HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

APPLICATION OF A LUMPED PARAMETER CODE FOR PREDICTION OF HYDROGEN DISTRIBUTION WITHIN CONTAINMENTS OF WATER REACTORS

Bury T.* and Składzień J.
*Author for correspondence
Institute of Thermal Technology,
Silesian University of Technology,
Konarskiego 22, 44-100 Gliwice,
Poland,
E-mail: tomasz.bury@polsl.pl

ABSTRACT

The lumped parameter code HEPCAL has been worked out in the Institute of Thermal Technology of the Silesian University of Technology for simulations of pressurized water reactor containments response to accidental conditions, especially during loss-of-coolant accidents (LOCA). Within the framework of this work the HEPCAL code has been applied for simulations of hydrogen behavior within containments of Advanced Boiling Water Reactor (ABWR) and European Pressurized Reactor (EPR). The focus has been put on hydrogen distribution thorough subcompartments of the containment building. A dynamics of creating flammable mixtures and operation of hydrogen removal systems were also the subjects of analysis.

INTRODUCTION

Two main problems related to a nuclear reactor operation are the presence of large amount of highly radioactive material in the core and so-called after heat power.

The system of barriers is utilized to prevent a release of radioactive materials to the environment from a nuclear reactor's core. These barriers, in case of water reactors, are the nuclear fuel structure, fuel cladding, walls of the primary cooling circuit and the containment building. Reliability of these barriers is very high and it is very unlikely to fail them all simultaneously. Nevertheless, engineered safety systems are installed to ensure required safety level. The containment building with all the safety systems is often called as the accident localization system.

Shutting down a nuclear reactor means stopping the chain fission reaction but the heat is still produced by fission products decay reactions. This is so-called residual heat or after heat power [1]. Therefore it is very important to assure sufficient core cooling in all operating modes and during accidents too.

Gaseous hydrogen may be generated in the overheated core region. The main source of this gas in the core region is the exothermic reaction of steam with the nuclear fuel cladding (zirconium alloy). Amounts of hydrogen produced by such reaction is proportional to the mass of zirconium reacted [2]. This gas may be released into the containment building either by a break in the primary cooling circuit during a loss-of-coolant accident, or by a safety relieve valve (as in Fukushima Dai-ichi nuclear power plant [3]). Mixing of hydrogen with the air in the internal atmosphere creates flammable mixtures. The problem of hydrogen combustion and detonation is one of crucial issues for containment integrity. Taking this into account it is very important to avoid such situations and make possible removal of this gas.

The hydrogen risk in nuclear reactor systems needs some mitigation features to be designed and applied. There are five main methods for preventing the hydrogen combustion. All of them require a knowledge of hydrogen distribution within containment structures. It is obvious that such information can be only partially obtained by means of physical experiments. Thus, the mathematical modelling and numerical simulations are widely applied for these purposes.

Within the framework of this work the HEPCAL code has been applied for simulations of hydrogen behavior within containments of Advanced Boiling Water Reactor (ABWR) and European Pressurized Reactor (EPR). The focus has been put on hydrogen distribution thorough subcompartments of the containment building. A dynamics of creating flammable mixtures and operation of hydrogen removal systems were also the subjects of analysis. Following problems appeared during the simulations have been analyzed in details:

- nodalization of systems under consideration – the lumped parameter approach utilizes control zone (volume) method usually and the control volumes are defined according to a real division of containment building on subcompartments;

this is not sufficient to obtain realistic distribution of hydrogen, the resolution of results is rather low,

- the lumped parameter code gives information about average value of thermodynamic parameters as the perfect mixing of agents within a control zone is assumed – this extends the predicted time of creating the flammable mixtures and moreover, thermodynamic consequences of hydrogen combustion are overestimated as the flammability limits are reached at higher mass of this gas in the mixture,
- lack of information about local behavior of hydrogen, stratification and hydrogen impact on the heat transfer conditions are very difficult to be modeled.

