ISSN 1392 - 1207. MECHANIKA. 2006. Nr.2(58)

Impact of the specified valves characteristics on the transient processes of nuclear reactor core cooling

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1. Introduction

The coolant flow distribution, pressure and flow rate values and core cooling intensity in the nuclear reactors of all types are controlled by means of numerous valves of different purposes, such as isolation and control valves, motor valves, pneumatic or manually activated valves, throttle valves, check valves, gate valves, pressure reduction valves etc. The importance to safety of these elements sharply increases at the accident conditions, when the coolant flow directions and parameters must be changed very quickly.

Accident analysis is one of the most important and complex procedure in the safety evaluation process of nuclear facilities. The validity of conclusions of accident analysis depends on reliability and uncertainty of neutronic and thermal-hydraulic calculations executed. RELAP5, ATHLET and other modern computer codes are widely used for thermal-hydraulic calculations. These codes were created for western type PWR and BWR nuclear reactors. The numerous attempts to validate these codes for the calculation of RBMK-1500 type reactors at the majority of cases were successful: the thermal-hydraulic models of the core, the main circulation circuit and the main safety assurance systems correspond the real phenomena in the reactor with satisfactory adequateness [1-4].

However, some of the models of separate safety related elements are not perfect due to misunderstanding or oversimplification of internal mass and heat transfer processes. The models of valves, junctions, pumps and other piping elements can be attributed to this group. For example, flow structure in these elements is assumed to be constant, the individual design particularities, possible flow slip, vortex motion and local streams' formation etc. are not taken into account [5]. Usage of such unsound assumptions reduces the accuracy and reliability of the results of thermal-hydraulic calculations. Further polishing and refinement of these models is required. While collation of models with relevant experimental data often is impossible due to the lack of such data, modern computational fluid dynamics codes can be employed for this purpose.

The results of an attempt to specify the hydraulic characteristics of the fast acting motor valves of emergency core cooling system as well as to demonstrate the impact of these characteristics to transient processes in the RBMK-1500 type reactor are presented in this paper. A finite element model of the valve has been developed an analysed in order to determine the change of the valve's pressure loss coefficient during it's opening/closure process. The possible impact of these changes to reactor cooling is demonstrated.

2. Modelling of fast acting motor valves

The fast acting motor valves are playing an important role in performing safety functions of the emergency core cooling system of the RBMK-1500 type reactor (Fig. 1). Both the structure and operation of an emergency core cooling system (ECCS) of RBMK-1500 are described and thoroughly analyzed in [6]. The main purpose of the ECCS – to maintain cooling of the reactor core in case of emergency (e.g., break in the main circulation circuit or the failure of some control system elements). The ECCS consists of two separate subsystems: the short term subsystem, which ensures cooling of the reactor core during the first 120 seconds after the break occurs, and the long term subsystem, which ensures cooling of the reactor core during the cool-down of the reactor. At first seconds of the transient processes after the break the estimated maximal ECCS flow rate is 1700 kg/s [6]. The short term subsystem of the ECCS consists of 3 independent trains each of which is capable to supply ~50% of the required capacity of coolant. Two of these trains obtain cooling water from accumulators *22* (Fig. 1) charged with compressed gas and the third train driven by the main feed water pumps *4* fed with water from deaerator tanks *2*. All three trains of the short term subsystem of the ECCS are controlled using the fast acting motor valves *12*, *26*, *29*. The initial coolant flow rate from ECCS depends on the up-stream accumulator pressure and the pressure decrease rate within the main circulation circuit (MCC); it also depends on the rate of opening and decreasing of hydraulic resistance of the fast acting motor valves.

In the case of loss of coolant accident valves *12*, *26* are triggered to open. At the initial stage of opening hydraulic loss coefficient of the valves sharply decreases, and after 2.5-3.0 seconds the required amount of cooling water should be thereby delivered to the group distribution header *15* of the damaged half of the reactor *8*. So, fastness of the emergency core cooling system's activation strongly depends on the hydraulic characteristics of the fast acting motor valves. Coolant flow rate, intensiveness of the reactor cooling and dynamic loading of coolant pipelines also depend on these characteristics. Thus, further substantiation of the real values of the hydraulic loss coefficients of the fast acting motor valves and the law of their changes during the valve's opening or closure is an actual problem.

