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EFFECT OF MODELLING CROSS-FLOW ON THE SIMULATION OF SBLOCA EXPERIMENTS OF PSB-VVER TEST FACILITY

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PSB-VVER TEST TESİSİNİN KKSKK DENEYLERİNİN BENZEŞİMİNDE ÇAPRAZ-AKIŞ MODELLENMESİNİN ETKİSİ

Abstract:

In this work, small break loss of coolant accident (SBLOCA) was modelled at PSB-VVER test facility. By using a RELAP5 input deck prepared during OECD PSB-VVER project, cross-flow flow between the thermalhydraulic channels is modeled. As the result of modelling lateral flow, the results of simulations were investigated for the realistic situations where the flow is mixed. The results of simulations were compared with the results obtained by simulating the cases where flow mixing was not modeled and effect of modelling cross-flow on the calculation of peak clad temperature, actuation time of the accumulator and the low pressure emergency core cooling system in addition to mass flow rate was observed. Code validation was performed by comparing PSB-VVER test facility experimental results with the simulation results obtained by changing the core nodalization in RELAP5 MOD 3.5 input file for cross-flow modelling.

Özet:

Bu çalışmada, PSB-VVER test tesisinde küçük kırıklı soğutucu kaybı kazası (KKSKK) modellenmiştir. OECD PSB-VVER projesi kapsamında hazırlanmış olan bir RELAP5 kodu girdi dosyası kullanılarak, termal-hidrolik kanallar arasında çapraz akış modellenmiştir. Çapraz akışın modellenmesi sonucunda akışın karıştığı gerçekçi durumlar için simülasyon sonuçları incelenmiştir. Bu simülasyon sonuçları, akışın karışmadığı durumla kıyaslanmış ve maksimum yakıt sıcaklığı, akümülatör ve düşük basınç soğutma sistemi devreye giriş zamanı, kütlesel akış hızı parametrelerinin çapraz akıştan nasıl etkilendiği gözlemlenmiştir. Kor nodalizasyonunda yapılan değişiklikler ve hesaplar RELAP5 MOD 3.5 veri dosyasına işlenerek elde edilen sonuçlar PSB-VVER tesisi deneysel sonuçları ile kıyaslanarak kod doğrulaması yapılmıştır.

Keywords: PSB-VVER, VVER, RELAP5, loss of coolant accident, small break, thermal-hydraulic analysis, code validation

Anahtar kelimeler : PSB-VVER, VVER, RELAP5, soğutucu kaybı kazası, küçük kırık, termal-hidrolik analiz, kod doğrulama

1. Introduction

The deterministic safety analysis of nuclear reactors are performed by simulating the accidents which cause an imbalance between the heat generation and heat removal such as SBLOCA. For the simulations verified computer codes are used.

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In order to validate the computer codes used for the accident analysis, experimental set ups are built and results of experimental data are used to compare them with the results of simulations of experiments. The validation includes comparing experimental data and simulation results for important phenomena such as, the timing of emergency core coolant injection, mass flow rates and the peak cladding temperature. Since it is limited while reactors are designed to prevent cladding failure, it is very important to have accurate simulation of the peak clad temperature.

As an effort for the accurate use of the codes, OECD PSB-VVER project aimed the validation of the thermal hydraulic codes to simulate transients and accidents that may happen at VVER-1000 systems (Melikhov et al, 2003). PSB-VVER facility was built by taking the designs of other test facilities into account. The geometry and operation parameters of the facility were determined and several experiments were performed at the facility. Five of these experiments including the SBLOCA experiment were simulated by using RELAP5 code and code validation was performed (Melikhov et al., 2004a; 2004b; 2004c; 2004 d).

In this study, SBLOCA experiment performed at PSB-VVER experimental set up was simulated with detailed core modeling to observe the effect of modeling cross-flow on the code predictions especially for the peak cladding temperature. To achieve this a RELAP5 MOD 3.5 input deck developed for the OECD PSB-VVER project was modified by performing a core nodalization which presents the core region as multiple channels connected in lateral direction. This is done to observe lateral motion of the flow, that is the cross flow in one dimensional modeling of the core.

