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EXTENSIONS OF SUBCHANFLOW FOR THERMAL HYDRAULIC ANALYSIS OF MTR-CORES

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ABSTRACT

As part of efforts to develop advanced multi-physics computational methods for safety analysis of research reactors with plate-type fuel, the subchannel thermal hydraulic code, SubChanFlow, has been extended and modified for the analysis of MTR-cores with plate-type fuel. A new heat conduction module for fuel plate and the corresponding heat transfer correlations for narrow rectangular channels of downward flow were implemented. The extended code is validated using experimental data of the RA-6 test facility. The results obtained show a good agreement between SubChanFlow predictions and measured cladding temperature along the core height. The deviations varies between $\pm 4\ ℃$ and $\pm 18\ ℃$ when the Colburn and Y. Sudo correlations are used, respectively. Main results and future work will be presented and discussed.

1. Introduction

In the last decades, the development of advanced simulation tools for the analysis of nuclear reactors has experienced an increase due to the remarkable improvement of computing resources. As a result, numerous simulation tools have been developed specifically for the thermo-hydraulic analysis of power reactors [1] [2].Despite the fact that research reactors are used in numerous fields, thermo-hydraulic analyses have been carried out with system code adaptations, heuristic methods, and geometric approximations that, although they allow obtaining acceptable simulations, are far from carrying out detailed analysis . Another problem that arises when using these adaptations is the direction of coolant flow and the use of correlations developed for fuel rod analysis [3] [4] [5] [6] .
In this paper, the extension of SubChanFlow for the analysis of research reactor with plate-type fuel is presented. To achieve this goal, a new heat conduction module for plates, model of downward flow, and correlations for rectangular narrow channels have been added. To validate the new version of SubChanFlow, the experimental data obtained in the test facility RA-6 is used [7] [8].

2. The thermal-hydraulic subchannels code SubChanFlow

SubChanFlow is a subchannel thermo-hydraulic code developed in the Karlsruhe Institute of Technology for analysis of fuel rod bundles and cores [9]. SubChanFlow enables both a subchannel and fuel assembly level thermo-hydraulic analysis of both hexagonal and square fuel assemblies. It is coupled with different deterministic and Monte Carlo codes for nodal or pin level core analysis taking into account the local feedback between neutronics and thermal hydraulics [10]. Single-phase and two-phase flow conditions are handled by solving a system of three mixed equilibrium equations for steady and transient flow situations. Additionally, a cross-flow model at the pin and fuel assembly level is available to describe the lateral exchange of mass, momentum, and energy between neighbouring cells [11].
Various coolant types can be used e.g. water (IAPWS-97), liquid metals (sodium and lead), and gases (helium, air etc.) as working fluids.

2.1 Short description of main physical models

Basic conservation equations:

The system of conservation equations is solved for each subchannel considering the heat transfer between the coolant of each subchannel with the corresponding fuel rods. Fig. 1 shows that in a fuel assembly, different subchannel types may exist and each subchannel is axially subdivided into meshes.

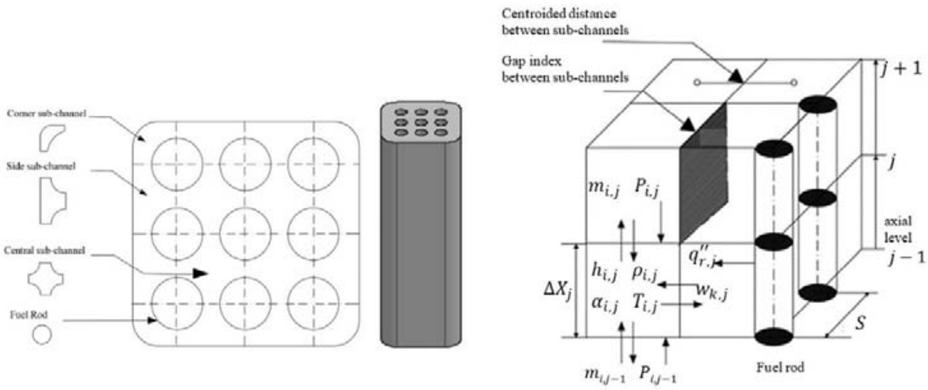

Fig. 1. Lateral and axial discretization of the thermal -hydraulic control volume

