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Application of the ATHLET and QUABOX/ CUBBOX coupled code system to ATWS Transient "Total Loss of Feedwater" in RBMK-1500

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The implementation of the coupling for 3D neutronic code QUABOX/ CUBBOX and the system code ATHLET for RBMK-1500 is presented. The new code system was applied to the analysis of the ATWS (Anticipated Transient without Scram) event 'Total Loss-of-Feedwater' for the Ignalina NPP. The physical processes during this transient are determined and their specific features are discussed. Results from the 3D kinetic solutions are presented. The point kinetic and 3D kinetic models are compared. The comparison shows that both models represent the main features of the transient. However, there are local differences that influence the transient behaviour and can be taken into account only by the 3D core model.

Key words: Ignalina NPP, RBMK-1500, core

1. INTRODUCTION

Deterministic safety analysis (frequently referred to as accident analysis) is an important tool for confirming the adequacy and efficiency of provisions within the defence in depth concept for the safety of nuclear power plants [1].

The computer codes developed for the transient analysis of the whole plant behaviour by system codes and the analysis of the reactor core behaviour by 3D neutronic models have achieved a high degree of realistic modelling [2]. Nevertheless, there is still a need for an improved modelling of accident conditions for transients with a strong coupling between neutronics and thermo-fluiddynamics. This can be achieved only by coupling a 3D neutronics code to a system code. Therefore a coupled version of the system code ATHLET and the 3D neutronic code QUABOX/CUBBOX for modelling RBMK-1500 reactors was developed. This paper presents results of the application of the coupled code to an ATWS event of the Ignalina NPP (Nuclear Power Plant).

2. DESCRIPTION OF CODE FEATURES

The ATHLET code

The system code ATHLET (Analysis of Thermal Hydraulics of LEaks and Transients) is applied for analysis of the RBMK type plant behaviour under accident conditions. It is a thermal fluid dynamic system code based on 1D pipe components with possible applications for anticipated and abnormal plant transients, small and intermediate leaks as well as large breaks [3]. The code has a modular structure, which allows comprising models for fluid dynamics, heat transfer and heat conduction, neutron kinetics and control systems.

The 6-equation system is the most general equation system of the current ATHLET version. It solves the mass and energy balances in the control volumes separately for liquid and vapour phases and separate momentum balances at the junctions.

Generally, the point kinetic model is used to describe the nuclear heat generation within the ATHLET code. The point kinetic model calculates the total fission power of a nuclear fuel rod assuming that the power is proportional to the average neutron flux. The neutron flux is a solution variable of the kinetic equations for one group of prompt and six groups of delayed neutrons, depending on the total reactivity. The total reactivity is determined by the feedback reactivity from the fuel temperature and coolant density changes. Within the point kinetic model the average behaviour of the reactor core is described; the local reactivity effects cannot be taken into account.

The QUABOX/CUBBOX code

The 3D core model QUABOX/CUBBOX [4, 5] was developed for Light Water Reactors (LWR) of Western types. Later the code was adapted to RBMK type reactors.

The 3D code model QUABOX/CUBBOX solves neutron diffusion equations with two energy groups of prompt neutrons and up to six groups of delayed neutron precursors. The coarse mesh method is based on a polynomial expansion of neutron flux in each energy group. The time integration is performed by the matrix-splitting method, which decomposes the solution into implicit one-dimensional steps for each spatial direction. The reactivity feedback is taken into account by the dependence of homogenised cross-sections on feedback parameters. The functional dependence can be defined in a very general and flexible manner.