In the literature, there are several studies performed to show the effect of modeling cross-flow on code predictions. In such a study, Reis et al. (2011) worked on modelling TRIGA research reactor core by increasing number of radial thermal-hydraulic channels from 13 to 91 and by defining cross-flow. Results of changing nodalization were analyzed. For 91 channels, consistency between the simulation results and experimental data improved, however, because of the increase in run time, it was suggested to use 13 channels to obtain reasonable results faster.

Mol et al. (2011) also worked on the nodalization and remodelled the TRIGA core with 91, 7 and 3 channels. The study showed that difference between the simulation results and the experimental data increases with decreasing channel numbers since the cross-flow behavior in the core is not simulated accurately. Due to the considerations related with the run time, study concluded that it is advantageous to use one channel to model the core.

The aim of this study is to present the effect of modelling reactor core by defining laterally connected channels while performing nodalization for the SBLOCA simulations. The purpose in having such a detailed core model is to observe the improvement in code predictions while using a one dimensional best estimate code for accident simulation.

2. Material and Methods

2.1 PSB-VVER Test Facility Description

PSB-VVER test facility have a substantial role in defining experimental validation and emergency response in case of accident. The PSB-VVER test facility designed in Russia. PSB-VVER is a large-scale integrated test facility of primary system of VVER-1000 V-320 power plant. Volume scaling and core power scaling factors are 1:300 and main equipment height is similar to VVER-1000 reactor (Melikhov et al., 2003)

In Figure 2.1 general view of the PSB-VVER test facility is presented. Test facility has 4 loops and each loop has circulation pump, steam generator, cold and hot leg. Maximum primary side pressure is 20 MPa and maximum secondary side pressure is 13 MPa. It has a

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reactor model including pressurizer, high pressure and low pressure active and passive emergency cooling systems, downcomer, core, core bypass and upper plenum.

On primary side, pressurizer can be connected to second or 4th loop which has surging and injection lines. Pressurizer is located vertically and built in real scale. Passive emergency core cooling system has 4 hydroaccumulators. Those are connected to reactor inlet and outlet in pairs. Both active systems are high and low pressure emergency cooling systems. Active emergency cooling system water can be injected to all hot legs in addition to injection to all cold legs the facility.

PSB-VVER facility has nickel and chromium heaters which simulate fuel rods.

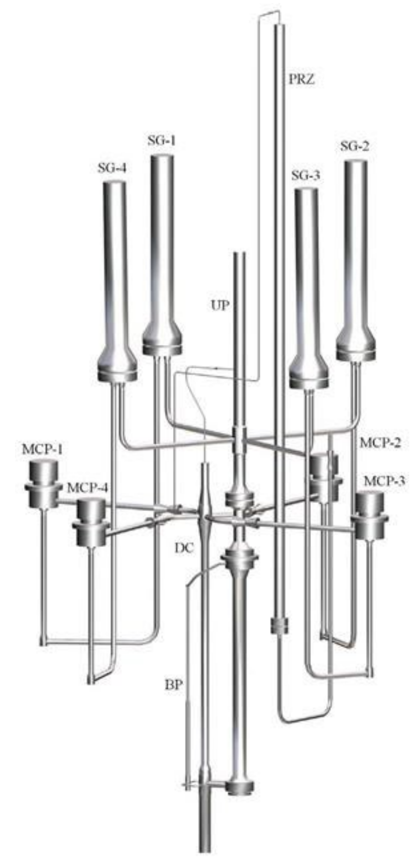

Figure 2.1 PSB-VVER Test Facility General View [2]

2.2. SBLOCA Experiment on PSB-VVER

A SBLOCA experiment was carried out at the PSB-VVER test facility and experimental data were used to validate RELAP5/MOD3.2 code (Melikhov et al., 2003). For the validation process, steady-state condition was simulated firstly, then transient condition was investigated.

Break system has a discharge line with isolation valves, break unit and catch-tank system. For the SBLOCA experiment, break was located at the cold leg of the fourth loop and break was simulated with a vertically upward aligned line between pressure vessel and main coolant pump. Flow was limited, as shown in Figure 2.2, by using a break nozzle which was edged 6 mm and 10 mm in diameter and 100 mm in length.

