NUMERICAL MODELING OF THE RADIANT HEATING OF A LIQUID

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UDC 536.3

A method is proposed for the numerical modeling of the interaction between intense radiation (of arbitrary spectral composition) and absorbing liquid.

Detailed study of the interaction of intense radiation with liquids is necessary for the development and construction of cooling systems for powerful light sources [1]. The distinguishing feature of this interaction is the rapid (10^{-6}-10^{-3} sec) effervescence of the liquid and the pressure rise in the system to hundreds of atmospheres. The difficulty in calculating p(t) is associated with the need for detailed description of the thermodynamic and optical properties of the liquid, vapor, and two-phase system in a broad range of pressure and temperature variation.

In [2], it was shown that below the boiling point the equation of state of the liquid

$$\rho=\rho_c F\left(\frac{p}{p_c},\ \frac{i}{i_c}\right) \tag{1}$$

ensures good accuracy in calculating the dependence of the pressure on the absorbed energy.

In the present work, a model is proposed for the interaction between intense radiation and the liquid, based on the detailed (tabular) description of the equations of state of liquid and vapor, rigorous specification of the binodal, and sufficiently correct assumptions regarding the thermodynamic properties of the two-phase liquid—vapor system. The model proposed takes account of the radiation spectrum of the source and the absorption spectrum of the liquid. The results of the calculations are in good agreement with experimental data in the broad range of variation of the variables.

The interaction of a powerful radiation pulse with a liquid layer is characterized by three times: the radiation pulse length τ_1; the time for sound to pass through the liquid-filled volume, $\tau_2 = \delta/c$; and the time for heating of this volume, $\tau_3 = \delta^2/\chi$. In experiments, as a rule, $\tau_2 \ll \tau_1 \ll \tau_3$, i.e., the pressure in the liquid equalizes more rapidly than significant change in the absorbed energy occurs, and heat transfer in the course of the pulse may be neglected. It may be said that the pressure "follows" the absorbed energy and depends only on the time (there is no pressure gradient).

The absorbing power of the cooling liquid is due to the solution of special impurities. In this case, the absorption is massive, and $\kappa = \mu\rho$ [3].

Consider a plane liquid layer illuminated by a radiation flux of intensity W. The radiation-transfer equation in the absorbing layer takes the form [4]

$$\cos\theta\,\frac{dI}{dx}=-\varkappa(x)\,I(\theta,\ x). \tag{2}$$

Then

$$I=I_0\exp\left(-\int\limits_0^x\frac{\varkappa(x')}{\cos\theta}\,dx'\right). \tag{3}$$

Taking into account that the energy liberation in the medium Q is related to the brightness as follows

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I. I. Mechnikov Odessa State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 1, pp. 104-109, January, 1986. Original article submitted October 22, 1984.

0022-0841/86/5001 0087$12.50

$$Q = \int \varkappa I d\Omega, \tag{4}$$

It is found that

$$Q = \int_0^{2\pi} d\varphi \int_0^{\pi/2} \varkappa I_0 \sin\theta \exp\left(-\int_0^x \frac{\varkappa dx'}{\cos\theta}\right) d\theta. \tag{5}$$

Suppose that the source surface emits according to the Lambert law, that is

$$I = \frac{W}{\pi} = \text{const}. \tag{6}$$

In this case

$$Q = 2W\varkappa\left[\exp\left(-\int_0^x \varkappa dx'\right) + \mathrm{Ei}\left(-\int_0^x \varkappa dx'\right)\right] \equiv W\rho\psi\left(\int_0^x \varkappa dx'\right) \tag{7}$$

where

$$\mathrm{Ei}(z) = -\int_0^z \frac{e^{-y}}{y} dy .$$

As is shown in [1], the equation of state for the given problem may expediently written in the form

$$\rho = \rho(i,\ p), \tag{8}$$

since in this case the system of equations describing the change in thermodynamic state of the liquid is written more simply

$$\frac{di_1}{dq} = \psi\left(\int_0^x \varkappa dx'\right), \tag{9}$$

$$\frac{di_2}{dp} = \rho^{-1}(i,\ p), \tag{10}$$

$$\int_0^\delta \rho(i,\ p)\, dx = \frac{M}{S}, \tag{11}$$

$$i = i_1 + i_2. \tag{12}$$

Here $q \equiv \int_0^t W(t')\,dt'$ is the energy absorbed by the liquid from unit surface at time t (i.e., q is the energy analog of the time).

The system in Eqs. (8)-(12) must be complemented by initial conditions: the initial state $\rho(0, x)$, $i(0, x)$ must be specified in the whole volume of the liquid.

The true (experimentally determined) absorption spectrum of the liquid and emission spectrum of the lamp are used in the calculations for more accurate reproduction of the experimental conditions. The spectra are introduced in Eq. (9) by means of the relation

$$\psi\left(\int_0^x \varkappa dx'\right) = \sum_\lambda \psi_\lambda\left(\int_0^x \varkappa_\lambda dx'\right), \tag{13}$$

where $\psi_\lambda\left(\int_0^x \varkappa_\lambda dx\right) = 2\eta_\lambda\mu_\lambda\left[\exp\left(-\int_0^x \varkappa_\lambda dx'\right) + \mathrm{Ei}\left(-\int_0^x \varkappa_\lambda dx'\right)\right]$; η_λ is the spectral efficiency of the radiation source; κ_λ is the absorption coefficient of the liquid at wavelength λ.