NUMERICAL TOOL

The lumped parameter code HEPCAL has been worked out in the Institute of Thermal Technology of the Silesian University of Technology for simulations of pressurized water reactor containments response to accidental conditions, especially during loss-of-coolant accidents. Original version of this code has been elaborated for the VVER 440/213 reactor containment with so-called bubble condenser tower [4, 5]. This system of pressure suppression is more characteristic for boiling water reactors.

The code, of the lumped parameter type, is aimed to predict changes of thermodynamic parameters within containment during LOCA. The whole containment is simulated by a couple of zones (volumes), connected to each other in the given way. The control volumes are connected through open channels, orifices, valves, membranes or siphon closures. For each zone homogeneous conditions (perfect mixing) are assumed. Considering this one may note that the applied model is a discrete one in reference to space and time also. Its base are the energy balance equations written for each specified control volume in the given time span (time step) $\Delta\tau$.

Energy streams flowing in and out of the control volume are associated primarily with heat transfer to walls and structures and intercompartment flows of media. A very important issue in modeling is taking into account operation of safety systems. Mass and energy streams resulting from operation of pumps, fans and other devices should be considered in the energy balance. These quantities as well as the initial internal energy U_1 are determined based on the values of thermodynamic parameters at the beginning of time step. Transforming general relationship for energy balance in a control zone one obtains:

$$U_2 = (\dot{E}_{in} - \dot{E}_{out})\Delta\tau + U_1 \qquad (1)$$

where $\dot{E}_{in}$ and $\dot{E}_{out}$ are the energy flow rates flowing into a control zone and flowing out of a control zone respectively. The right hand side components of the equation (1) are known, so the internal energy at the end of the time step can be calculated. Unknown thermodynamic parameters at the end of the time step are functions of the internal energy U_2.

Such approach allows for one dimensional analysis and determination of time dependent changes of basic thermodynamic parameters (temperature, pressure) within the containment building. It should be clearly stated that the model does not include processes taking place within the primary cooling circuit. Data considering the coolant leakage (mass flow rates and specific enthalpy) are the boundary conditions for HEPCAL code. These information are take from external programs.

The mathematical basis of the model describing changes of thermodynamic parameters consist of the equations of mass and energy balance for specified phases and equations of state [4-6]. The equations of mass and energy balance apply to the time step $\Delta\tau$, however the equations of state concern to the end of each time step. All the equations are nonlinear and their form depend on the state of the specified agents in the control volume. The basic set of equations constituting the mathematical model consists of:

- equations of the energy and mass balance for each control volume,
- equations describing intercompartment flows,
- equations of state for the specified gaseous agents (air, steam, hydrogen),
- equations describing additional phenomena, e.g. heat transfer to the walls and structures, operation of safety systems.

As thermodynamic nonequilibrium between states is assumed the basic equations mentioned earlier may have different form, depending on an actual state of water and steam within the control zone. The model includes six possible cases:

- lack of water, superheated steam,
- subcooled water, superheated steam,
- subcooled water, saturated steam,
- saturated water, superheated steam,
- saturated water, saturated steam,
- lack of water, saturated steam.

Determination of unknown parameters is a gradual process. In the first step mass and energy streams are determined, eg. leak of coolant from the primary circuit, media flows through the intercompartment junctions, mass flow rate of water from the spraying system, accumulation of heat in walls and structures. Heat transfer between phases is also calculated in this step. All these quantities regard to the beginning of time step and allow for determining the internal energy of gas and liquid.

Taking this into account the amounts of media, as well as the internal energy at the end of time step are computed in the second step. The amounts of steam and water and their internal energies initially are determined neglecting the phase changes during the time step.

The values of the basic thermal parameters are determined in the third step. For calculation of these parameters from equations listed above are chosen these ones which are valid for actual state of media within the control volume. Eventually one gets a system of n nonlinear equations, which is solved using the Newton-Raphson's method. A number of equations in the system depends on current state of agents in the control zone. The calculating process is repeated in each time step for every control zone as far as the desired accuracy is achieved.

Values of remaining unknown parameters (pressures, volumes and final masses of agents) are computed in the last step from basic thermodynamic laws and geometrical relationships.