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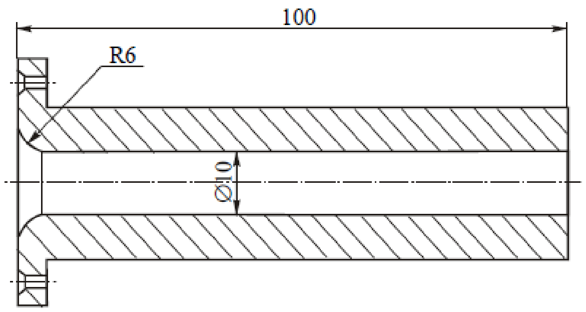

Figure 2.2 Break nozzle [1]

2.3 SBLOCA Analysis Nodalization and Input File

In this work, as presented in Figure 2.3, core was sectioned into three thermal hydraulic channels (numbered as 780, 781, 782 in the RELAP5 input file and presented as such in this paper).

In RELAP5 input file, for the renodalization, core region, lower plenum core inlet and upper plenum core outlet parameters were modified. In addition, flow areas, flow rates, and hydraulic diameters for the channels and axial peaking factor and power generated in each channel were recalculated and related component cards were changed.

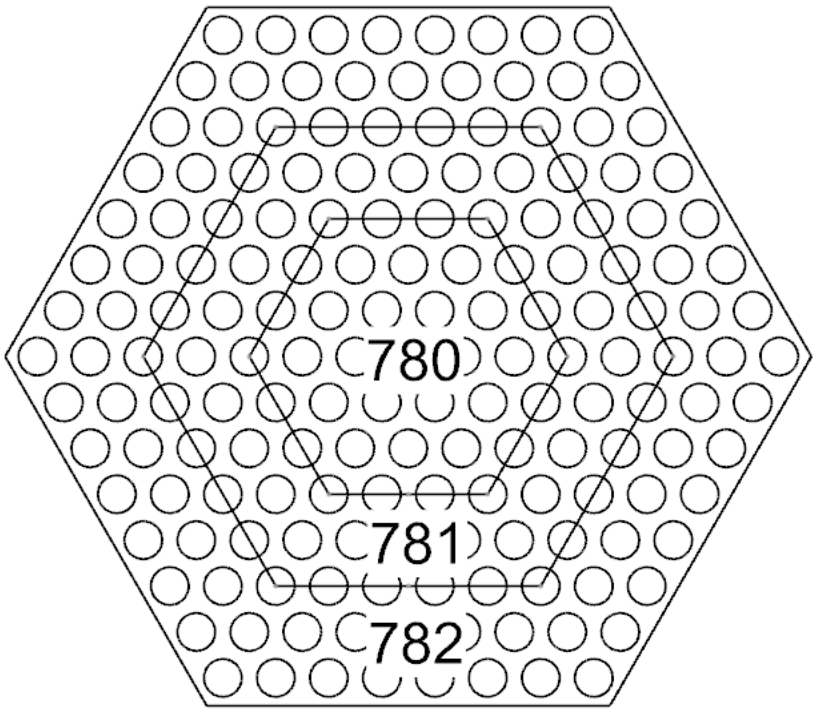

Figure 2.3 Core Nodalization with 3 channels

In the original input and transient decks, power control and measurement system cards were also modified to correctly model:

- the reactor trip due to fuel rod temperature;
- the differential pressure for lower plenum, core and upper plenum;

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- the central channel or hottest channel control variables for low pressure injection system tanks.

Reactor model is used to simulate fuel element, upper plenum, downcomer, lower plenum, and core bypass.

In the original input file, the core was modelled as a single pipe component and upper and lower plenum connections were modelled as single junction. Fuel rod which had 17 axial nodes and 18 sections heated between 4th and 17th nodes. For these sections, heat structure card was also defined.

In the input file modified in this study, core thermal hydraulic channels were modelled as separate pipe components. Lower plenum and upper plenum connections were modelled as multiple junction. Axial node number was same as the original deck, also all channels had 18 volumes. Three different channels were connected to one inlet and one outlet. (Figure 2.4)

For each channel, flow rate was determined by taking their flow areas into account. Also, since the outflow from lower plenum enters into core by pass through two narrowing sections, outside channels had three different flow rates.

