DOI 10.1007/s10891-015-1294-3

Journal of Engineering Physics and Thermophysics, Vol. 88, No. 5, September, 2015

HEAT TRANSFER IN PHASE TRANSFORMATIONS

EVAPORATION OF WATER IN THE PROCESS OF MOVEMENT OF ITS LARGE MASSES THROUGH A HIGH-TEMPERATURE GAS MEDIUM

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A numerical investigation of the heat transfer in large monolithic water masses and water masses with different spaces filled with water vapor and gases, moving through high-temperature gases at temperatures higher than 1000 K under the conditions of phase transformations, has been performed. The completeness of evaporation of the water from a water mass moving in a high-temperature gas medium was numerically estimated with account for the degree of inhomogeneity of the water mass.

Keywords: *heat of vapor formation, heat transfer, evaporation of water, water mass, flame zone, combustion, high-temperature gases.*

Introduction. A primary problem of the modern technologies of fire fighting with the use of water or water emulsions is the minimization of the mass of a liquid m_{liq} necessary for suppression of a fire and the provision of the completeness of the fire-fighting process [1–3]. However, the value of m_{liq} is estimated empirically as a rule, which leads every so often to a substantial overestimation of the mass of the liquid used for the fire suppression. In this case, the efficiency of use of an extinguishing liquid is determined without regard for both the intensity of vapor formation and the decrease in the temperature of the liquid in a combustion region that is due to the endothermal evaporation effect, which is explained by the absence of experimental data on the temperature and concentration fields of the combustible and oxidizer in combustion regions as well as theoretical data on the change in the thermal state of a medium after a large mass of a extinguishing liquid is introduced into it.

The mechanism of evaporation of single water drops and their groups in the process of movement of water through high-temperature (more than 1000 K) gases (combustion products) were determined in a number of numerical investigations [4–9]. However, the models obtained in them cannot be used formally for analysis of the movement of a large water mass, which is explained by the fact that the physical processes occurring in single water drops and in a water mass in the process of their movement through a high-temperature gas medium are different because of the difference between a water drop and a water mass in their structure. A single water drop can be considered as a monolithic formation, while a water mass represents a formation with a heterogeneous structure that is deformed in the process of movement of the water mass, evidently, in three directions, with the result that, in the water mass there can arise vertical and horizontal spaces (Fig. 1) that change the thermophysical properties of the water and, consequently, the conditions of heat transfer in it.

The aim of the present work is to analyze the processes of evaporation of an inhomogeneous water mass in the process of its movement through a high-temperature gas medium and to determine the possibility of use of different approaches [4–9] to the simulation of the movement of a large water mass under the conditions of its intense evaporation.

Formulation of the Problem. Under real conditions, a large water mass moving through high-temperature gases is deformed as a result of the formation of gas and vapor spaces in it. In the present work, the most typical cases of deformation of such a water mass with the formation of vertical (Fig. 1b), horizontal (Fig. 1c), and inner (Fig. 1d) spaces in it are considered.

The problem on the evaporation of water in the process of its movement through a high-temperature gas medium was solved in the plane formulation (Fig. 1). The longitudinal and transverse sizes of the air spaces in a water mass