The model applied in the HEPCAL code allows to determine the thermal parameters (temperature, pressure, density) in the specified volumes and the mass flow rates as well as the energy transfer rates between the control zones. The spraying system work is taken into account as well as the heat transfer between phases and heat accumulation in the structures of the containment.

GENERAL CHARACTERISTICS OF THE ANALYSED SYSTEMS

European Pressurized water Reactor (EPR)

The European (or Evolutionary) Pressurized water Reactor (EPR) is the third generation reactor with the thermal output varying from 4300 to 4600 MW (depending on local conditions). This AREVA's design constitutes an evolutionary approach which utilizes proven in practice safety solutions known from the second generation nuclear power plants [7]. The most important safety functions are ensured by diversified systems. The different trains of the safeguard systems are installed in four physically separated divisions of the plant. Four-fold redundancy is used for the main safeguard systems (safety injection, emergency steam generator feed water supply) and the associated support systems (electrical power supplies and cooling systems).

The reactor building is located in the center of the nuclear island. Containment is surrounded by safeguard and fuel buildings that contain the safety systems. All safety-related systems are designed with a four-fold redundancy and located in physically separated divisions [8].

The inner containment is a pre-stressed concrete cylindrical wall with an elliptical head and a reinforced concrete base mat (as shown in Fig. 1). A metallic liner fitted on the inner surface ensures the leak tightness of the containment. The inner containment shell can withstand a build-up in pressure, even that occurring after the double ended break of the main primary coolant pipe. The outer containment is formed by a reinforced cylindrical wall, resting on the same base mat as well as the central part of the reinforced concrete dome which serves as protection against external hazards [9].

The reactor building, the fuel building and the four safeguard buildings are protected against external hazards, such as earthquake and explosion pressure waves. All these buildings are situated on a common raft. This construction provides a very good resistance to the external hazard loads. Compliance with safety objectives related to severe accidents led to the incorporation of particular design measures; the main design measures are [8]:

- High-pressure core melt situations can endanger the integrity of the containment. In existing NPP units, the high reliability of the depressurization and residual heat removal systems make it possible to practically exclude this risk. In the EPR, a supplementary line of defense is provided: a set of motor-driven valves activated by the reactor operators palliates the potential failure of the other lines of defense.
- Exclusion of violent phenomena that can result from the production of hydrogen is provided by passive catalytic recombiners (47) to consume hydrogen. The pressure increase that would result from the combustion of hydrogen is taken into account in the containment design.
- Corium spreading and cooling can take place in a dedicated room next to the bottom of the reactor pit, whose walls and floor are covered with sacrificial concrete. A cooling structure under the spreading area allows for extraction of the residual heat, cooling and quick solidification of the corium. Erosion of the structural concrete of the base mat is thus prevented. An entirely passive valve arrangement allows for covering the layer of hot material and for feeding the cooling structure with water from the In-Containment Refueling Water Storage Tank (IRWST), located next to the corium spreading chamber. In a second phase, after twelve hours, the Containment Heat Removal system is started which cools the spreading area.