Trying to substantiate the real values of hydraulic loss coefficients of the fast acting motor valves and the law of their changes during the initial stage of the valve's opening or closure process, the finite element model of the flow in such valve was created (Fig. 2). All important design elements, their configuration and dimensions of the

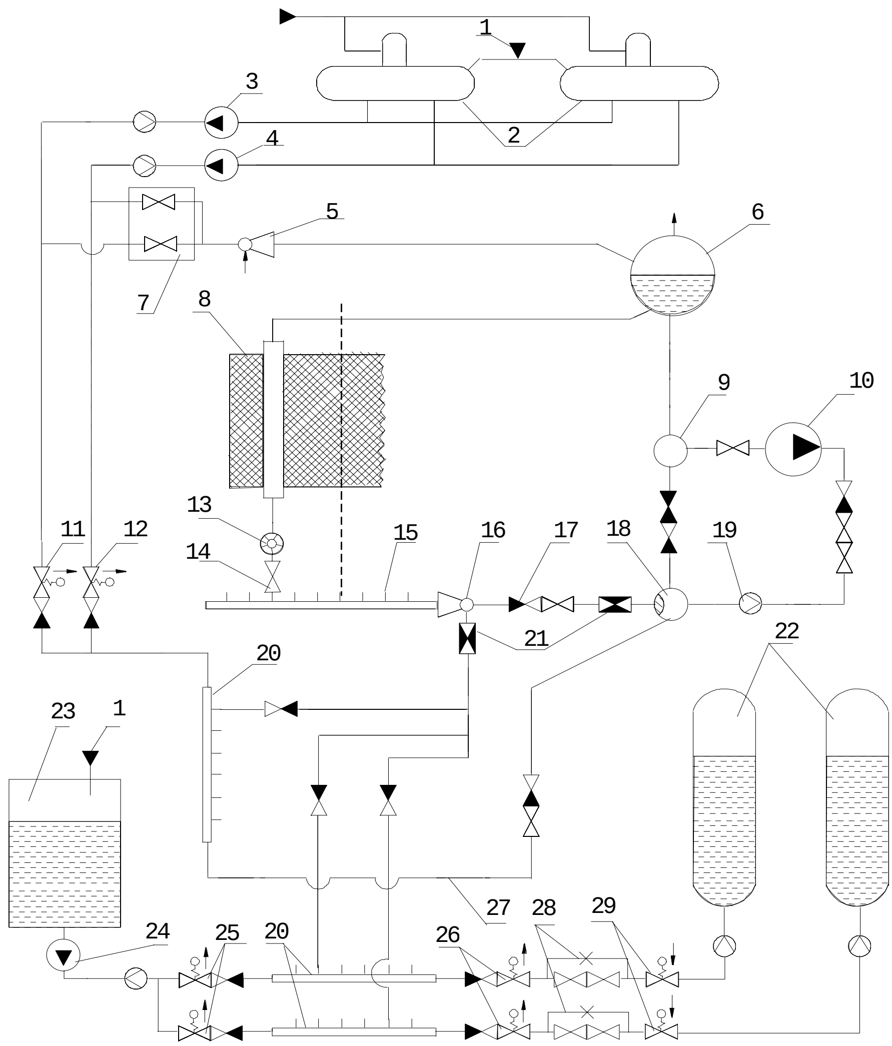

Fig. 1 Schematic diagram of the MCC and emergency core cooling system of reactor RBMK-1500 at Ignalina NPP [6]: *1* – make-up from demineralised water reservoir; *2* – deaerators; *3* – auxiliary feed water pump; *4* – main feed water pump; *5* – mixer; *6* – steam separator; *7* – main feeder and auxiliary feeder; *8* – reactor; *9* – suction header; *10* – main circulation pump; *11*, *12*, *25*, *26*, *29* – fast acting motor valves; *13* – ball type flow/rate meter; *14* – isolation and control valve; *15* – group distribution header; *16* – mixer for the main coolant and the ECCS water; *17* – check valve; *18* – pressure header; *19* – throttling type flow/rate meter; *20* – ECCS header; *21* – flow limiters; *22* – ECCS accumulators; *23* – hot condensate chamber of accident localization system; *24* – ECCS pump; *27* – ECCS bypass line; *28* – throttle bypass line