The equation of state of the liquid in the form $\rho = \rho(i, p)$ is encountered in the literature. For numerical calculations, it is specified by tables compiled from the data of

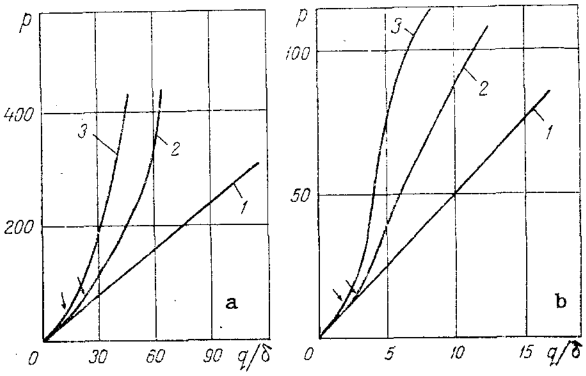

Fig. 1. Dependence of the liquid pressure on the energy supplied: a) water-based liquid; Λ = 10 (1), 35 (2), 85 (3); b) alcohol-based liquid; Λ = 17 (1), 60 (2), 240 (3); p, bar; q/δ, J/cm³.

[5, 6]. At intermediate points, the values of the functions are obtained by interpolation from the four closest points belonging to the same phase. The phase-equilibrium curve required for calculation in the boiling region is represented by a tabular dependence of the densities and specific enthalpies of the vapor and liquid on the pressure.

In the numerical solution of the problem, the differential Eqs. (9) and (10) are approximated by the difference equations

$$(i_1)_l^{j+1,\,s+1} - (i_1)_l^j = \Delta q \psi \left(\int_0^x \frac{\varkappa_l^{j+1,\,s} + \varkappa_l^j}{2}\, dx' \right), \tag{14}$$

$$(i_2)_l^{j+1,\,s+1} - (i_2)_l^j = (p^{j+1} - p^j) \left[\left(\frac{1}{\rho} \right)_l^{j+1,s} + \left(\frac{1}{\rho} \right)_l^j \right] \Big/ 2, \quad i_l^j = (i_1)_l^j + (i_2)_l^j,$$

on the spatial grid $x_0 = 0;\ x_l = x_{l-1} + h_l;\ l = 1, \ldots, N$. The variable grid step h_l is chosen so that the grid points are compressed toward the point x_0, where the energy liberation is a maximum. The superscript j denotes the time layer, and the superscript s denotes the iteration for time layer j + 1. Convergence of the iteration is determined from the mass-conservation law

$$\sum_{l=1}^{N} \rho_l^{j+1,s_m} (x_l - x_{l-1}) = \frac{M}{S},$$

where s_m is the number of the last iteration for the layer j + 1.

The use of the equation of state in the form $\rho_l^j = \rho[i_l^j, p^j]$ implies that the thermodynamic properties of the material may be regarded as approximately uniform within the limits of a thin layer. This assumption also determines the choice of the number of layers (N). But, for any N, the heating conditions may be such that some of the material — one or a few layers — transforms from the liquid to the gas state before the pressure rises above the critical value.

Suppose that in conditions characterized by large temperature gradients metastable and unstable states are not realized. In this case, the material inside the elementary layer $(x_l - x_{l-1})$ is a mixture of liquid and vapor for some part of the time Δt. If in the course of the calculation the enthalpy of the layer i_l^j at a pressure p^j exceeds the liquid enthalpy at the equilibrium line $i_L(p^j)$ but does not reach the vapor enthalpy $i_V(p^j)$, the state of the liquid is regarded as of two-phase type. Knowing the heat of phase transition $\lambda(p) = i_V(p) - i_L(p)$, it may be supposed that $\eta = (i - i_L)/\lambda$ is the proportion of vapor and $(1 - \eta) = (i_V - i)/\lambda$ is the proportion of liquid. In this case, the "mean specific volume" V is taken in the form

$$V(p, i) = \eta(p, i) V_V(p) + (1 - \eta) V_L(p).$$

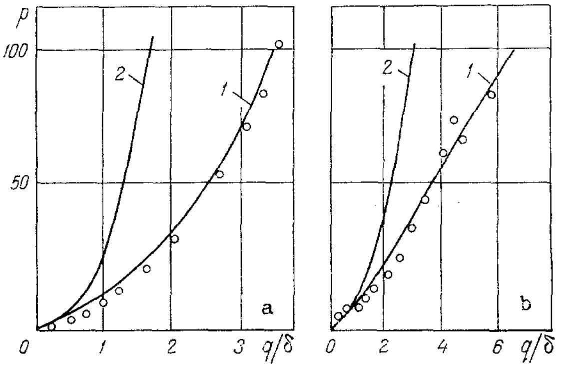

Fig. 2. Comparison of the theoretical and experimental results: 1) results of numerical modeling; 2) results of calculation by the model of [3]; the points correspond to experimental measurements; a) water-based liquid, $\Lambda = 900$; b) alcohol-based liquid, $\Lambda = 245$.