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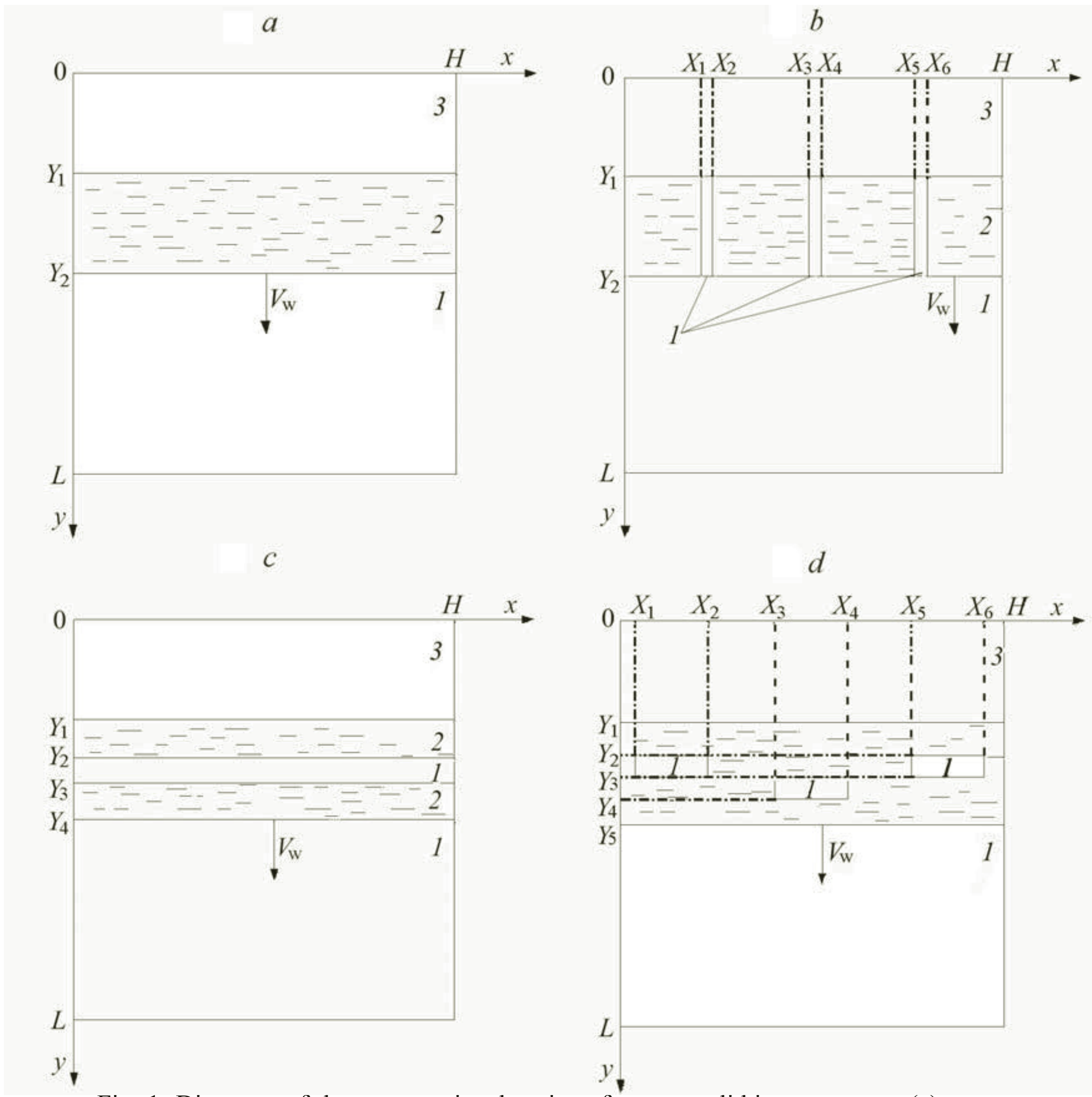

Fig. 1. Diagrams of the computational regions for a monolithic water mass (a), water masses with vertical (b) and horizontal (c) subregions and a water mass with several spaces at depth (d): 1) vertical combustion products; 2) water; 3) water vapor.

were selected so that they are much smaller than the characteristic sizes of the water mass at the initial instant of time. The distance that these spaces pass in the fire zone of a combustion region, where they interact with the high-temperature gases, was assumed to be relatively small (from several units to several tens of meters) and dependent on the height of the flame and the type of a fire. It was assumed that, for the time of movement of a water mass (from several units to several tens of seconds), its characteristic sizes can increase by two or three times; in this case, the sizes of the spaces formed as a result of the deformation of the water mass comprise not more than 10% of its size.

The movement of a water mass in the flame zone of a combustion region is accompanied by fairly intensive vapor formation everywhere over the volume of the water mass. Under the conditions of high temperatures, the rate of evaporation of water reaches a maximum value corresponding to the intensity of its boiling at a definite pressure. Therefore, the pressure of water vapor outflowing from the vapor-formation zone prevents the increase in the longitudinal and transverse sizes of the water mass relative to its initial sizes. The above-described elementary physical processes are characteristic of water masses of any dimensions (from several centimeters to several meters). Of the heat-transfer processes that can take place under the conditions being considered, of greatest importance is the heat conduction of the water mass, the accumulation of heat in it in the process of heating of water before it begins to evaporate, and the evaporation of water at all the boundaries (outer and inner) of the water mass (Fig. 1).

