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Development of the heat and mass transfer model for the study of the temperature traces water droplets in a flame

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Abstract. The heat and mass transfer model is developed with using Ansys Fluent. The typical temperature of gases in the trace of water droplets is determined (initial temperature of gases 1170 K). Several types for the location of water droplets are studied: two successive water droplets; two parallel water droplets; five water droplets in checkerboard order. The hypothesis about gas temperature reduction in the trace of a moving liquid is confirmed.

1 Introduction

At the present time the development of new oil and gas accumulations is in progress. Oil and gas are highly flammable matters. Because of this, there are special requirements for the development and operation of oil and gas accumulations. The main emphasis is given to ensuring the fire safety [1 - 4]. The most common methods of fire extinguishing are water mist fire suppression system [1, 3] and fire extinguishing with using big water mass [2, 4].

Over the last years researches are conducted [1 - 3]. The main objectives of these researches aimed at improving the efficiency of means and methods of atomization. Unfortunately, the fact is not taken account that the water droplets during motion in high-temperature gases reserve temperature traces which reduce the temperature in the combustion zone due to the evaporation of water droplets.

The goal of the present work is development of heat and mass transfer model for the study of the temperature traces water droplets in a flame with using Ansys Fluent.

2 Physical model of heat and mass transfer

When formulating heat and mass transfer problem, we assumed that the initial temperature of water droplets is T_w=300 K. Temperature of high-temperature gases is T_g=1170 K. Water droplets are heated by conduction in the flow of high-temperature gases. It was assumed that the thermal characteristics of the materials are not dependent on temperature.

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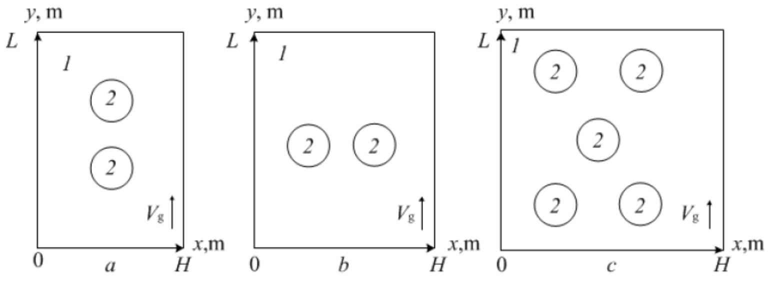

Fig. 1. Scheme of solution area for two successive water droplets (*a*); two parallel water droplets (*b*); five water droplets (*c*): *1* – high-temperature gases, *2* – water droplets

3 Mathematical model and decision methods

The processes under study are described by the system (Fig. 1) of non-stationary partial differential equations.

For high-temperature gases ($0<x<H$, $0<y<L$):

continuity equation:

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}=-\omega\text{, at }\omega=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}$$

motion equation:

$$\frac{\partial\omega}{\partial t}+u\frac{\partial\omega}{\partial x}+v\frac{\partial\omega}{\partial y}=\gamma\left(\frac{\partial^2\omega}{\partial x^2}+\frac{\partial^2\omega}{\partial y^2}\right)+\beta g_{\mathrm{y}}\frac{\partial T_1}{\partial x}\text{, at }u=\frac{\partial\psi}{\partial y},\ v=\frac{\partial\psi}{\partial x}$$

energy equation:

$$\left(\frac{\partial T_1}{\partial t}+u\frac{\partial T_1}{\partial x}+w\frac{\partial T_1}{\partial y}\right)=a_1\left(\frac{\partial^2 T_1}{\partial x^2}+\frac{\partial^2 T_1}{\partial y^2}\right)$$

water vapor diffusion equation:

$$\rho_2\left(\frac{\partial C_{\mathrm{w}}}{\partial t}+u\frac{\partial C_{\mathrm{w}}}{\partial x}+w\frac{\partial C_{\mathrm{w}}}{\partial y}\right)=\rho_2 D_2\left(\frac{\partial^2 C_{\mathrm{w}}}{\partial x^2}+\frac{\partial^2 C_{\mathrm{w}}}{\partial y^2}\right)$$

balance equation:

$$C_{\mathrm{g}}+C_{\mathrm{w}}=1$$

For water droplets ($0<r<R_{\mathrm{d}}$, $0<\varphi<2\pi$):

thermal conductivity equation

$$\frac{\partial T_3}{\partial t}=a_3\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T_3}{\partial r}\right)+\frac{1}{r^2\sin(\varphi)}\frac{\partial}{\partial\varphi}\left(\sin(\varphi)\frac{\partial T_3}{\partial\varphi}\right)\right]$$

Initial conditions (t=0): $T=T_0$, C_w=0, C_g=1, ψ=0, ω=0 at $0<x<H$, $0<y<L$; $T=T_0$ at $0<r<R_d$, $0<\varphi<2\pi$.

