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CALCULATION OF HEAT TRANSFER IN FLUID AROUND GAS-VAPOUR BUBBLES

Abstract

In this paper the mathematical model for calculating heat transfer in the fluid that surrounds the oscillating gas – steam bubble. The mathematical model takes into account the changing thermal and physical characteristics the liquid, changing the size of bubbles, heat exchange processes at its border.

Keywords: heat transfer coefficient, dispersed phase, mathematical model, heat transfer

1. Introduction

There are a number of technological processes which are based on the use of gas-vapor bubbles, surface cleaning, cavitation, homogenization fuel mixing colloidal solutions, water degassing, distillation of petroleum products, foaming in the food industry and in the manufacture of thermal insulation materials, transportation of natural gas as a hydrate and many others. Typically the formation and existence of gas-vapor bubbles accompanied by intense heat and mass transfer processes at phase interface. The small size surfaces and speed these processes led to the widespread use of mathematical modeling for their research. Mathematical models can determine the most influential factors and optimize technological processes. To be able to describe the various hydrodynamic, heat exchange and mass transfer processes mathematical model should adequately take into account the thermal treatment of fluid that surrounds the gas-vapor bubble.

1.1. Overview of recent sources of research and publications

For consideration of heat exchange processes on the boundary of separation medium mathematical model of gas-vapor bubbles should contain equations describing the heat transfer of fluid in the environment. In [1] the temperature of the liquid is described by an exponential function, which is independent of the time direction of the wall of bubbles. Some authors take the temperature of the liquid constant [2, 3], and thermodynamic processes in gas-vapor environment of bubbles of adiabatic. However, these assumptions are possible only to a very limited group of tasks. In works [4, 5] the analytical solution of the problem of unsteady heat conduction in the layer of fluid that surrounds oscillating bubbles. For obtain solutions, the author asked the following simplifying assumptions: finite liquid layer in which there heat exchange processes and parabolic nature of the temperature distribution in the thickness of this layer. Because of these assumptions in solving this problem solution is obtained in which the heat exchanger of fluid layer, equal to the radius of the bubbles and is not dependent on thermal and physical characteristics of fluid. In work [6] process of heat transfer in the liquid is not considered, and its temperature is determined only on the basis of the combined boundary conditions. Some authors [7] consider heat exchange of fluid layer is so thin that the curvature of the surface of bubbles cannot be ignored.

1.2. Selection not solved earlier of parts the general problem

To improve the accuracy of mathematical models of gas-vapor bubbles must be considered in the process of heat transfer fluid surrounding the gas-vapor bubble. The features of this problem is the movement of the walls of bubbles, the rate of which, in certain moments of time can be up to several

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hundred meters per second. Temperature mode of gas inside the bubbles also varies widely. Consequently, the thermophysical characteristics of fluid on the boundary of the bubble can also significantly vary.

1.3. Problem statement

The aim of this work is to create a digital mathematical model of heat transfer in the fluid around the vapor bubbles which changes its size. The liquid should be variable thermophysical characteristics.

2. Basic material and results

For the development of mathematical models of heat transfer fluid used in the following simplifying assumptions:
- gas-vapor bubble has a spherical shape;
- near the surface bubbles given boundary conditions of the second kind.

To determine the temperature on the inner surface of the bubbles should be considered in the process of heat transfer fluid. It is done by heat conduction and convection. To calculate of heat transfer by heat conduction usually used Fourier heat equation. To take account of convection can be effective coefficient of thermal conductivity.