It is worthwhile to solve the problem on the determination of the fraction of water in a water mass that evaporates in the process of its movement through a high-temperature zone. This problem was formulated with some assumption, namely, without considering the possible decrease in the heat flow directed to the evaporation surface that is due to the inflow of water vapor to the zone found between the water mass and the high-temperature gases, the convective heat exchange in the zone separating the water from the flame, the increase in the mass flow rate of the water vapor in the space in which it moves, in the pressure of the vapor in this space, and in its size with decrease in the fraction of the evaporated water in the water mass, and the possible fairly large decrease in the intensity of heat supply to the evaporation boundary and the attendant decrease in the rate of phase transition and in the fraction of the evaporated water due to the above-indicated processes. It is assumed that a water mass moving in a high-temperature gas medium is shaped as a parallelepiped (Fig. 1) during the time of its movement. In real practice, such a water mass can be deformed. At the same time, as noted above, the water vapors flowing over all the sides of a water mass at a pressure higher than the atmospheric pressure prevent the destruction and significant deformation of the water mass and, therefore, the large change in its shape. It is assumed that the effect of possible circular parallelism of a water mass having a large transverse size [6–9] is insignificant and that the gas spaces in it are rectangular in shape (Fig. 1). It is evident that, under real conditions, both the vertical and horizontal boundaries of these spaces can be curves. However, small deformations of the indicated spaces at practically constant areas of their evaporation surfaces cannot significantly influence the intensity of evaporation of the liquid from the boundaries of the spaces and the velocity of heat transfer in these inhomogeneous formations.

Since the problem on the heat conduction of a water mass is solved in the plane formulation, the three-dimensionality of this process can be taken into account without any serious methodical complexities in the writing of its mathematical model. However, in this case, as numerous examples show [10–14], the time of calculations increases by several tens times even without change in the main characteristics of the heat-transfer process [10, 12]. The experience of solving such problems [10, 12] shows that the space effects, even those that are due to the complex geometry of the object being considered, substantially influence its integral characteristics.

In the formulation of the problem on the heat transfer in a water mass moving through a medium, the possible energy transfer in the water mass due to the thermal radiation in it was not taken into account because this effect is of secondary importance in the temperature range being considered. It was assumed that, because of the intensive evaporation of water at all the outer boundaries of the water masses being investigated, the temperature of the water in them cannot be higher than the temperature of its boiling. The velocity of movement of water in a high-temperature region V_w was taken as a parameter of the problem and was changed in the real range 1–5 m/s [4–9]. In this case, the velocity V_w can be determined experimentally or theoretically from the solution of the problem on the movement of one or several water drops under the conditions of evaporation of water due to its intensive heating [4–9].

Mathematical Model and Methods of Its Solution. The model of heat transfer in a water mass under the conditions of the water–water-vapor–high-temperature-gas phase transitions (Fig. 1) includes typical nonstationary partial differential equations of heat conduction [15]. For a water mass with several spaces (Fig. 1d), this model represents the following system of equations:

$X_1 < x < X_2$, $X_5 < x < X_6$, $Y_2 < y < Y_3$; $X_3 < x < X_4$, $Y_3 < y < Y_4$; $0 < x < H$, $Y_5 < y < L$:

$$\frac{\partial T_1}{\partial t} = a_1 \left[\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} \right], \tag{1}$$

$Y_1 < y < Y_2$, $0 < x < H$; $Y_2 < y < Y_3$, $0 < x < X_1$, $X_2 < x < X_5$, $X_6 < x < H$; $Y_3 < y < Y_4$, $0 < x < X_3$, $X_4 < x < H$; $Y_4 < y < Y_5$, $0 < x < H$:

$$\frac{\partial T_2}{\partial t} = a_2 \left[\frac{\partial^2 T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} \right], \tag{2}$$