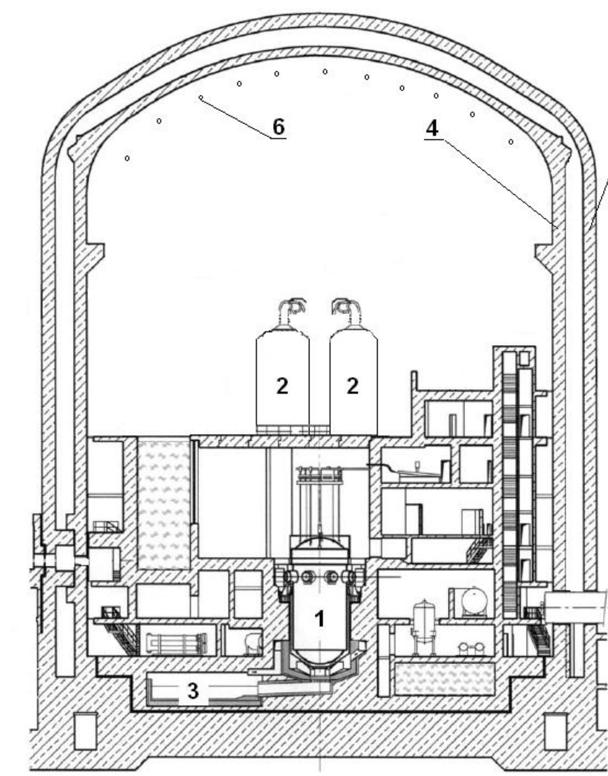

Figure 1 Simplified cross section of the EPR containment – prepared according to [8]
(1 – reactor pressure vessel, 2 – steam generators, 3 – core catcher, 4 – inner containment, 5 – outer containment, 6 – spraying system nozzles)

The containment is segregated into two zones delineating areas that are accessible during normal operation from those that are inaccessible. In the event of an accident, communication is established between these zones by opening mixing dampers and foil barriers, thereby transforming the containment into a single convective volume. This transformation into a single convective volume is performed by the CONVECT system, which equalizes pressure between the containment compartments and promotes efficient mixing of the atmosphere by establishing a global convective pathway [10].

Advanced Boiling Water Reactor (ABWR)

The Advanced Boiling Water Reactor is the third generation design developed by General Electric and Hitachi, and based on older versions of this type reactors. Standardized electrical output is 1350 MW. Simplified active safety systems have been applied in this design.

A milestone in enhancing safety of boiling water reactors has been the elimination of external recirculation cooling loops [11]. Pipes and external recirculation pumps have been replaced with ten internal pumps installed in the bottom part of reactor pressure vessel – see Fig. 2. Therefore a number of potential leak locations has been reduced, as well as professional exposure level during services and maintenance. The power supply demand for the internal pumps is twice lower than for external ones, so overall efficiency of power plant increases [12]. Modernized reactor power control system with step electrical engines allows for more precise reactivity control.

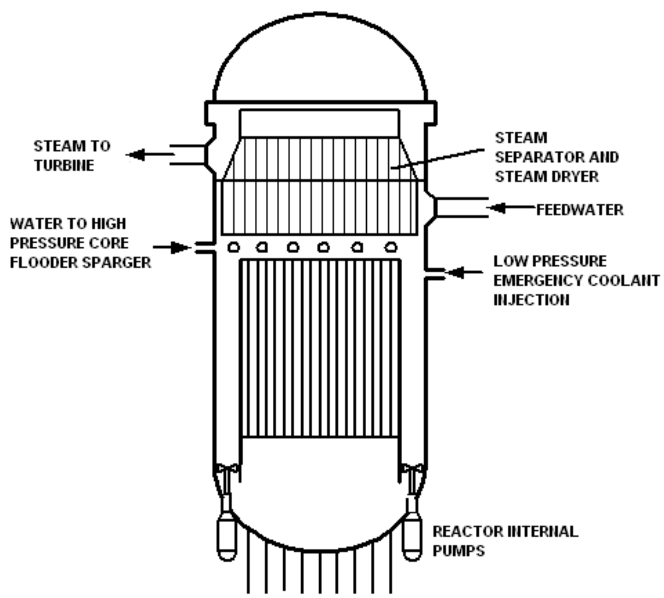

Figure 2 Simplified sketch of the ABWR reactor pressure vessel

The ABWR reactor primary containment consists of a steel liner inside a reinforced concrete structure. A simplified sketch of the ABWR reactor building is shown in Fig. 3. The reinforced concrete containment vessel is divided into a drywell and a suppression chamber (wetwell) by the diaphragm floor and the reactor pressure vessel pedestal.

In case of the reinforced concrete containment vessel pressure increase due to a LOCA, steam is condensed in the suppression pool. The noncondensable gases transported with the steam escape to and are contained in the free air volume of the wetwell. This passive pressure suppression system is supported by an active spraying system which nozzles are distributed in the drywell and wetwell. A nitrogen atmosphere can be developed in the primary containment to prevent a hydrogen explosion. Flammability control system in the ABWR reactor has two recombiners installed into the secondary containment. The recombiners process the combustible gases drawn from the primary containment drywell. This system is activated when a LOCA occurs.

