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Thermal analysis of the Loss-of-Coolant Accident within the containment of the WWER-440 and WWER-1000 nuclear reactors

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The paper presents selected results of the analysis of thermal and mass flow transient processes within the containments of the WWER-440 and the WWER-1000 nuclear reactors during Loss-of-Coolant Accidents based on the mathematical model and computer code for LOCA simulation. General assumptions of the mathematical model (with lumped parameters) are briefly presented. Changes of thermal variables (temperature, pressure etc.) are governed by the fundamental thermodynamic equations. All these equations have the nonlinear, integral form. The whole area of the containment is divided into several control volumes. Control volumes are joined in a given mode (orifices, valves, siphon closures etc.). The liquid phase (water) and the gaseous phase (air, steam and hydrogen) can appear in a control volume. Thermal equilibrium within an individual phase and a non-equilibrium state between phases is assumed. Heat accumulation in the walls and internal structures of the containment is taken into account and heat transfer between liquid and gaseous phases is also considered. The working mathematical model can be used for the analysis of different scenarios of LOCA within the containment of the PWR and BWR reactors. Later on the sample results of calculations of changes of pressure and temperature within the containment of the WWER-440 nuclear reactor and within the full containment of the WWER-1000 reactor are presented.

1. INTRODUCTION: THE AIM OF THE PAPER

Environment protection system of the PWR nuclear power plant should minimize the consequences of the release of radioactive substances into the environment either in the case of normal operation or in the case of an accident in the power plant. It is obvious that this latter case is especially important [1]. Safety of the nuclear power plant is established on the several levels [1]. We can mention here the fuel element, the fuel element can, the primary circuit and the containment.

The most important element of the whole safety system of a nuclear power plant with the PWR or BWR reactor is the containment — hermetic building which encloses the reactor, all the elements of the primary circuit, pressure suppression systems (if they exist), ventilation systems etc. The substantial tasks of the whole containment system are:

- protection against the release of radioactive products into environment,
- resistance against all the accidents including LOCA,
- suppression of the internal pressure to a level less than atmospheric pressure,
- removal of the most dangerous isotopes released during a nuclear accident.

To perform all these tasks the containments are usually supplied with several auxiliary systems: pressure suppression systems (active and passive spraying, water condensers, drywells etc.), ventilation systems, systems of hydrogen recombination etc.

One of the most dangerous accidents which can occur in a nuclear power plant of the PWR or BWR type is the Loss-of-Coolant Accident (LOCA). LOCA is caused by the rupture of the primary circuit. In the few seconds after a LOCA has begun the mixture of the coolant and the radioactive products of fission and activation releases from the primary circuit. To minimize the extremely dangerous consequences of LOCA the pressurized water reactors are supplied with highly developed safety systems. The majority of the pressurized and boiling water reactors are supplied with a so called full pressure containments, [2]. The WWER-440 reactors are usually supplied with so called Accident Localization System (ALS). This type of containment includes several pressure suppression systems including active spraying systems, water condensers (wetwells), air traps (drywells) and passive spraying system. The main element of the ALS is the wetwell tower that consists of several water condensers and air traps. When comparing with full pressure containments the pressure suppression system of the WWER-440 reactor enables greater reduction (even twice) of the maximum pressure within the containment during LOCA.

The scheme of the Accident Localization System of the WWER-440 reactor is shown in the Fig. 1. The containment encloses the reactor (1), steam generators (2) and elements of the primary circuit and pressure suppression system. The water condensers (3) are located in the wetwell tower (6). The water condenser has the shape of a chamber filled with a solution of water and boric acid. Water condensers are joined to the internal area of containment through the siphon closures (5). Through the non-return valves condensers are also joined to the air traps (4). The non-return valves enable gas to flow only in one direction — from the condenser to the air trap.

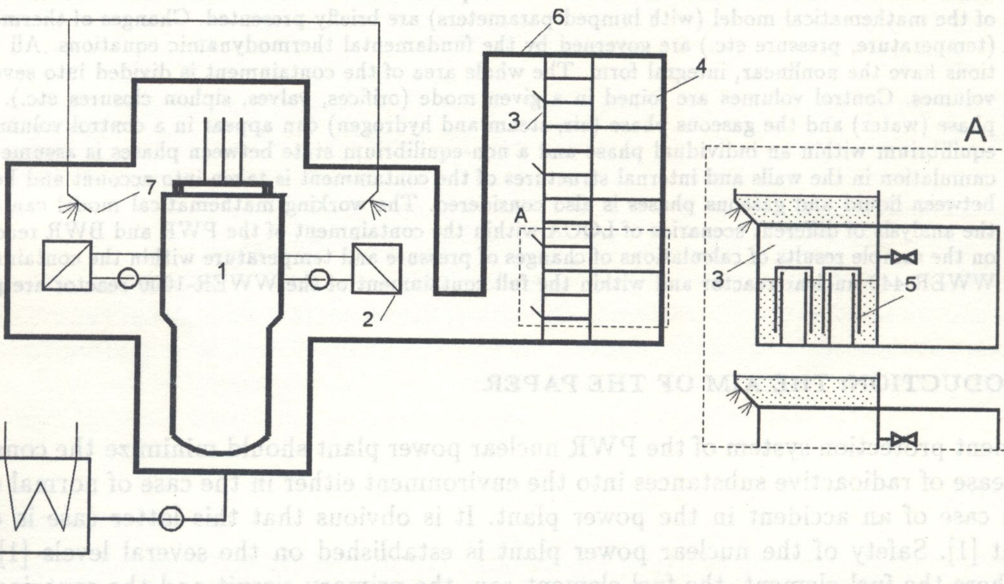

Fig. 1. Scheme of the containment of the WWER-440 nuclear reactor; (1) reactor, (2) steam generator, (3) water condenser, (4) air trap, (5) siphon closure, (6) tower, (7) active spraying system

At the initial stage of LOCA the air-steam mixture flows through the siphon closure into the water condensers. One assumes that the steam fully condenses when flowing through the siphon closure. Due to the different velocity of heat accumulation within the internal structures of the containment the pressure within different rooms of containment slightly differs. After the several seconds the pressure inside the water condensers becomes insignificantly greater than the pressure in the area of the ALS tower that initiates the suction of water from the condensers. Water flows down to the special basins and is then self-sprayed in the area of the ALS tower. The droplets of water cool the gas-steam mixture, which accelerates the condensation of the steam in the area of containment. The pressure within the containment then decreases relatively fast. As a result of this the maximum pressure within the containment of the WWER-440 reactor should not exceed 0.24 MPa.