$0 < x < H$, $0 < y < Y_1$; $Y_1 = V_w t$, $Y_5 = L_w + V_w t$:

$$\frac{\partial T_3}{\partial t} = a_3 \left[\frac{\partial^2 T_3}{\partial x^2} + \frac{\partial^2 T_3}{\partial y^2} \right], \tag{3}$$

with the initial conditions ($t = 0$)

$0 < x < H$, $0 < y < Y_1$; $Y_1 < y < Y_2$, $0 < x < H$; $Y_2 < y < Y_3$, $0 < x < X_1$, $X_2 < x < X_5$, $X_6 < x < H$; $Y_3 < y < Y_4$, $0 < x < X_3$, $X_4 < x < H$; $Y_4 < y < Y_5$, $0 < x < H$:

$$T = T_0 ,$$

$X_1 < x < X_2$, $X_5 < x < X_6$, $Y_2 < y < Y_3$; $X_3 < x < X_4$, $Y_3 < y < Y_4$; $0 < x < H$, $Y_5 < y < L$:

$$T = T_{\text{c.p}} ,$$

and the boundary conditions ($0 < t < t_{\text{w}}$)

$$x = 0 , \quad x = H , \quad 0 < y < Y_1 : \quad T = T_{\text{c.p}} , \tag{4}$$

$$x = 0 , \quad x = H , \quad Y_1 < y < Y_5 : \quad T_1 = T_2 , \tag{5}$$

$$x = 0 , \quad x = H , \quad Y_5 < y < L : \quad T = T_{\text{c.p}} , \tag{6}$$

$$\begin{gathered} x = X_1 , \quad x = X_2 , \quad x = X_5 , \quad x = X_6 , \quad Y_2 < y < Y_3 : \\ -\lambda_1 \frac{\partial T_1}{\partial x} = -\lambda_2 \frac{\partial T_2}{\partial x} - Q_{\text{e}} W_{\text{e}} , \quad T_1 = T_2 , \end{gathered} \tag{7}$$

$$x = X_3 , \quad x = X_4 , \quad Y_3 < y < Y_4 : \quad -\lambda_1 \frac{\partial T_1}{\partial x} = -\lambda_2 \frac{\partial T_2}{\partial x} - Q_{\text{e}} W_{\text{e}} , \quad T_1 = T_2 , \tag{8}$$

$$y = 0 , \quad 0 < x < H : \quad \frac{\partial^2 T_3}{\partial y^2} = 0 , \tag{9}$$

$$y = Y_1 , \quad 0 < x < H : \quad -\lambda_2 \frac{\partial T_2}{\partial y} = -\lambda_3 \frac{\partial T_3}{\partial y} , \quad T_2 = T_3 , \tag{10}$$

$$\begin{gathered} y = Y_2 , \quad y = Y_3 , \quad X_1 < x < X_2 , \quad X_5 < x < X_6 : \\ -\lambda_1 \frac{\partial T_1}{\partial y} = -\lambda_2 \frac{\partial T_2}{\partial y} - Q_{\text{e}} W_{\text{e}} , \quad T_1 = T_2 , \end{gathered} \tag{11}$$

$$y = Y_3 , \quad y = Y_4 , \quad X_3 < x < X_4 : \quad -\lambda_1 \frac{\partial T_1}{\partial y} = -\lambda_2 \frac{\partial T_2}{\partial y} - Q_{\text{e}} W_{\text{e}} , \quad T_1 = T_2 , \tag{12}$$

$$y = Y_5 , \quad 0 < x < H : \quad -\lambda_1 \frac{\partial T_1}{\partial y} = -\lambda_2 \frac{\partial T_2}{\partial y} - Q_{\text{e}} W_{\text{e}} + \varepsilon\sigma(T_1^4 - T_2^4) , \tag{13}$$

$$y = L , \quad 0 < x < H : \quad T = T_{\text{c.p}} . \tag{14}$$

The mass flow rate of the evaporating water was calculated by the formula

$$W_{\text{e}} = \varphi \rho_2 V_{\text{w}} . \tag{15}$$

In the process of simulation, the longitudinal size of a water mass $L_w = Y_5 - Y_1$ was calculated in each time step in much the same manner as in the models proposed in [4–9] and the transverse size of the water mass H_w was assumed to be constant. The system of nonstationary partial differential equations (1)–(3) with the boundary conditions (4)–(14) was solved with the use of methods and algorithms described in [4–9]. For estimating the reliability of the results of a numerical simulation, the conservatism of the difference schemes used was verified by analogy with [10, 12].