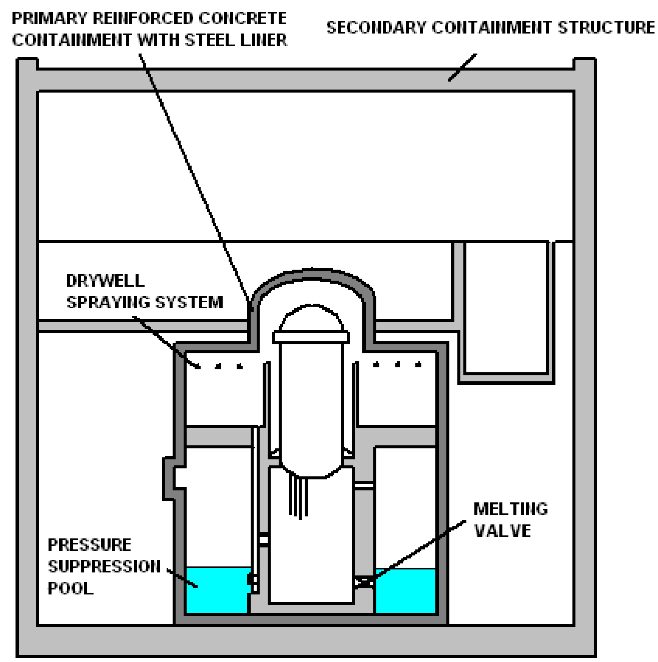

Figure 3 Simplified cross section of the ABWR containment

RESULTS OF ANALYSIS

According to the HEPCAL code requirements the containment structure has to be divided into control zones – nodalized. Usually the geometry and dimensions of a control volume correspond to the real dimensions of the specified compartment of the accident localization system.

It should be noted here that information concerning parameters of coolant (mass flow rates, enthalpy) flowing out of the primary circuit are effects of using external codes and are put into the HEPCAL code as the boundary conditions.

Considering the aim of this work the most important results are the time dependent hydrogen concentration trends and these are presented here after.

European Pressurized water Reactor (EPR)

The containment of the EPR has the free volume of 80 235 m^3. The arrangement of subcompartments and connections between them allow for natural circulation flows, thus promoting efficient mixing of the internal atmosphere contents, as mentioned earlier. The structure of the EPR containment is very complex. It is usual during thermal hydraulic analyses of such systems to simplify them by treating subcompartments of the containment connected by open channels as one control volume. Thus, in first approach the analyzed EPR containment has been divided into five control zones: reactor pit + core catcher – 1460 m^3, steam generator boxes – 14 500 m^3, annular space near the primary containment wall – 22 000 m^3, upper dome – 42 000 m^3, space between primary and secondary containment – 12 260 m^3.

The accident scenario under consideration is a hot leg LOCA of an effective break diameter equal to 100 mm. The pipe rupture occurs in the steam generator boxes. It has been assumed that no emergency cooling systems were available during the accident and the steam-zirconium reaction was the source of gaseous hydrogen in the case.

The simulations have been realized twice: without operation of passive recombiners and considering operation of that system. The initial conditions are as follow:

- accessible area: temperature 30°C, pressure 101,1 kPa, relative humidity 50%;
- inaccessible area: temperature 42°C, pressure 101,1 kPa, relative humidity 50%.

A catalytic recombiner is passive device – no external energy is needed for its operation, and is self starting also at low temperatures and wet conditions. The recombiner consists of a vertical channel or stack equipped with a catalyst cartridge in the lower part. Such design creates so-called "chimney effect" – a gas mixture flows through the recombiner by means of natural circulation. The basis of the operation of passive autocatalytic recombiner is the exothermic reaction of hydrogen and oxygen present in the containment atmosphere taking place on catalyst surface. The catalytic cartridge contains plates or spheres coated with noble metals: palladium or platinum. The simplified diagram of a PAR is shown in Fig. 4.