The containment of the WWER-440 reactor is also supplied with several ventilation systems. We can distinguish here the systems of air supply, systems of air offtake and recirculation systems for air cleaning.

In contrast to the WWER-440 reactors the WWER-1000 reactors are built with the classical full pressure containment (see Fig. 2). This type of containment is supplied with the active spraying system (and auxiliary system of cooling of the reactor core). The maximum admissible pressure within the containment (about 0.45 MPa) here is almost twice that within the containment of the WWER-440 reactor.

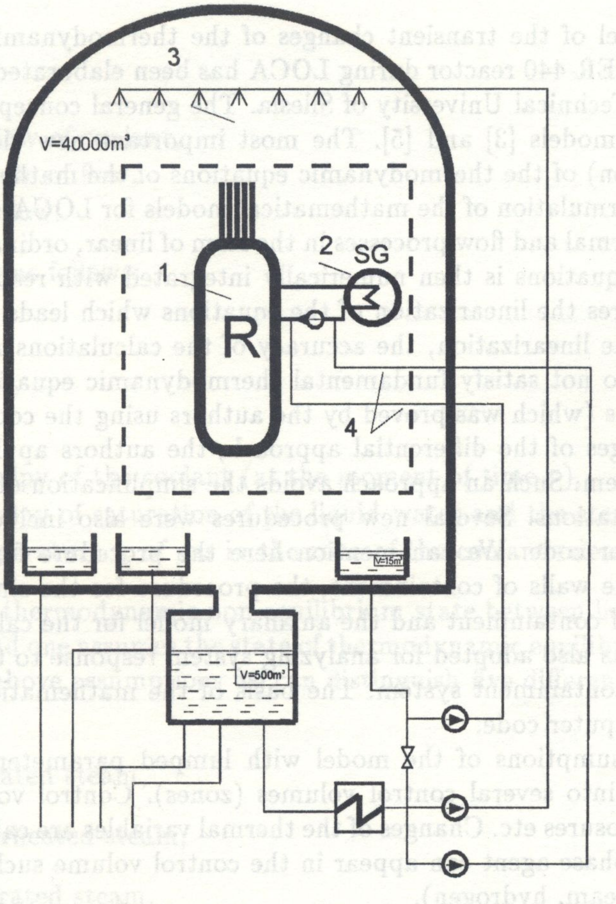

Fig. 2. Scheme of the containment of the WWER-1000 nuclear reactor; (1) reactor, (2) steam generator, (3) spraying system, (4) auxiliary core cooling system

The knowledge of the transient changes of the thermodynamic parameters (especially pressure changes) within the containment during LOCA is a very important factor with respect to the problems of nuclear safety. It is also important information for designers and constructors of the containment systems. However, it is obvious that research on this problem cannot be carried out in full scale experiments. Hence, mathematical modelling supported by laboratory experiments is widely and successfully used to analyze different LOCA scenarios for the various types of nuclear reactors.

Several mathematical models and computer codes for LOCA simulation and computations of changes of the thermodynamic parameters within the containments of nuclear reactors are already in existence [3,4]. The majority of these codes refer to the simulation of LOCA within the full pressure containment of PWR reactor and cannot be directly used for LOCA analysis within the accident localization system of WWER-440 reactor. Essential aims of this paper are:

- formulation of the mathematical model and evaluation of the computer code for the computations of changes of the thermodynamic parameters (especially pressure and temperature) within containments of the WWER reactors during LOCA,
- analysis of the selected scenarios of LOCA within the containments of the WWER reactors,

- analysis of the sensitivity of the changes of thermal variables within the containment during LOCA and on the changes of the operation parameters of the pressure suppression systems.

2. GENERAL ASSUMPTIONS OF THE MATHEMATICAL MODEL

The mathematical model of the transient changes of the thermodynamic parameters within the containment of the WWER-440 reactor during LOCA has been elaborated in the Institute of Thermal Technology of the Technical University of Silesia. The general conception of the mathematical model is based on the models [3] and [5]. The most important new element is the idea of the formulation (and solution) of the thermodynamic equations of the mathematical model.

The most common formulation of the mathematical models for LOCA simulation (e.g. [3, 5]) describes the transient thermal and flow processes in the form of linear, ordinary differential equations. The set of differential equations is then numerically integrated with respect to the time variable. Such an approach requires the linearization of the equations which leads to a simplification of the model. As a result of the linearization, the accuracy of the calculations might be low. Very often results of calculations do not satisfy fundamental thermodynamic equations: state equations and energy balance equations (which was proved by the authors using the code HEPRO, [5]).

To avoid disadvantages of the differential approach, the authors applied a nonlinear, integral formulation of the problem. Such an approach avoids the simplification of the model and improves the accuracy of computations. Several new procedures were also included by the authors into the model and computer code. We can mention here the procedure for the calculations of the heat accumulation in the walls of containment, the procedure for the simulation of the hydrogen generation in the area of containment and the auxiliary model for the calculations of the spraying efficiency. The model was also adopted for analyzing system response to the different inefficiencies of the elements of the containment system. The basis of the mathematical model has been fully implemented in the computer code.

According to the assumptions of the model with lumped parameters the whole area of the containment is divided into several control volumes (zones). Control volumes are joined by the orifices, valves, siphon closures etc. Changes of the thermal variables are calculated for each separate control volume. A two-phase agent can appear in the control volume such as liquid phase (water) or gaseous phase (air, steam, hydrogen).

The thermal state of an agent is specified by the following thermodynamic parameters: total pressure of gas p_{tot}, partial pressure of air p_{a}, steam p_{p} and hydrogen p_{h}, temperature of gas t_{g} and temperature of water t_{w}. The amount of agent in the control volume is defined by the amount of air G_{a}, amount of steam G_{s}, amount of hydrogen G_{h} and amount of water G_{w}.

The general assumptions of the mathematical model are as follows:

- The model is discrete with respect to both space and time.
- Two phases can appear in the control volume: gaseous (air, steam, hydrogen) and liquid (water).
- Non-equilibrium state between phases is assumed to appear. Water can be in the saturated state ($t_{\mathrm{w}} = t_{\mathrm{s}}(p_{\mathrm{tot}})$) or can be subcooled ($t_{\mathrm{w}} < t_{\mathrm{s}}(p_{\mathrm{tot}})$). Steam can be superheated ($t_{\mathrm{g}} > t_{\mathrm{s}}(p_{\mathrm{p}})$) or saturated ($t_{\mathrm{g}} = t_{\mathrm{s}}(p_{\mathrm{p}})$).
- Heat transfer between liquid and gaseous phases and heat transfer to the walls of the containment (including the heat accumulation in the walls of containment) is considered.
- Gaseous agents are treated as the semi-ideal gases.
- It is assumed that steam fully condenses when flowing through the siphon closure.
- Operation of active and passive spraying systems, work of ventilation systems, generation of the after-shutdown heat in the core of reactor, generation of the hydrogen etc. are simulated by the model.

