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SURET Is A New Form Of Subchannel Thermohydraulic Calculations

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ABSTRACT

SURET (SUbchannel REactor Thermohydraulics) subchannel analysis code has been developed by the Centre for Energy Research to simulate the behavior of mixing vane which was introduced in the new type of fuel assembly at Paks Nuclear Power Plant. The new fuel rods and its cladding are thinner than the ones used before and some of the spacer grids have been supplemented by mixing vanes to intensify the mixing in the assembly. SURET has been developed based on COBRA 3c. Their calculating modules are similar but slightly different energy equation is solved in SURET reducing significantly the computational time. SURET was originally developed for offline calculations. After performing some tests, it became clear that it is suitable for online monitoring applications, too. For online calculations we applied more efficient algorithms for matrix inversion, optimizing the so-called inner calculations. With these changes, we could significantly speed up the calculations (0.3 sec for the overall VVER-440 core) which was required for the application of SURET subchannel calculation in the online VERONA core-monitoring system. These modifications did not lead to any reduction of accuracy of the results computed. The new approach has already been integrated into VERONA and commissioned in the 2nd unit of Paks NPP. We have to install the new approach in the other units of the plant before the upcoming campaigns. We also designed a new graphical interface for SURET to support the user's offline calculations, especially during the input preparation process and evaluation of results. The implementation of this new interface is an ongoing process.

1 INTRODUCTION

A new type of fuel assembly has been introduced at Paks Nuclear Power Plant (NPP) in order to improve its fuel economy. The reactor thermal power could be increased due to the higher moderating ratio which is achievable with the thinner fuel rods and claddings in the new design. Seven spacer grids in different axial levels of the assembly are maintained by mixing vane to intensify the mixing in the assembly and to homogenize the coolant temperature, decreasing its maximal value. These spacer grids with mixing vane are shown in Figure 1 [1].

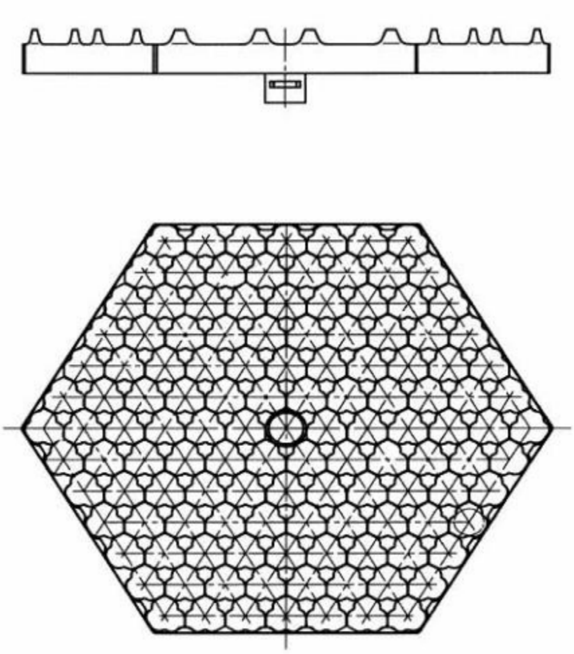

Figure 1. Spacer grid with mixing vane in the new assembly design

COBRA subchannel analysis is used at the beginning of each fuel cycle in Paks NPP to prove that the thermalhydraulic parameters will not violate the operational limits during the cycle. For these calculations, COBRA does not have the ability to simulate the cross-flow due to the new mixing vanes.

To simulate the effect of mixing vanes we developed our own subchannel analysis code called SURET (SUbchannel REactor Thermohydraulics) which is based on COBRA 3c.