real valve were taken into account. It was assumed, that one phase incompressible liquid (water) is flowing through the valve at constant temperature. The steady state of turbulent flow, uniform velocity distribution at the inlet and constant pressure value at the outlet of the valve also were assumed. After choosing some flow rate value, the values of velocity, pressure and other hydrodynamic parameters were calculated in all nodes of the valve's cavity, using the continuity and momentum conservation equations and adequate solving technique [7]

$$\nabla\left(\rho \boldsymbol{U}\right) = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{U}}{\partial t} = -\frac{1}{\rho}\nabla p + \upsilon \nabla^2 \boldsymbol{U} + \boldsymbol{S}_M \tag{2}$$

where ρ is fluid density; U is velocity vector; t is time; p is local hydrodynamic pressure; υ is kinematic viscosity; S_M is source term vector.

On the basis of determined local values of adequate hydrodynamic parameters the hydraulic pressure loss coefficient ζ of the valve was calculated [8]

$$\zeta = \frac{2\left(p_1 - p_2\right)}{\rho v^2} \tag{3}$$

where p_1 and p_2 are the average values of hydrodynamic pressure at the inlet and at the outlet of the valve; v is average fluid velocity at the inlet of the valve.

Analysing the change of water velocity distribution in the valve cavity it was determined, that during the valve opening/closure the flow structure varies significantly (Fig. 2). At the very beginning of the valve opening (when H/D = 0.02-0.20) the large part of flow strikes against the lower edge of the bottom hole in the valve body and passes into the bottom cavity. The intensive vortex motion occurs in this region, and substantial amount of fluid energy is dissipated. When the rate of valve's opening grows up, energy loss in this region gradually decreases.