There are several concepts involved in the modelling of the separation of phases within the coolant during the release from the primary circuit. The authors assumed that the total rate of flow of coolant is shared between liquid and gaseous phases according to the following relationships:

$$\dot{G}_\mathrm{s} = \dot{G} \cdot z\,, \tag{1}$$

$$\dot{G}_\mathrm{w} = \dot{G} \cdot (1 - z)\,, \tag{2}$$

where:

G – total rate of flow of coolant,
G_w – liquid water rate of flow,
G_s – steam rate of flow.

Parameter z is defined as follows:

$$z = \frac{i(\tau) - i'(t_\mathrm{g})}{i''(t_\mathrm{g}) - i'(t_\mathrm{g})}\,, \tag{3}$$

where:

$i(\tau)$ – specific enthalpy of the coolant (at the moment of time τ),
i', i'' – specific enthalpy of saturation of the liquid water and the steam (for the temperature t_g of gas in the zone of the coolant release).

One assumes that the thermodynamic non-equilibrium state between liquid and gaseous phases appears. On the other hand one assumes the state of thermodynamic equilibrium within the separate phase. According to the above assumptions we can distinguish five different states of agents within the control volume:

a) lack of water, superheated steam,

b) subcooled water, superheated steam,

c) subcooled water, saturated steam,

d) saturated water, superheated steam,

e) saturated water, saturated steam.

Calculation of the two-phase flow processes (the flow of two-phase agent through the orifices, valves etc.) is based on the works [4, 5, 15]. However, the model of the mass transport processes does not however include the diffusive mass transfer (the extremely high dynamics of thermal processes during LOCA justify such an assumption).

Several individual problems have also been solved and included within the model. We can mention here the problem of calculating the efficiency of the spraying systems and the modelling of heat conduction and heat accumulation in the walls of the containment.

The intensity of heat transfer between gas and water being sprayed out by the active and passive spraying system is determined by the spraying efficiency η_s:

$$\eta_\mathrm{s} = \frac{i_1 - i_0}{i_\mathrm{max} - i_0}\,, \tag{4}$$

where:

i_0 – initial specific enthalpy of droplet,
i_max – theoretical maximum enthalpy of droplet,
i_1 – final specific enthalpy of droplet.

The method of the calculating the spray efficiency η_s and the analysis of the influence of efficiency η_s on the changes of thermal variables within the containment of the WWER-440 reactor are presented in works [7, 13].

Not all the processes taking place in the core of the reactor are included in the model. Transient distribution of the flow rate and specific enthalpy of coolant being released from the primary circuit are simulated by the code RELAP.

The modelling of changes of the thermodynamic parameters in the control volume is based on the fundamental thermodynamic equations: energy balance equations, mass balance equations and state equations. Equations of the energy and mass balance refer to the time step $\Delta\tau$. The state equations refer to the end of the each time step $\Delta\tau$. All these equations have nonlinear but algebraic form and do not include derivatives of thermal variables with respect to time. The individual form of the equations depends on the state of agents within the control volume. Basic thermodynamic equations of the model are expressed in the following general form:

- equation of the energy balance for the gaseous phase

$$F_1 = (G_s+G_{we}-G_{sc})i_s - p_s V_g + (G_a c_{va} + G_h c_{vh})t_g + G_{sc} i'_s(t_g) - G_{we} i''_s(t_w) - U_{g1} - \Delta E_g = 0\,, \tag{5}$$

- equation of the energy balance for the liquid phase

$$F_2 = \delta_1 \left[(G_w - G_{we} + G_{sc})c_w t_w - G_{sc} i'_s(t_g) + G_{we} i''_s(t_w) - U_{w1} - \Delta E_w\right] = 0\,, \tag{6}$$

- equation expressing the sum of the agents volumes

$$F_3 = \vartheta_w (G_w - G_{we} + G_{sc}) + \vartheta_s (G_s + G_{we} - G_{sc}) - V_{tot} = 0\,, \tag{7}$$

- equation expressing the sum of the partial pressures

$$F_4 = \delta_2 [p_a + p_h + p_s(t_g) - p_s(t_w)] = 0\,, \tag{8}$$

where:

i – specific enthalpy,
c – specific heat,
V – volume,
G_{we} – amount of water being evaporated during the time step $\Delta\tau$,
G_{sc} – amount of steam being condensed during the time step $\Delta\tau$,
U_{g1}, U_{w1} – internal energy of gas and water at the beginning of time step $\Delta\tau$,
$\Delta E_g, \Delta E_w$ – sum of energy flow rate flowing into the control volume (enthalpy of gas and water and heat fluxes),
$\delta_1 = 0$ or 1.

Superscripts $'$ and $''$ refer to the saturated state of water and steam respectively.

As mentioned above the remaining equations of the model are state equations for the gases (air, steam, hydrogen) and the state equation for the liquid water. Air and hydrogen are treated as the ideal gases. Well known nonlinear algebraic state equations [5] for steam (semi-ideal gas) and water are used in the model.

The model of mass flow between control volumes through orifices and valves and the model of mass flow through the siphon closure is based upon the assumptions and numerical procedures presented in the works [3, 5].

It is necessary to calculate the transient temperature field in the walls of the containment in order to consider the effects of heat transfer and heat accumulation. The numerical Control Volume Method (CVM) was applied by the authors. Equations of the temperature at the discrete net of difference nodes are derived from the energy balance of the difference element. The *explicit* difference scheme for integrating along the time interval was applied here. The number of the unknown quantities depends on the thermal state of the agents in the control volume. We can distinguish five possibilities:

a) lack of water, superheated steam, unknowns: t_g, p_p ($p_p < p_s(t_g)$),

b) subcooled water, superheated steam, unknowns: t_g, t_w, p_p ($p_p < p_s(t_g)$),

c) subcooled water, saturated steam, unknowns: t_g, t_w, G_{sc},

d) saturated water, superheated steam, unknowns: t_g, t_w, G_{we},

e) saturated water, saturated steam, unknowns: t_g, t_w, G_{we}, G_{sc}.

