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Verification of VVER-1200 NPP Simulator in Normal Operation and Reactor Coolant Pump Coast-Down Transient

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Abstract

Verification of operation parameters of VVER-1200 NPP Simulator installed at Nuclear Training Center, VINATOM has been performed. This simulator has been supplied for Vietnam in the framework of IAEA TC Project VIE2010 on Developing Nuclear Power Infrastructure—Phase II hosted by the Vietnam Atomic Energy Agency (VAEA). The comparison of the main parameters in nominal power operation with design data given in safety analysis report of VVER-1200/V392M as well as Ninh Thuan FSSAR is presented. In this study, the reactor coolant coast-down transient is investigated using the VVER-1200 NPP simulator. The simulated results performed in the simulator through switching off one reactor coolant pump in comparisons with experiment results performed in VVER-1000 reactor are given. The similarity between the measured and simulated results shows that the thermal hydraulic characteristics and the control protection systems are modeled in a reasonable way. A good agreement in operating parameters was found between the VVER-1200 NPP simulator and VVER-1200/V392M's PSAR.

Keywords

Simulator, Human Machine Interfaces, VVER Type Reactor, Reactor Coolant Pump, Control Rod Bank

1. Introduction

In the design of pressurized water reactor (PWR), the reactor coolant pump (RCP) is one of the important components in the nuclear steam supply system (NSSS). The RCP forces the coolant through the reactor core and steam generator to maintain a balance of heat transfer in a coolant loop. The operating conditions of the RCP have an important influence on the coolant mass flow rate and thermal behavior of NSSS. For instant, in accident conditions with loss of power supply, the RCP ensures coolant circulation in the coast-down to permit a smooth transition to the natural circulation mode [1].

Investigation of flow transients in reactor coolant system due to the RCP coast-down is not only important in the safety analysis, but also in normal operations of VVER as well as Western PWR reactors due to decrease of coolant flow through the core. For PWR, such as KWU PWR design, one RCP trip did not make reactor trip, instead operation is continued at reduced power [2]. However, in Westinghouse design, if a RCP trips at power levels greater than 10^{-4}% of nominal power, a reactor trip will occur [3]. Thus, operation with one or two RCPs switched off is a noticeable feature of VVER nuclear power plant (NPP). Several reactor operation transients and international benchmarks for investigating and evaluating the RCP switching off and on have been performed. The benchmarks were carried out in the VVER-1000 NPPs by switching off one of four working RCPs in commissioning experiment at Balakovo-1 [4]. In EU-PHARE SRR 195 project at Balakovo-4 [4] the benchmarks of switching off of one of two working feed water pumps were done. In particular, switching on of one from three working RCPs in the EU VALCO project at Kozloduy-6 [4] and switching-off of one of four operating RCPs at nominal reactor power in the coolant transient benchmark—Kalinin-3 (NEA/OECD) [5] were benchmarked. The purpose of these benchmarks is verification and validation of the models used in simulation codes. Many experiments and simulations are also carried out by Russian researchers on the VVER-1000/V320 NPPs. In this study, the measurements carried out in Rostov unit-1 [6] are used and the results are compared with those obtained in the simulator. It is also noted that the first VVER-1200 NPP has been put into operation since August 2016 [7]. Thus, the further studies using the simulator should be compared with available data from the real plant in the future.

The purpose of this work is to verify operation parameters of the simulator to confirm that the VVER-1200/V392M is simulated in the simulator through comparison with VVER-1200 SAR [8] [9]. The real-time simulation was also investigated through switching off one RCP in comparisons with PSAR [9] and experiments conducted in VVER-1000 reactor [6].

2. Verification of Simulator in Nominal Power Operation

2.1. VVER-1200 Is an Evolution of VVER-1000 Reactor

According to PSAR and FSSAR of VVER-1200 [8] [9], the reactor is operated with four loops at nominal power. At the reduced power levels to 67%, 50% and 40% the reactor is operated with three loops, two opposite loops and two adjacent loops, respectively.

The VVER-1200 reactor is an evolution of the VVER-1000 reactor. VVER-1200 and NSSS are designed by Gidro Press in an attempt to improve performance and safety of the reactor. The design of VVER-1200 is based on more than 1400 reactor-year experiences in operation of VVER [10]. There are two versions named VVER-1200/V491 and VVER-1200/V392M (**Figure 1**) with different design of safety systems developed by JSC SPb AEP, St. Peterburg and JSC Atom Energo Proekt, Moscow.