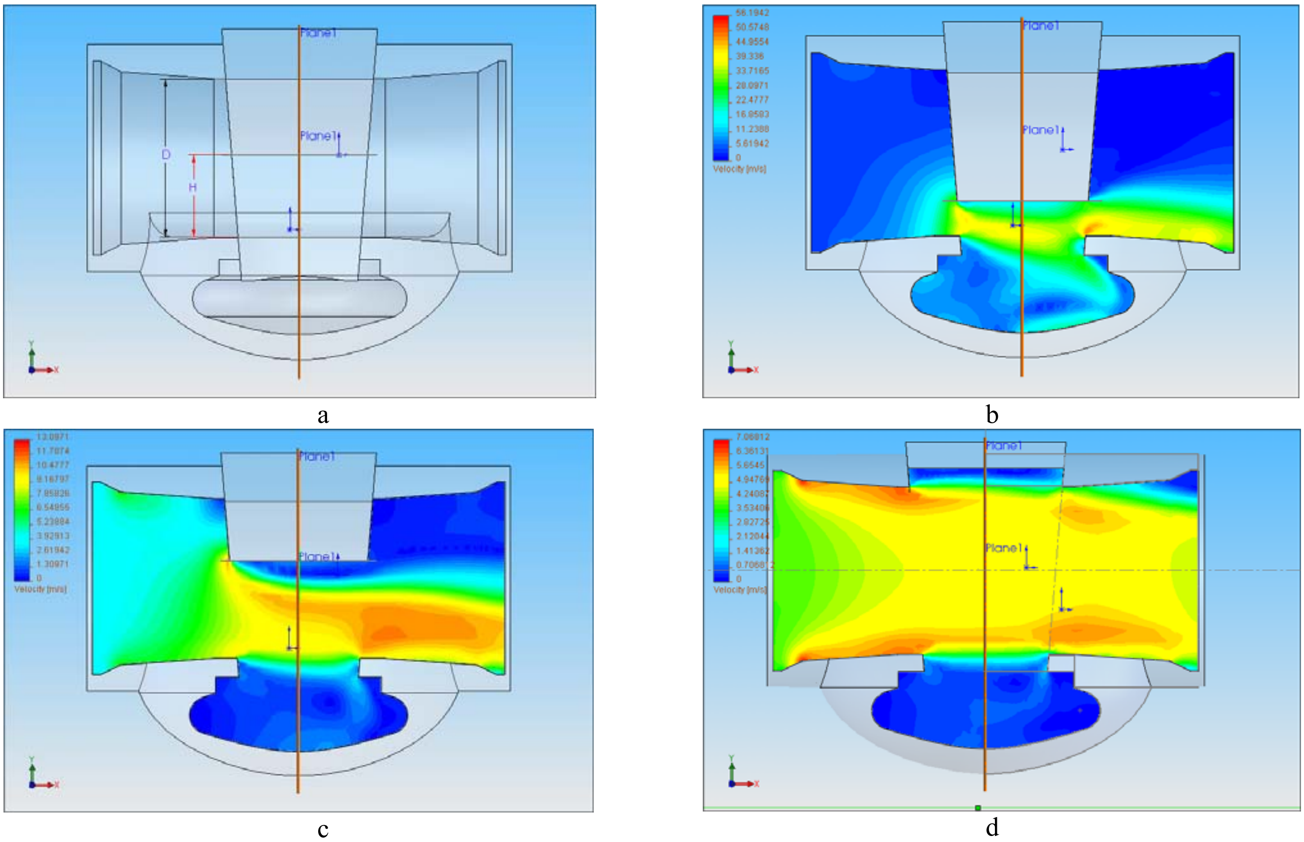

Fig. 2 Computational model of the fast acting motor valve (a) and fluid velocity distribution (b, c, d) for three fixed positions of the valve‘s retaining gate (when the relative valve’s gap size $H/D = 0.198$; 0.578; 1.0 respectively)

Calculations were performed for numerous fixed positions of the valve‘s retaining gate, changing the flow rate, Reynolds’ numbers values and the relative valve’s opening rate in the range of $H/D = 0.02$-1.0. The summary results illustrating the change of the valve’s pressure loss coefficient during the valve’s opening/closure process are presented in the Fig. 3. At the very beginning of the valve opening (when $H/D = 0.02$-0.10) the value of the valve’s pressure loss coefficient sharply decreases. These data are particularly valuable estimating the important role of the fast acting motor valves in performing of safety functions of ECCS.

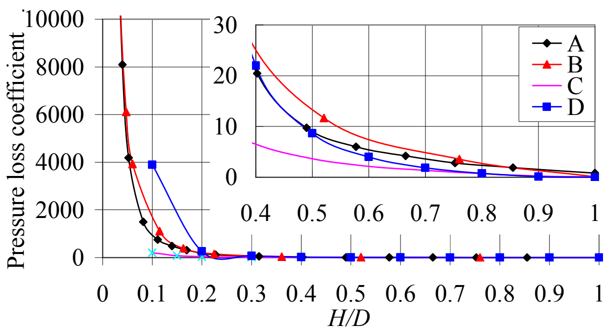

Fig. 3 Dependence of the valve’s pressure loss coefficient on the relative valve’s gap size H/D: A, B – fast acting valve pressure loss coefficients calculated by COSMOS/FLOWORKS and CFX5.6 codes respectively; C, D – experimental pressure loss coefficients for the two valves of similar design [8]

Striving to verify adequateness of the created valve’s computational model and correctness of the obtained results, two computational fluid dynamics (CFD) codes COSMOS/FLOWORKS and CFX5.6 were used in parallel, and collation of the collected simulation data with adequate experimental data [8] also was accomplished.

The results, presented in the Fig. 3, demonstrate quite good correspondence between data of numerical simulation and the experimental data. The character of change of the valve’s pressure loss coefficient during the valve’s opening/closure process is fairly congruent for both analysis methodologies. For the measurable rate of the valve opening (when the relative valve’s gap size $H/D>0.20$) the values of the valve’s pressure loss coefficient, obtained from numerical simulation, are practically coincident with relevant values, obtained experimentally for high capacity manually operated valve of similar design [8]. When the relative valve’s gap size is small ($H/D < 0.20$), computationally predicted values of the valve’s pressure loss coefficient lie in the midst of appropriate experimentally obtained values for two valves with small differences in design of its retaining gate. These results also show, that even negligible changes or deviations from initial valve’s design can make a big impact on its hydraulic resistance.

The thorough analysis of the valve’s design also shows that due to overlapping of sealing surfaces of the retaining gate and the valve body a particular zone of insensibility is possible at the very beginning of the opening process. This peculiarity can partially change the timescale of valve’s response to the signal for opening.

