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The Three-Dimensional Thermal-Hydraulic Code BAGIRA[a]

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Abstract - *BAGIRA – a thermal-hydraulic program complex was primarily developed for using it in nuclear power plant simulator models, but is also used as a best –estimate analytical tool for modeling two-phase mixtures flows. The code models allow consideration of phase transients and the treatment of the hydrodynamic behavior of boiling and pressurized water reactor circuits. It provides the capability to explicitly model three-dimensional flow regimes in various regions of the primary and secondary circuits such as, the mixing regions, circular downcomer, pressurizer, reactor core, main primary loops, the steam generators, the separator-reheaters. In addition, it is coupled to a severe-accident module allowing the analysis of core degradation and fuel damage behavior. Section II will present the theoretical basis for development and selected results are presented in Section III. The primary use for the code complex is to realistically model reactor core behavior in power plant simulators providing enhanced training tools for plant operators.*

I. INTRODUCTION

BAGIRA – a thermal-hydraulic program complex was primarily developed for using it in nuclear power plant simulator models[1], but is also used as a best –estimate analytical tool for modeling two-phase mixtures flows. The code models allow consideration of phase transients and the treatment of the hydrodynamic behavior of boiling and pressurized water reactor circuits.

It provides the capability to explicitly model three-dimensional flow regimes in various regions of the primary and secondary circuits such as, the mixing regions, circular downcomer, pressurizer, reactor core, main primary loops, the steam generators, the separator-reheaters. In addition, it is coupled to a severe-accident module allowing the analysis of core degradation and fuel damage behavior. An example of severe accident calculations can be found in Reference 2.

Section II will present the theoretical basis for development and selected results are presented in Section III. The primary use for the code complex is to realistically model reactor core behavior in power plant simulators providing enhanced training tools for plant operators.

II. BASIC PHYSICS MODEL FOR GENERALIZED OF MULTI-PHASE MIXTURE FLOW.

1) The mixture consists of the liquid and gaseous (steam + non-condensed gas) phases.
2) The mixture temperature is in disequilibrium: temperatures of the phases could be different from each other and from the saturation temperature.
3) The mixture velocity is in disequilibrium: two alternative versions are considered for phase velocity calculation:
4) Drift model;
6) A model using two impulse equations for phases.
7) Non-stationary, three-dimension flows (where it is necessary) of mixture are analyzed.
8) Description of transport of up to 6 components in gaseous phase and of 6 components in the liquid phase.

II.A. Set of equations

The following is based on considering mass and momentum conservations:

$$\rho = \alpha_l \rho_l^0 + \alpha_g(\rho_v^0 + \rho_a^0) \qquad \rho_l = \alpha_l \rho_l^0$$

$$\rho_a = \alpha_g \rho_a^0$$

$$E = \alpha_l \rho_l^0 U_l^0 + \alpha_g(\rho_v^0 U_v^0 + \rho_a^0 U_a^0)$$

and

$$H_g = \alpha_g(\rho_v^0 U_v^0 + P_v) + \alpha_g(\rho_a^0 U_a^0 + P_a)$$

where the low indices *l, v, a* mean, respectively, the mixture components: liquid, steam and non-condensed gas. The index *g* is the homogeneous mixture of steam and gas and $\alpha_l + \alpha_g = 1$.

Based on the above assumptions, the set of hydrodynamics equations are the following:

Equation of mixture mass balance:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = s_l + s_v + s_a$$

$$\frac{\partial \rho_l}{\partial t} + \nabla \cdot \rho_l \mathbf{v}_l = s_l + J_{vl}$$

non-condensed gas mass balance:

$$\frac{\partial \rho_a}{\partial t} + \nabla \cdot \rho_a \mathbf{v}_g = s_a$$

Mixture internal energy balance:

$$\frac{\partial E}{\partial t} + \nabla \cdot \mathbf{F}_h = \nabla \cdot P\mathbf{w} + s_l h_l + s_v h_v + s_a h_a + Q$$

Gas medium enthalpy balance:

$$\frac{\partial H_g}{\partial t} + \nabla \cdot \mathbf{F}_{hg} = \alpha_g \frac{\partial P}{\partial t} + \alpha_g \mathbf{v}_g \cdot \nabla P +$$

$$+ J_{ev}\left(U_{vs} + \frac{P}{\rho_{vs}^0}\right) + Q_{gq} - Q_{g\sigma} + s_v h_v + s_a h_a$$

Mixture momentum equation:

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \mathbf{v} \cdot [\nabla \cdot (\rho \mathbf{v})] + \rho(\mathbf{v} \cdot \nabla) \cdot \mathbf{v} =$$

$$= -\nabla P + \rho \mathbf{F}_e + \mathbf{F}_{fric}$$

In the above equations the following designations are used:

$$\nabla = \vec{e}_x \frac{\partial}{\partial x} + \vec{e}_y \frac{\partial}{\partial y} + \vec{e}_z \frac{\partial}{\partial z}$$

$$\mathbf{F}_h = \mathbf{F}_{hg} + \rho_l^0 \alpha_l U_l^0 \mathbf{v}_l$$

$$\mathbf{F}_{hg} = (\rho_v^0 U_v^0 + \rho_a^0 U_a^0)\alpha_g \mathbf{v}_g$$

where:

$\vec{e}_x$, $\vec{e}_y$, $\vec{e}_z$ - direction vectors with the directions along axis *x, y, z* relatively,

and $$\mathbf{w} = \alpha_l \mathbf{v}_l + \alpha_g \mathbf{v}_g$$

$$\mathbf{v} = \rho_l^0 \mathbf{v}_l + (\rho_v^0 + \rho_a^0)\mathbf{v}_g$$

The relationship between condensation and vaporization intensity is written as:

$$J_{vl} = - J_{lv},$$

and the full pressure of the mixture as the sum of the partial pressures as:

$$P = P_v + P_a;$$

The following correlation is used for the definition of J_{lv} :

$$Q_{l\sigma} + Q_{g\sigma} = J_{lv}(h_g^{(s)} - h_l^{(s)})$$

where the upper index *s* indicates saturation condition.

The above relations may be used to construct a system of equations and solve numerically for the variables. During the numerical solution of the above set of equations, high order terms proportional to phases velocities differences is considered negligible and are not taken into consideration.

II.B. High accuracy numerical solution for the multi-phase set of equations

The modular program complex BAGIRA was designed *from the very beginning* as a 3-dimensional thermal-hydraulic code incorporating different flow models. It considers turbulent heat- and mass transfer. The mixture flow enthalpy includes a convection and turbulent component. In consequence, the corresponding equations for turbulent mass transfer can be calculated. The conservation equations are integrated using a numerical scheme in each of the fluid cells. Unknown values of pressure and velocity components are included in the numerical scheme in implicit form, i.e. included in deriving an approximation to the time derivatives and also in the appropriate physical correlations.

For the turbulent mixing calculation the Prandtl model is used, together with the concept of mixing length. Figure 1 and 2 indicates two examples of typical three-dimensional thermal-hydraulic calculations. Both figures indicate the effect of boiling water flux impact on the wall surfaces is shown perpendicular to the direction of flow.

In the following an example of three-dimension calculation is shown. In this specific example, Figure 1a, the boiling water flux impact on the wall surface is shown, perpendicular to the direction of flow.

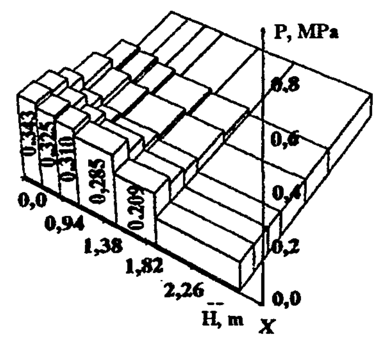

Figure1a. Pressure distribution on the wall surface during boiling water flux impact, 0.017 sec. after flow discharge (H – distance from the center of the flux impact).

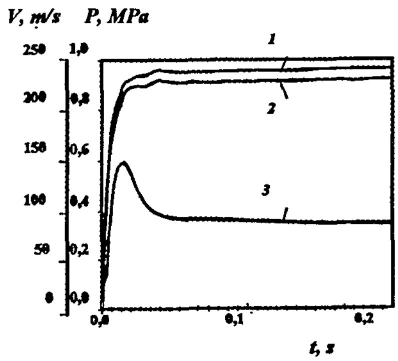

Figure 1b. The velocity and the pressure in the point of surface where the center of flux impact is, as the time function:
1 – Velocity of steam;
2 – Velocity of the drops of water;
3 – Pressure.

II.C. Closure Correlations

The numerical models use high-accuracy closure relations describing the heat and force interactions between the phases and the volume node walls. The following flow regimes are taken into consideration in the volume nodes and in the transient areas for limits between the modes.