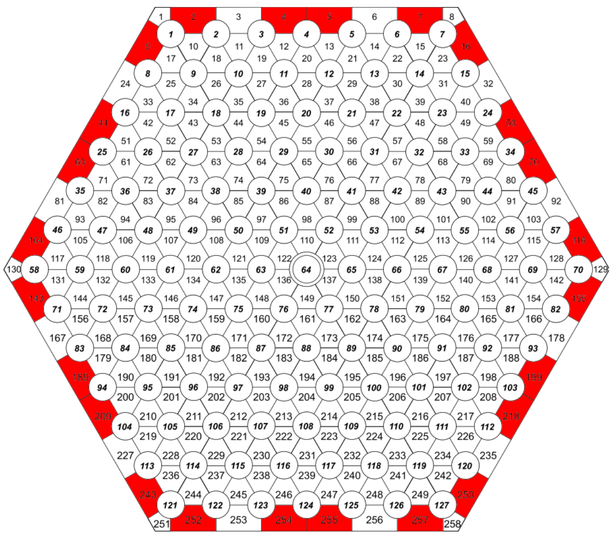

Figure 2. Subchannels of VVER-440 assembly and mixing vane included subchannels highlighted red

Figure 2. shows the locations of the subchannels in the assembly and the subchannels with mixing vanes with red highlights.

In the following sections, we are presenting the modifications, which make it possible to simulate the behavior of the mixing vanes. The subchannel calculations are compared with the CFD calculations that were obtained by the Budapest University of Technology and Economy [2]. Finaly, we are showing the SURET integration to the VERONA core-monitoring system and our vision about a modern subchannel code with graphical interface.

2 DESCRIPTION OF MODEL

SURET was developed on the base of COBRA 3c. There is only water without any steam in the core of VVER-440 type NPPs in normal state, so we omitted the two-phase flow extensions of the code. We have also modified the input data treatment. Finally, we also introduced two minor modifications in the model and these are the keys to successfully simulating the new system with mixing vane.

2.1 Modified energy equation

Our modified energy equation which is used in SURET is the following:

$$\frac{1}{u''}\frac{\partial h_i}{\partial t}+\frac{\partial h_i}{\partial x}=\frac{q'_i}{m_i}-\left(h_i-h_j\right)\frac{w'_{ij}\tilde{l}_{ij}}{m_i}-\left(t_i-t_j\right)\frac{c_{ij}}{m_i}+\left(h_i-h^*\right)\frac{w_{ij}}{m_i}. \quad (1)$$

where the first term on the right hand side of the equation is the power-to-flow ratio of a subchannel and gives the rates of enthalpy change if no thermal mixing occurs. The second term accounts for the turbulent enthalpy transport between all interconnected subchannels. With our modification it is capable to simulate the effect of the mixing vane. The value of $\tilde{l}_{ij}$ is increased in the connections where one of the assigned subchannels has a mixing vane (highlighted on Figure 2.) and it takes the value one everywhere else. The third term takes into account mixing due to thermal conduction and the last term is responsible for modeling of the transfer of thermal energy carried by the diversion crossflow [3].

The turbulent crossflow between adjacent subchannels is calculated as:

$$w'_{ij}=\beta\cdot s_k\cdot\bar{G}, \quad (2)$$

where $\beta=0.002$ is the turbulent mixing parameter, s_k is the gap between two subchannels, where k identifies the subchannels which are connected, $\bar{G}=\frac{m_i+m_j}{A_i+A_j}$ is the sum of the mass flows of connected subchannels divided by the sum of their cross-sections.

2.2 The effect of mixing vanes to the local resistant factor of spacers

The effect of the momentum loss and mixing can be simulated by well-adjusted resistant factors of the spacers. Several calculations have been performed to investigate the effect of the local resistant factors on mixing. In one part of the calculations, we adjusted the resistant factors as if there were not any mixing vane in the assembly. At the simulation of the effect of the mixing vanes, we increased the value of the resistant factor in those nodes which contain mixing vane.

2.3 CFD comparison

Calculations were verified by separate effect tests and validated by comparing its results with the ones obtained by CFD calculations. We have found that the difference in temperature maximum based on SURET and some benchmark CFD calculations were less than 0.15 °C. Also, the distributions of outlet water temperature obtained by SURET fits CFD data reasonable well as it is shown in Figure 3.