The main differences between two designs are the safety systems. For example, in the VVER-1200/V392M design, the safety system consists of two-stage

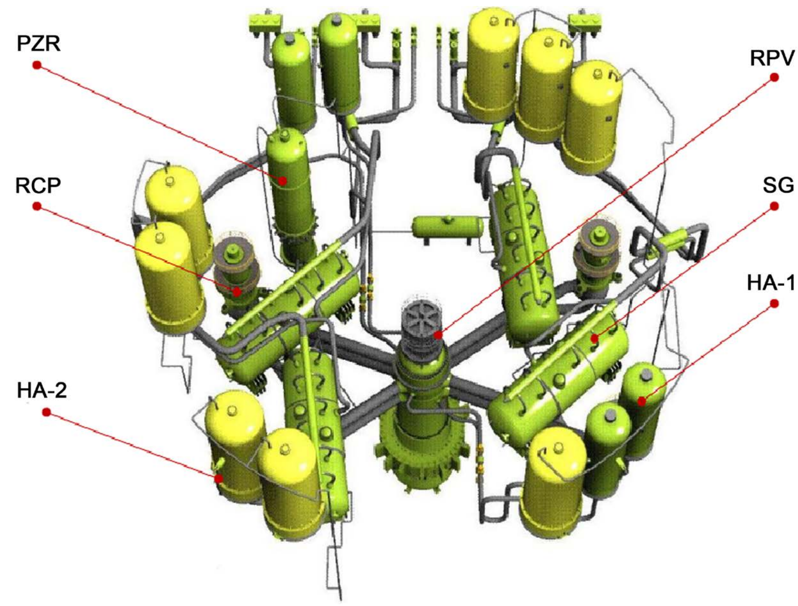


Figure 1. VVER-1200/V392M Nuclear Steam Supply System [7].

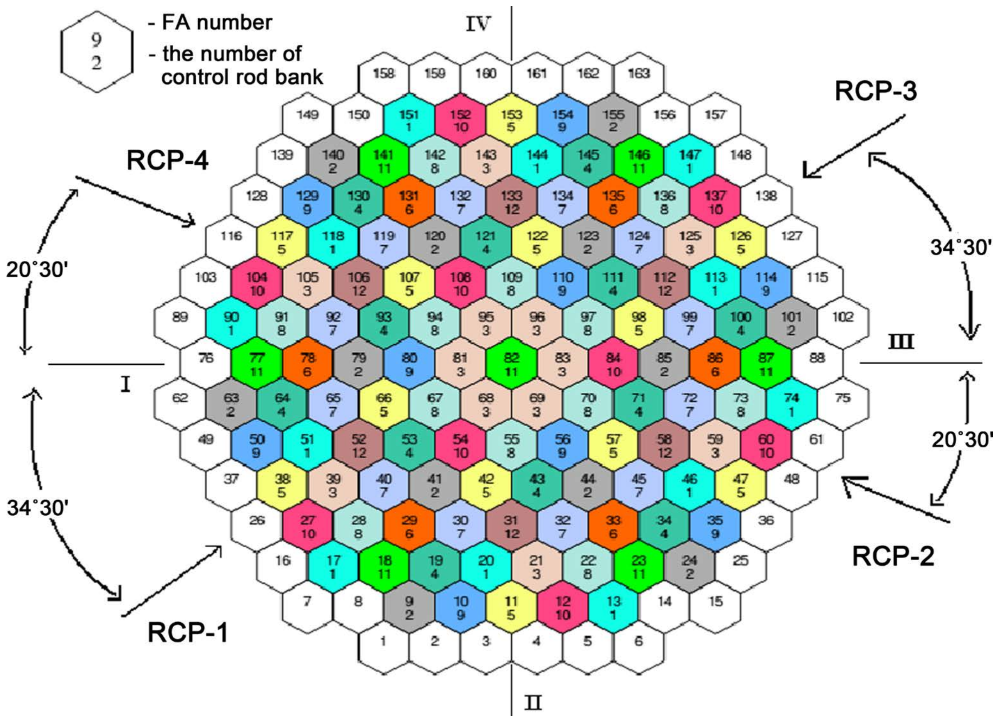


Figure 2. Reactor core with control rod banks (The arrows show the nominal positions of the inlet nozzles).

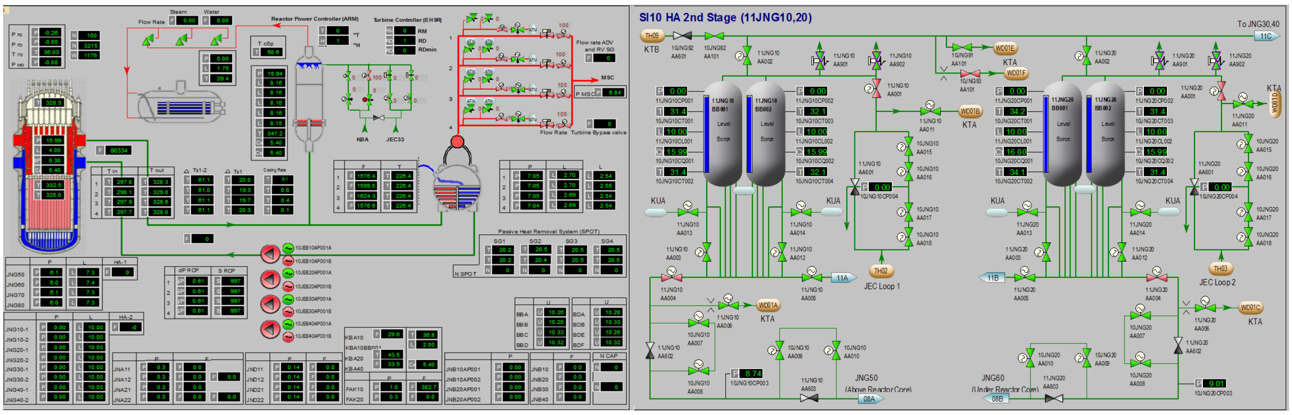


Figure 3. HMI of primary system and second stage hydro accumulators (HA-2) in the simulator.