The analysis of the transient processes in the cooling systems of nuclear reactors usually is performed, using the codes (RELAP5, ATHLET etc.), developed for thermal-hydraulic calculations of light water reactors. In these codes the hydraulic resistance of the separate piping elements is estimated on the basis of universal simplified model of smooth or abrupt cross-section area change [5]. In this paper this approach is called “default” [9]. Energy dissipation due to possible flow slip, vortex motion and local streams’ formation, design particularities of complex flow control devices (especially valves) are not taken into account in these codes.

The analysis of modelling results demonstrated, that the obtained dependencies of the changes of hydraulic loss coefficient in respect of relative valve opening (closure) rate substantially differ from those commonly used in thermal-hydraulic calculations of nuclear reactors. This difference is extremely big at the very beginning of the valve opening process, when the value of the valve hydraulic resistance is the most important to flow of coolant transmitted to the group distribution header.

The comparison of characteristics of the change of the valve’s pressure loss coefficient in respect of relative gap cross section area during the valve’s opening/closure process calculated by RELAP5 and CFD codes CFX5.6 and COSMOS/FLOWORKS is presented in Fig. 4. It is evident that pressure loss coefficient at the initial stage of valve opening calculated by CFD codes is much higher than calculated by RELAP5.

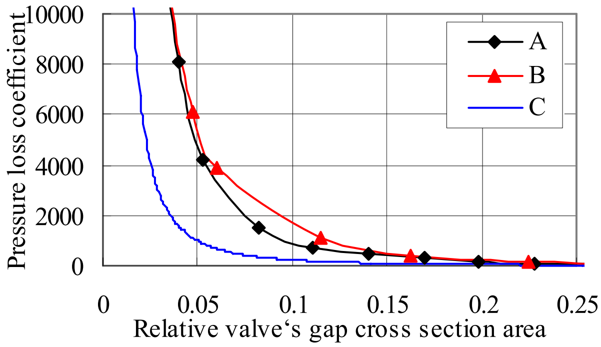

Fig. 4 Comparison of the fast acting motor valve pressure loss coefficient values calculated using COSMOS/FLOWORKS (A curve), CFX5.6 (B curve) and RELAP5 (C curve) codes

3. Modelling of the reactor cooling

A case of the maximum design basis accident (a guillotine break in a pressure header of the main circulation pump) is scrutinized in this paper. This type of loss of coolant accident is the most dangerous, because the rupture of ultimate diameter pipe leads to the biggest loss of coolant capacity and maximum decreasing of the reactor cooling intensiveness [2].

The above mentioned loss of coolant accident was simulated using the RELAP5 code [9, 10]. Alongside with the other usual initial conditions [1-3] some specific assumptions and time scale settings, established from accident beginning, were used in the created RBMK-1500 model [11]. Three separate cases were calculated with the same initial conditions but using different values of fast acting motor valves’ pressure loss coefficient. In the first case the values of the valve’s pressure loss coefficient were calculated using the ”default” approach of RELAP5 and two others - using the values of the valve’s pressure loss coefficient calculated by codes CFX5.6 and COSMOS/FLOWORKS and then implemented into RELAP5 model.

The series of thermal- hydraulic calculations of the maximum design-basis accident initiated by full break of the main circulation pump pressure header were performed. The obtained dependencies of the changes of hydraulic loss coefficient in respect of relative valve opening (closure) rate as well as those commonly used in thermal-hydraulic code RELAP5 were used. The results of calculations show, that in the initial stage of accident flow of coolant going from emergency core cooling system via fast acting motor valves to the group distribution headers grows more slowly and arrives to the maximum value later if assuming valves’ characteristics obtained from CFD modelling. The lower reactor core cooling intensity slightly changes further in course of the accident development, and the fuel element’s surface maximum temperature reaches approximately 20-60˚C higher values, than that obtained using “default” RELAP5 approach. Because this temperature exceeds the maximum value limited by acceptance criterion, the results gained demonstrate serious impact of adequateness of the valves’ hydraulic characteristics to the results of transient processes’ thermal-hydraulic calculations.

The most important transient processes of the reactor cooling, controlled by means of the fast acting motor valves, are happening until 20 s after the initial event occurred. Therefore, some results of calculations for the above mentioned three cases during this initial period of accident are presented in the Figs. 5-7 and analyzed in more details.