The density $\rho(p, i) = V^{-1}(p, i)$.

To verify that the given model is adequate, experiments are performed to determine the reaction of the absorbing liquids to the action of radiation.

The results of the calculation are expediently written in the form of the dependence of the pressure in the system on the energy supplied. This dependence is also important from a practical viewpoint: it may be used to predict the point at which the permissible pressure in the system is exceeded and to predict failure of the lamp.

So as not to be limited to specific conditions of radiation-source operation and absorption spectrum, it is convenient to convert (in presenting the results) to the spectral-mean absorption coefficient $\varkappa$. The optical thickness $\Lambda = \int_0^\delta \varkappa dx = \mu \int_0^\delta \rho dx = \mu M/S$ characterizes the absorbing power of the liquid.

The results of numerical modeling by the given method for liquids based on water and alcohol are shown in Fig. 1 (the change in Λ in the numerical calculation is specified as the change in concentration of the absorbing dye μ, which corresponds to the experimental conditions; calculations continue until $p = 2p_c$). It is evident that, at small energy inputs (before the onset of boiling), the dependence of the pressure on the energy supplied is near-linear in accordance with the results of approximate calculations [1-3]. From the onset of boiling (arrows indicate the appearance of vapor phase in Fig. 1), the dependence becomes sharper, which is due to the appearance of gas with considerably lower density at the same pressures. Sharp increase in pressure may cause failure of cooling-system elements, as noted above.

An important practical result following from Fig. 1 may be noted: at small $\Lambda(\sim 10)$, the liquid is heated without boiling. These conditions of heating lead to a lower pressure (at the same energy input). Reduction in pressure is associated with a more uniform temperature distribution over the volume, since the derivative $(\partial p/\partial T)_V$ increases with increase in T.

The results of numerical modeling, the data of [3], and the experimental results are shown in Fig. 2. It is evident that numerical calculation by the method proposed in the present work gives good agreement with experimental results, whereas the calculation of [3] gives only the qualitative form of the corresponding dependence.

Note that taking account of the nonparallel motion of the rays and the spectral features of the radiation distribution gives corrections of ~10%, which is within the limits of experimental accuracy.

NOTATION

ρ, density; p, pressure; i, specific enthalpy; τ_1, radiation pulse length; τ_2, time for sound to pass through the liquid-filled volume; τ_3, time to heat liquid; c, velocity of sound; χ, thermal diffusivity of liquid; κ, absorption coefficient; W, radiation intensity; θ, angle between ray and normal to the layer; I, energy brightness of radiation; Q, energy liberation in medium; M, liquid mass; S, area of illuminated surface; η, spectral efficiency of radiation source; Ω, solid angle; φ, azimuthal angle; λ, heat of phase transition; Λ, optical thickness; V, liquid-filled volume; h, grid step; δ, thickness of liquid layer in the direction perpendicular to propagation of the radiation; F, universal function calculated within the framework of similarity theory, Indices: c, critical area.

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INTENSIFICATION OF MASS-EXCHANGE PROCESSES BY AN ELECTRIC FIELD IN A CAPILLARY POROUS SOLID—LIQUID SYSTEM

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UDC 664.1.033.001.5

An experimental study is performed of mass-exchange processes during extraction in a capillary porous solid—liquid system in an electric field. The experimental data are generalized to a critical function.

Electrical fields are widely used to intensify heat and mass exchange in various chemical and technological processes such as absorption, drying, etc. [1, 2]. Moreover, they can be used in the production of sugar, plant oils, and other extraction processes which remove organic substances from plant materials. In this case use of the field can improve the quality of the product obtained [3].

It is well known that internal molecular mass transfer (within the capillary porous body) to the body—liquid boundary in the case of sucrose extraction is characterized by the sucrose diffusion coefficient in the plant tissue, the value of which depends on the physicochemical properties of the body and the temperature. Transfer of material from the surface of the capillary porous body into the flow of liquid being extracted is characterized by a mass-transfer coefficient, the value of which is dependent on hydrodynamic conditions of the process. We have experimentally established the value of the sucrose diffusion coefficient in a capillary porous body during extraction in an electric field in a previous study [4].

Below we will present the results of a study of mass exchange in extraction of sugar from a layer of capillary porous body into a liquid over various ranges of electric field intensity and temperature to clarify the effect of the hydrodynamic factor. To do this a device was created (Fig. 1) which generated a specific extraction rate through the layer of capillary porous substance with the quantity and concentration of extractant being measured at various times. The apparatus consisted of a thermostat, extractor, regulating valves, and measurement vessels.

Technical Thermophysics Institute, Academy of Sciences of the Ukrainian SSR, Kiev. Translated from Inzhererno-Fizicheskii Zhurnal, Vol. 50, No. 1, pp. 109-113, January, 1986. Original article submitted October 16, 1984.

0022-0841/86/5001-0091$12.50