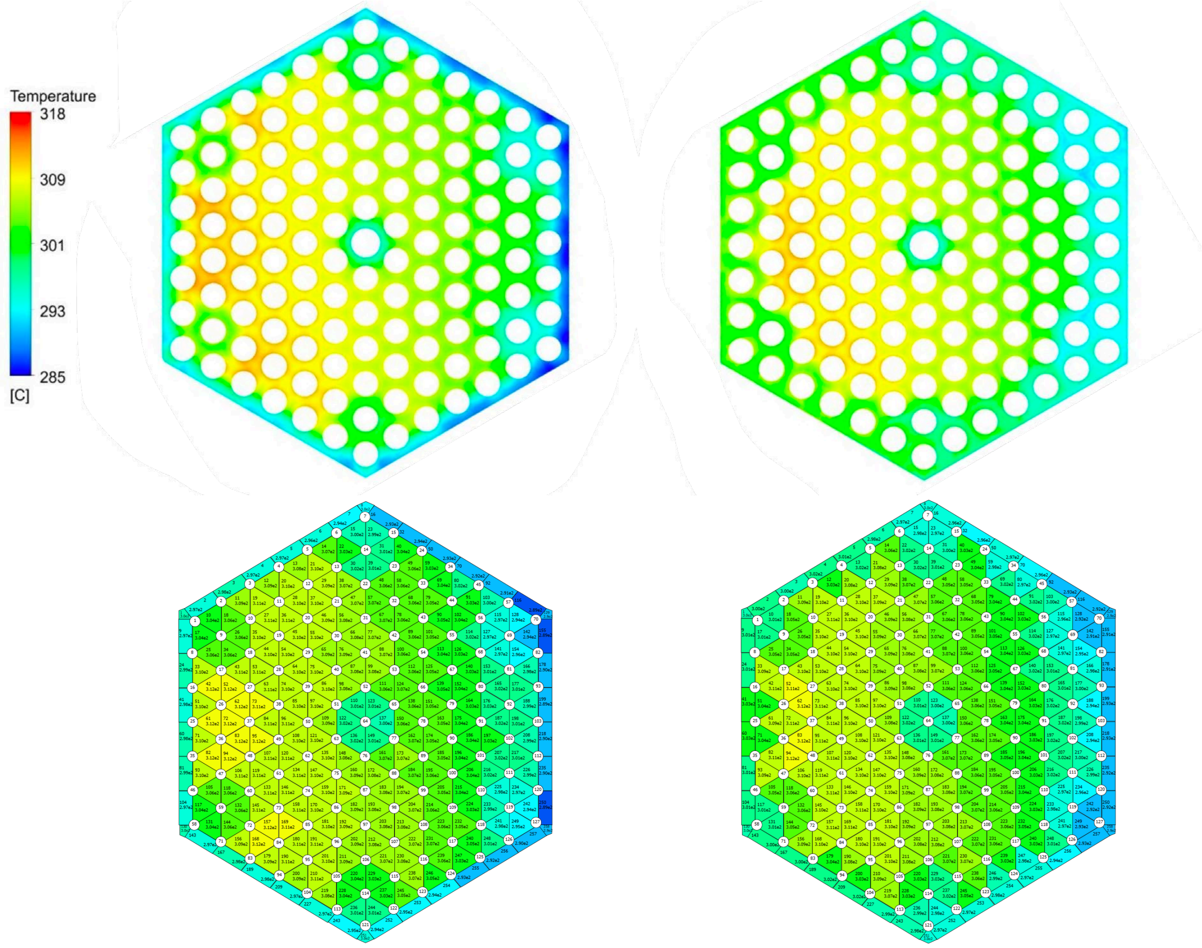

Figure 3. Distributions of outlet temperature (top: CFD; bottom: SURET; left: without mixing vane, right: with mixing vane)

3 VERONA INTEGRATION

SURET was originally developed for offline calculation. After performing some tests it became clear that it is suitable for online monitoring application, too. The objective was to get more accurate temperature calculations at the outlet of fuel assemblies than before using SURET as a part of the VERONA (VVER On-Line Analysis) on-line core monitoring system of Paks NPP. For this purpose, we had to reduce the computational time of SURET because in the online systems a full calculation has to be done in less than 2 seconds without any accuracy degradation.