3. DESCRIPTION OF THE PLANT AND REACTOR CORE MODELLING

In the code ATHLET model, both loops of the main circulation circuit of the Ignalina NPP are represented. The core is represented by 16 core subregions: the left core side is divided into six zones and the right into ten zones, where the hot channel is shown as a separate region. In the ATHLET model, the thermal-hydraulic channels representing the core channels are subdivided into 18 axial nodes to determine the thermal-hydraulic properties in axial direction. The channels are connected on one end to the group distribution header by the lower water communication line via its flow control valve. The other end of the channels is connected to the drum separator (DS) volume by the steam–water communication line. Automatic regulators of pressure and water level in DS are included. Both coolant circulation loops are modelled. Steam paths that remove the vapour from drum separators are represented explicitly, including steam lines, steam relief valves, etc. The feed water system and the Emergency Core Cooling System (ECCS) are represented explicitly.

The model of the 3D neutronic kinetics in the QUABOX/CUBBOX code takes into account each fuel assembly and control assembly of the core configuration. The RBMK model of QUABOX/CUBBOX simulates each of the 2488 channels of the core with homogeneous properties described by neutron macroscopic cross-sections. These cross sections are calculated by transport codes. The core channels consist of 1661 technological channels used for fuel assemblies, additional absorbers and some unloaded channels. Additionally there are the channels of the CPS system with 211 control rod channels, 436 reflector channels with graphite rods, 156 reflector-cooling channels and 24 channels containing several types of sensor instrumentation located inside the core. The reactor core region in the QUABOX/CUBBOX model has 32 axial nodes. This mesh results in 28 axial nodes in the fuel region and two axial nodes in each of the top and bottom reflector regions. Simulation of the LAC (Local Automatic Control) system is used for automatic control of the radial power distribution by special control rod groups.

4. THE COUPLING APPROACH

The coupling approach is based on a general interface, which separates data structures from neutronics and thermo-fluid dynamic code and performs data exchange between the system code ATHLET and the neutronic code QUABOX/CUBBOX. Both codes keep their capabilities, a detailed model of the primary circuit in ATHLET and a full core modelling in QUABOX/CUBBOX are used. The main physical parameters that must be exchanged between fluid dynamics and neutronics are:

- the power density distribution; it is the result of the neutronics calculation and must be transferred to the fluid dynamics,
- the distribution for fuel temperature, coolant density and coolant temperature; these parameters are the result of the fluid dynamic model and must be transferred to the neutronics.

The time-integration of fluid dynamics and neutronics is performed with different time step sizes, which are synchronized appropriately.

5. ANALYSIS OF THE ATWS TRANSIENT

The ATWS transient is the most significant group of beyond design basis accidents: for the application of the coupled code system a loss of feedwater accident was chosen. A total loss of feedwater flow may be caused by various reasons and the rate of feedwater flow reduction can be different. For the analysis of the transient it is assumed that the feedwater flow decreases to zero within two seconds, producing an enveloping scenario of the transient [1]. Postulating ATWS conditions, none of the trip signals generated during the transient is credited. For comparison, cases with and without the active LAC system were calculated to show the influence of local automatic control protection system rod movement on the transient.

The results from the calculation of transient with the ATHLET coupled code system and QUABOX/CUBBOX are presented; the time functions of the main physical parameters are shown in Figures 1–5.

The loss of feedwater causes a strong decrease of mass flow rate in the primary circuit after about 125 s, which approaches to zero after 230 s. This is shown in Fig. 1 for the inlet and outlet conditions