As an example, we consider the most probable situation, i.e. variant c) — subcooled water and saturated steam. In such a case the unknown quantities are t_g, t_w and G_{sc}. Equations (5), (6) and (7) are used for calculating the unknown quantities:

$$\begin{aligned} F_i &= F_i(t_g, t_w, G_{sc}), \quad i = 1,2,3, \\ i_p &= i''_p(t_g), \quad G_{we} = 0, \quad \vartheta_w = \vartheta_w(t_w), \quad \vartheta_s = \vartheta''_s(t_g), \\ p_p &= p_s(t_g), \quad \delta_1 = 1, \quad \delta_2 = 0. \end{aligned}$$

3. SOLUTION OF THE NONLINEAR PROBLEM

The calculations of all the unknown quantities (for each time step and for each control volume) consist of several stages. Firstly, one calculates all the mass and energy fluxes: i.e. the leakage of coolant from the primary circuit, the flow rates of agents through the orifices, siphon closures and valves, water flow rate in the active and passive spraying systems, heat accumulation in the containment structures, heat transfer to the environment etc. Heat transfer between gaseous and liquid phase is also calculated at this stage. All these calculations refer to the values of thermal parameters at the beginning of time step . Then one calculates the internal energy of the gas U_{g1} and water U_{w1} in each control volume. Eventually, one obtains a set of n nonlinear equations in the following general form:

$$F_i(x_1, x_2, \ldots, x_n) = 0, \qquad i = 1, 2, \ldots, n, \tag{9}$$

where x_i denotes unknown parameters. The number of equations n depends on the current state of agents within the control volume.

The nonlinearities of the equations result from several reasons:

- the energy balance equations (5) and (6) are nonlinear with respect to the thermal variables,
- the state equations and caloric equations (describing specific enthalpy) for H_2O are generally nonlinear with respect to the temperature (moreover, the individual form of the state equation depends on the value of temperature).

The nonlinear problem (9) has been solved applying the Newton-Raphson method [10, 12]. Such an approach gives more accurate numerical results than the linear, differential approach [3, 5] used in the solution of the problem. According to the Newton method the initial equation (9) is transformed into the form

$$\sum_{j=1}^{n} a_{ij}\delta x_j = -F_i(x_1^0, x_2^0, \ldots, x_n^0), \qquad i = 1, 2, \ldots, n, \tag{10}$$

where:

x_j^0 – estimated value of parameter x_j,
δx_j – correction of the x_j^0.

Coefficients a_{ij} are calculated according to the relationship:

$$a_{ij} = \frac{\partial F_i}{\partial x_j}, \qquad i, j = 1, 2, \ldots, n. \tag{11}$$

The required accuracy is obtained by applying an iterative procedure. At the last stage of the algorithm all the remaining unknown quantities (i.e. partial pressures, total volumes of gas and water, amount of agents etc.) are calculated. The computational procedure described above is then repeated for each control volume and the each time step $\Delta\tau$.

4. ANALYSIS OF LOCA WITHIN THE CONTAINMENT OF THE WWER-440 REACTOR

The computer code was used for analyzing different scenarios of LOCA for the WWER-440 nuclear reactor [6–14], including the separate problem of calculating the hydrogen concentration within the containment [6]. The area of the containment was divided into 5 (or 9) control volumes (see Fig. 3):

1. steam generator boxes (15130 m^3),
2. tower of ALS (6535 m^3),
3. water condensers (8388 m^3 + 1364 m^3 of water),
4. air traps (16137 m^3),
5. reactor compartment (4864 m^3).

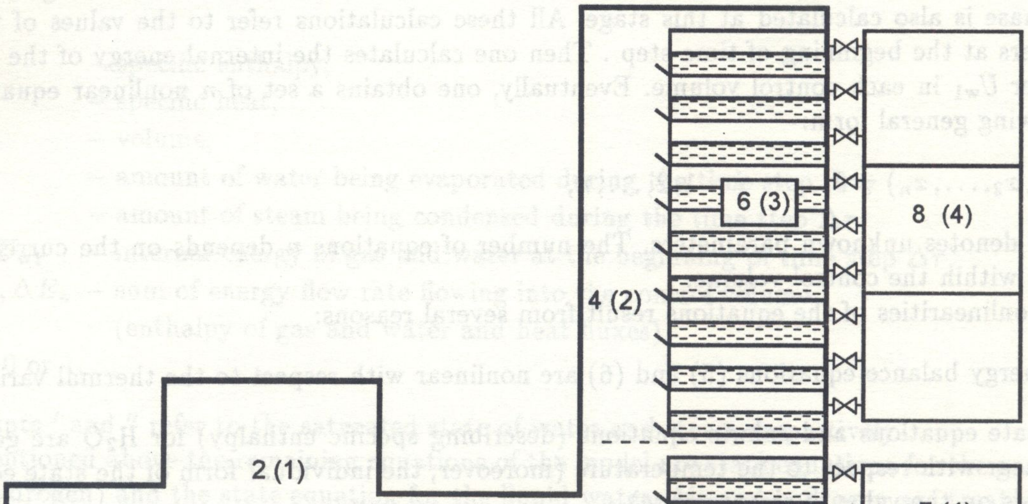

Fig. 3. Scheme of the nodalization of containment of the WWER-440 reactor

Sample results of calculations of transient pressure and temperature changes within the containment of the WWER-440 reactor during LOCA are presented in Figs. 4 and 5. One assumes that all the elements of the containment and all the pressure suppression systems work normally. In such a case, the maximum pressure appears in the steam generator rooms after about 12 seconds of LOCA. The maximum pressure is lower than the admissible one for the containment of the WWER-440 reactor i.e. $p_{\max} = 0.245\,\mathrm{MPa}$.

