Numerical simulation of the surfactants effect on the Taylor bubble in the PHP

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Abstract. Numerical simulation of the motion of a Taylor gas bubble in a heated small-diameter tube is carried out. Two models are used to describe the dependence of surface tension on temperature. In the first model, the surface tension decreases with temperature, and in the second, it increases, which corresponds to pure water and an aqueous surfactant solution. It is shown that the derivative sign affects the thickness of the liquid film around the bubble.

1. Introduction
In the modern world, there is a steady trend towards a decrease in the scale of technological processes in various fields of technology. At the same time, the intensity of local heat generation in electronic devices increases. When cooling them, it is advisable to use two-phase heat exchangers, such as heat pipes, microchannels, and spray systems [1,2].

A pulsating heat pipe (PHP) or oscillating heat pipe has been proposed by Akachi [3]. Since then, the use of pulsating heat pipes has been considered a promising avenue for use in the fields of solar energy, geothermal energy, in the aerospace industry and for cooling electronic components due to the special advantages of PHP (Khandekar et al. [4]; Groll and Khandekar [5]; Khandekar et al. [6]): simple structure and low cost: PHPs are made from a long tube that is bent in several places. A characteristic feature of the PHP is the absence of a wick, which is present in traditional heat pipes, which are very popular in production. According to the results of Shang et al. [7] the equivalent thermal conductivity of PHP can be an order of magnitude higher than the thermal conductivity of copper.

Due to the uniqueness and simplicity of operation, the PHP has a number of obvious advantages: with stable operation of the PHP, the oscillatory movements of liquid plugs and vapor bubbles set in motion a two-phase mixture in the pipe. Evaporation and condensation of the working fluid, caused by heat absorption and dissipation, is the driving force behind the vibrations in the pipe. Although the structure of the PHP is very simple, the relationship between the hydrodynamic and thermodynamic effects in the process of heat and mass transfer in the PHP makes the mechanism of operation of the PHP very complex and difficult to fully understand (Zhang and Faghri [8]; Khandekar et al. [9]).

It is known, for water, the surface tension decreases with increasing temperature. This leads to the fact that forces appear on the surface of the liquid film, which are directed from the hotter region to the colder one. In some cases, this leads to intense thinning of the film and further rupture with the formation of a dry spot. As shown by Semenov et al. [10], the addition of some surfactants can change the dependence of surface tension on temperature, i.e. it leads to its increase with temperature. Therefore, this should have the opposite effect, i.e. to provide an inflow of liquid to a warmer area and thus prevent the liquid film from breaking.
In this work, we simulate the motion of a gas bubble through the heated region in the channel for two cases. In the first case, the dependence of the surface tension corresponding to pure water was used, and in the second, to an aqueous solution of SLS.

2. Methods

The model equations were solved in the OpenFoam package using the compressibleInterFoam solver. This solver is designed to simulate two compressible, immiscible, non-isothermal phases. Numerical modeling was carried out in a two-dimensional approximation. Figure 1a schematically shows the computational domain. To solve problems in the axisymmetric approximation, a grid in the form of a sector with a small angle is used. A uniform mesh was used along the pipe, the number of cells was 2000. An irregular mesh with the number of cells equal to 125 was used along the radius. The mesh was smoothly thickened from the axis of symmetry to the wall so that the ratio of the sizes of the maximum and minimum cells was 10. The properties of the liquid used correspond to the properties of water, and gas - air.

![Figure 1a](image.png)

Figure 1a. Schematic representation of the computational domain

Figure 1b schematically shows the boundary conditions. A granular condition with a fixed parabolic velocity profile is set at the input. The reduced velocity of the liquid at the inlet was 0.1 m/s. At the exit, a granular condition with a fixed pressure equal to atmospheric under nominal conditions. The condition of adhesion and impermeability is imposed on the wall.

3. Results

As a result of numerical simulation, the evolution of a gas bubble through a heated region in a tube 1.8 mm in diameter was calculated for two different dependences of surface tension: with a positive and a negative derivative.
Figure 2. Field of the volumetric liquid content at different points in time (red - liquid, blue - gas). Surface tension decreases with increasing temperature. On the left is a general view of the bubble, on the right is an enlarged area with a liquid film on the wall.

It is shown that in the case when the surface tension decreases with increasing temperature (corresponds to the surface tension of water), the liquid film breaks during heating (Figure 2). The influence of numerical errors at the moment of rupture is large, since when the film is thinned, the number of cells filled with liquid turns out to be small (3-4 cells, 3-5 μm).

Figure 3. Field of the volumetric liquid content at different times (red - liquid, blue - gas). Surface tension increases with increasing temperature. On the left is a general view of the bubble, on the right is an enlarged area with a liquid film on the wall.

However, a calculation under similar conditions with an inverse dependence of the surface tension coefficient on temperature (corresponds to the surface tension of an aqueous solution of SLS) shows that in this case the liquid film has a much greater thickness (15-20 μm), which makes it less likely to rupture (Figure 3).

4. Conclusion
Numerical simulation of the motion of a Taylor gas bubble in a heated tube 2 mm in diameter was carried out. Simulation was carried out for two different dependences of surface tension. In the first
case, corresponding to pure water, the surface tension decreased with increasing temperature. This dependence leads to the emergence of a Marangoni surface force, which causes the outflow of liquid from a more heated area, reducing the thickness of the liquid film. In the second case, the surface tension increased with increasing temperature. This dependence can be observed for some aqueous surfactant solutions, in particular SLS. In this case, the Marangoni forces lead to an increase in the thickness of the liquid film.

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