Hydro Accumulators (HA-1 and HA-2) as seen in HMI of the simulator [11] (**Figure 3**.)

For the reactor pressure vessel (RPV) of VVER-1200, the major developments based on VVER-1000 are:

- Increase of RPV dimensions provides essential decrease in radiation impact on the RPV wall [12] with height from 10,897 mm to 11,185 mm, inner diameter from 4150 mm to 4250 mm and wall thickness (core shell) from 192.5 mm to 197.5 mm. The fuel length changes from 3530 mm to 3730 mm, so that the reactor power increases while the total number of fuel assemblies (FA) in reactor core is kept unchanged (163 FAs).

- In VVER-1000, there are 61 control rods divided into 10 groups (banks) while there are up to 121 control rods divided into 12 groups in VVER-1200 design (**Figure 2**). The absorbing materials are B4C and $Dy_2O_3TiO_2$ while only B_4C used in VVER-1000.

From thermal-hydraulics aspect, it is reasonable to compare the experiment with the simulation results owing to no large changes in geometry of reactor pressure vessel

2.2. Technical Features of the Simulator

The simulator is supplied by Western Service Co. (WSC), US with 3KEYMASTER™ modeling tools which include 3KEYMASTER™ Instructor Station, The simulator covers the full range of plant operations from plant cold shutdown to hot standby, hot zero power, and to full range of power maneuvers as well as all possible transients. These models combine to form the engineering simulator as defined by IAEA [13].

The simulator can be operated in real-time or accelerated time mode. The advantage of using a real-time simulator is that user can understand the response of the systems which correctly represents the real system, without delay or limitations as pre-recorded scenarios. The evolution of NPP simulators with real time is described in [14].

The simulator is intended to simulate the VVER-1200/V392M technology [11]. It consists of more than 150 human machine interfaces (HMIs) which represent the technology schemes of NPP. The HMIs cover from component cooling system (CC), containment (CH), condensate pump (CP), reactor core (CR), chemical and volume control system (CVCS), condenser water (CW), electrical systems (ED, EG), feedwater (FW), heating and ventilation system (HV), instrumentation air (IA), main steam (MS), control system (Control), safety systems (RD, SI), service water (SW), turbine systems (TC, TU) and waste processing systems (WD).

2.3. Verification of the Simulator in Nominal Power Operation

Verification of simulator for normal operation and transients has been performed. To shorten the time to start-up and bring reactor into critical state and full power operation, the ICs (Initial Condition) are set up so that user can start operate the reactor in predefined scenarios. The beginning of cycle (BOC) is initiated and main parameters for normal operation are reported in Table 1. The parameters are in compliance with design data [8] [9]. So, it is expected to ensure that specified learning objectives can be achieved and the simulator performs in accordance with VVER-1200 NPP design. The following section describes a transient with one RCP coast-down. This is intended to verify a real-time simulation as well as response of the simulator.

3. Simulation of Reactor Coolant Pump Coast-Down Transient

3.1. RCP Coast-Down Transient and Sequence of Events

In the operation of VVER-1200 which permits one or two RCPs to be switched

Table 1. Comparison of NPP parameters in nominal power operation.

Parameter	VVER1200 Simulator	Ninh Thuan Project [8]	NNPP-2 PSAR [9]
Reactor thermal power, MW	3212	3212	3200 + 128
Nominal electric power, MW	1178 - 1183	1186	1198
Reactor Outlet pressure, MPa	15.9 ÷ 16.1	16.2 ± 0.3	16.2 ± 0.3
Reactor coolant flow rate, m^3/h	86,333 ± 5	88,000 (+2100 − 3100)	86,000 ± 2900
Reactor coolant inlet temperature, ˚C	297.6	298.2 +2/−4	298.2 +2/−4
Reactor coolant outlet temperature, ˚C	328.8	328.6 ± 4	328.9 ± 5
Reactor heat up, ˚C	30.5	30.7	30.7
Pressurizer level, m	8.13 ± 0.01	8.17 ± 0.15	8.17 ± 0.15
SG water level, m	2.7 ± 0.01	2.7 ± 0.05	2.7 ± 0.05
SG steam pressure, MPa	7.0 ± 0.02	7.0 ± 0.1	7.0 ± 0.1
Feed water temperature, ˚C	226.8 ± 0.15	225 ± 5	225 ± 5
Feed water flow in SG1/2/3/4, t/h	1614 ÷ 1668	1602 (+112)	1602 (+112)
Operation at load of (% Nnom): - 4 RCPs - 3 RCPs - 2 RCPs (opposite) - 2 RCPs (adjacent)	100% 66% 49.5% 40%	100% 67% 50% 40%	100% 67% 50% 40%