- bubbly
- slug
- circular
- disperse-circular
- inverted circular
- inverted slug
- emulsion
- disperse

The following heat exchange modes between phases and walls are taken into consideration:

- convection in liquid
- convection in steam
- convection between two-phase medium
- subcooled boiling
- saturated boiling
- transition film boiling
- film boiling
- condensation.

II.D. Numerical Scheme Used in the BAGIRA Code

- Thermal-hydraulic loop and components are modeled by set of rectangular, connected nodes.
- Semi-implicit numerical scheme is used approximating mixture-parameters in the nodes. The implicit values are the pressure, mass flow-rate of mixture and interphase heat flows.
- All mass and energy values are linearized using the mass flow-rate of the mixture and the density gap decay at the boundaries between the nodes.
- The set of main equations are transformed a set of linear equations in pressure at every new time step. When the values of pressure are defined at the new time step, all other variables could be calculated.

III. BAGIRA CODE VERIFICATION

In order to validate the code a number of different experiments were used to analyze its accuracy and predicting capability. These results illustrate the capability of BAGIRA to accurately predict difficult experimental results.

III.A. Integrated Test Experiments

The first set of data indicated on Figure 2a and 2b are from an integrated thermal-hydraulic facility. It describes an experiment with an 11% leak from the upper plenum together with the activations of the emergency core cooling system (ISB-VVER, ENIC, Electrogorsk, 1999)

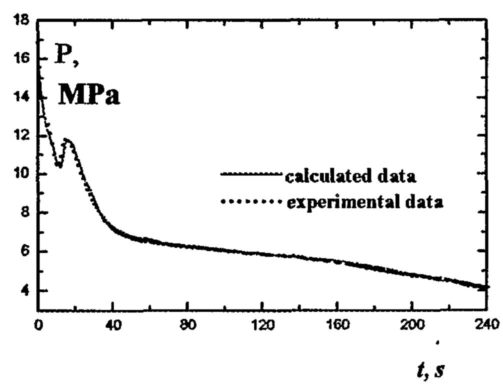

Figure 2a. Pressure behavior in the upper plenum

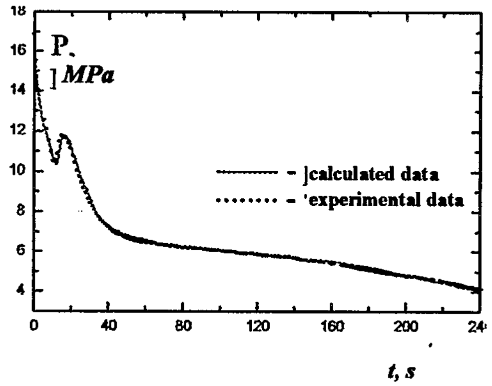

Figure 2b. Pressure behavior in the pressurizer

The next two figures indicate the results of an analysis of the PACTEL natural circulations stepwise coolant inventory reduction experiments (PACTEL, VTT, Finland, 1994).

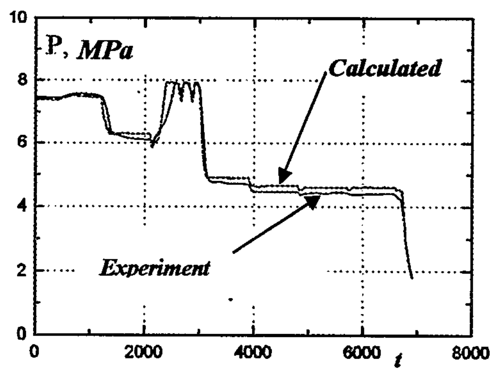

Figure 3a. Dependence of the pressure from time in the pressurizer

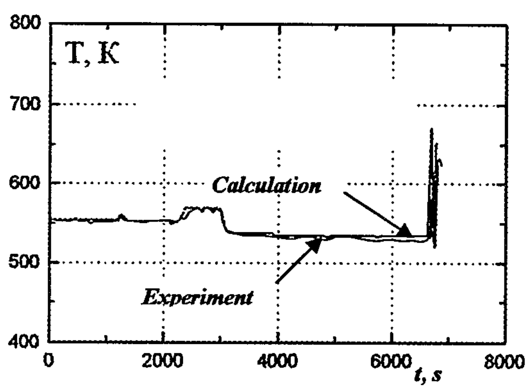

Figure 3b. T_{vel} simulator wall temperature as function of time (level 2017mm from beginning of heating area)

III.B. Differential Experimental Data

Experimental data was also obtained and analyzed measuring the blowdown thrust force during coolant flow discharge from a tank (Odessa Polytechnic Institute)[3, 4]. The analysis shown in Figure 4 again indicates excellent agreement with the data.