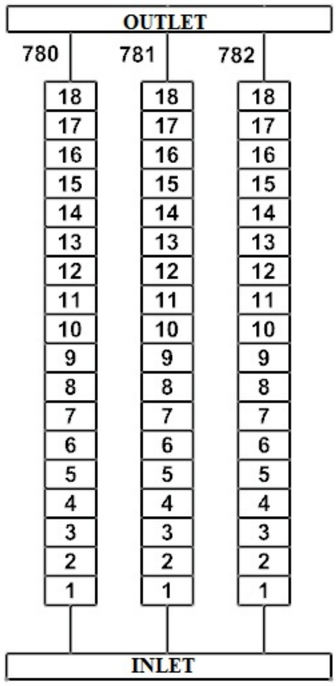

Figure 2.4 Axial Core Nodalization for 3 Channels

2.4 Cross-Flow Effect

In this study, cross-flow was simulated between channels and its effect on accident scenario was examined. Figure 2.5 shows the nodalization for 3 thermal hydraulic channels. For the simulations two different cases were examined. In the first case, for 3 channels with 18 lateral volumes were connected to each other in lateral direction, and the original input file was modified accordingly. For the second case, the cross-flow was defined only from central channel to mid-channel (780-781), and mixing ratio for the channel was defined lower than the one defined for the first case. Figure 2.5 presents the cross-flow defined between channels and how the nodalization is modified.

Table 2.1 presents PSB-VVER parameters and Table 2.2 shows initial and boundary conditions for the simulations.

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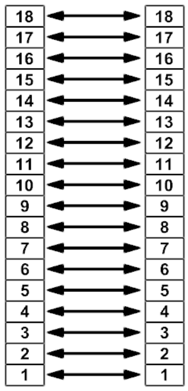

Figure 2.5 Cross-flow nodalization

Table 2.1 PSB-VVER Parameters [1]

Core model	Hexagonal
Channel length	168 mm
Channel Flow Area	1,351x10^{-2} m^2
Channel Cross Section	2,4517x10^{-2} m^2
Channel Hydraulic Diameter	9,97x10^{-3} m
Core Diameter	192 mm-260 mm
Fuel rod number	168
Fuel rod height	3,530 m
Central rod number	1
Central rod diameter	10 mm
Fuel rod diameter	9,1 mm
Pitch	12,75 mm
In-core flow rate	24,182 kg/s
Axial sections	18

Table 2.2 PSB-VVER Initial and Boundary Conditions [2]

Core power	1130 kW
Primary side pressure	15,5 MPa
Downcomer coolant inlet temperature	282 ^{o}C
Upper plenum coolant outlet temperature	310 ^{o}C
Pressurizer level	2,98 m
Secondary side pressure	6,9 MPa

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Steam generator level	1,89 m
Hydroaccumulator pressure	4 MPa
Hydroaccumulator level	4,54 m
Pressurrizer electric-load cut off	0 sn
Main pump stop, SG control valves closing, feed-water supply stop, core bypass	Primary side pressure=13 MPa
Hydroaccumulators injection start	Primary side pressure=4,2 MPa
Hydroaccumulators injection stop	Level=0,56 m
High pressure injection system	Not used
Low pressure injection system actuation	Fuel rod temperature=500°C
Break diameter	10 mm

In order to calculate the cross-flow between the channels as presented in Figure 2.5, the loss coefficient that will be taken into account in pressure drop calculation in lateral direction must be inputted to the RELAP5 input deck. The loss coefficient is function of Reynolds number which is calculated by using the flow velocity in between the coolant channels in lateral direction. In this study, Gunter-Shaw correlation was used to calculate the pressure drop in lateral direction first, then calculated pressure drop is used to evaluate the loss coefficient [8].

