Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 1, 2021, Pages. 7091 - 7097
Received 15 December 2020; Accepted 05 January 2021.

Gas-Liquid Mixture Flowing Out of a Hole under Falling Pressure

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Abstract

An effective and reliable mathematical model is the effective method for calculating the cells' parameters, allowing to calculate the hydrodynamics and characteristics of heat and mass transfer of two-phase vapor-liquid flows with non-condensing gases in the heated channels of power installations in emergencies, is developed. The effects of the influence of non-condensing gas dissolved in water on the hydrodynamics and heat exchange in the two-phase flow, accompanied by a decrease in pressure, starting from the steady state of the circuit of power plants at nominal parameters have been studied. A marked effect of the separated non-condensing gas from the liquid on the flow hydrodynamics during the pressure drop is shown.

Keywords: gas-liquid mixture, power plants, hydrodynamics and heat and mass exchange, mathematical model, integral conservation laws, multiphase flows, numerical modeling.

In thermal and nuclear power plants, water is used as the working body. In emergency operation modes of thermal and nuclear power plants, there is a release of non-condensing gases dissolved in water, such as air, nitrogen, argon, hydrogen, etc. When the pressure in the flow drops, gas is released from the liquid with bubbles' formation. These gases can significantly impact hydrodynamics and heat and mass exchange in unsteady and emergency operation modes of thermal and nuclear power plants [1].

These effects are not considered in existing mathematical models of multiphase flows for calculating hydrodynamics and heat exchange[2-10]. Consideration of non-condensable gas in the steam-liquid flow allows to adequately simulate real processes (heat and mass transfer of gas-liquid flow, heat conduction in channels, convective heat transfer, heat exchange crisis, heat transfer behind the crisis) arising in an emergency, non-stationary situations of power plants. This can qualitatively change the picture of hydrodynamics and heat and mass exchange processes, in contrast to the processes that do not consider the influence of non-condensing gases.

It is necessary to introduce a noncondensable gas component to describe such processes, which requires another additional continuity equation. For the combined gas field, an assumption of homogeneity and thermal equilibrium is made.

Numerical modeling is a convenient method to investigate such problems. The mathematical model should include the equations of conservation of mass, momentum and energy for the carrying phase, and the equations describing the process of gas-phase formation and their development as a result of changes in the surrounding fluid parameters interphase mass transfer. Therefore, it is necessary to derive ratios to account for non-condensing gas, gas release intensity and related terms.

Integral conservation laws taking into account force, thermal and mass interactions of phases have a form of three mass conservation equations for liquid, vapor and non-condensing gas assuming that vapor velocity is equal to gas velocity [11-12]:

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$$\frac{\partial \rho_\ell}{\partial t} + \nabla^i (\rho_\ell \cdot V_{\ell i}) = S_\ell - J_{\ell v}$$

$$\frac{\partial \rho_v}{\partial t} + \nabla^i (\rho_v \cdot V_{gi}) = S_v + J_{\ell v}$$

$$\frac{\partial \rho_n}{\partial t} + \nabla^i (\rho_n \cdot V_{gi}) = S_n$$

two energy conservation equations for liquid and vapor-gas mixture:

$$\frac{\partial H_\ell}{\partial t} + \nabla^i (H_\ell \cdot V_{\ell i}) = \alpha_\ell \frac{\partial P}{\partial t} + \alpha_\ell \cdot V_{\ell i} \cdot \nabla^i P - J_{\ell v} \cdot h_\ell^{o(S)} + Q_\ell - Q_{\ell\sigma} + S_\ell \cdot h_\ell^{o^*}$$

$$\frac{\partial H_g}{\partial t} + \nabla^i (H_g \cdot V_{gi}) = \alpha_g \frac{\partial P}{\partial t} + \alpha_g \cdot V_{gi} \cdot \nabla^i P + J_{\ell v} \cdot h_v^{o(S)} + Q_g - Q_{g\sigma} + S_v \cdot h_v^{o^*} + S_n \cdot h_n^{o^*}$$

and the two phase momentum conservation equations:

$$\frac{\partial (\rho_\ell \cdot V_{\ell j})}{\partial t} + \nabla^i (\rho_\ell \cdot V_{\ell i} \cdot V_{\ell j}) = -\alpha_\ell \cdot \nabla^j P + \rho_\ell \cdot g_j - F_{\ell j} + F_{g\ell j} + S_\ell \cdot V_{\ell j}^* + J_{v\ell} \cdot V_{v\ell j}$$

$$\frac{\partial (\rho_g \cdot V_{gj})}{\partial t} + \nabla^i (\rho_g \cdot V_{gi} \cdot V_{gj}) = -\alpha_g \cdot \nabla^j P + \rho_g \cdot g_j - F_{gj} - F_{g\ell j} + S_v \cdot V_{vj}^* + S_n \cdot V_{nj}^* - J_{v\ell} \cdot V_{v\ell j}$$

Heat fluxes $Q_{l\sigma}$ (from water to the interface) and $Q_{g\sigma}$ (from the vapor-gas phase to the interface) are calculated in [6,13].