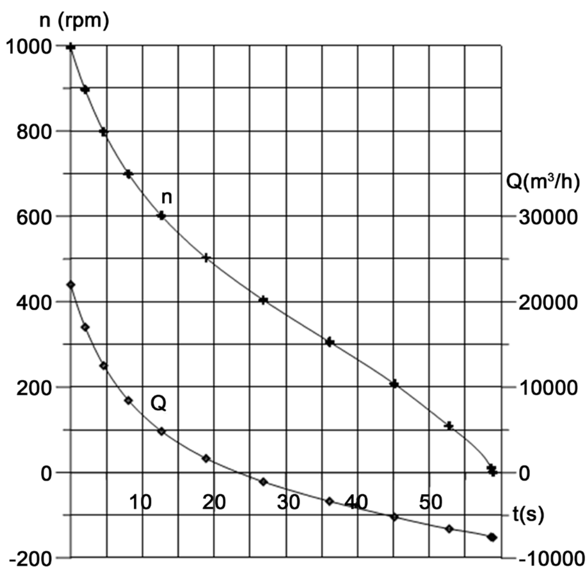
off, the reactor control is equipped with preventive emergency protection system [9]. The signals from the system initiates control protection system (CPS) with control rods and drives will reduce power or prohibit power rise, so that it can avoid the reactor trip and prevent violation of safety limits and conditions. Fast power setback (FPS) system automatically reduces reactor power by insertion of automatic control banks by power setback-1 (PS-1) and prohibits reactor power rise by prohibiting withdrawal of the CPS rods. Figure4a shows the flow rate of RCP-1391 of VVER-1200 NPP and its rotation speed when one out of four operating RCPs trips compared with the results obtained in the simulator (**Figure 4(b)**). RCP #3 as seen in **Figure 3** is switched off in the simulator for analysis.

Two seconds after the RCP switch-off, the power control system responded by inserting the control rod bank #7 from top to bottom within four seconds. As a result, the core power decreased down to about 61% of nominal power within 10 s. Also, the control rod bank #12 started moving in at a rate of 2 cm/s. The initial axial position was at 317.2 cm. The slow insertion of control rod bank #12 down to an axial position of 281cm resulted in a further power decrease to about 55% of nominal power.

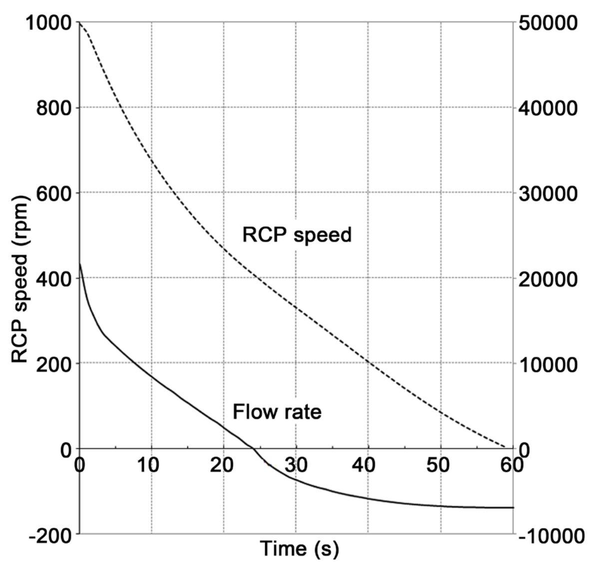
The reactor was stabilized at the level of 64% by the automatic power control with the move up of bank #12 to the position of 327 cm. Due to RCP-3 switch-off, the mass flow rate decreases and then the reverse flow from cold leg to hot leg of this loop is started within 23 seconds. Initially, the primary pressure decreased, later on the primary pressure increased again to maintain the heat balance. The sequence of main events is given in **Table 2**.

3.2. Variation of Operation Parameters during Transient

The decrease of mass flow rate through reactor core (**Figure 5**) will make fuel



(a)



(b)

Figure 4. Mass flow rate of RCP and rotation speed when one out of four operating RCPs trips [9] (a) and observed in the simulator (b).

Table 2. Sequence of main events.