Results and Discussion. The numerical investigations of the heat-transfer processes and phase transformations in the water masses, presented schematically in Fig. 1, were carried out at the following values of the parameters of the problem [16–18]: the initial temperature of the water in a water mass $T_0 = 300$ K, the temperature of the gases (combustion products) $T_{c.p} = 1170$ K, the evaporation heat of water $Q_e = 2.26$ MJ/kg, the initial sizes of the water mass $H_w = 1$ m and $L_w = 0.15$ m, the dimensions of the computational region $H = 1$ m and $L = 15$ m, the dimensions of the spaces in the water mass $H_s = 0.02$ m and $L_s = 0.15$ m (Fig. 1b), $H_s = 1$ m and $L_s = 0.015$ m (Fig. 1c), $H_s = 0.1$ m and $L_s = 0.04$ m (Fig. 1d), and the velocity of movement of water $V_w = 1$–5 m/s. The thermophysical characteristics of the water in a water mass (density, heat conduction, heat capacity), the water vapor, and the high-temperature gases were taken to be equal to the analogous characteristics of typical combustion products [16–18]. The quantity φ was used as an integral parameter of the problem, characterizing the evaporation of water.

Of interest is the calculation of the fraction of the evaporated water in a water mass supplied to the flame zone of a combustion region under the typical conditions corresponding to the conditions of a real fire and the study of the influence of the spaces in this moving water mass on the intensity of vapor formation. The parameter φ was calculated on the assumption that the temperature of the water at the boundary of the phase transition is maximum, i.e., it is equal to the boiling temperature $T_e = 373 \pm 5$ K. Analysis of the physical model of heat-transfer in a water masses moving through a high-temperature gas medium (Fig. 1) and the results obtained in [4–9] show that the temperatures at the front surfaces of such a water mass and of its spaces can differ from the water boiling temperature T_e. Therefore, the values of the parameter φ for the spaces having different geometries can be different (Fig. 1b–d). It has been established that, for all the water masses being investigated, independently of the number of spaces in them, the parameter φ at their front surface is equal to $0.21 \cdot 10^{-3}$ and the values of φ are very different for the conditional spaces of these water masses. For example, for a water mass with a structure shown in Fig. 1b, the integral parameter φ is equal to $0.08 \cdot 10^{-3}$. For a water mass with spaces oriented transversely in it relative to the direction of movement of the water (Fig. 1c), $\varphi = 0.03 \cdot 10^{-3}$, and, for a water mass containing local spaces positioned deep in it (Fig. 1d), $\varphi = 0.01 \cdot 10^{-3}$. These substantial differences between the values of φ in different water masses can be explained by the differences between the temperatures in the neighborhood of the phase boundaries inside them and the temperatures at their front surfaces. For example, it has been established that the temperature T_e is maximum at the front surface of a water mass and is minimum at its depth.