By using Tables 2.1 and 2.2 and equations (1), (2), (3), (4) and (5), cross-flow data presented in Table 2.3 were calculated. [8]

$$\Delta p_{tr} \equiv \frac{s}{l} K_G \frac{\rho\vartheta^2}{2} \tag{1}$$

$$\Delta p_{tr} = \frac{0.96}{(Re_{D_\vartheta})^{0.145}} \left(\frac{P}{D_\vartheta}\right) \rho\vartheta^2 \left(\frac{D_\vartheta}{P}\right)^{0.4} \tag{2}$$

$$W_{ij} = 0.258\dot{m} \tag{3}$$

$$\vartheta = \frac{W_{ij}}{\rho 3(P-D)}$$

$$\vartheta = \frac{W_{ij}}{\rho 5(P-D)} \tag{4}$$

$$Re = \frac{\rho\vartheta D_\vartheta}{\mu} \tag{5}$$

In equations (1)-(5), Δp_{tr} presents pressure drop between the neighboring channels in lateral direction, s and l presents the distance between the fuel rods and center of neighboring channels, respectively (their ratio is taken as 0.5 in this study). K_G is the loss coefficient that must be calculated and used in RELAP5 input deck. In the equations, ρ is the density of the coolant, v is the flow velocity in between the coolant channels in lateral direction, Re_{Dv} is the

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Reynolds number. P and D represents the distance between the center of the fuel rods and diameter of the fuel rods, respectively. D_v is equivalent diameter for the lateral geometry (Todreas and Kazimi, 1990) and $W_{ij}$is the lateral mass flow rate. Finally μ is the viscosity.

By using Equation (3), the lateral mass flow rate per length is calculated for each channel. The calculated mass flow rate is then used in Equation (4) to calculate the flow velocity in between the channels in lateral direction. The coefficients 3 and 5 represent the distance between the fuel rods through which the lateral flow occurs.

The calculated flow velocity is used in Equation (5) to determine the Reynolds number. Finally this calculated Reynolds number is used in Equations (1) and (2) to evaluate the loss coefficient.

Table 2.3 presents the loss coefficients calculated for the lateral connections between channels to be used in the input deck. Here, it is very important to note that, the presented loss coefficients were calculated approximately by using the steady state conditions and during the accident, they must be recalculated to account for the changing conditions.

Table 2.3 Calculated Cross-Flow Parameters that are used in the Input Deck

Cross-Flow Component Number	Connecting Channel Component Number	W_{ij} (kg/m.s)	V (m/s)	Loss Coefficient (K_G)
719	780-781	0,93	0,115	1,15
720	781-780 781-782	1,683 1,683	0,207 0,621	1,04 0,89
721	782-781	3,64	0,268	0,93

3. Results

With the modified nodalization and the modified input deck, 4 cases were simulated. The simulated cases are:

- Case 1: Three channels are not connected in lateral direction
- Case 2: Three channels are connected to each other and related lateral flow loss coefficients were calculated and defined in the modified deck
- Case 3: Only central channel is connected to its neighbor channel
- Case 4: Only one channel was modelled as in the original deck.

The simulation results with the related experimental data were compared and the results are presented in Tables 3.1 through 3.3.

Table 3.1 shows peak clad temperature at the hottest channel and time to reach that temperature.

Table 3.2 shows the response of accumulators during operation and the pressures at which accumulators start and stop the injection.

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Table 3.3 shows low pressure injection system's actuation time, peak clad temperature and primary side pressure at the time of actuation.

Table 3.1 Peak Clad Temperature

	Case 1	Case 2	Case 3	Case 4	Experiment
Time (s)	2494	2544	2502	2526	2500
Temperature (^{0}C)	526,38	519,4	530	518,25	532,29

Table 3.2 Accumulator Injection

	Case 2	Case 4	Experiment
Start time(s)	370	364	414,491
Pressure (MPa)	4,1909	4,1993	4,1990
Stop time (s)	1356	1312	1452,178
Pressure (MPa)	1,2344	1,2366	1,1460

Table 3.3 Low Pressure Injection System

	Case 2	Case 4	Experiment
Start time(s)	2506	2482	2446
Pressure (MPa)	0,5940	0,6262	0,6850
Clad temperature (^{0}C)	500,48	500,09	500,13

In Figure 3.1, for the hottest channel and for Case 2, the vertical and cross-flows for the node which is located at the inlet of heated channels are presented to compare the amount of vertical and lateral flows. In this figure, vertical flow rate shows the flow rate from inlet to outlet of the node in axial direction, whereas cross-flow rate shows the flow rate through the node in the lateral direction.

Figure 3.2 shows cross-flow rates for all volumes of the hottest channel at the time at which the peak clad temperature is calculated for Case 2. The figure indicates the amount of cross-flow in axial direction.