We denote by «x» coordinate at which changes the radius of bubbles. To determine the unknown temperature on the surface bubbles can apply nonlinear heat equation Fourier bullet considering the mobility of its walls [1]

$$\frac{\partial\left(\rho_r c_r T_{(x,\tau)}\right)}{\partial\tau}+\dot{x}\frac{\partial\left(\rho_r c_r T_{(x,\tau)}\right)}{\partial x}= =\frac{1}{x^2}\frac{\partial}{\partial x}\left(\lambda_r x^2\frac{\partial T_{(x,\tau)}}{\partial x}\right) \qquad (1)$$

where: $\dot{x}$ – the rate of change of the radius bubbles, m/s; λ_r – effective coefficient of thermal conductivity of fluid, W/(m°C); c_r – heat capacity of fluid, J/(kg°C); ρ_r – density, kg/m^3. Given the continuity of flow conditions when through any surface bullet of radius x per unit time is the same mass of liquid $\rho_r\dot{x}4\pi x^2=\rho_r\dot{R}4\pi R^2$, equation (1) can be written as

$$\frac{\partial T_{(x,\tau)}}{\partial\tau}= =\frac{1}{x^2}\frac{\partial}{\partial x}\left(\frac{\lambda_r}{\rho_r c_r}x^2\frac{\partial T_{(x,\tau)}}{\partial x}-\dot{R}R^2T_{(x,\tau)}\right) \qquad (2)$$

As a result of heat exchange processes in the border of bubbles liquid may change its thermophysical characteristics, so the problem will be solved as nonlinear.

Considering the fact that bubbles near the surface known specific heat flux (q), write the boundary condition of the second kind

$$-\lambda_r\frac{\partial T}{\partial x}(x=R,\tau)=q \qquad (3)$$

To describe the thermal conductivity in the liquid around the bubbles divide layer of liquid that surrounds bubble to a number of concentric shells. Define mass distribution of each shell

$$m_{r(2)}=2K_r m_{r(1)}$$

$$m_{r(i)}=K_r m_{r(i-1)}$$

where: $m_{r(1)}$ – mass shell 1st (inner) layer; $m_{r(i)}$ mass each of the next shell; K_r – coefficient of proportionality. This coefficient is used to optimize its calculations and typical values are within 1.5÷2. He is chosen so as to achieve maximum speed calculations for a given accuracy.

Determine the temperature on the inner surface of the first (inner) shell. Then, in the inner shell, which has a boundary condition differential equation will have the form

$$m_{r(1)}c_{r(1)}\frac{dT_{(R,\tau)}}{d\tau}= =-F_R q-\frac{4\pi\lambda_{r(1)}\left(T_{(R,\tau)}-T_{(R+\delta 1)}\right)}{\frac{1}{r_{(R)}}-\frac{1}{r_{(R+\delta 1)}}} \qquad (4)$$

For ease of calculation denote

$$K_1=\frac{\lambda_{r(1)}}{\frac{1}{r_{(R)}}-\frac{1}{r_{(R+\delta 1)}}}=\frac{\lambda_{r(1)}}{\frac{1}{R}-\frac{1}{R+\delta 1}} \qquad (5)$$

Now the differential equation that determines the temperature on the surface of the inner layer of bubbles is of the form

$$\frac{dT_{(R,\tau)}}{d\tau}= =\frac{4\pi}{m_{r(1)}c_{r(1)}}\left(-R^2q-K_1\left(T_{(R,\tau)}-T_{(R+\delta 1)}\right)\right) \qquad (6)$$

In the absence of mass transfer processes mass of 1st layer remains intact, because

$$m_{r(1)} = \frac{4}{3}\pi\rho_{r1}\left[\left(R+\delta 1\right)^3 - R^3\right] = \text{const}$$

Where can define the outer radius of the 1st shell

$$R+\delta 1 = \sqrt[3]{r_R^3 + \frac{3m_{r(1)}}{4\pi\rho_{r1}}} = \sqrt[3]{R^3 + \frac{3m_{r(1)}}{4\pi\rho_{r1}}} \quad (7)$$

For all next shells can write the following equation

$$m_{r(i)}c_{r(i)}\frac{dT_{(x,\tau)}}{d\tau} = $$
$$= \frac{4\pi\lambda_r\left(T_{(i-1)} - T_{(i)}\right)}{\frac{1}{r_{(i-1)}} - \frac{1}{r_{(i)}}} - \frac{4\pi\lambda_r\left(T_{(i)} - T_{(i+1)}\right)}{\frac{1}{r_{(i-1)}} - \frac{1}{r_{(i)}}} \quad (8)$$