Figure 2 shows typical isotherms obtained for the water masses being considered. It is seen that the temperatures in the neighborhood of the boundaries of the liquid and the high-temperature gases differ by 25–40 K. At the front surfaces of the water masses, $T_e = 373 \pm 5$ K, and, in their spaces T_e decreases to 340–360 K. As a consequence, the parameter φ is much larger at the front surface of a moving water mass than at its depth. It is significant that, when the velocity V_w increases to a maximum value equal to approximately 5 m/s [4–9], the mass flow rate of the evaporating water decreases by several times [7–9] as compared to the above-indicated values. Because of this, the determined values of φ can be considered as upper estimates relative to the value of this parameter attained under real conditions of suppression of a fire by a nonatomized water. The isotherms presented in Fig. 2 also show that the temperatures in the wake of the indicated water masses are substantially different. For example, in the case where a water mass contains spaces, the temperature in its wake is decreased by 20–30 K (Fig. 2b–d) as compared to that in the case illustrated in Fig. 1a, which is explained first of all by the increase in the area of the vapor-formation surface. Despite the large decrease in the parameter φ in the spaces of a water mass ($0.01 \cdot 10^{-3}$–$0.08 \cdot 10^{-3}$) relative to the value of this parameter at its front surface ($0.21 \cdot 10^{-3}$), additional evaporation of water can take place in these spaces. However, analysis of the isotherms obtained (Fig. 2) points to the substantial narrowing of the “temperature” wake downstream of a water mass moving through high-temperature gases. It was established that, in the process of movement of a water mass deep into the flame zone of a combustion region, even at a distance of 4–5 m from its input, the temperature of the water in the water mass becomes close to the temperature of the combustion products $T_{c.p}$ due to the intensive supply of them to the side surface of the water mass. Even in the case of movement of a monolithic water mass through the flame zone of a combustion region (Fig. 1a), the temperature in its wake is much higher as compared to the temperatures of the water and the vapor in the small "near-wall" region of the water mass (Fig. 3). This result points to the inefficiency of local supply of water to a combustion region for suppression of the combustion process.