The character of the coolant flow rate change during the first 20 s after the initial event occurred is presented in the Fig. 5. Using the values of the fast acting motor valve’s pressure loss coefficient calculated according to the default methodology of RELAP5, flow rate of the coolant delivered from the short term subsystem of ECCS to the group distribution headers grows very sharply and reaches the maximum value at 6-8 s. Using the values of the fast acting motor valve’s pressure loss coefficient obtained from the calculations by CFX5.6 and COSMOS/FLOWORKS, flow rate of the coolant delivered from the short term subsystem of ECCS to the group dis-

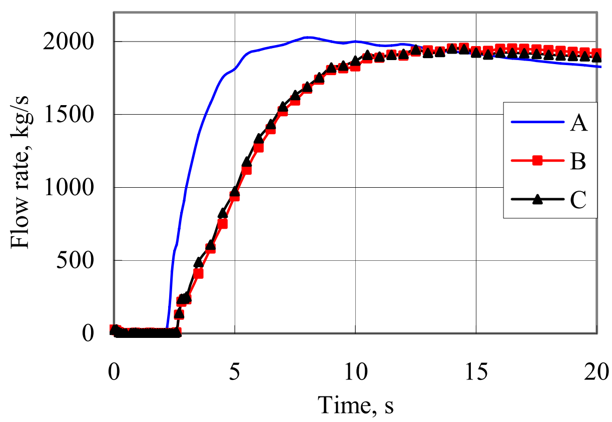

Fig. 5 Change of coolant flow rate from the short term emergency core cooling subsystem to the group distribution headers, calculated using RELAP5 code: A, B, C– results of calculations using fast acting valve characteristics obtained by means of “default” RELAP5 valve’s model, calculated by CFX code and by COSMOS/FLOWORKS code, respectively

tribution headers grows much slower and reaches the maximum value at 12-14 second. The obvious delay in the coolant flow rate increasing is the result of bigger values of the fast acting motor valve's pressure loss coefficient obtained from the valve's simulation using the CFD codes.

The different hydraulic resistance of the fast acting motor valve for the analyzed cases also results in different flow rates delivered to the maximal power fuel channels of the broken MCC loop, cooling intensiveness and changes of maximal temperature of fuel element surface of the broken MCC loop (Figs. 6, 7).

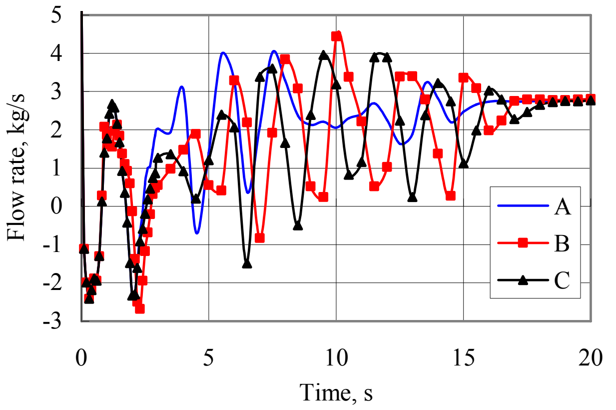

Fig. 6 Change of coolant flow rate delivered to the maximal power fuel channels of the broken MCC loop, calculated using RELAP5 code and estimating the different fast acting valve characteristics. The A, B, C meaning the same as on Fig. 5

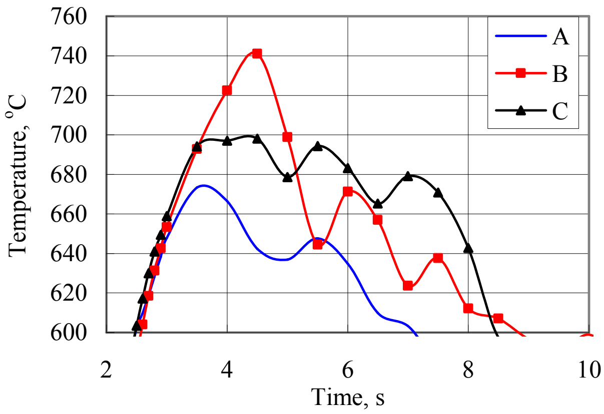

Fig. 7 Change of maximum temperature of fuel element cladding in the maximal power fuel channel of the affected MCC loop, calculated using RELAP5 code and estimating the different fast acting valve characteristics. The A, B, C meaning the same as on Fig. 5