3.1 Using band matrices

The most time-consuming function of SURET is the calculation of the diversion crossflow. We have to solve a system of equations which depends on the subchannels parameters (flow, pressure) and it has to be solved for every single connection between the subchannels. Practically we have to solve $\underline{\underline{A}} \cdot \underline{x} = \underline{b}$ at every single axial level, where $\underline{\underline{A}}$ is a large matrix. The COBRA solves it with general matrix inversion. In our case, the VVER geometry gives us a band matrix for $\underline{\underline{A}}$. Accordingly, changing the matrix inversion method and taking into account that it is a band-matrix, we were able to reduce the computational time to almost half of the original one.

3.2 Multi-thread calculations

There are several calculations in SURET where we have to solve an equation for every single subchannel. These equations depend on the results obtained in the underlying axial levels but not from the solutions of the same level other subchannels, therefore these calculations can be performed in parallel. Due to this change, the computational time could be reduced a lot, but still the most time-consuming task, the calculation of the diversion crossflow could not run in parallel. However, each assembly of a VVER-440 type reactor have a wall so it is possible to calculate these assemblies in parallel because the assemblies do not interact with each other. After we made calculations with the band-matrix optimized matrix inversion and parallelization where every assembly has its own thread the running time was around 1 minute, which was still not low enough for the use of online calculations.

3.3 Sync and async separation

In order to achieve our aim, we still had to reduce the computation time by one order of magnitude, therefore we split the calculations into two parts.

The most important result of the online SURET calculation is the outlet water temperature which can be obtained by solving the energy equation (1). Its value depends on several calculated parameters, which have different rate of change. In nominal state, the slower changing parameters are the flowrate, crossflow rate, and pressure and the calculation of these parameters is the most time-consuming. Taking into account their slow change the recalculation of these parameters was detached from the overall computation.

So, SURET could be run in two separate modes.

All calculations are completed in asynchronous mode and it gives the pressure, flowrate, and crossflow rate to the synchronous calculation. The sync mode gets data from the async mode and from the VERONA (inlet water temperature, inlet water flowrate, power distribution). It solves only equation (1) to obtain the results of the distribution for the outlet water temperature. While async needs 1 minute to run a cycle, sync runs around 0.3 seconds.

The two modes had to run in parallel with different cycle times according to our original plans. After every async run the sync mode updates the flowrates, based on the results of the last async calculation. After many tests, it was demonstrated that using only one async calculation and providing stable flowrate parameters for the sync mode, the accuracy of the solution is reasonable throughout the overall campaign. We made several calculations, and the maximum outlet water temperature of sync calculations differed less than 0.2 Celsius degree from the measured temperature.

3.4 Result of VERONA integration

Before we integrated SURET into the VERONA core-monitoring system, there was a campaign with some slim assemblies used for testing purposes. We made calculations with SURET on a test VERONA system. We investigated the differences between the calculated outlet water temperature calculated by SURET and the measured ones. These comparisons were made for the new slim assembly design and the previously used assemblies too. The relative frequency of these differences is shown for every type of assembly in Figure 4.