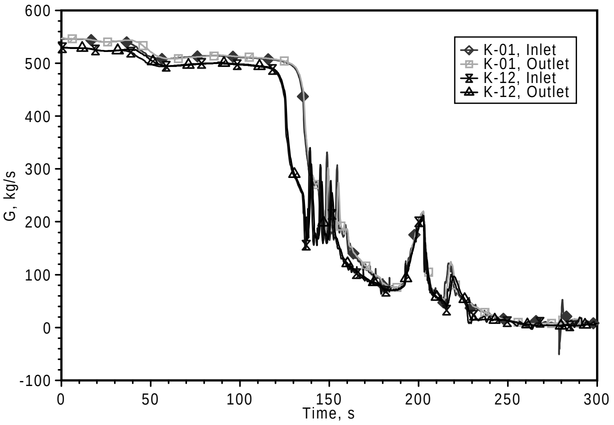

Fig. 1. Mass flow in the regions K-01 and K-12 at the core Inlet and Outlet

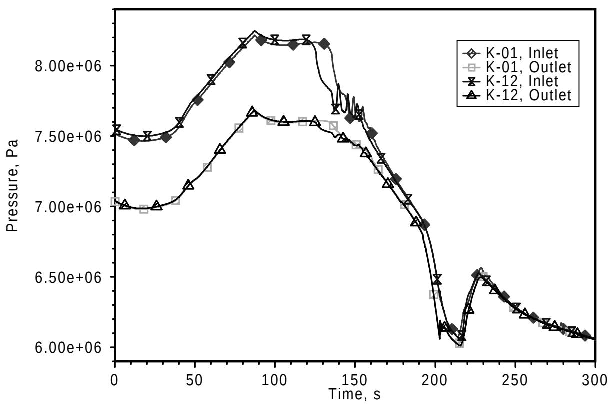

Fig. 3. Pressure in the regions K-01 and K-12 at the core Inlet and Outlet

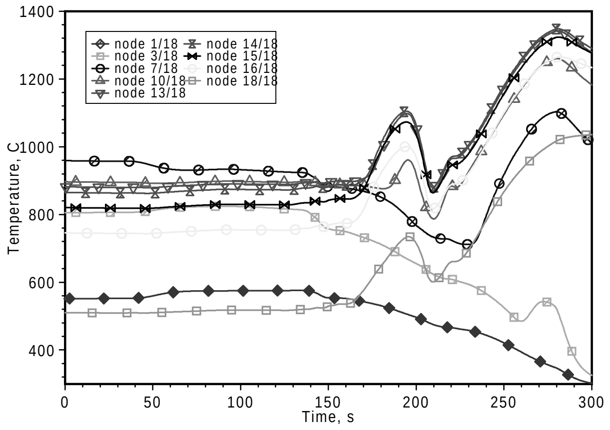

Fig. 4. Maximum fuel temperatures at different nodes of the core region K-01

of the core regions K-01 and K-12, which represent the symmetrical average core regions at the left and the right half of the core.

The decrease of the flow rate causes an increase in the void fraction at the core outlet after about 40 s and after 150 s the void fraction at the core outlet becomes equal to 1 (Fig. 2).

At about the same time the mass flow reaches a set point level for cavitation protection of the main circulation pumps and the pumps are stopped. After about 160 s voiding also starts at the core inlet.

The behaviour of pressure at the core inlet and outlet is presented in Fig. 3. The increase of void fraction causes an increase of pressure after about 40 s, which is stopped after 85 s due to an opening of relieve valves. The pressure significantly decreases again after reduction of the flow rate through the core channels.

The behaviour of fuel temperature for the core region K-01 at a different axial height (node 1–18) is shown in Fig. 4. After about 170 s the fuel temperature rises strongly at the top part of the core due to starting dry-out and worse cooling conditions. The maximum fuel temperature rise occurs in a core height about 560 cm corresponding to node 14.

However, at the bottom of the core the fuel temperature behaves in a different manner and decreases. At the bottom of the core the cooling is still sufficient, and the fuel temperature is going down because the power is decreasing (Fig. 6). At about 190 s a short period of improved cooling is observed, due to the mass flow peak at 200 s (Fig. 1), and the fuel temperature decreases again for a short time. At this time period instabilities are observed and flow rate oscillations occur.