The results, presented in the Fig. 7, obviously show that lower core cooling intensiveness at the initial stage of accident partially changes the further course of transient phenomena, and surface temperature of fuel elements with maximum power for a short time can rise significantly higher. So, comparing the analyzed cases with different values of the valve's pressure loss coefficient it is possible to state, that using the results of valve's CFD modelling, numerically predicted surface temperature of fuel elements in the reactor core with maximum power after the guillotine break in a pressure header of the main circulation pump can reach 20-60°C higher value with respect to the case using the default pressure loss calculation methodology of RELAP5. Such possible increase of temperature of fuel elements surface is very important from the viewpoint of reactor safety and should be taken into account during the safety analysis of nuclear power plant.

4. Conclusions

1. The results of an attempt to specify hydraulic characteristics of the fast acting motor valves using the computational fluid dynamics codes are presented.

2. The significant difference was identified between the characteristics of change of the fast acting motor valve's pressure loss coefficient during the valve's opening/closure process calculated by computational fluid dynamics codes and using default approach of RELAP5.

3. The impact of different characteristics of change of the fast acting motor valve's pressure loss coefficient on transient processes in the emergency core cooling system of the RBMK-1500 type reactor during the maximum design basis accident is demonstrated.

4. The applied approach of modern computational fluid dynamics codes' employment for the modelling of separate elements of safety related systems and usage of modelling results in the thermal-hydraulic calculations of nuclear reactors seems to be fairly perspective, if adequate and reliable experimental data are not available.

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PATIKSLINTŲ VOŽTUVŲ CHARAKTERISTIKŲ ĮTAKA PEREINAMIESIEMS BRANDUOLINIO REAKTORIAUS AUŠINIMO PROCESAMS

R e z i u m ė

Straipsnyje pateikti greitaveikių vožtuvų su elektros pavara hidraulinių charakteristikų skaitinės analizės rezultatai. Nustatytas didelis skirtumas tarp apskaičiuotų vožtuvo slėgio nuostolių koeficiento kitimo charakteristikų vožtuvo atsidarymo ir uždarymo proceso metu ir analogiškų charakteristikų, paprastai naudojamų branduolinių reaktorių šiluminių-hidraulinių skaičiavimų programose. Pasikeitus vožtuvo hidrauliniam pasipriešinimui pačioje avarinio proceso pradžioje, sumažėja iš avarinės reaktoriaus aušinimo sistemos tiekiamo aušinimo skysčio debitas. To pasekoje sumažėja aktyviosios zonos aušinimo intensyvumas ir padidėja kuro elementų paviršiaus maksimali temperatūra.

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IMPACT OF THE SPECIFIED VALVES CHARACTERISTICS ON THE TRANSIENT PROCESSES OF NUCLEAR REACTOR CORE COOLING

S u m m a r y

The results of computational analysis of hydraulic characteristics of the fast acting motor valves are presented in this paper. The significant difference is identified between calculated characteristics of the change of the valve's pressure loss coefficient during the valve's opening/closure process in respect to those used as default approach in codes for thermal-hydraulic calculations of nuclear reactors. The change of valve's hydraulic resistance at the very beginning of an accident causes the reduction of coolant flow rate delivered from the emergency core cooling system, abatement of core cooling intensiveness and the increase of maximal temperature of fuel element surface.

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ВЛИЯНИЕ УТОЧНЕННЫХ ХАРАКТЕРИСТИК КЛАПАНОВ НА ПЕРЕХОДНЫЕ ПРОЦЕССЫ ОХЛАЖДЕНИЯ ЯДЕРНОГО РЕАКТОРА

Р е з ю м е

В статье приводятся результаты численного анализа гидравлических характеристик быстродействующих клапанов с электроприводом. Установлено существенное расхождение между рассчитанными характеристиками изменения коэффициента гидравлического сопротивления клапана во время его открытия/закрытия и аналогичными характеристиками, обычно применяемыми в программах для термогидравлических расчетов ядерных реакторов. Изменение гидравлического сопротивления клапана в самом начале аварийного процесса вызывает уменьшение расхода охлаждающей жидкости, подаваемой из системы аварийного охлаждения реактора, снижение интенсивности охлаждения активной зоны и повышение максимальной температуры оболочек топливных элементов.

Received September 23, 2005

DOI: 10.5755/j02.mech.14556