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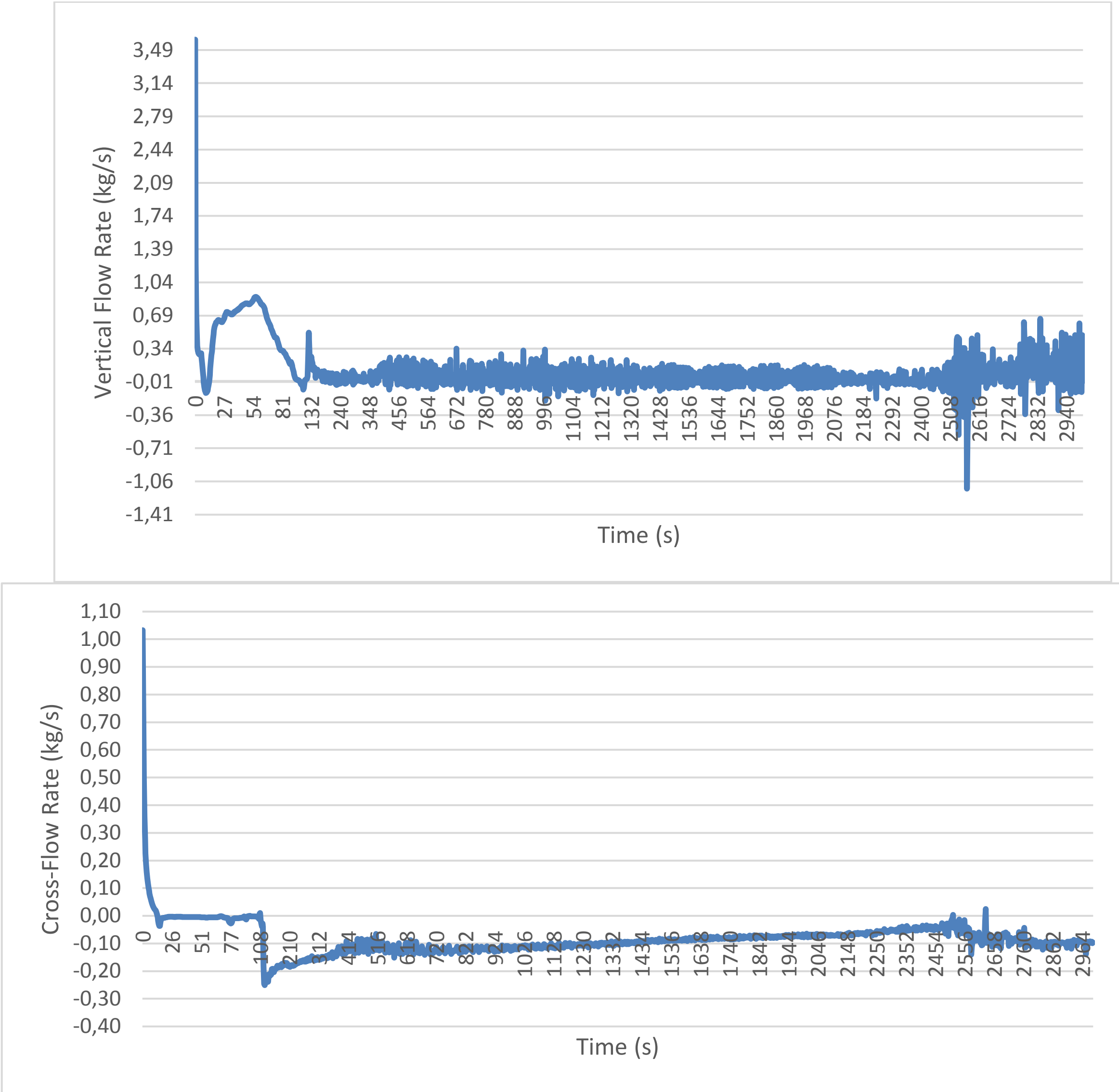

Figure 3.1 Vertical and Cross-flow at the Inlet of Heated-Part as the result of the simulation of Case 2