Time, s	Event
0	RCP #3 is switched off
2	Control rod bank #7 drops into the core within 4 s
3	PZR heater (Group #1) is on
10	Bank #12 moves in at a rate of 2 cm/s
13	PZR heaters (Group #3, 4) are on
23	Reverse flow from cold leg to hot leg of loop #3 started
35	Temperature in hot leg #3 decreases lower than cold leg
55	Mass flow rate through reactor core reaches steady state
285	PZR heaters (Group #3, 4) are off
350	PZR water level and core pressure are stabilized
420	End of transient

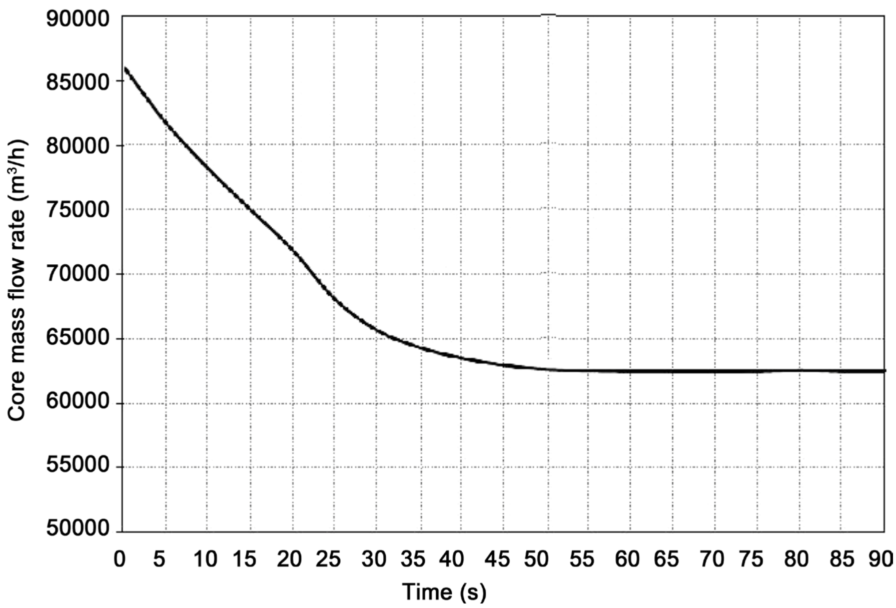


Figure 5. Coolant mass flow rate through reactor core.

and coolant temperatures slightly higher, resulting in a small negative reactivity insertion within 30 seconds as seen in Figure 6. However, the negative reactivity insertion is resulted by the drop of control rod bank #7 (Figure 9(b)). From Figure 6, it is seen that the reactivity insertion by control rods get the maximum value of −0.4%Δk/k within 1.5 seconds.

As seen in Figure 7(b) the temperature in cold leg (inlet nozzle) at first decreases as reactor power decreases. After that it increases due to RCP coast-down finished within 23 seconds and reverse flow through the loop is initiated (Figure 4(b)). This results in the decrease of average temperature in upper plenum and difference in the thermal power of SG in the operating loops.

As three main coolant pumps continued operating, the temperature differences between these hot legs and the corresponding cold legs decreased proportionally to the thermal power reduction. Then temperature in the loops stabilized at a new level. The temperature difference between cold legs and hot legs is similar for simulator and VVER-1000 measurements as seen in Figure 7(a), Figure 7(b) and Figure 8(a), Figure 8(b), respectively.

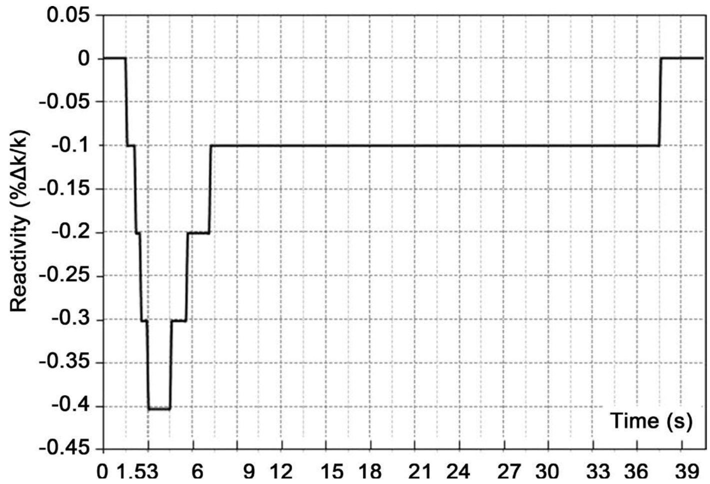


Figure 6. Variation of reactivity during transient.