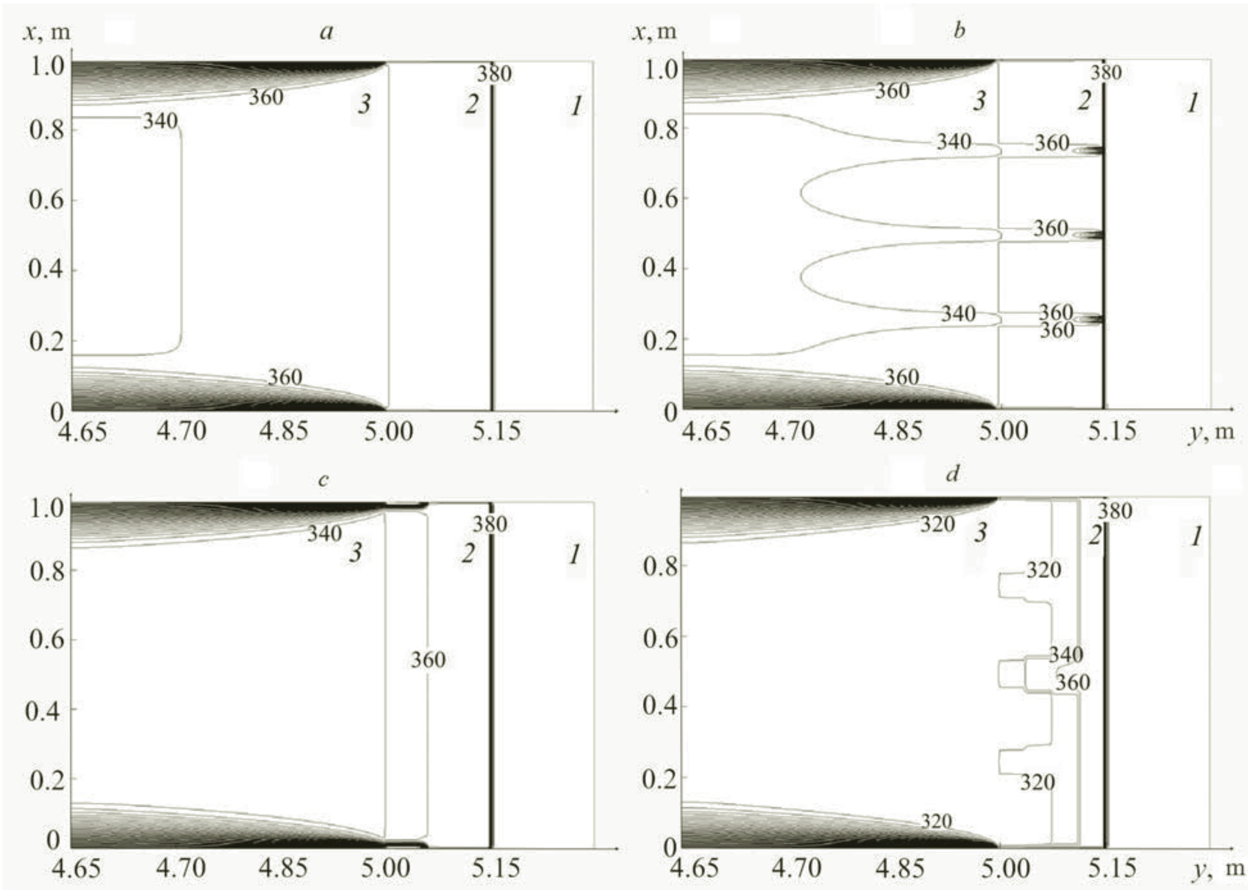

Fig. 2. Isotherms calculated for a monolithic water mass (a), water masses with vertical (b) and horizontal (c) spaces, and a water mass with several spaces at depth (d) at an instant of time $t = 5$ s: 1) combustion products; 2) water; 3) water vapor.

The determined fraction of water evaporated in a water mass is somewhat larger than the possible real one, because the temperature of a flame can be lower than the temperatures being considered (1070 K). Moreover, problem (1)–(5) was formulated without regard for the fact that, in the neighborhood of the phase-transition boundaries, there arise vapor layers that can decrease the rate of vapor formation. The numerical estimates made show that the fraction of water evaporated from the water masses being considered, which are fairly typical in size and dispersivity, in the process of their movement through a high-temperature gas medium comprises less than 0.1% of the initial quantity of water in them. This allows the conclusion that practically all the water supplied locally to a combustion region passes through its flame zone and only its small part is evaporated.

Analysis of the results of the numerical calculations carried out in [6–9], of the analytical investigations performed in [19–22], and of the experiments conducted in [23–25] shows that the coefficient of useful use of a liquid supplied to a combustion region for suppression of a fire can be substantially increased by atomization of this liquid for the purpose of increasing the area of its evaporation surface. This conclusion [6–9] conforms well with the results of the numerical investigations performed in the present work. For example, it was established that, for the water masses with fairly typical spaces, shown in Fig. 1b–d, the fraction of the evaporated water is larger as compared to that in a relatively monolithic water mass (Fig. 1a). Therefore, it makes sense to supply finely dispersed water, i.e., a water mass with a substantially (by many terms) increased area of the vapor-formation surface, to the flame zone of a combustion region. In this case, as the results of analysis of the effect of coagulation of individual liquid drops [6–9] show, it would be reasonable not only to atomize an extinguishing liquid in the transverse directions but also to supply it to a combustion region by layers with a time delay between them.