The time functions of fuel temperature at node 14 (at the core height 560 cm), representing the maximum temperature, are shown for each of the 16 core regions in Fig. 5. The qualitative behaviour of fuel temperature is the same for all core regions; however, the time points when the temperatures start to rise or maximum values are reached are different. The results from the coupled code system allow seeing the local maximum values of the fuel tempe-

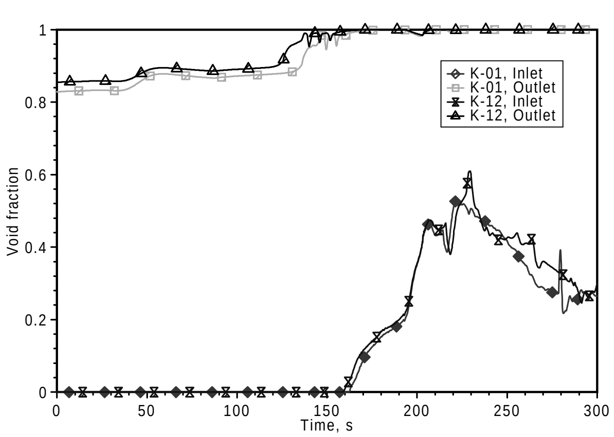

Fig. 2. Void fraction in the regions K-01 and K-12 at the core Inlet and Outlet

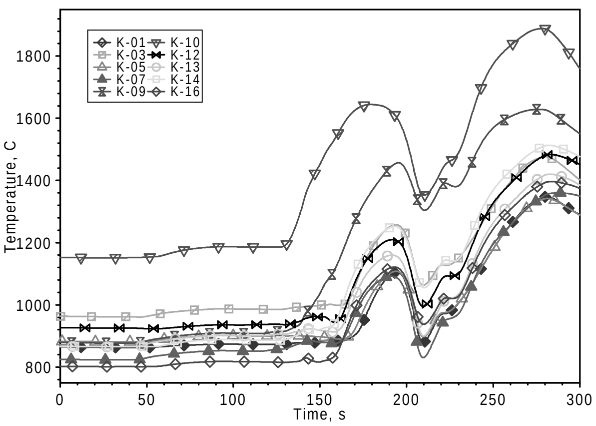

Fig. 5. Maximum fuel temperatures at different regions of core at node 14 (at the core height 560 cm)

rature, and the hot channel K-10 shows a maximum fuel temperature of 1885 °C.

Comparison of models

The 3D kinetic model results from the ATHLET and QUABOX/CUBBOX coupled code system are compared with results from the non-coupled version of the ATHLET code, where the power is calculated by the point kinetic model. In the coupled code version local feedback effects are taken into account, whereas in the point kinetic model only the average core behaviour is described.

In Fig. 6 the time functions of power from a point kinetic and two 3D kinetic variants are shown. For comparison, in one of the 3D kinetic cases the local power control (LAC system) is active, in the second 3D kinetic variant no control rods are moving and the power behaviour is only determined by the reactivity feedback of the coolant density and the fuel temperature. Since the void reactivity effect is small, the transient is mainly determined by the fuel temperature feedback. Due to the fuel temperature rise mainly in the upper part of the core (Fig. 5) a strong fuel temperature feedback occurs, inserting negative reactivity. Without an active LAC system the power starts to decrease after about 120 s. The results show that the LAC system is capable to compensate the reactivity feedback only for about 10 additional seconds. The strong fuel temperature feedback reduces the reactor power to about 10% in 150 s.

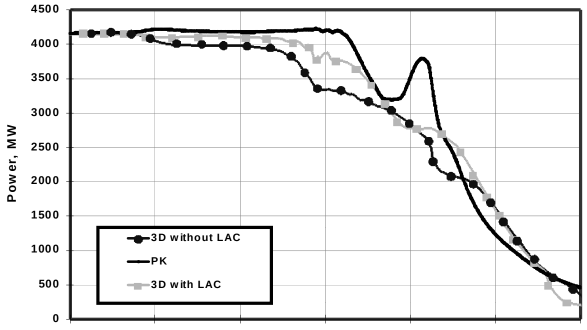

Fig. 6. Total reactor power of point kinetic solutions and 3D neutronics with and without LAC system

The point kinetic case was calculated without the LAC model. The result from point kinetics shows qualitatively the same behaviour as the 3D kinetic solution. However, there are some differences. At about 205 s a significant intermediate power peak is observed, which is absent in the 3D case. The power peak is caused by a short period of improved cooling at this time point. This improved cooling is also seen in the 3D calculation after 180 to 200 s (see Fig. 5). However, different regions of the core react differently and also the time points are shifted; therefore in the total power of the 3D kinetic result this effect is not as significant as in the point kinetic case. For the point kinetic model, the whole reactor is assumed to react instantaneously to reactivity changes and no local differences can show any influence.