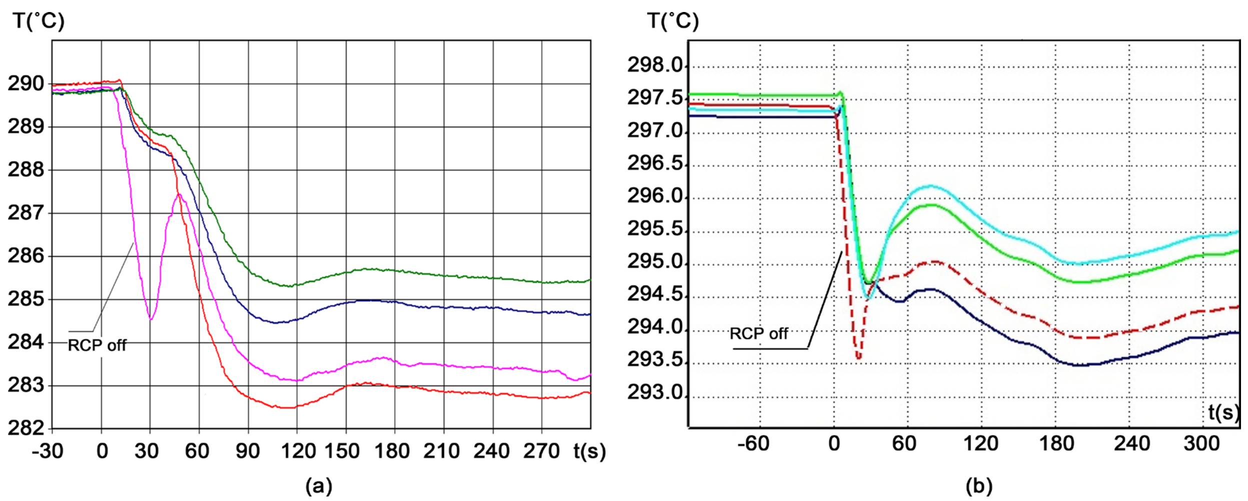


Figure 7. (a) Changes of coolant average temperature in cold legs measured in VVER-1000 [6]; (b) Changes of coolant average temperature in cold legs simulated by the simulator.

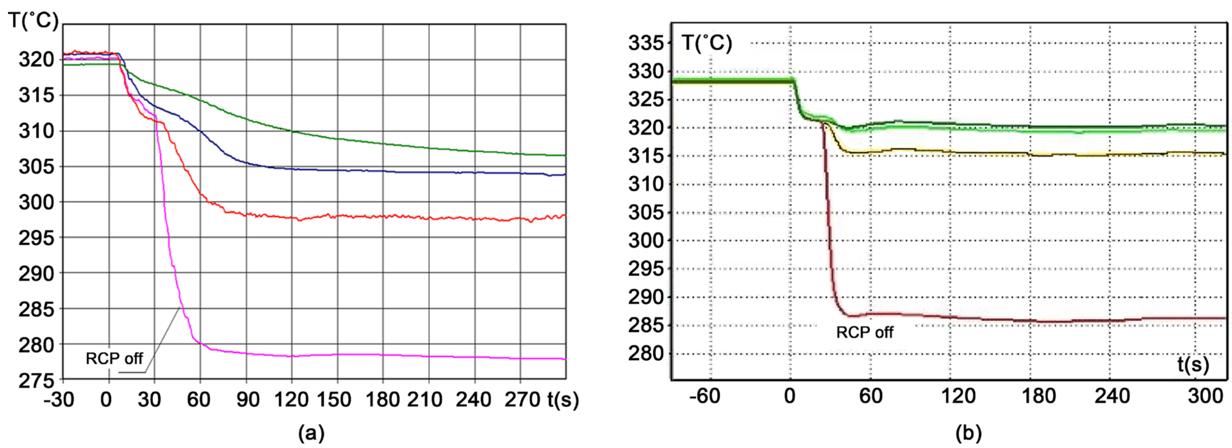


Figure 8. (a) Changes of coolant average temperature in hot legs measured in VVER-1000 [6]; (b) Changes of coolant average temperature in hot legs simulated by the simulator.

3.3. Real-Time Simulation of Movement of Control Rod Banks

In the design of control and protection systems (CPS), the drives of control rods are grouped into 12 groups (banks) which can be controlled independently. The group banks #1-8 are for protection and banks #9-12 are for control and protection. Banks #9-12 are used to control reactor power following scram or power setback signals sent by automatic controller as mentioned above. When reactor is operating at rated power, all of control rod groups are in the top position above the core, except for group #12. At full power, this bank is maintained within the control range, at the core height from 70% to 95% [9]. This is similar to group #10 in VVER-1000 [6].

The design requirement for control rods drop into the core is from 1.2 to 4.0 s after reactor SCRAM actuation [9]. In the transient, bank #7 was fully inserted into the core from 100% to 0% within 4 seconds as observed in the simulator (**Figure 9(b)**). According to the measurement system established at the NPP, the positions of control rod bank are given with respect to the position of the lower end switches. In the simulator, they are located at 380 cm higher than the bottom of the reactor core. The length of the reactor core is 373 cm and the position of control rod corresponds to the bottom of the core. That means at 100% insertion of control rod the indicator is zero as seen in HMI of the simulator.

The difference in movements and positions of control rod banks in VVER-1000 and VVER-1200 should be investigated in more detail. However, it is seen that the position of bank #10 for VVER-1000 changes corresponding to power change (**Figure 9(a)**) while in case of VVER-1200 NPP simulator, **Figure 9(b)** shows that the control rod bank #7 dropped into the core to lower the reactor power within 4 seconds and after 10 seconds from first position of 317.2 cm (83%), bank #12 moves down to compensate with power decreasing tendency, then after stabilization of temperature in reactor core bank #12 reached the last stable position of 327 cm (86%). In average, the moving speed of bank #12 is about 2 cm/s and compatible with design [9].