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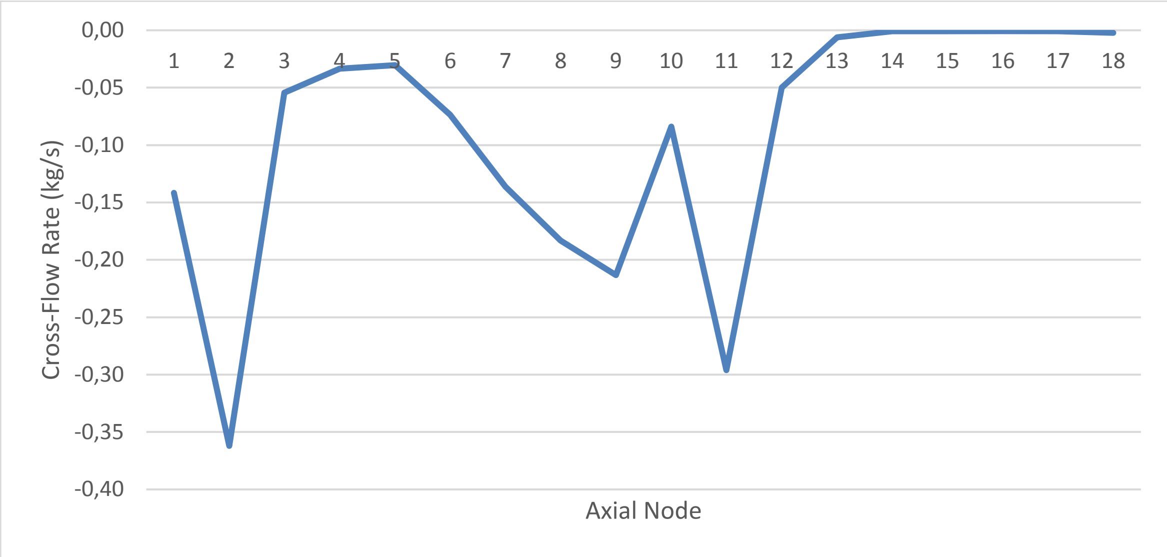

Figure 3.2 Cross-flow at Core Volumes (2544th sec.) for Case 2

4. Conclusion

As mentioned before, accurate calculation of peak clad temperature that would be observed during a SBLOCA is very important to understand the effect of temperature rise on the cladding integrity. In this study, in order to accurately simulate the cladding temperature, models prepared to simulate the SBLOCA experiments performed at PSB-VVER test set up was modified to take the cross-flow into account. As a result, it was observed that modelling cross-flow on the SBLOCA simulations supplied a contribution to simulation of such accidents.

In this study, the results were presented for the hottest channel since the peak cladding temperature is expected to occur in this channel.

When cross-flow is modelled, since the pressure of the hottest channel drops slowly, hydroaccumulators actuate later. Because of lower pressure drop and delay in reaching the low pressure injection system actuation temperature, low pressure injection system actuates later.

When peak clad temperature values at Table 3.1 are considered, it can be observed that for the case at which 3 channels are connected in lateral direction, and hence when the cross-flow is taken into account, the calculated peak clad temperature is lower than the one calculated for the case without the cross-flow since it takes more time to reach that temperature in the latter case. This is due to the cooling effect of the cross-flow.

In the conservative scenario, at which the central channel water volume and loss coefficient were reduced, i.e. when cross-flow is defined only from central channel, peak clad temperature rises faster and reaches to a higher value. This indicates that precise calculation of loss coefficients is important to accurately model the cross-flow.

Figure 3.1 shows that the lateral flow is not small comparing to the vertical flow and it must be taken into account for the simulations.

Figure 3.2 represents the cross-flow in axial direction in the hottest channel at the time of when the peak clad temperature is calculated. The figure indicates that, due to the higher loss coefficients at the volumes located at the lower sections of the core, channel losses flow more and peak clad temperature occurs where the channel losses mass in the lateral direction.

In the course of this study, it is observed that, in order to model cross-flow realistically, loss coefficients in lateral direction must be calculated in detail. To achieve this issue, the use

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of subchannel analysis codes for the modelling of the cross-flow is suggested for the future work to simulate the PSB-VVER SBLOCA experiment more realistically.

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