Given the of nonlinearity of problem difference of temperature adjacent layers easier to replace the temperature difference between the middle layer and its edges (borders)

$$\frac{dT_{(r_i,\tau)}}{d\tau} = \frac{4\pi}{m_{r(i)}c_{r(i)}}\left(K_3\left(T_{(r_i-\delta i,\tau)} - T_{(r_i,\tau)}\right) - \right.$$
$$\left. + K_1\left(T_{(r_i,\tau)} - T_{(r_i+\delta i,\tau)}\right)\right) \quad (9)$$

The temperature at the external borders, *i*-th shell

$$T_{(r_i+\delta i,\tau)} = \frac{K_1T_i + K_2T_{i+1}}{K_1 + K_2} \quad (10)$$

The temperature on the inner border

$$T_{(r_i-\delta i,\tau)} = \frac{K_4T_{i-1} + K_3T_i}{K_4 + K_3} \quad (11)$$

The coefficients K_1, K_2, K_3, K_4 determined by the following formulas:

$$K_1 = \frac{\lambda_{r(i)}}{\frac{1}{r_{(i)}} - \frac{1}{r_{(i)} + \delta_{(i)}}} \quad (12)$$

$$K_2 = \frac{\lambda_{r(i+1)}}{\frac{1}{r_{(i)} + \delta_i} - \frac{1}{r_{(i+1)}}} \quad (13)$$

$$K_3 = \frac{\lambda_{r(i)}}{\frac{1}{r_{(i)} - \delta_{(i)}} - \frac{1}{r_{(i)}}} \quad (14)$$

$$K_4 = \frac{\lambda_{r(i-1)}}{\frac{1}{r_{(i-1)}} - \frac{1}{r_{(i)} - \delta_i}} \quad (15)$$

Medium-radius *i*-th shell is given by

$$r_{(2)} = \sqrt[3]{R^3 + \frac{3}{4\pi}\frac{m_{r(1)}}{\rho_{r1}} + \frac{3}{8\pi}\frac{m_{r(2)}}{\rho_{r2}}} \quad (16)$$

Since the mass of the first shell is not divided in half – for the 2nd shell radius is determined by the following formula

$$r_{(2)} = \sqrt[3]{R^3 + \frac{3}{4\pi}\frac{m_{r(1)}}{\rho_{r1}} + \frac{3}{8\pi}\frac{m_{r(2)}}{\rho_{r2}}} \quad (17)$$

The outer radius i-th shell

$$r_{(i)} + \delta_i = \sqrt[3]{r_{(i)}^3 + \frac{3m_{r(i)}}{8\pi\rho_{r(i)}}} \quad (18)$$

The inner radius *i*-th shell

$$r_{(i)} - \delta_i = \sqrt[3]{r_{(i)}^3 - \frac{3m_{r(i)}}{8\pi\rho_{r(i)}}} \quad (19)$$

For the solution of differential equations (6) and (9) the method of Runge-Kutta 4th order. In order to assess the adequacy of the developed mathematical model a computer program was written and performed a series of mathematical experiments.

Output data. The duration of estimated time interval of 100 ns. Time step 0.001 ns, specific heat flux 10 MW/m^2. The initial diameter of the bubbles 0.1 mm, initial temperature of the water +5°C. Calculated of layers 10, coefficient K_r = 1.5. Thermal conductivity, density and heat capacity of water held constant at temperature +5°C.

Figure 1 and 2 shows the results of calculation cooling wall bubbles constant specific heat flow conditions for increasing its radius of speeds $\dot{R}$ = 100 m/s. In Figures 3÷4 also, the speed – 50 m/s. Obtained results show that during the compression of bubbles changing temperature conditions just closest to the interfacial boundary of layers of fluid. “Depth” heat wave penetration is about 0.1 the initial radius of bubbles. During the expanding bubbles changing temperature mode layers at a distance of more than 3 initial radius bubble. When reducing the size of bubbles decreases the total heat flow, resulting in slower heat exchange processes, Figure 3.