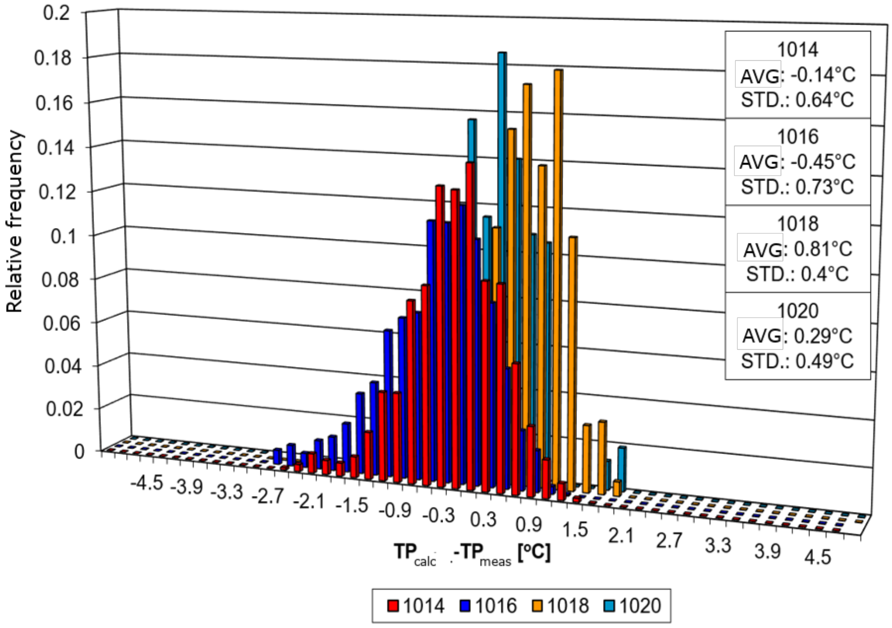

Figure 4. Relative frequency of the difference between the calculated and measured outlet water temperature depend on the assembly type

The accuracy expectation for our calculation is a maximum difference of 0.5 Celsius degree. Figure 4 shows the accuracy is fulfilled in every assembly type except assembly type 1018. Although our calculation was conservative in these assemblies, there is further investigation needed to resolve this difference.

4 GRAPHICAL INTERFACE FOR SURET

During the development of SURET, we decided to make the input more modernized than the COBRA used. Initially SURET used the same structured text as COBRA with group cards, then we changed it to a more understandable XML format. This new format not only used the COBRA dataset, but it became capable to describe the whole core with different assemblies and the connections between them. Figure 5. illustrate the readability changes between the original COBRA and the new SURET XML format input.

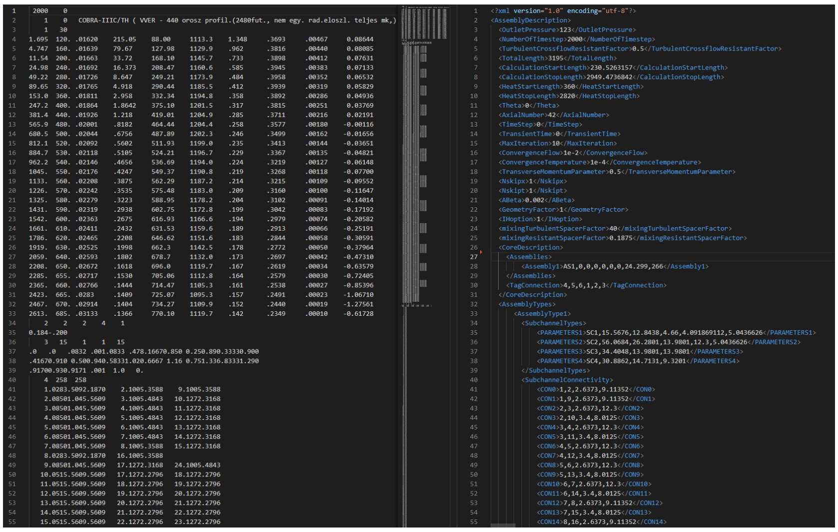

Figure 5. COBRA (left) and SURET (right) input illustration

The XML format is more convenient to use but if anything changes with the assembly geometry, it is time-consuming to create a new one. The user has to change the values of every single connection that are part of the changes. It seemed we could make an algorithm to do this manual work so we decided not only to make the algorithm but also a graphical interface for it.