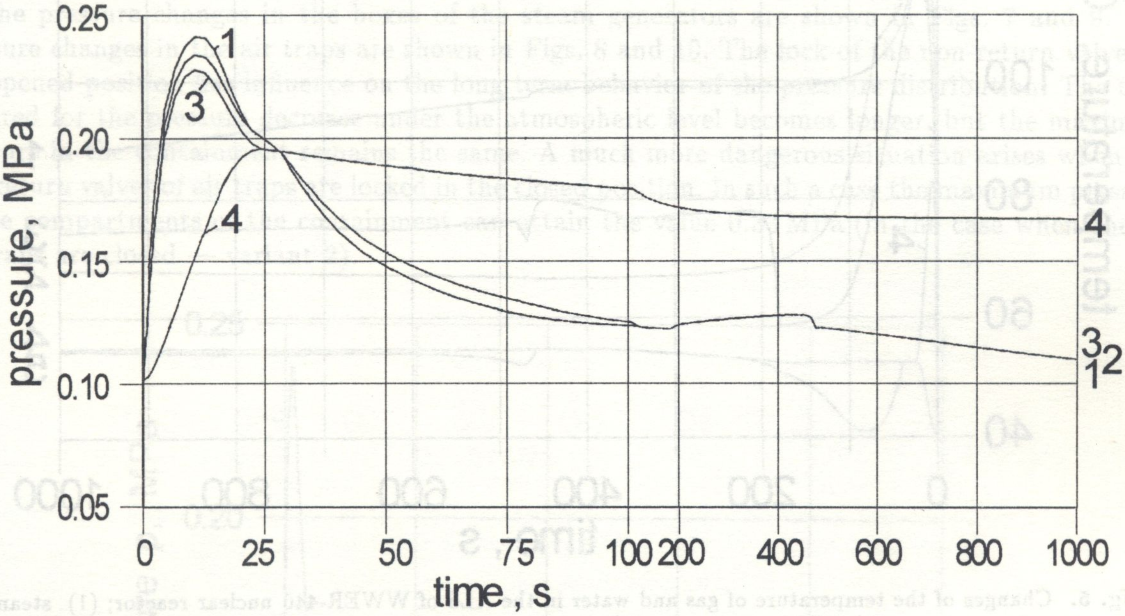

Fig. 4. Changes of the pressure in the containment of the WWER-440 nuclear reactor; (1) steam generator rooms, (2) tower, (3) water condenser, (4) air trap

An elaborated model and computer code was also used for the simulation of several scenarios of LOCA in the case of an inefficiency in the elements of the pressure suppression systems. Several of these variants are listed below:

a) two valves of the air traps are locked,

b) spraying system incapacitated,

c) one air trap opened,

d) ventilation valve of the air trap opened,

e) three water condensers emptied,

f) all the water condensers emptied.

Variant f) refers to the probable sequence of two LOCA: *small* and *large*. In such a scenario the *small* LOCA can cause suction of water from condensers. In the case the *large* LOCA, all the water condensers of the containment might remain empty.

The results of calculations of the pressure changes in the boxes of the steam generators are presented in Fig. 6. When comparing with the basic scenario (curve p), the maximum pressure is slightly greater for the cases a) and e). A significant difference can be observed for the variant f). The time required for the pressure suppression under the atmospheric level is generally considerably longer. The only exception is variant a).

The system of water condensers and air traps plays the dominant role in the pressure suppression process in the containment of the WWER-440 reactor. The proper functioning of air traps depends on the condition on the non-return valves that join them to the water condensers. In the case of any

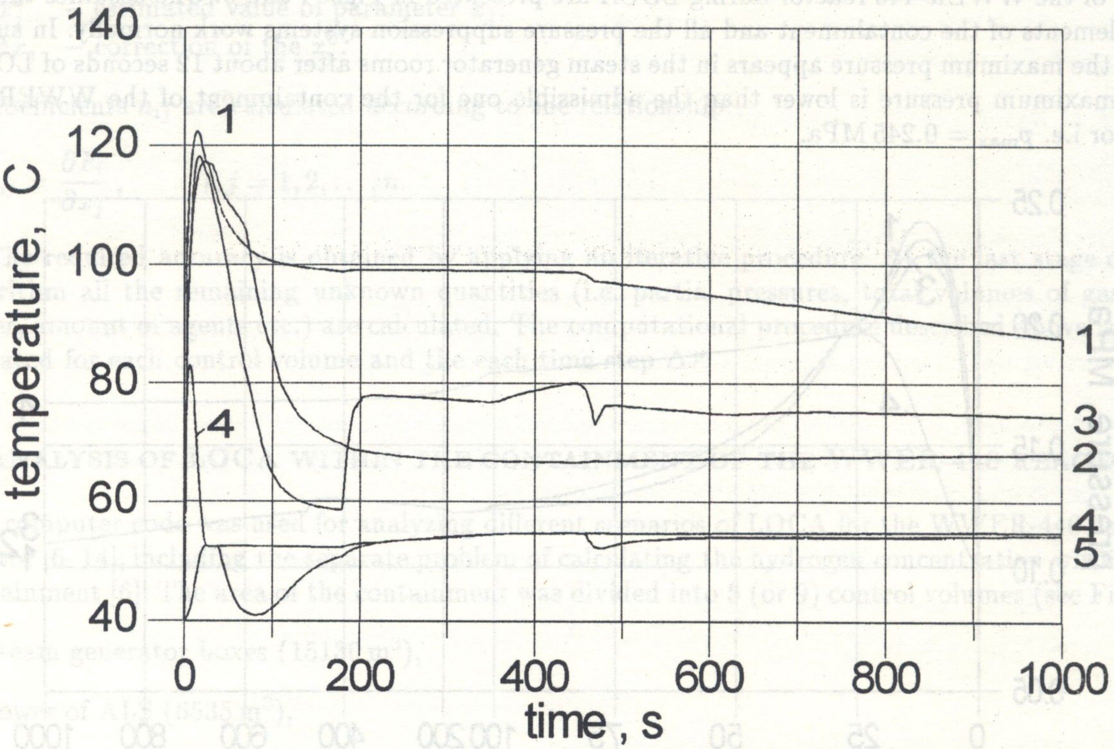

Fig. 5. Changes of the temperature of gas and water in the ALS of WWER-440 nuclear reactor; (1) steam generator rooms — gas, (2) ALS tower — gas, (3) steam generator rooms — water, (4) water condensers — gas, (5) water condensers — water