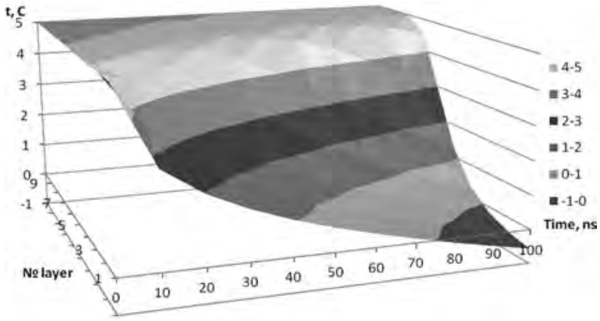

Fig. 1. Diagram of temperature fields in the water that surrounds bubble (phase transition in water is not considered). The calculation results for $\dot{R}$ = 100 m/s

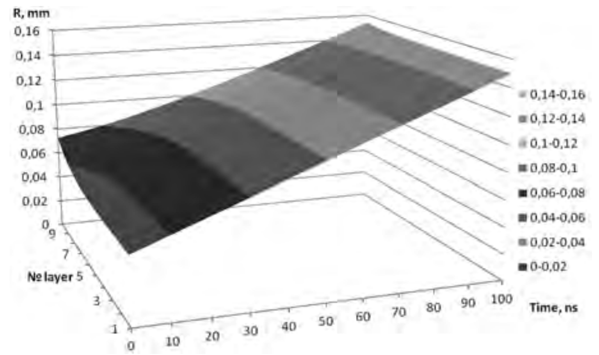

Fig. 2. The diagram radius changes in the calculated of layers at $\dot{R}$ = 100 m/s

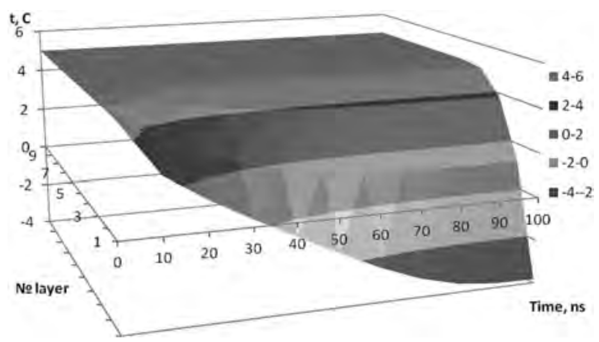

Fig. 3. The diagram of temperature fields in the water that surrounds bubble (phase transition in water is not considered). The calculation results for $\dot{R}$ = 50 m/s

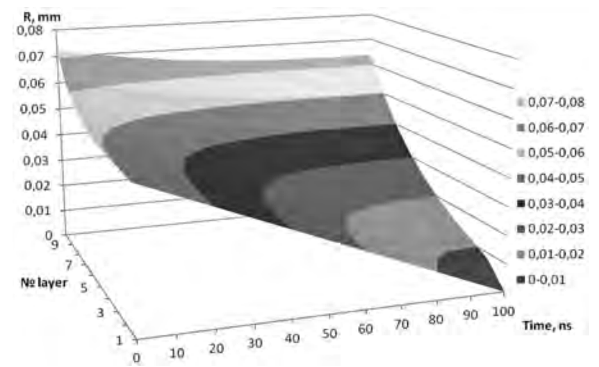

Fig. 4. The diagram radius changes in the calculated of layers at $\dot{R}$ = 50 m/s

3. Conclusions

Developed the mathematical model for calculating heat transfer in the fluid that surrounds the oscillating gas-steam bubble. The model takes into account the changing thermal and physical characteristics the liquid, changing the size of bubbles, heat exchange processes at its border. Created computer program for the calculation of this mathematical model. Obtained distribution of temperature fields in the liquid during the transition. The proposed calculation method can be used to determine the thermal and physical characteristics of fluid and vapor in a variety of technological processes related to boiling fluid cavitation and the formation of gas hydrates.

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