Boundary conditions at $t>0$:

$$T=T_g,\ C_w=0,\ C_g=1,\ \frac{\partial\psi}{\partial y}=V_g \text{ at } y=0,\ 0<x<H;$$

$$\frac{\partial^2 T}{\partial y^2}=0,\ \frac{\partial^2 C_w}{\partial y^2}=0,\ \frac{\partial^2 C_g}{\partial y^2}=0,\ \frac{\partial\psi}{\partial y}=0 \text{ at } y=L,\ 0<x<H;$$

$$\frac{\partial T}{\partial t}=0,\ C_w=0,\ C_g=0,\ \frac{\partial\psi}{\partial x}=0 \text{ at } x=0,\ 0<y<L;$$

$$\frac{\partial T}{\partial t}=0,\ C_w=0,\ C_g=0,\ \frac{\partial\psi}{\partial x}=0 \text{ at } x=H,\ 0<y<L$$

Boundary conditions for liquid – gas were set taking into account vaporization [5]:

$$R=R_1,\ 0<\varphi<2\pi,\ \lambda_3\frac{\partial T_3}{\partial R}=\lambda_2\frac{\partial T_2}{\partial R}-W_eQ_e,\ \rho_2D_2\frac{\partial C_w}{\partial r}=W_e$$

Nomenclature: x, y – coordinates of the Cartesian coordinate system, m; u, v – x and y components of convection velocity of the gas-vapor mixture, m/s; ψ – flow function, m^2/s; ω – rotation vector velocity, s^{-1}; t – time, s; γ – kinematic viscosity, m^2/s; β – thermal expansion coefficient, K^{-1}; g_y – acceleration of gravity, m/s^2; T – temperature, K; a – thermal conductivity, m^2/s; C_w – concentration of water vapor; D – diffusion coefficient, m^2/s; C_g – concentration gases ($0<C_g<1$); r, φ – coordinate of the spherical systems; R_d – radius of droplet, m; H, L – dimensions of solution area, m; T_0 – initial temperature, K; T_g – temperature of gases, K; T^* – temperature of gases in the trace of droplets, K; Q_e – water vaporization heat, J/kg; W_e – evaporation rate, kg/(m^2·s); V_g – velocity of high-temperature gases, m/s; symbols: *1* – high-temperature gases, *2* – water vapor, *3* – water liquid.Equations should be centred and should be numbered with the number on the right-hand side.

4 Results and discussion

Fig. 2 shows temperature and velocity fields of high-temperature gases for systems (Fig. 1). The resulting temperature fields illustrate that over time the temperature of gases in the trace of droplets changes. This is primarily due to intensive evaporation of water droplets and a corresponding decrease in the droplet size. The water evaporation area is maximized when water droplets are moving in the beginning.