6. CONCLUSIONS

- The system code ATHLET was coupled with the 3D neutronic code QUABOX/CUBBOX for the realistic simulation of specific accident conditions for the RBMK-1500.
- The new model was applied to the analysis of the Total Loss-of-Feedwater event.
- A comparison of the results from the coupled code system ATHLET and QUABOX/CUBBOX with the results from the non-coupled point-kinetic model version shows that both models can represent the main features of the transient. Differences of the results, however, exist due to the different influences from the local feedback behaviour in the core, which can only be taken into account by the 3D kinetic model.
- It has been shown that the automatic control system is capable only for a short time to keep the power constant for such a transient.

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ATWS ĮVYKIO „MAITINIMO VANDENS PRARADIMAS" MODELIAVIMAS RBMK-1500 REAKTORIUI, PANAUDOJANT PROGRAMINIŲ PAKETŲ KOMPLEKSĄ ATHLET IR QUABOX/CUBBOX

Santrauka

Programinius paketus ATHLET ir QUABOX/CUBBOX sukūrė GRS kompanija Vokietijoje. Šie programiniai paketai yra pritaikyti ir RBMK reaktoriaus skaičiavimams atlikti.

Straipsnyje pateikti skaičiavimų, atliktų panaudojus programinių paketų kompleksą ATHLET ir QUABOX/CUBBOX, rezultatai ATWS įvykiui „Maitinimo vandens praradimas" Ignalinos AE. Pateikta 3D modelio palyginimas su taškinės kinetikos modeliu.

Iš palyginimo matyti, kad abu modeliai išlaiko panašų fizikinių parametrų kitimo pobūdį. Tačiau iš rezultatų, skaičiavimus atlikus panaudojant programinių paketų kompleksą, galima tiksliau nustatyti vietinius parametrus aktyviojoje zonoje bei surasti jų maksimalias reikšmes. Buvo įvertinta LAC sistemos įtaka; pažymėtina, kad ATWS įvykiui „Maitinimo vandens praradimas" ši sistema pajėgia išlaikyti reaktoriaus pastovią galią tik trumpą laiką.

Raktažodžiai: Ignalinos AE, RBMK-1500, aktyvioji zona

Лаймуте Курене

МОДЕЛИРОВАНИЕ СОБЫТИЯ ТИПА ATWS „ПОТЕРЯ ПИТАТЕЛЬНОЙ ВОДЫ" ОБЪЕДИНЁННЫМ ПРОГРАММНЫМ КОМПЛЕКСОМ ATHLET И QUABOX/CUBBOX ДЛЯ РЕАКТОРА РБМК-1500

Резюме

Программные коды ATHLET и QUABOX/CUBBOX были созданы в Германии компанией GRS и приспособлены для расчетов разных типов реакторов, в том числе и РБМК.

В данной статье представлены результаты расчётного моделирования объединённым программным комплексом ATHLET и QUABOX/CUBBOX, произведенного для события типа ATWS „Потеря питательной воды" для реактора РБМК-1500 модели 3Д, а также дано сравнение с моделью точечной кинетики. С помощью объединенного программного комплекса можно точнее определить локальные параметры в активной зоне, а также определить их максимальные значения.

Оценено влияние системы LAC; можно заметить, что при возникновении события типа ATWS „Потеря питательной воды" данная система поддерживает постоянную мощность только короткий период времени.

Ключевые слова: Игналинская АЭС, РБМК-1500, активная зона