The basic conservation equations in finite difference form written as follows:

Mass conservations

$$A_i \frac{\Delta X_j}{\Delta t}\left(\rho_{i,j} - \rho_{i,j}^{n}\right) + \left(m_{i,j} - m_{i,j-1}\right) + \Delta X_j \sum_{k\in i} e_{i,k} w_{k,j} = 0 \tag{1}$$

Axial momentum conservation

$$\begin{aligned}\frac{\Delta X_j}{\Delta t}\left(m_{i,j} - m_{i,j}^{n}\right) + m_{i,j}U'_{i,j} + \Delta X_j \sum_{k\in i} e_{i,k} w_{k,j} U'^{*}_{k,j} \\ = -A_i\left(P_{i,j} - P_{i,j-1}\right) - gA_i\Delta X_j \rho_{i,j} cos\theta \\ - \frac{1}{2}\left(\frac{\Delta X f \Phi^2}{D_h \rho_l} + K v'^{*}\right)_{i,j} \left|m_{i,j}\right| \frac{m_{i,j}}{A_i} - f_T \Delta X_j \sum_{k\epsilon i} w'_{k,j}\, U'_{i,j} - U'_{n,j}\end{aligned} \tag{2}$$

Lateral momentum conservation

$$\frac{\Delta X_j}{\Delta t}\left(w_{k,j} - w_{k,j}^{n}\right) + \left(\bar{U}'_{k,j} w_{k,j} - \bar{U}'_{k,j-1} w_{k,j-1}\right) = \frac{S_k}{l_k}\Delta X_j \Delta \mathrm{p}_{k,j-1} - \left(K_G \frac{\Delta X v'_k}{s_k l_k}\right)_j \left|w_{k,j}\right| w_{k,j} \tag{3}$$

Enthalpy conservation

$$\begin{aligned}\frac{A_i}{\Delta t}\left[\rho_{i,j}\left(h_{i,j} - h_{i,j}^{n}\right) + h_{i,j}\left(\rho_{i,j} - \rho_{i,j}^{n}\right)\right] + \frac{1}{\Delta X_j}\left(m_{i,j} h_{i,j}^{*} - m_{i,j-1} h_{i,j-1}^{*}\right) \\ + \sum_{k\in i} e_{i,k} w_{k,j} h_{k,j}^{*} = \sum_{r\epsilon i} P_r \Phi_{i,r} q''_{r,j} \\ - \left[\sum_{k\epsilon i} w'_{k,j}\left(h_{i,j} - h_{nj}\right) + \sum_{k\epsilon i} C_k s_k \left(T_{i,j} - T_{nj}\right)\right] + \sum_{r\epsilon i} r_Q\, \Phi_{i,r} q'_{r,j}\end{aligned} \tag{4}$$

In order to mathematically close the system of equations, many empirical correlations are needed e.g. for the wall friction, wall /coolant heat transfer and wall heat flux, as well as for the void fraction.

3. Extension of SubChanFlow

For the application of SubChanFlow to investigate the thermal hydraulic behaviour of MTR-cores, a new heat conduction module for plates, the modelling of downward coolant flow, and different correlations dedicated to rectangular channel analysis were added to the code.

3.1 Heat conduction for plate

A new module was implemented to solve the 1D heat conduction equation for a thin plate in contact with coolant at both sides at temperature T_f, Fig. 2.