We will use the main integral variables:

$$\rho_\ell = \rho_\ell^o \cdot \alpha_\ell,\ \rho_v = \rho_v^o \cdot \alpha_g,\ \rho_n = \rho_n^o \cdot \alpha_g,\ H_\ell = \rho_\ell \cdot h_\ell^o,\ H_g = \rho_v \cdot h_v^o + \rho_n \cdot h_n^o$$

These variables are easily recalculated from the integral conservation laws. Knowing them, it is necessary to be able to calculate all local variables. The local variables can be calculated from the conditions of equality of temperatures of steam and non-condensing gas and equality of pressures of liquid and gas phases. We will use the ideal gas model as a model of non-condensing gas.

The influence of emitting gases will be the strongest in the underheated liquid. Among dissolved gases, we can limit ourselves to nitrogen for the time being, since, as applied to the first circuit of the NPP, nitrogen is present in it in specific operating modes. If we consider unheated water, it is not necessary to consider the dynamics of air bubbles in the framework of the two-speed model, as there are relatively few of them. Regarding the choice of a specific mode for calculations, probably, of interest is the process of liquid flow (accompanied by a decrease in pressure), starting from the stationary state of the circuit at nominal parameters: pressure P=60 bar, liquid temperature T=550 C. In the first approximation, the first circuit of NPP can be modelled by a vessel (with volume V=60 m^3), from which the outflow occurs at a given flow rate. The flow rate value for the test calculation can be set manually as a boundary condition.Further, it is of interest to compare

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pressure-time dependences obtained with and without emitting gas.

In the present paper, we consider the simplest case, the emission of only non-condensing gas dissolved in a resting liquid, without considering the evaporation of water, under decreasing pressure. In this case, one calculation cell is sufficient, to begin with. As non-condensing gas, we will limit ourselves to nitrogen.

We simulate the outflow of liquid from a tank in which a diaphragm (orifice) is installed. At the initial moment of time, pressure in a tank with volume V=60 m3 is P=60 bar, liquid temperature T=550 C, S=0.05 m2, and no steam and non-condensable gas. Parameters of steam and nitrogen can be determined from conditions of equality of partial pressure of steam and steam temperature pressure at a liquid temperature.

At the initial moment we consider that the maximum possible amount of non-condensable gas is dissolved (no more can be dissolved at this pressure). As soon as the pressure in water has dropped (and the pressure will drop immediately after the first step, because we will take away some mass of water and energy of water according to the formula for the flow rate of liquid, G) so much gas can no longer be dissolved in water according to Henry's law.

Consequently, this difference in mass of the non-condensing gas will be released explicitly. Henry's law introduces the relative mole fraction of the dissolved gas. That is, you have to calculate the number of moles of water. Multiply it by the relative mole fraction of the dissolved gas and get the number of gas moles. If we assume that all gas is released in gaseous form (e.g. pressure has dropped to zero), all gas is released in gaseous form.

Some numerical simulation results of the liquid outflow from a vessel in which an orifice is installed are presented. The effects of extracted nitrogen on flow hydrodynamics have been analyzed. Fig.1 shows a typical pressure-time dependence obtained with and without evolved gas (top line), at a given initial liquid temperature Tl = 328 K. It can be seen from Fig.1, that the pressure without considering the nitrogen emission, is significantly lower than the calculated pressure including nitrogen emission. This can be explained by the influence of nitrogen bubbles on the hydrodynamics of the flow.