As mentioned above, although there are minor changes in NSSS designs between VVER-1200 and VVER-1000 reactor, the results obtained on the simulator

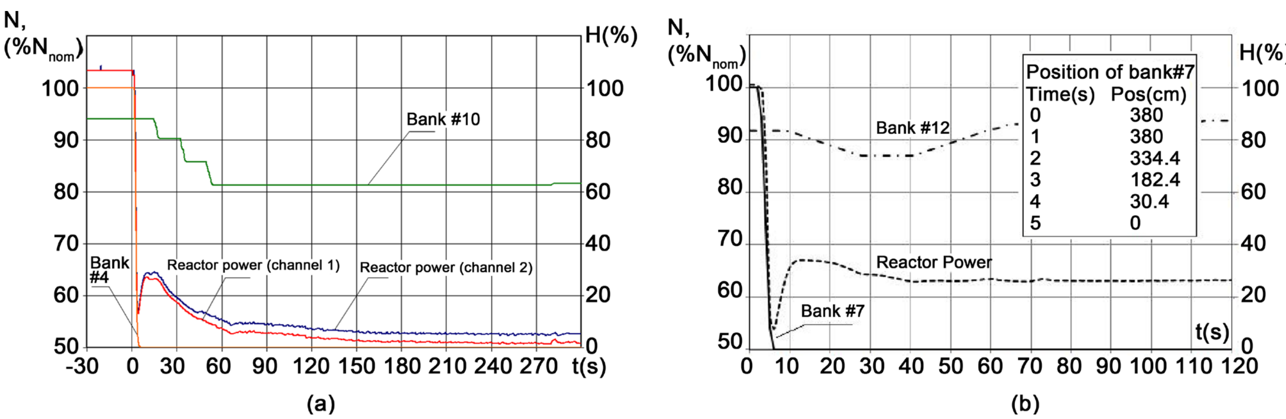


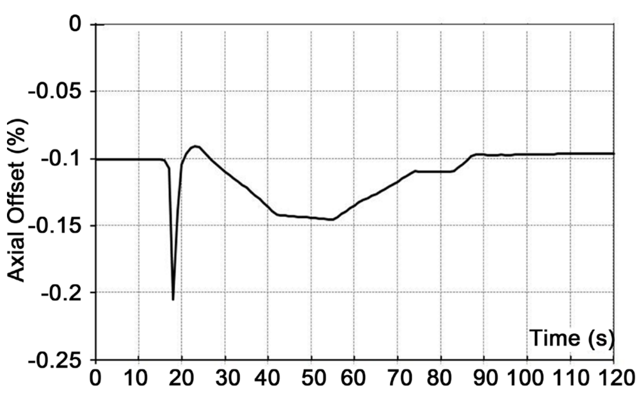
Figure 9. (a) Changes of reactor power and positions of CR banks #4 and #10 measured in VVER-1000 [5]; (b) Changes of reactor power and positions of CR banks #7 and #12 simulated by the simulator.

are in good agreement with the experiment and design data.

3.4. Axial Offset and Reactor Stability

During normal operation and transients, the control rod banks are moved in their control range to maintain power distribution within the predefined limits. The axial offset (AO) is defined as difference between power density in the upper and lower pats of the core with the current reactor power. Value of AO higher than recommended range may result in non-uniformity of the neutron flux and axial xenon oscillations, the occurrence of which will negatively affect the time duration for reaching stabilization of the reactor. Under certain circumstances, non-uniformity of the neutron flux in the reactor core can lead to transient situations. Therefore, for the safety and efficient operation of the reactor it is necessary to minimize the deviation of AO, especially when reactor power is 80% of nominal power or higher [8]. The variation of AO in this case and the limits for VVER reactor [15] are shown in **Figure 10(a)** and **Figure 10(b)**, respectively. The variation of about ±0.2% is quite acceptable in comparison with ±5% as recommended.

The mismatching of the turbine-generator load and the reactor power at the beginning of transient results in the change of steam pressure in the SGs and in the main steamline. The vapor pressure change in the SGs is given in **Table 3**. Three seconds after RCP switched off, as PZR pressure decreased to the set point of heater, heater group #1 is on. The heater groups #3, 4 are on when set points reached within 13 seconds. This results the increase of primary pressure as seen in **Figure 11(b)**. After 30 seconds the heater groups #3, 4 are off and primary pressure became stable.