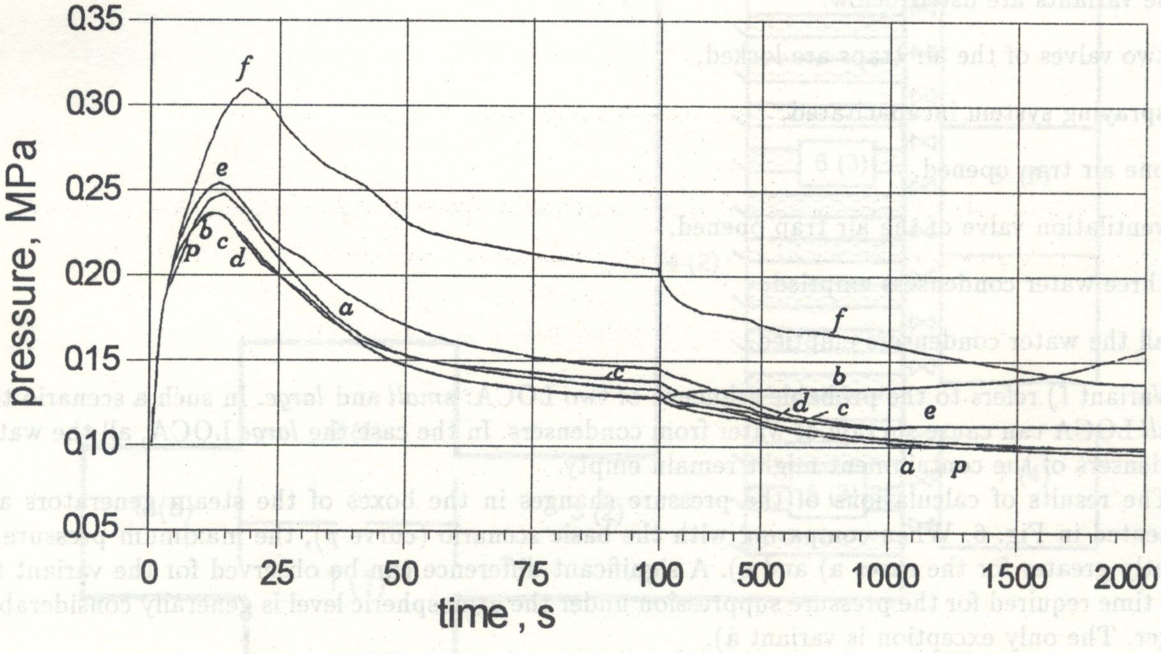

Fig. 6. Pressure changes in the steam generator rooms (*p* — normal work of ALS)

damage of non-return valves (which can be caused, for example, by a hydraulic stroke), the process of pressure suppression can be significantly disturbed. To simulate such a scenario, two situations were analyzed:

a) the valves locked in the opened position,

b) the valves locked in the closed position.

The pressure changes in the boxes of the steam generators are shown in Figs. 7 and 9. The pressure changes in the air traps are shown in Figs. 8 and 10. The lock of the non-return valves in the opened position has influence on the long term behavior of the pressure distribution. The time required for the pressure decrease under the atmospheric level becomes longer, but the maximum pressure in the containment remains the same. A much more dangerous situation arises when the non-return valves of air traps are locked in the closed position. In such a case the maximum pressure in the compartments of the containment can attain the value 0.33 MPa (in the case when the all air traps are closed — variant 2).

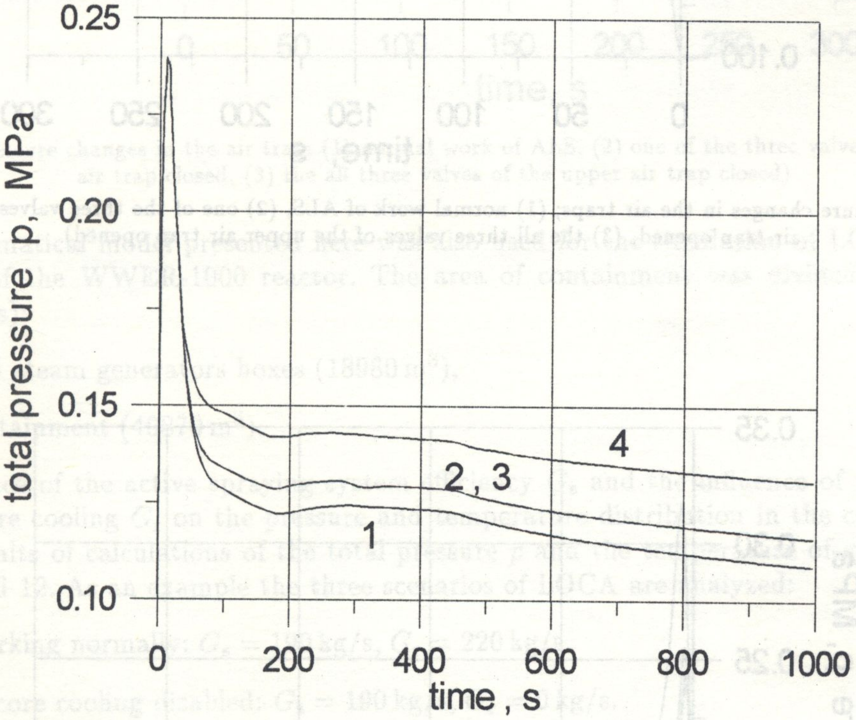

Fig. 7. **Pressure changes in the steam generator rooms; (1) normal work of ALS, (2) one of the three valves of the upper air trap opened, (3) the all three valves of the upper air trap opened, (4) the all valves opened)**

5. ANALYSIS OF LOCA WITHIN THE CONTAINMENT OF THE WWER-1000 REACTOR

The mathematical model and computer code can be used for the simulation and analysis of LOCA within the full pressure containments of the pressurized water reactors and boiling water reactors. In general, construction of the containments of PWR nuclear reactors is less complicated than BWR reactors (and WWER-440 reactor). This type of containment is not usually supplied with the passive pressure suppression systems i.e. wetwells and drywells. An example of such a construction can be the containment of the WWER-1000 reactor (see Fig. 2) that is supplied with the active spraying system. The main task of the spraying system here is the long-term pressure suppression and the removal of the radioactive isotopes from the containment area. The WWER-1000 reactor is also supplied with the auxiliary post-accident system of reactor core cooling.