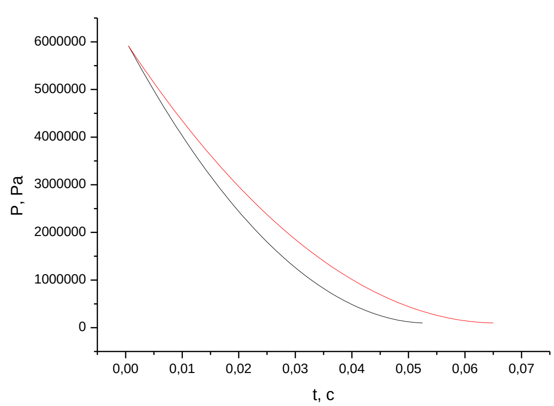

Figure 1. Pressure variation over time with and without considering the nitrogen release

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Figure 2 shows the change in temperature of nitrogen and water (dashed lines) over time. At first, the nitrogen released from water has the temperature of the water. Subsequently, due to expansion of the mixture (caused by efflux), the nitrogen also expands, and while water expands little due to weak compressibility (and consequently the water temperature weakly decreases), the nitrogen expands strongly. As a result of this nitrogen expansion, its temperature decreases noticeably. The nitrogen coming back from the water will again have water temperature, but the nitrogen released earlier will have a temperature noticeably lower than the water temperature.

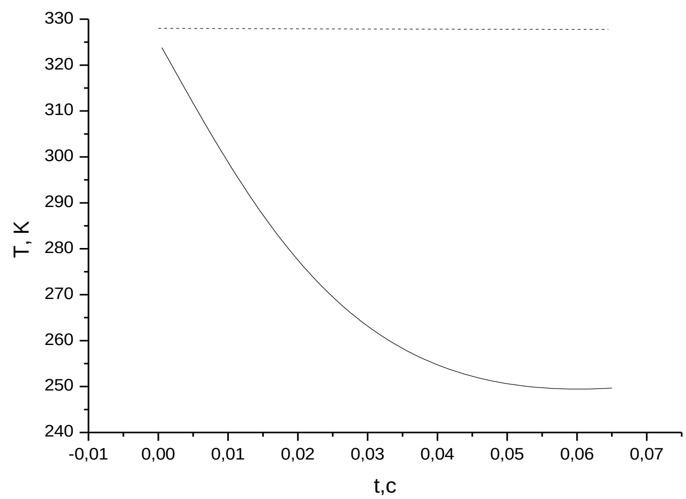

Fig.2. Changes in temperature of nitrogen and water over time

Figure 3 shows the change in nitrogen density over time. Figure 3 shows that the density of nitrogen decreases significantly over time.

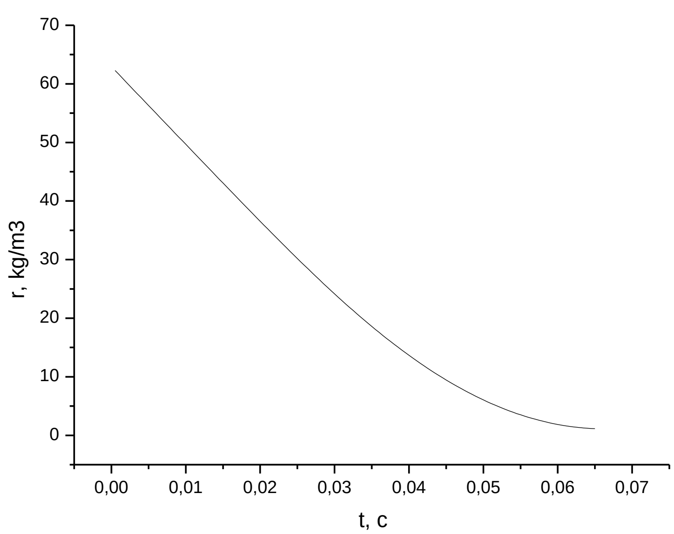

Fig.3. Nitrogen density variation with time

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Fig. 4 shows the total nitrogen released over time in the vessel. From Fig. 4 shows that over time 1.2 kg of nitrogen is released from the vessel. The intensity of nitrogen release also increases monotonically (Fig.5).