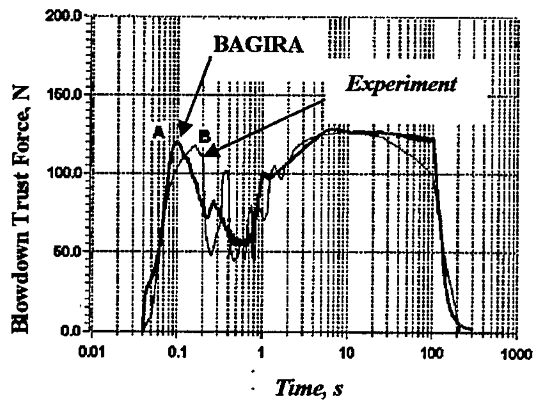

Figure 4. Blowdown thrust force analysis

III.C. Reference Operating Plant Data

The first set of data was obtained from the Novovoronezh Unit 5 VVER-1000 horizontal steam generators[5]. The design operation mode proposes a flux passing down in the gap between the vessel and flange of the primary separator. Measurements of some local parameters were made at the Novovoronezh NPP unit 5

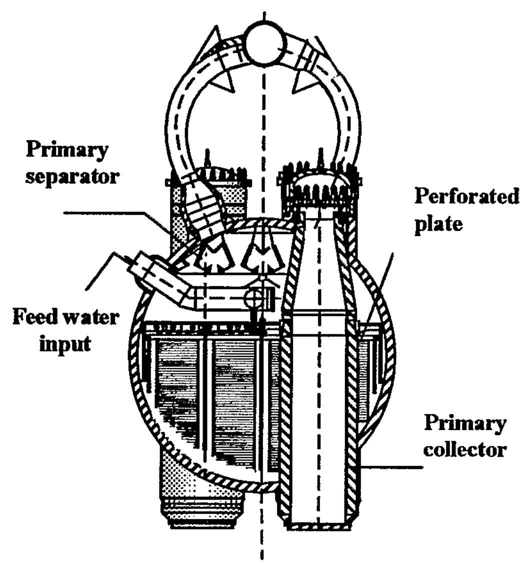

Figure 5. Novovoronezh VVER-1000 horizontal SG

In the gap between SG vessel and primary separator flange, a steady rising flux results from the «hot» side of heat-exchange bundle. Water is carried from the gap into the area over the primary separator and that raises a humidity of steam extracted from the SG and reduces the effectiveness of the SG. This rising flux cannot be modeled correctly with one-dimensional modeling due to its spatial features. For detailed investigations of the behavior of the various parameters near the inlet header it is necessary to use multi-dimensional analysis.

Two specific parameters are shown in Figure 6a and 6b, the volumetric mixture velocity and the void fraction behavior in the SG as a function of power level. The data reflects values collected between the gap of the SG vessel and the primary separator flange on the "hot" side of the heat exchanger bundle.

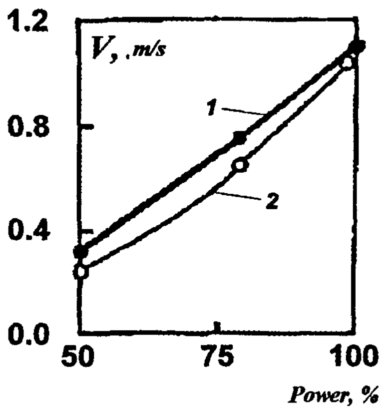

Figure 6a. Volumetric mixture velocity as function of power (1 - BAGIRA, 2 – Plant Data)

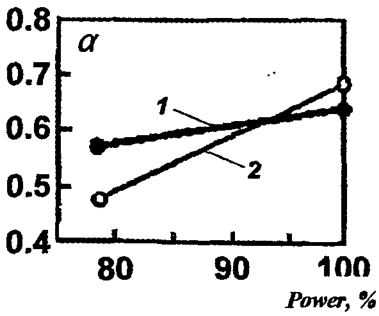

Figure 6b. Void fraction as function of power (1 -BAGIRA, 2 – Plant Data)

The second set of plant data was collected from the Kalinin VVER-1000 nuclear power plant[6]. In this plant event two of the four main reactor coolant pumps (MCP) were switched off.

In this mode cold water flows to the upper plenum above the reactor core due to the recirculation flow in the loops of the switched off MCP, and it leads to asymmetric temperature distribution as shown at the picture below.

