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Numerical simulation of the vapour-droplet systems hydrodynamics taking into account particles' coagulation and fragmentation

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Abstract. The purpose of the work is description of the processes occurring in the liquefied natural gas heater-gasifier having small duration of transition process upon transition to the stationary mode at the flow volume change on the basis of mathematical modeling of the thermo- and hydrodynamics of multiphase mist flows with swirling of the stream.

1. Introduction

The current of a gas mixture in the Field-tube which is the concentric canal formed by internal and external cylindrical surfaces is researched for the purpose of calculation of parameters of the tube heater of the liquefied natural gas (LNG). The difference of the offered device from the existing analogs consists that on an input in the internal cylinder liquid is sprayed and further moves in the form of a vapour-droplet mixture. Because regasification is carried out as a result of heating and evaporation of a vapour-droplet mixture, process happens without formation of the critical phenomena, to a small inertance regarding the flow volume. The external surface of the device heats up, there is a heating of a moving gas mixture and evaporation of drops of liquid. The device can be used as the heat-absorption element of the LNG tube heater-gasifier intended for heating of natural gas on an input of gas distribution stations. In the course of the gas suspension motion, depending on the mode of a current and value of an external heat flow, there can be processes of coagulation, fragmentation, evaporation of drops influencing flow pattern and flow characteristics of the device. For the heat-absorption element design parameters and its operating regime – dispersibility on an input, input-output pressure differential and external heat flow values – choice it is required to simulate the processes accompanying the vapour-droplet mixture current. In this work the model allowing describing a polydisperse mixture flowing taking into account different fractions particles' coagulation and fragmentation is described.

2. Technological heater

The classical scheme of the re-gasifier heating dripping liquid is quoted in [1]. The heated medium, for example, purified natural gas, from the trunk pipeline comes via the connecting pipe 4 to an internal cavity 6 of the internal heat-exchanging pipe 2, then goes out through the open end of an internal pipe 2, turns and gets into the external cavity 7 formed by a annular gap between external 1 and internal 2 heat pipes. The gas heated in annular gaps of heat-exchange pipes comes to the output connecting pipe 5 and is transported to the reduction block of gas-distribution station (Figure 1).

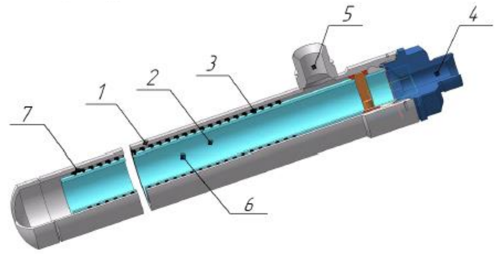

Figure 1. The diagrammatic representation of the technological heater (Field-tube) in section.

3. Mathematical model of the processes occurring in Field-tube

The carrier phase motion equations:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=-\frac{\rho v}{y},\ ,\ \frac{\partial(\rho u)}{\partial t}+\frac{\partial}{\partial x}\left(\rho u^2+p-\tau_{xx}\right)+\frac{\partial}{\partial y}\left(\rho uv-\tau_{xy}\right)=\frac{\rho uv-\tau_{xy}}{y}-\sum_{i=1,n}F_{xi}+\alpha\frac{\partial p}{\partial x},$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial}{\partial x}\left(\rho uv-\tau_{xy}\right)+\frac{\partial}{\partial y}\left(\rho v^2+p-\tau_{yy}\right)=\frac{\rho v^2-\tau_{yy}}{y}-\sum_{i=1,n}F_{yi}+\alpha\frac{\partial p}{\partial y},$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}=\frac{\rho vw}{y}-\sum_{i=1,n}F_{zi}, \tag{1}$$

$$\frac{\partial e}{\partial t}+\frac{\partial}{\partial x}\left(\left[e+p-\tau_{xx}\right]u-\tau_{xy}v+\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left[e+p-\tau_{yy}\right]v-\tau_{xy}u+\lambda\frac{\partial T}{\partial y}\right)=$$

$$=-\frac{\left[e-\tau_{yy}\right]v-\tau_{xy}u+\lambda\frac{\partial T}{\partial y}}{y}-\sum_{i=1,\ n}Q_i-\sum_{i=1,\ n}\left(\left|F_{xi}\right|\left(u-u_i\right)-\left|F_{yi}\right|\left(v-v_i\right)\right)+\alpha\left(\frac{\partial(pu)}{\partial x}+\frac{\partial(pv)}{\partial y}\right).$$

Here ρ, u, v, w, u_i, v_i, w_i, E, λ, μ, d_i, σ – density of the carrying medium, the carrying medium and disperse phase fractions velocity components, specific total energy, coefficients of heat conductivity and viscosity of the carrier phase, *i*-fraction's drop diameter and liquid's surface tension coefficient [2].