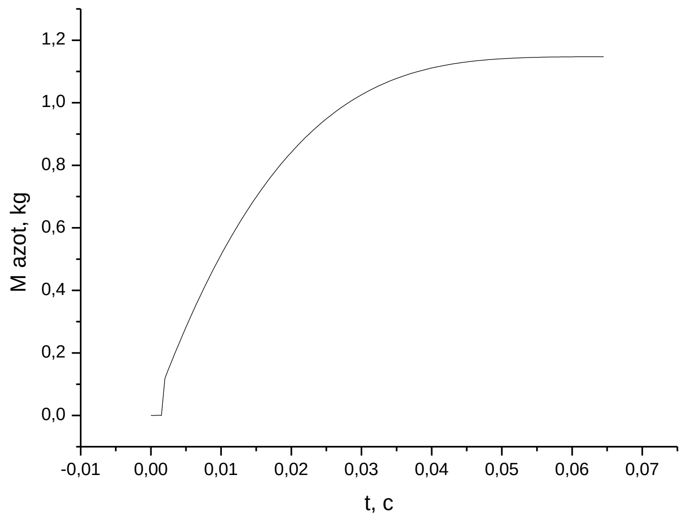

Figure 4. Total nitrogen release by time in the cell

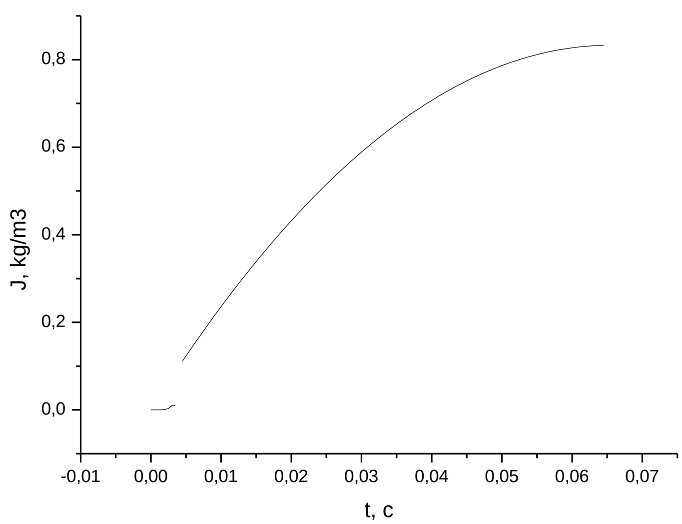

Fig. 5. Nitrogen release intensities

Fig.6 shows the total release of volumetric nitrogen concentration over time. It can be seen that release of nitrogen, although very small, this, as shown by the results of calculations, significantly affects the hydrodynamics of the flow.

Thus, the test calculations have shown the efficiency of dissolved gas extraction from the

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liquid, while a diaphragm, behind which there is a region of sharp pressure drop, is necessary for the beginning of the formation of non-condensing gas bubbles.

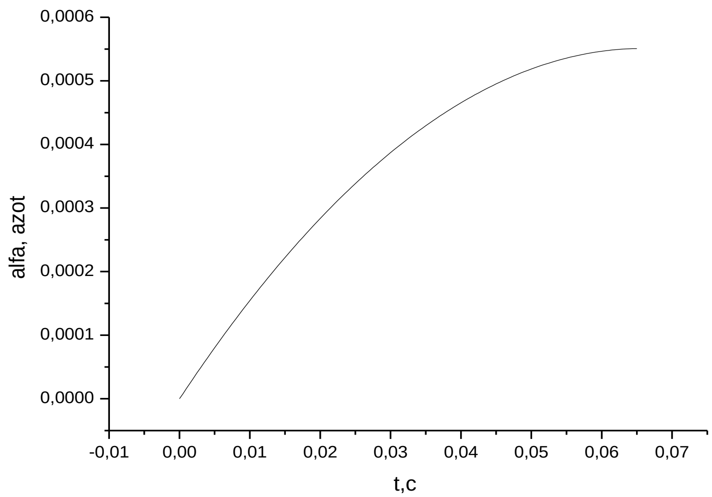

Fig.6. Total volumetric nitrogen concentration release over time

List of accepted symbols

c_V	-	heat capacity of non-condensing gas (J/(kg.degree)
$F_{\ell j}$	-	j-th component of the fluid friction force (positive with force against motion (N/m3)
F_{gj}	-	j- a component of the frictional force of the gas phase (positive with the force against motion (N/m3)
h_v^{oS}	-	enthalpy of steam at the saturation line near the interfacial surface
h_ℓ^{oS}	-	enthalpy in the liquid at the saturation line near the interfacial surface
$h_{\ell v}$	-	heat of vaporization (J/kg)
$J_{v\ell}$	-	phase transition speed from liquid to vapor phase (kg/(m3sec))
P	-	pressure (m2 N/m2);
R	-	gas constant (m2/(sec2grad))
S_i	-	external mass inflow of the i-th phase (kg/m3s))
T	-	temperature (C0)
h_i^o	-	enthalpy of the -th phase per unit mass of the phase (J/kg)
H_i	-	internal energy of the -th phase per unit volume of the whole medium (J/m3)
V	-	phase velocity (vector) (m/sec)
α	-	Volume concentration
ρ_i^o		true density of the -th phase equal to the mass of the -th phase in the unit volume of the phase (kg/m3)

Lower indexes

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g - gas (steam and non-condensable gas)
ℓ - liquid
n - non-condensable gas
v - vapour

Lower indexes
s - saturation line parameters
$*$ - external inflow (outflow) parameters

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