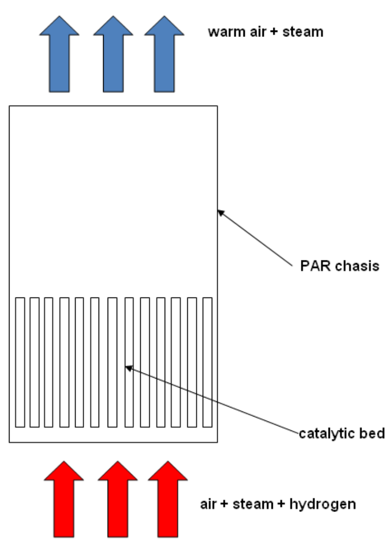

Figure 4 Passive autocatalytic recombiner

The system under consideration is equipped with 41 passive autocatalytic recombiners of FR1-1500T type and 6 devices of FR1-380T type of the AREVA company. The nominal capacity of these PARs is almost 220 kg of hydrogen per hour for reference conditions (absolute pressure 150 kPa, temperature 60°C and hydrogen concentration of 4%). The PARs start their operation at the hydrogen concentration equal to 2% (volume fraction) [13]. Capacity of hydrogen recombiners depends on parameters at the inlet (pressure, temperature, velocity and composition of gaseous mixture). In this analysis it has been assumed constant hydrogen recombination rate and equal to the nominal value.

In Fig. 5 there are presented hydrogen concentration trends for steam generator boxes (break zone) obtained from the computations.

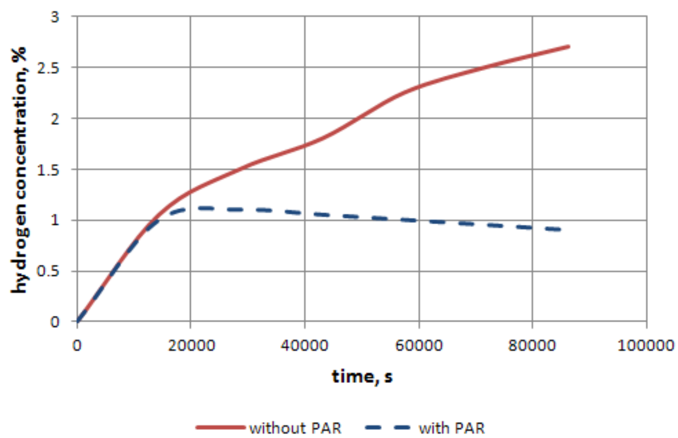

Figure 5 EPR containment analysis – hydrogen concentration within break zone

The hydrogen concentration remains below the threshold concentration necessary for combustion (4%) taking into account no hydrogen recombination from the 47 catalytic devices. Figure 5 also shows when all PARs are functioning, the hydrogen concentration remains below a level of 1,5 %, therefore, hydrogen concentration does not threaten containment integrity.

Advanced Boiling Water Reactor (ABWR)

The structure of the ABWR containment is much simpler than EPR one. Therefore it has been divided into three control zones: upper drywell (UDW) – 5400 m^3, lower drywell (LDW) – 1900 m^3, wetwell (WW) – 9500 m^3 including 3500 m^3 of water in the suppression pool.

The analysis performed for the ABWR concerns design basis LOCA – rupture of the feed water line. Following initial conditions have been assumed during simulations:

- drywell area: temperature 57°C, pressure 107,0 kPa, relative humidity 20%;
- wetwell area: temperature 35°C, pressure 107,0 kPa, relative humidity 100%.

It is also very important that the internal atmosphere within the ABWR containment was pre-inerted with nitrogen and initial oxygen concentration is 3,5%.

The time dependent hydrogen concentration for analyzed case is presented in Fig. 6. The results concern the case with two hydrogen recombiners working.