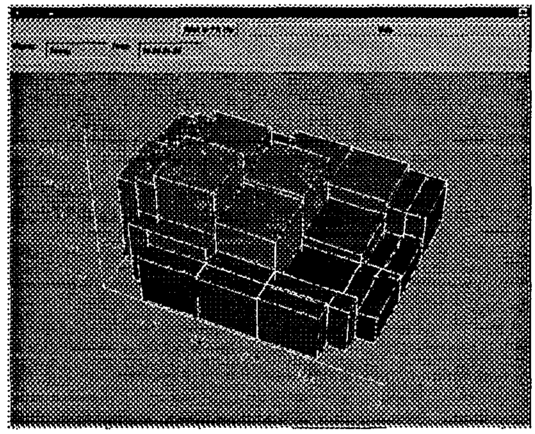

Figure 7. Coolant temperatures profile above a VVER-1000 reactor core after two MCPs turned off.

The third set of data was collected at the Zaporizhzhya Unit 3 nuclear power plant[7] where again two of the MCPs were turned off sequentially in loop No. 2 and 3.

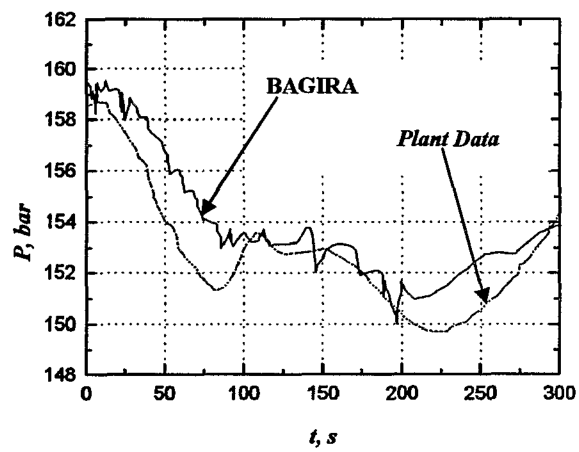

Figure 8a. Pressure in the pressurizer

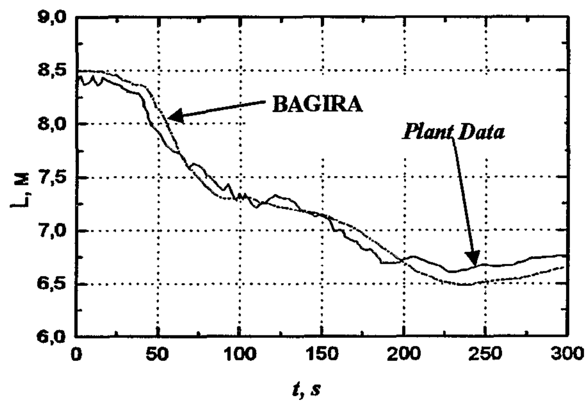

Figure 8b. Level in the pressurizer

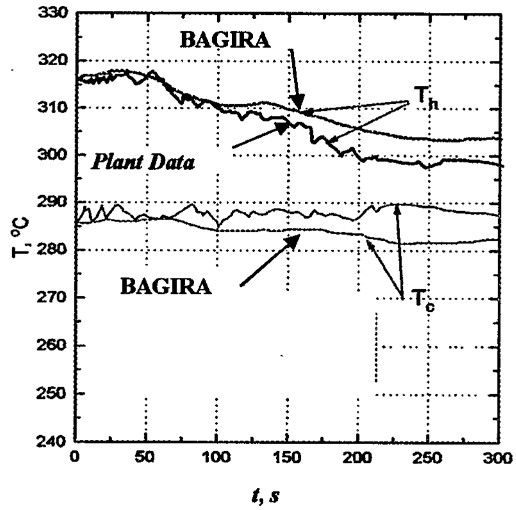

Figure 8c. Reactor coolant temperature in hot (T_h) and cold (T_c) leg of loop No. 1.

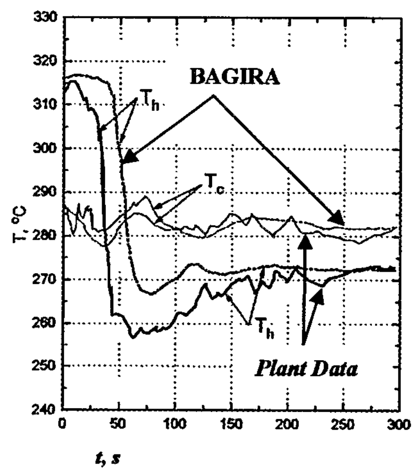

Figure 8d. Reactor coolant temperature in hot (T_h) and cold (T_c) leg of loop No. 2.