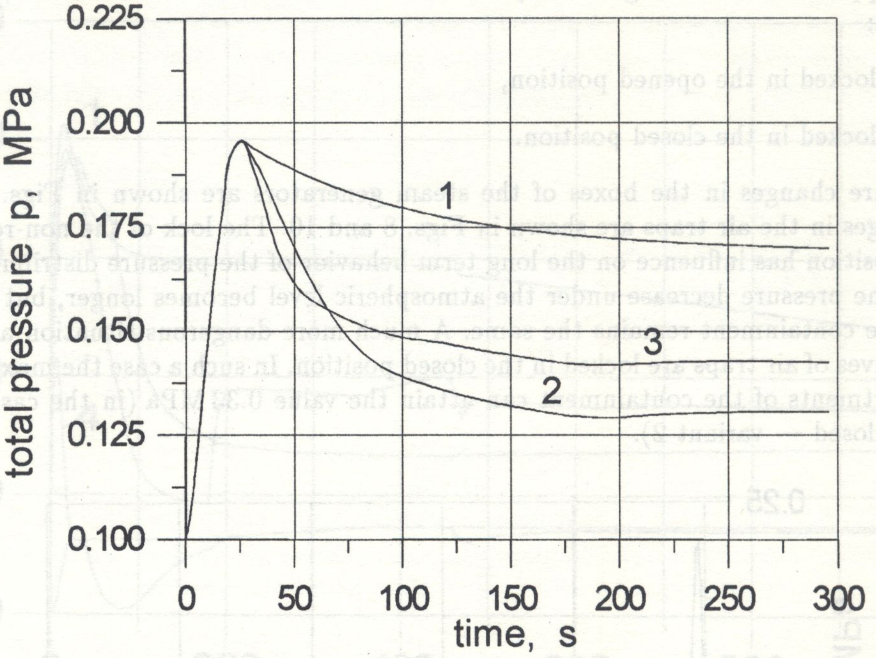

Fig. 8. Pressure changes in the air traps; (1) normal work of ALS, (2) one of the three valves of the upper air trap opened, (3) the all three valves of the upper air trap opened)

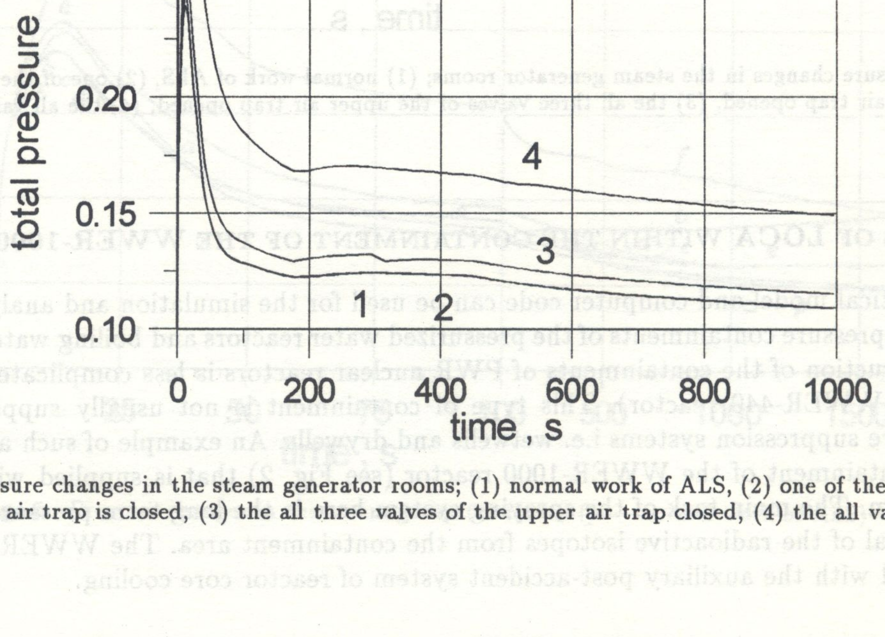

Fig. 9. Pressure changes in the steam generator rooms; (1) normal work of ALS, (2) one of the three valves of the upper air trap is closed, (3) the all three valves of the upper air trap closed, (4) the all valves closed)

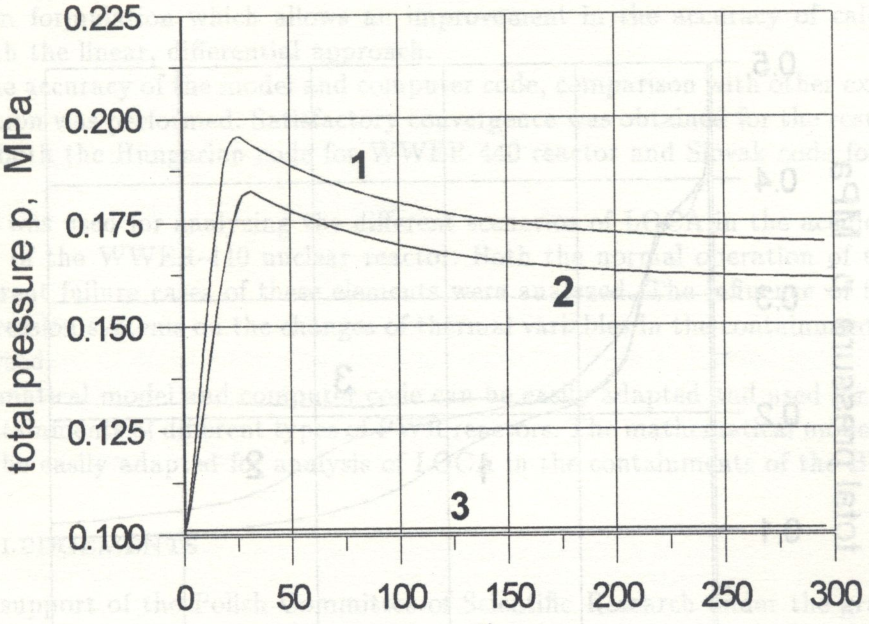

Fig. 10. Pressure changes in the air trap; (1) normal work of ALS, (2) one of the three valves of the upper air trap closed, (3) the all three valves of the upper air trap closed)

The mathematical model presented here was also used for the simulation of LOCA within the containment of the WWER-1000 reactor. The area of containment was divided into 2 control volumes (zones):

1. reactor and steam generators boxes (18980 m^3),
2. area of containment (40870 m^3).

The influence of the active spraying system efficiency G_s and the influence of the efficiency of the reactor core cooling G_r on the pressure and temperature distribution in the containment was analyzed. Results of calculations of the total pressure p and the temperature of gas t_g are shown in Figs. 11 and 12. As an example the three scenarios of LOCA are analyzed:

1. System working normally: $G_s = 190\,kg/s$, $G_r = 220\,kg/s$.
2. System of core cooling disabled: $G_s = 190\,kg/s$, $G_r = 0\,kg/s$.
3. Spraying system working with 50% of nominal efficiency: $G_s = 95\,kg/s$, $G_r = 220\,kg/s$.

As shown in Fig. 11 the maximum pressure in the containment does not exceed 0.43 MPa in all of the three analyzed situations. During normal operation of cooling systems, the time required for pressure suppression under the atmospheric level is about 4 hours. The failure of the core cooling system does not cause the most significant change in the pressure distribution. The greatest influence on the pressure changes has the efficiency of active spraying system G_s. In the case where the system works with the 50% of the nominal efficiency (curve no. 3) the pressure in the containment do not drop under the value 0.22 MPa (within the considered period of time).