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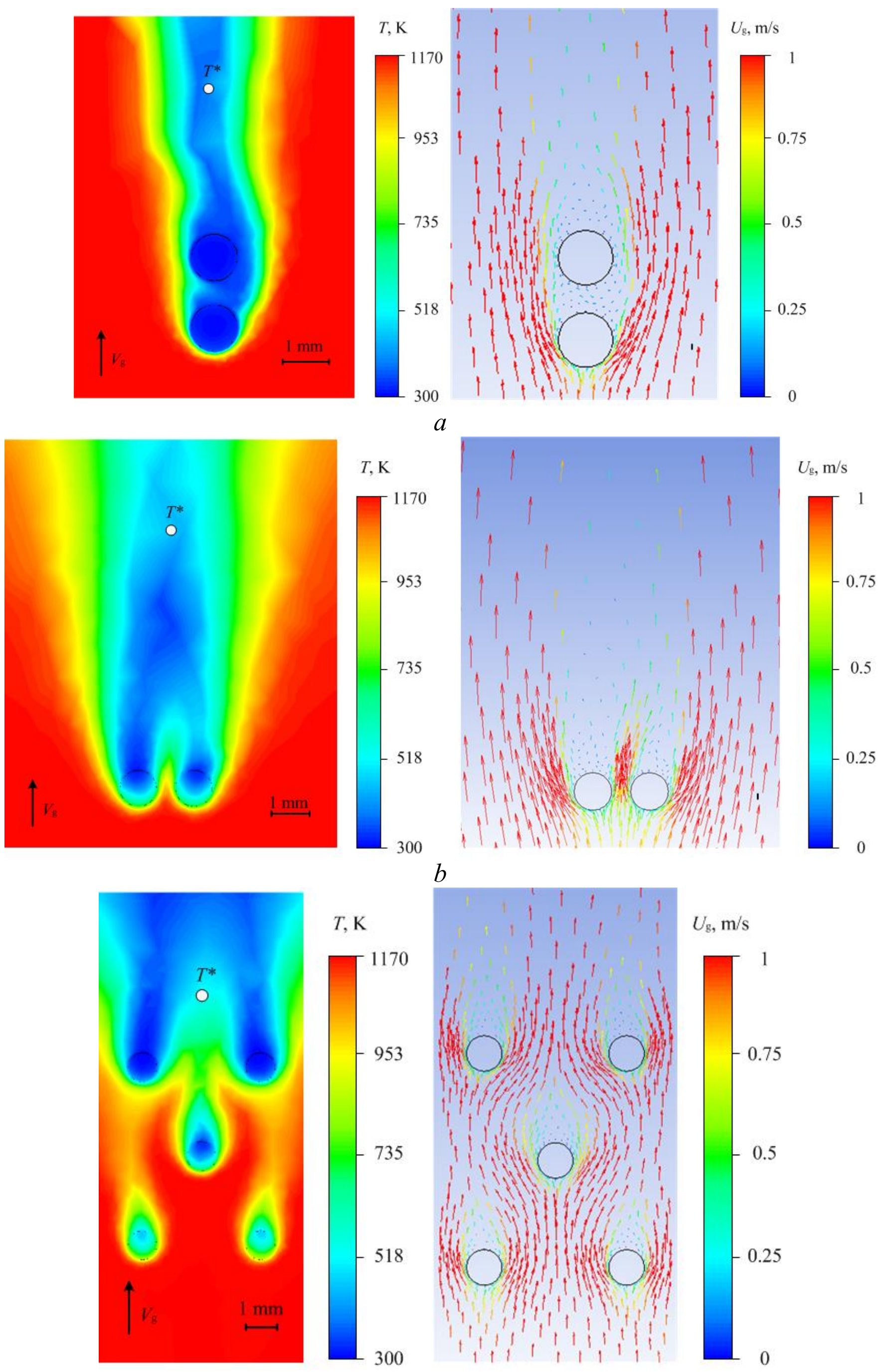

Fig. 2. Temperature fields and velocity fields with two successive water droplets (*a*); two parallel water droplets (*b*); five water droplets (*c*).

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The resulting temperature fields prove the hypothesis that aerodynamic and temperature traces of an aerosol and non-sprayed water are significantly different. Moreover, the transverse dimensions of the temperature traces of droplets are considerably different, especially the areas with a temperature which is substantially lower than the initial one (by several hundred degrees).

Moreover, the deceleration and turning of the evaporating droplets influence the temperature trace. In particular, sizes of droplets are reduced when moving through the counter flow of combustion products. Then after deceleration and turning, droplets begin to move in the same direction with the flow and again have a significant influence on the temperature in the trace due to evaporation. As a result, the lifetimes of the temperature trace are several times greater than for the massif and an individual droplet.

The mathematical simulation also illustrates different causes and mechanisms of a temperature reduction in the trace of sprayed and non-sprayed water. In particular, in the case of an aerosol, evaporation plays a decisive role. Aerosol droplets are heated up to the maximum possible temperatures corresponding to the intense vaporization. In the case of the large droplets and water massifs, the intensive vaporization was not observed. This is because the evaporation area is small. Thus, the liquid is heated at relatively low rate due to the large sizes of massifs. As a consequence, in the case of massifs and large droplets, the temperature is decreased significantly only in a small vicinity of their trajectory. This is due to the fact that water accumulates gas energy.

5 Results and discussion

As a result of numerical simulation models are designed for different schemes of heat and mass transfer location of several water droplets to vary the distance between them. The results are important for the development of fire extinguishing technologies in the fields of oil and gas industry.

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