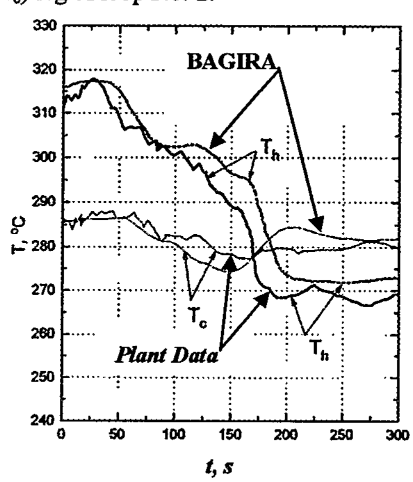

Figure 8e. Reactor coolant temperature in hot (T_h) and cold (T_c) leg of loop No. 3.

IV. CONCLUSION

The calculation results, made during the verification of BAGIRA code show that the code complex is able to model with high-accuracy all important conditions of two-phase flows in the circuits of NPP. It could be successfully used for the safety analysis of different NPPs and could provide the basis of a plant training simulator.

BAGIRA may be used for the modeling of the following processes in the NPP reactors:

- Coolant mixture in the upper and lower plenums of the reactor,
- Analysis of the temperature variation of the input and output regions of the reactor core,
- Natural and forced circulation,
- Boiling and condensation at the interphase surfaces, solid walls and flow paths,
- Boiling coolant flow through ruptures in the circuit and protection mechanisms,
- Internal circulation in the horizontal steam generator, steam separation, and steam line moisture removal ,
- Transport of boric acid and radioactive fission products,
- Heat transfer from the reactor core fuel element to the coolant in a random aggregate state,
- Steam-zirconium reaction, fire in the fuel assembly cladding, separation and distribution of hydrogen in the containment,
- Heat-up and cool-down of the primary circuit, and heat loss to the environment.

Based on the validation of the thermal-hydraulic code BAGIRA, it is expected that the modeling of three-dimension effects would provide a definite improvement of existing analysis especially of the following specific regimes:

- Coolant mass flow-rate change in one or several loops;
- Removal of one or more primary loops and consequent plant operation ,
- Loss of heat removal on the secondary,
- Insertion of positive or negative reactivity in a limited region of the reactor core;
- Malfunction of the containment spray systems.

The effective numerical scheme, used in BAGIRA, allows a great deal of flexibility in modeling complicated, non-stationary modes of a nuclear power plant in real-time. The real-time capability allows using BAGIRA as the basis for developing complex power plant training simulators with an enhanced thermal-hydraulic capability leading to the possibility of complex training scenarios involving three-dimensional effects during normal and abnormal plant transients.

At the present time a number of plant simulators based on the BAGIRA have already been successfully implemented at Russian NPPs with the different type of reactor designs:

- VVER-1000: Kalinin full-scope simulator
- RBMK: Kursk and Smolensk full-scope simulators, Chernobyl analytical simulator
- Natural circulation reactor: Bilibino analytical simulator.

NOMENCLATURE

ρ – mixture density
ρ_l – liquid density
ρ_a – non-condensed gas density
E – specific internal energy of the mixture
H_g – specific enthalpy of homogeneous steam-gaseous mixture
α_l – liquid volume fractions
α_g – steam-gaseous volume fractions
ρ_l^0 – liquid phase density
ρ_v^0 – steam phase density
ρ_a^0 – non-condensed gas phase density
U_l^0 – liquid phase internal energy
U_a^0 – steam phase internal energy
U_v^0 – non-condensed gas phase internal energy
P_v – steam partial pressures
P_a – liquid partial pressure
t – time;
v – mixture velocity
v_l – liquid velocity
v_g – steam-gaseous phase velocity
w – mixture mass flow rate
s_l, s_v, s_a – mass sources
h_l, h_v, h_a – sources or flow enthalpies [J/kg];
J_{vl} – rate of steam condensation intensity
J_{lv} – rate of water vaporization intensity
P – full pressure of steam-gaseous phase
P_v, P_a – partial pressures
Q – heat flow from wall to mixture
Q_{gq} – heat exchange intensity between liquid and gaseous phases
$Q_{g\sigma}$ – heat exchange intensity between gaseous phases
$\mathbf{F}_e$ – outside force acting on the flow mass
$\mathbf{F}_{fric}$ – friction force between flow and wall (pipelines walls, valves, etc.).

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