6. CONCLUSIONS

The mathematical model and computer code for the simulation of the Loss-of-Coolant Accident presented here enables the calculations of short- and long-term behavior of thermodynamic parameters within containments of PWR nuclear reactors. The authors applied a non-linear approach

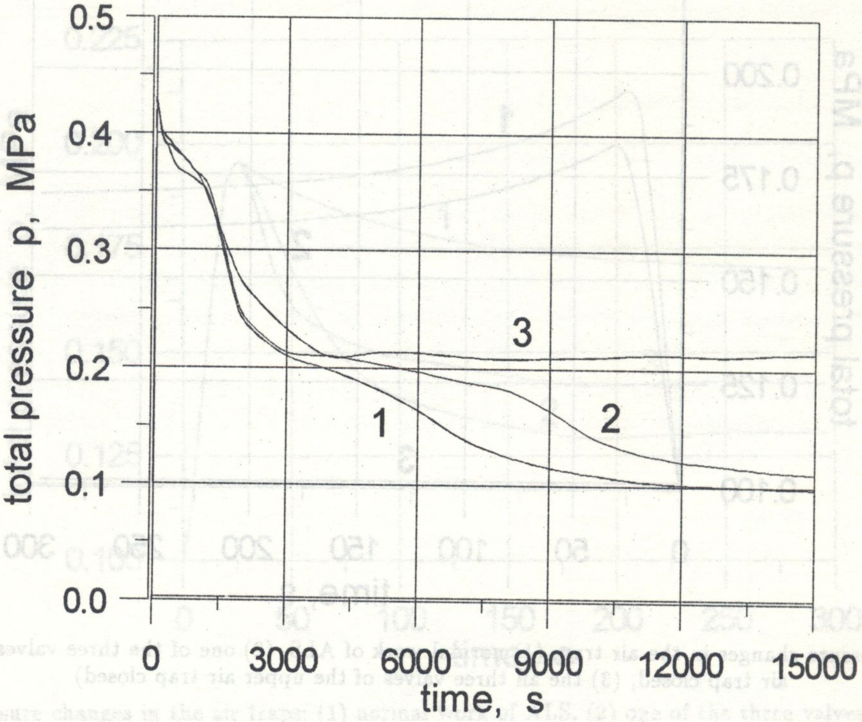

Fig. 11. Changes of the total pressure in the steam generator room; (1) $G_s = 190\,\mathrm{kg/s}$, $G_r = 220\,\mathrm{kg/s}$, (2) $G_s = 190\,\mathrm{kg/s}$, $G_r = 0\,\mathrm{kg/s}$, (3) $G_s = 95\,\mathrm{kg/s}$, $G_r = 220\,\mathrm{kg/s}$)

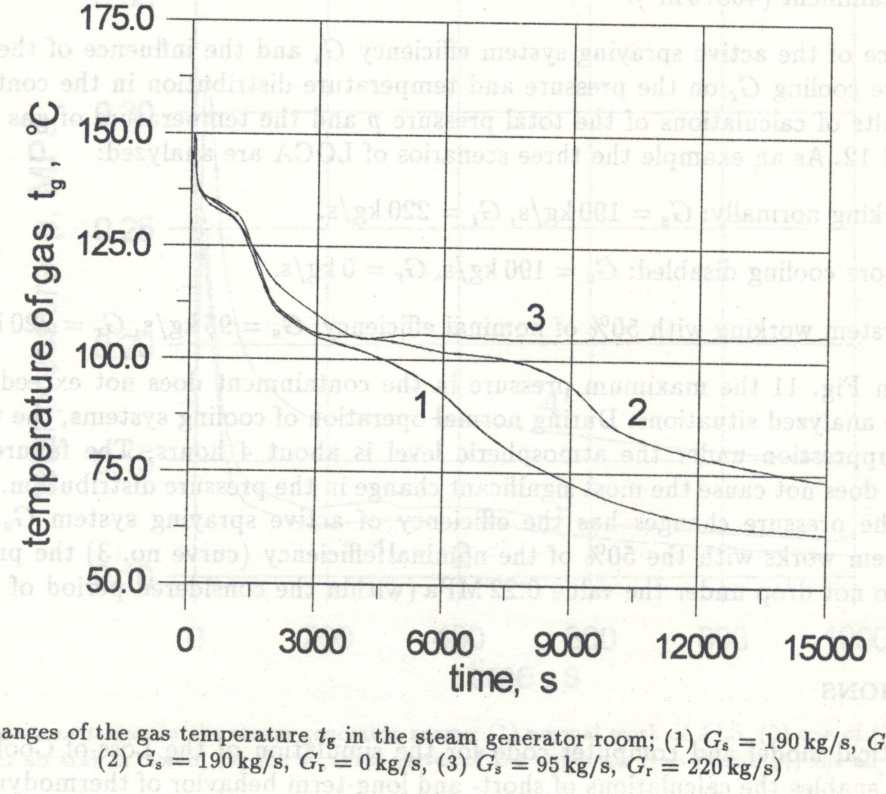

Fig. 12. Changes of the gas temperature t_g in the steam generator room; (1) $G_s = 190\,\mathrm{kg/s}$, $G_r = 220\,\mathrm{kg/s}$, (2) $G_s = 190\,\mathrm{kg/s}$, $G_r = 0\,\mathrm{kg/s}$, (3) $G_s = 95\,\mathrm{kg/s}$, $G_r = 220\,\mathrm{kg/s}$)

to the problem formulation which allows an improvement in the accuracy of calculations when comparing with the linear, differential approach.

To check the accuracy of the model and computer code, comparison with other existing codes for LOCA simulation was performed. Satisfactory convergence was obtained for the results of calculating involving both the Hungarian code for WWER-440 reactor and Slovak code for WWER-1000 reactor.

The model was used for analyzing the different scenarios of LOCA in the accident localization system (ALS) of the WWER-440 nuclear reactor. Both the normal operation of the elements of ALS and different failure cases of these elements were analyzed. The influence of the work of the pressure suppression systems on the changes of thermal variables in the containment during LOCA was also analyzed.

The mathematical model and computer code can be easily adapted and used for LOCA simulation in the containments of different types of PWR reactors. The mathematical model and computer code can also be easily adapted for analysis of LOCA in the containments of the BWR reactors.

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