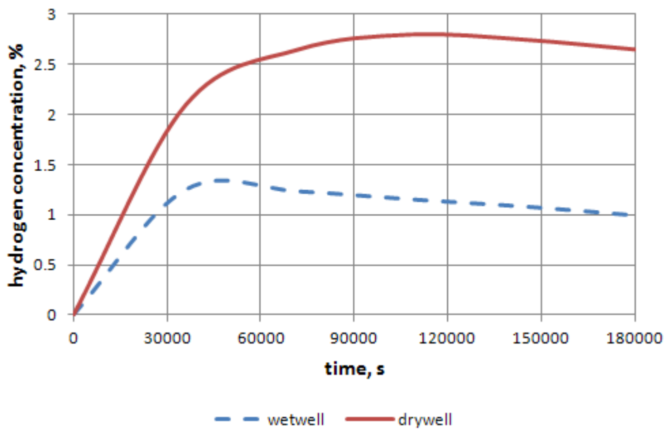

Figure 6 EPR containment analysis – hydrogen mass flow rate within break zone

One can see that the hydrogen concentration is much higher in the drywell. There are two pathways of hydrogen flow into the wetwell area: by the connecting valves along with the air-steam mixture and via the recombiners located in the secondary containment. As hydrogen is a light gas it will gather in upper parts of subcompartments and it will flow rather upward to the recombiners. So, only a small fraction of this gas may achieve the wetwell by this way.

CONCLUSIONS

Some reactor type specific issues have been observed during the simulations. Operation of active spraying system in the pressurized water reactor containment very efficiently reduces the overpressure but simultaneously it is favourable for generation of flammable mixtures. Similar effect can be observed in the wetwells area of boiling water reactor containment – the air, steam and hydrogen mixture inflows into a wetwell under the water level and thus the steam condenses, pressure is reduced but the risk of crossing the flammability limits is higher.

Hydrogen removal systems in both analyzed containments utilize passive autocatalytic recombiners (PAR). An efficient hydrogen removal requires a number of such devices to be installed in different places of containment structure. Operation of a PAR is strongly influenced by a local composition of gaseous mixture flowing in the device, as well as by local thermodynamic parameters. These information are unavailable in the lumped parameter approach. Therefore, results of simulations may be burdened with significant level of uncertainty.

ACNOWLEDGMENTS

This work has been realized within framework of the strategic research project “Technologies supporting development of safe nuclear power” financed by the National Centre for Research and Development.

REFERENCES

[1] Lamarsh J.R., and Baratta A.J., Introduction to nuclear engineering, Prentice Hall, New York 2002.

[2] De Boeck B., Introduction to severe accidents. Especially the containment behaviour. *AIB VINCOTTE NUCLEAR*, Report AVN 97/013, 1997.

[3] International Atomic Energy Agency: Nuclear Emergency Response Headquarters – Government of Japan: Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety. IAEA, Vienna, June 2011.

[4] Fic A., and Skorek J., Mathematical model of transient thermal and flow processes in containment of a PWR nuclear reactor, *Archiwum Energetyki*, Vol. 1-2, 1993, pp. 19-32.

[5] Skorek J., and Składzień J., Thermal analysis of the loss-of-coolant accident within the containment of the WWER-440 and WWER-1000 nuclear reactors, *Computer Assisted Mechanics and Engineering Sciences*, Vol. 1, No. 3/4, 1994, pp. 217-231.

[6] Bury T., Analysis of thermal and flow processes within containments of water nuclear reactors during loss-of-coolant accidents. PhD thesis. Institute of Thermal Technology, Silesian University of Technology, Gliwice, 2005. (in Polish)

[7] AREVA, EPR – the path of greatest certainty, August 2007, www.areva.com

[8] Debontride, B., Design of EPR, Proceedings of the International Conference on Nuclear Power Plants for Poland, Warsaw, Poland, 2006, pp. 10.1-10.11.

[9] Framatome-ANP, Pressurized water reactor 1600 MWe (EPR), http://www.framatome-anp.com, 2005.

[10] AREVA, Applicability of AREVA NP containment response evaluation methodology to the U.S. EPR™ for large break LOCA analysis, Technical Report No. 10299-NP, Revision 1, AREVA NP Inc., July 2009.

[11] International Atomic Energy Agency: Status of advanced light water reactor designs 2004. IAEA TecDoc No. 1391, IAEA, Vienna 2004.

[12] GE Nuclear Energy: Advanced Boiling Water Reactor – Plant General Description. General Electric, 2000.

[13] AREVA, AREVA passive autocatalytic recombiner, Document G-008-V1PB-2011-ENG, AREVA, Paris, 2011.