The disperse phase consists of a number of fractions formed by same size particles which dynamics is described by the fraction's average density conservation equation, components of an impulse conservation equations and the thermal energy conservation equation:

$$\frac{\partial \rho_i}{\partial t}+\frac{\partial(\rho_i u_i)}{\partial x}+\frac{\partial(\rho_i v_i)}{\partial y}=-\frac{\rho_i v_i}{y},$$

$$\frac{\partial\left(\rho_i u_i\right)}{\partial t}+\frac{\partial}{\partial x}\left(\rho_i u_i^2\right)+\frac{\partial}{\partial y}\left(\rho_i u_i v_i\right)=-\frac{\rho_i u_i v_i}{y}+F_{xi}-\alpha\frac{\partial p}{\partial x},$$

$$\frac{\partial\left(\rho_i v_i\right)}{\partial t}+\frac{\partial}{\partial x}\left(\rho_i u_i v_i\right)+\frac{\partial}{\partial y}\left(\rho v_i^2\right)=-\frac{\rho v_i^2}{y}+F_{yi}-\alpha\frac{\partial p}{\partial y},$$

$$\frac{\partial\left(\rho_i w_i\right)}{\partial t}+\frac{\partial}{\partial x}\left(\rho_i u_i w_i\right)+\frac{\partial}{\partial y}\left(\rho v_i w_i\right)=-\frac{\rho v_i w_i}{y}+F_{zi}, \tag{2}$$

$$\frac{\partial e_i}{\partial t}+\frac{\partial}{\partial x}\left(e_i u_i\right)+\frac{\partial}{\partial y}\left(e_i v_i\right)=\mathrm{Nu}_i\frac{6\alpha_i}{\left(2r_i\right)^2}\lambda\left(T-T_i\right),\ \rho_i=\alpha_i\rho_{i0},\ e_i=\rho_i C_{pi}T_i.$$

Here α_i, ρ_i, e_i, T_i – volume content, average density, thermal energy and the disperse phase temperature; C_{pi}, ρ_{i0} – heat capacity and substance density of dispersed fraction *i*. The system of equations of each dispersed fraction motion contains the equation for an impulse azimuth component, written down in the assumption of azimuth symmetry of a stream at its rotation. The Benedict-Webb-Rubin state equation has been applied as the thermal equation of state for the carrier phase [3]:

$$p = RT\rho + \left(BRT - A - \frac{C}{T} \right)\rho - \left(bRT - a \right)\rho + a\alpha\rho + \frac{c\rho}{T}\left(1 + \gamma\rho \right)\exp(-\gamma\rho), \qquad (3)$$

coefficients a, A_0, b, B_0, c, C_0, α, ρ are determined by the known values of density, pressure and temperature of methane in a vaporous state.

The system of equations of two-phase polydisperse gas-suspension motion was written in the generalized movable coordinates [4, 5, 6] and was solved by an explicit second-order Mac-Cormack method with the nonlinear correction scheme [7, 8].

4. Disperse phase fractions' drops coagulation and fragmentation

Drops' coagulation and fragmentation occur depending on the Weber number values for disperse fraction particles. If Weber's number for a particle of *i*-fraction is less than critical value (We_{cr} = 2-10), then at its collisions with smaller fractions' particles, coagulation take place therefore mass, concentration, an impulse and temperature of *i*-fraction particle change. This process is described by Smoluchowski Lagrangian model [6]. If *i*-fraction particle Weber number is more than critical, then the motion of such particle is followed by the gas-dynamic fragmentation leading to reduction of *i*-fraction particle mass. As the drop destruction mechanism the dish-shaped type of fragmentation connected with boundary-layer separation [9, 10], which is implemented at $We_{cr} \leq We < 1.7 \cdot 10^4/Lp^{0.5}$ can be chosen.

Calculations were conducted on the block structured meshes constructed for three subareas (Figure 2). Boundary conditions on blocks docking lines were set taking into account the direction of a current. Pressure on an input to a subarea I and pressure at the output from area III was set. Carrying medium and disperse fractions velocities in the area I was set in initial time point. Medium was assumed motionless in II and III areas at $t = 0$.

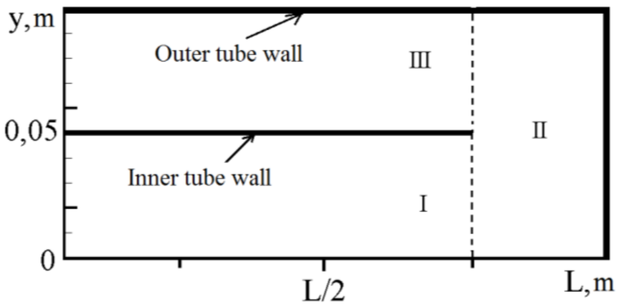

Figure 2. Diagrammatic representation of computational region: I, II, III - block structured mesh's subareas.

As a calculation result gas-dynamic functions fields of the carrying medium and a number of disperse fractions which particles, depending on Weber number participated in coagulation and fragmentation processes have been received.

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