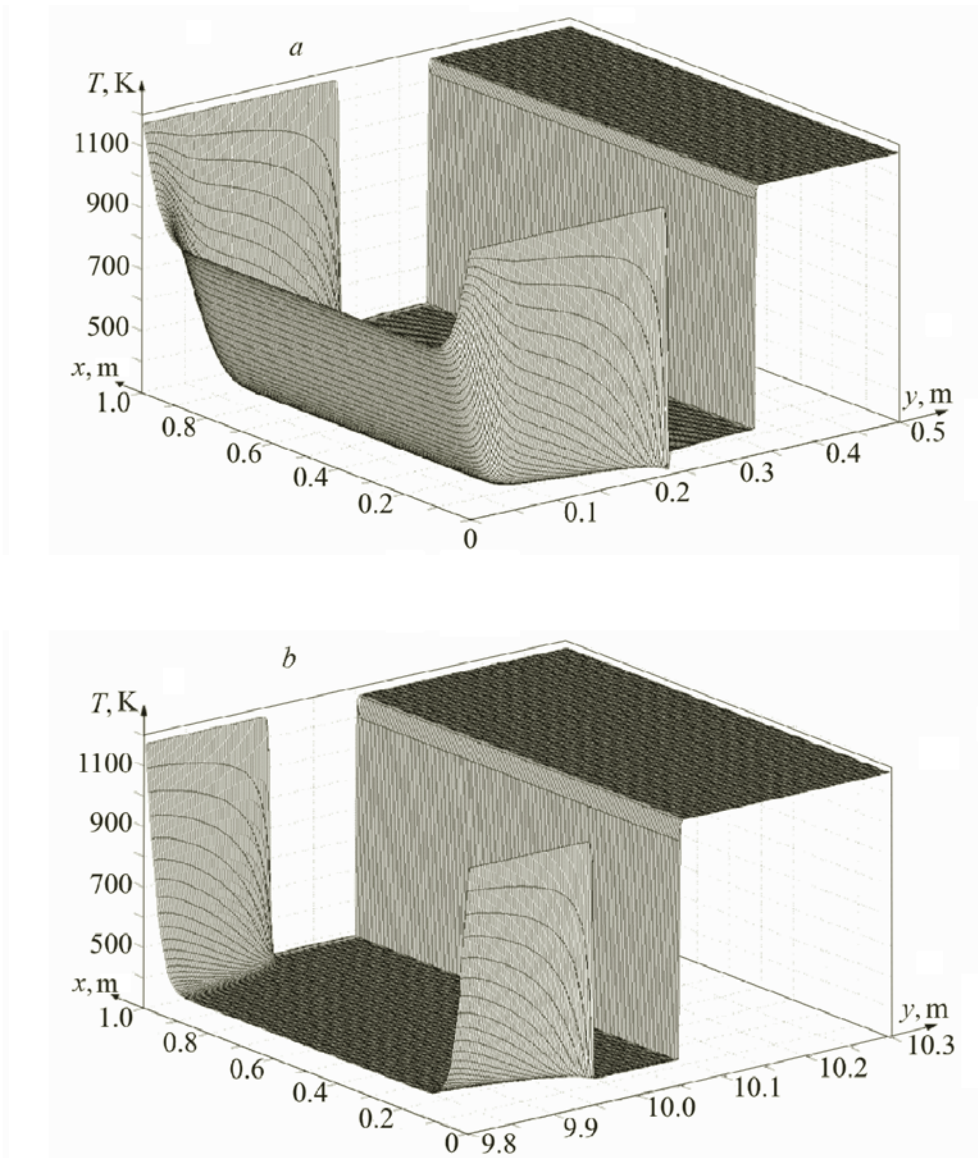

Fig. 3. Temperature field in a system with a monolithic water mass at t = 0.25 (a) and 10 s (b).

CONCLUSIONS

1. The larger part of water in a more or less monolithic water mass moving through the high-temperature gases in a combustion region is practically not evaporated, with the result that the thermal effect of the endothermic phase transitions in this water mass is used insufficiently for decreasing the temperature in the flame zone of the combustion region.

2. In the case of supply of a large water mass to a combustion region without special atomization, it is impossible to provide intensive vapor formation.

3. For intensification of evaporation of a large water mass in a combustion region, it is advantageous to substantially increase the area of its surface, which can be attained by deformation of the surface of the water mass, atomization of water in it, formation of drop flows, and breaking of liquid drops. Methods of intensification of these processes are being fairly actively developed [26–33].

This work was carried out with financial support from the Russian Scientific Foundation (project No. 14-39-00003).

NOTATION

a, thermal conductivity, m^2/s; C, specific heat capacity, J/(kg·K); H and L, sizes of the computational region, m; H_s and L_s, sizes of a space in a water mass, m; L_w, longitudinal size of a water mass, m; M_w, mass of water used for suppression of a fire, kg; Q_e, thermal effect of water evaporation, J/kg; t, time, s; t_w, time of existence (movement through a flame) of a water mass in the gas phase, s; T, temperature, K; T_0, initial temperature of water in a water mass, K; T_e, boiling temperature of water in a water mass, K; $T_{c.p}$, temperature of the combustion products, K; V_w, velocity of movement of a water mass, m/s; W_e, mass velocity of the evaporating water flow, kg/(m^2·s); x and y, Cartesian coordinates, m; ε, reduced emissivity factor; λ, heat conduction, W/(m·K); ρ, density, kg/m^3; σ, Stefan–Boltzmann constant ($\sigma = 5.669 \cdot 10^{-8}$ W/(m^2·K^4)); φ, fraction of evaporated water. Subscripts: c.p, combustion products; e, evaporation; w, water; 0, initial state of water.

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