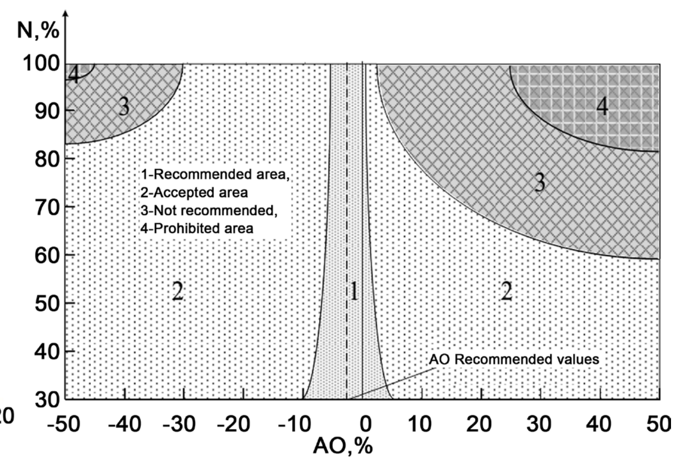


Figure 10. (a) Axial Offset in RCP coast-down transient in the simulator; (b) Recommended AO domain values depending on the power level of the VVER reactor [15].

Table 3. Pressure change in the SGs.

Parameter	Simulator	PSAR [9]
Loops with operating RCPs, MPa	6.95	7.0
Loop #3 with switched off RCP, MPa	6.78	6.8

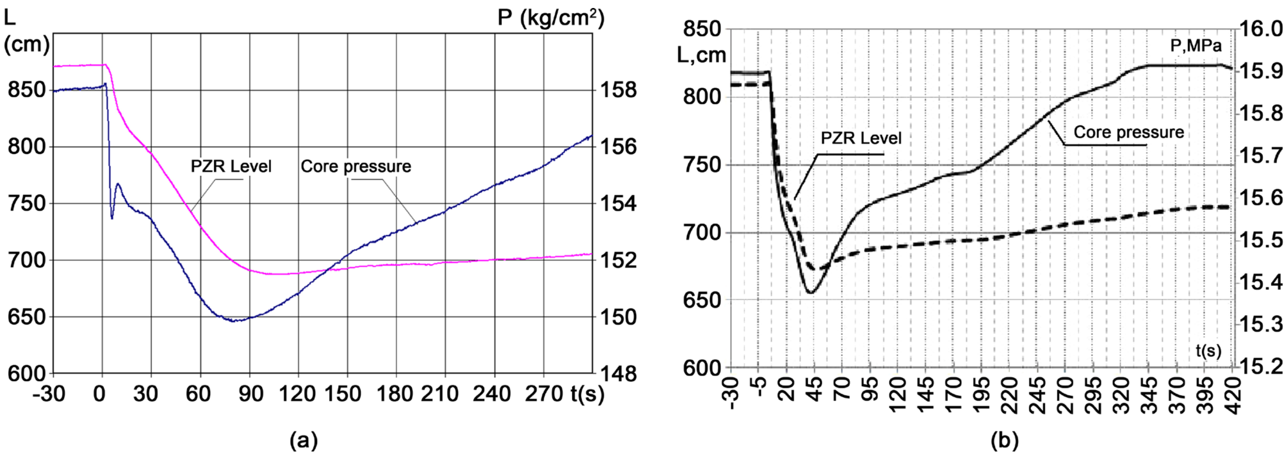


Figure 11. (a) The changes of water level in PZR and Core pressure measured in VVER-1000 [6]; (b) The changes of water level in PZR and Core pressure simulated by the simulator.

The coolant flow through a loop #3 (RCP switched off) into the upper plenum does not influence on the coolant flow on the opposite side due to the fact, that the azimuthal angle between the two neighboring loops of one half is 55˚, the angle to the next loop is 125˚ (**Figure 3**). However, this makes change in upper plenum average temperature due to the reverse flow from cold leg to hot leg of loop #3, especially the change in the upper plenum average temperature results in the change of water level in PZR (**Figure 11(a)**, **Figure 11(b)**).

4. Conclusions

The verification has been performed to check the VVER-1200 NPP simulator by comparisons main parameters in nominal power operation with design data given in safety analysis report of VVER-1200/V392M [9] as well as Ninh Thuan FSSAR [8]. A good agreement was found between VVER-1200 NPP simulator and VVER-1200/V392M's PSAR.

The thermal hydraulic parameters in case of RCP coast-down transient simulated are given in comparison with VVER-1000 experiment data [6]. The axial offset which is a quantitative measure of the reactor stability has been considered.

The difference in control rod numbers and groups divided in VVER-1000 and VVER-1200 as well as automatic control procedures may lead to the different response of working bank #12 as observed. There is the similar insertion of protection control rod bank #4 (VVER-1000) and bank #7 (VVER-1200). Further studies on the control and protection systems of VVER-1200 should be performed to confirm their validity.

A good agreement in tendency between the measured and simulated results shows that the thermal hydraulic characteristics and the control protection system are modeled in a reasonable way in the simulator. A real-time process is verified in which drop time of control rod banks is within a range specified by design. As the results, it is concluded that the implementation of the simulator is not only used for education and training, but also for R&D with better understanding of operation processes and safety systems in modernized VVER nuclear reactors.

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