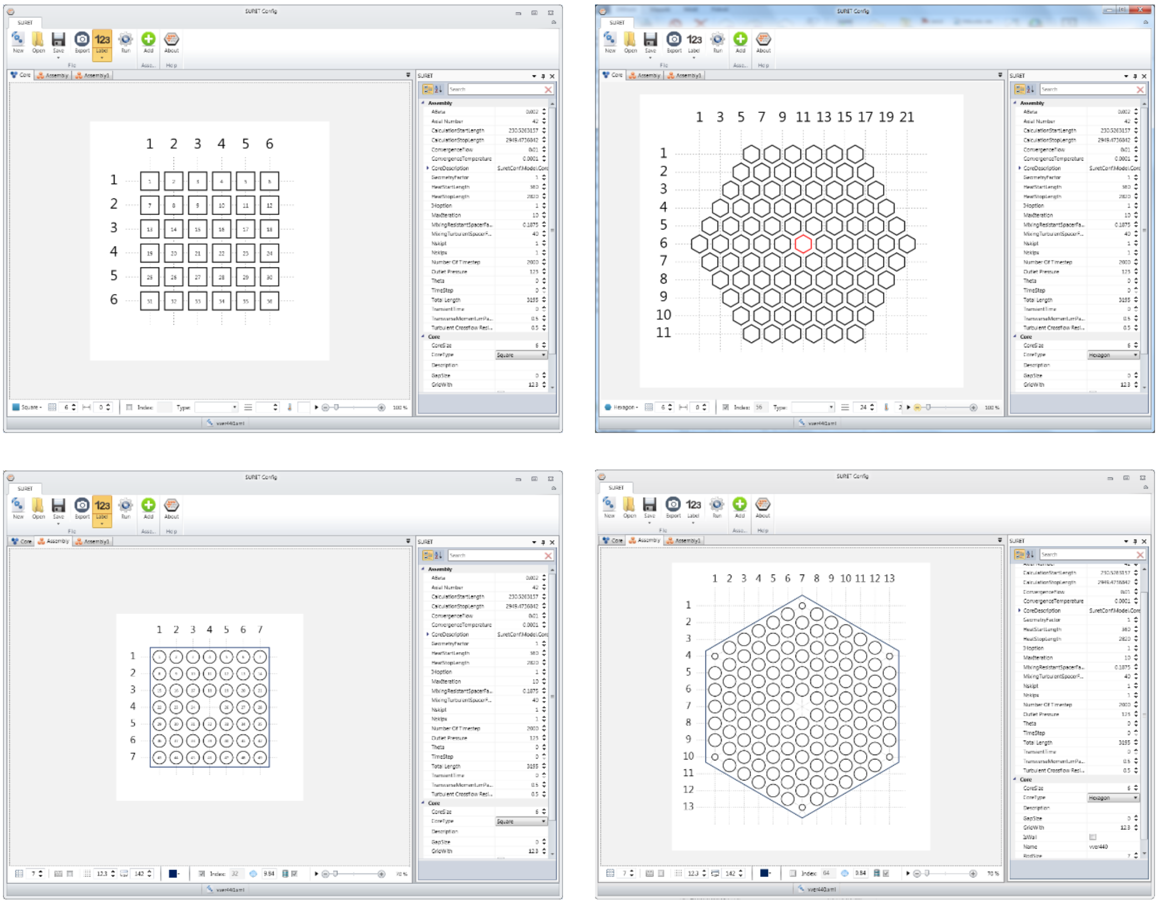

Figure 6. Square (left) and hexagonal (right) core designer (top) and assembly designer (bottom)

There are two parts of the graphical designer. The first part is the core designer where the user can decide which geometry want to use. There is a square and a hexagonal option. The user can create a core design with different types of assemblies. The second part is the assembly type designer. Here we can adjust the size of the assembly and the properties of the included rods (number, size). These designers are shown in Figure 6.

This graphical interface creates the XML file input for SURET automatically. We are working on the method to create the power distribution input and also to display the results of the calculations. Our goal is to create a standalone software where we can do the subchannel calculation all in one place from defining the geometry to processing the results.

5 CONCLUSION

We proved that SURET is able to calculate the themohydraulic parameters of the new fuel design with reasonable accuracy.

In section 4 we have shown that we could reduce the computational time of SURET from 5 minutes to 0.3 seconds using a specific matrix inversion method and separating the calculations into a synchronous and an asynchronous part. The application of these modifications did not lead to any reduction of accuracy of the results computed and it is capable to be part of the VERONA core-monitoring system.

We created a software that is capable to create input files for SURET calculation for a wide variety of core and assembly configurations. This is an ongoing project with established tasks for the future to create a standalone, flexible, modern subchannel calculation software.

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