions of temperature along a heated up wall at the time 20s for amplitude of vibrations \( A=10^{-4} \)m.

The results simulation of the task-2 presented in figure 6 show the effect of vibrations on the temperature of the heated wall. The temperature of the wall decreases with increasing frequency of vibrations, that is, the heat flux from the heated wall is intensify by vibration. The results of simulation showed the same tendency when taking into account the boiling of the liquid (figure 6, red line 4). The increase in heat transfer under vibrations is confirm of the results on the increase in the temperature gradient on the wall under vibration influence obtained earlier in other problems and solved by other numerical approaches.

At the moment when the temperature of the wall as a result of its heating is higher than the saturation temperature with water, the process of evaporation (boiling) begins on the wall. Due to the boiling, heat is removed from the heated walls (this is cooling more if compared to the wall temperature with and without boiling), steam is formed as a result of boiling, and then there is partial condensation of steam in the water flow. This is illustrated in figure 7, where the dependence of the concentration of the vapor phase content (average) \( C_{\text{vap}} \) at the outlet boundary from channel as versus time for the case of boiling at the above parameters is shown.

3. Conclusion
The review of the considered papers showed great interest of scientists and engineers to the studying of the boiling using of numerical simulation. The review also showed the need to continue a comprehensive study (jointly experimentally, theoretically and numerical simulation) of the boiling process, both in normal and special conditions (weightlessness, vibration, rotation, etc.).

The results of the solution of task-1 showed the influence of the wetting angle and the area of the spot air film on the heat flow, the heated surface for various of Grashof and Marangoni numbers. In the case of the absence of natural and thermo-capillary convective flows (\( Gr = 0, \ Ma = 0 \)), weak fluid flow can occur. This slow fluid flow caused by surface tension forces and a changing in the initial shape of the film (bubble(s)), which affects to the value of the Nusselt number.

For task-1 with the examined parameters (\( 10^7 \leq Gr \leq 10^6, \ Ma \leq 10^5 \)), natural convection has a stronger effect on the Nusselt number than thermo-capillary convection. When thermo-capillary convection is taken into account only thermo-capillary convection (\( Ma \leq 10^5, \ Gr = 0 \)), the Nusselt number enhancing in time more in case of the presence of one bubble (one spot of air film) on the heated wall than in the presence of two bubbles (two spots of air film).

The results of the solution of task-2 showed the effect of vibrations on the temperature of the heated wall of the vertical layer with running water. Controlled harmonic vibrations of the wall intensify heat exchange, and wall temperature decreases with increasing frequency of vibrations. The results of the numerical simulation showed the same tendency when taking into account the subcooled nucleate boiling of the liquid.
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