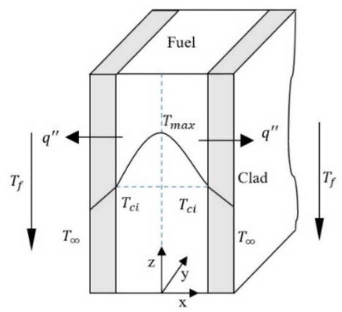

Fig. 2. 1D conduction through a wall

In order to solve Equation 5, a finite volume method is used and in combination with the Thomas algorithm the linear system is solved [12] .

$$\rho C_p \left(\frac{\partial T}{\partial t}\right) = \frac{\partial}{\partial x} K_p \left(\frac{\partial T}{\partial x}\right) + \dot{q} \qquad \textbf{(5)}$$

3.2 Downward flow

To describe the downward flow and consider the gravity forces in Equation 2, the definition of the angle (θ) and hence the term $\cos(\theta)$ in the axial momentum conservation has been extended for this range: $0° \leq \theta \leq 180°$, Fig. 3. In this approach, all other characteristics of the code were retained, see Fig. 4.

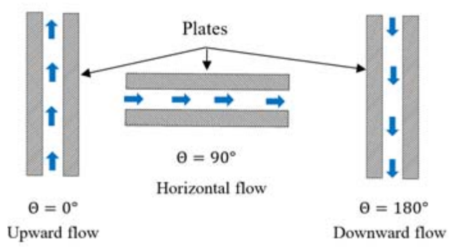

Fig. 3. Fluid direction

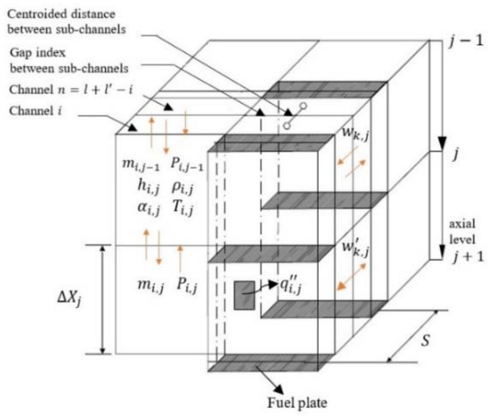

Fig. 4. Control volume for mass momentum and energy balance

3.3 Empirical correlations

After a literature review [10], [11], [12], [13], [14] heat transfer correlations for MTR-cores considering up and downward were selected. In Tab 1 and 2, a list of these correlations for the heat transfer and friction is shown.

Tab 1: Heat transfer correlation for plate

Institution/Reactor	Correlation	Name/Ref
ORNL/HFIR	$Nu = 0.027Re^{0.8}Pr^{\frac{1}{3}}\left(\mu_b/\mu_w\right)^{0.14}$ $1.14 \times 10^4 < Re < 1.65 \times 10^5$ The bulk-to-wall viscosity factor, 1.02	Sieder-Tate [13]
MIT/MITR	$Nu = 0.023Re^{0.8}Pr^{1/3}$ $6.5 \times 10^3 < Re < 20 \times 10^3$	Colburn [14]
JAERI/JRR-3	$Nu = 0.023Re^{0.8}Pr^{0.4}$ $500 < Re < 50 \times 10^3$	Dittus-Boelter [15]
JAERI/JRR-3	$Nu = \frac{0.0296Re^{0.8}Pr}{[1 + 1.54Pr^{-\frac{1}{4}}Re^{-0.1}(Pr-1)]}$ $Re > 10^4$	Y. Sudo [16]
ORNL/HFIR	$Nu = \frac{(f/8)(Re-1000)Pr}{[1 + 12.7(f/8)^{1/4}(Pr^{2/3}-1)]}$ $3000 < Re < 5 \times 10^6$	Gnielinski [17]

Tab. 2: Pressure drop for plate

Friction factor	Equations	Name/Ref.
Laminar	$f = \frac{96}{Re}$ $Re < 2300$	Lie Li [18]
Turbulent	$f = 0.3164Re^{-0.25}$ $3000 < Re < 10 \times 10^4$	

In Fig. 5, the flowchart of the extended SubChanFlow code is shown, where the modules dealing with plates as fuel can be seen within the modular structure of the code.

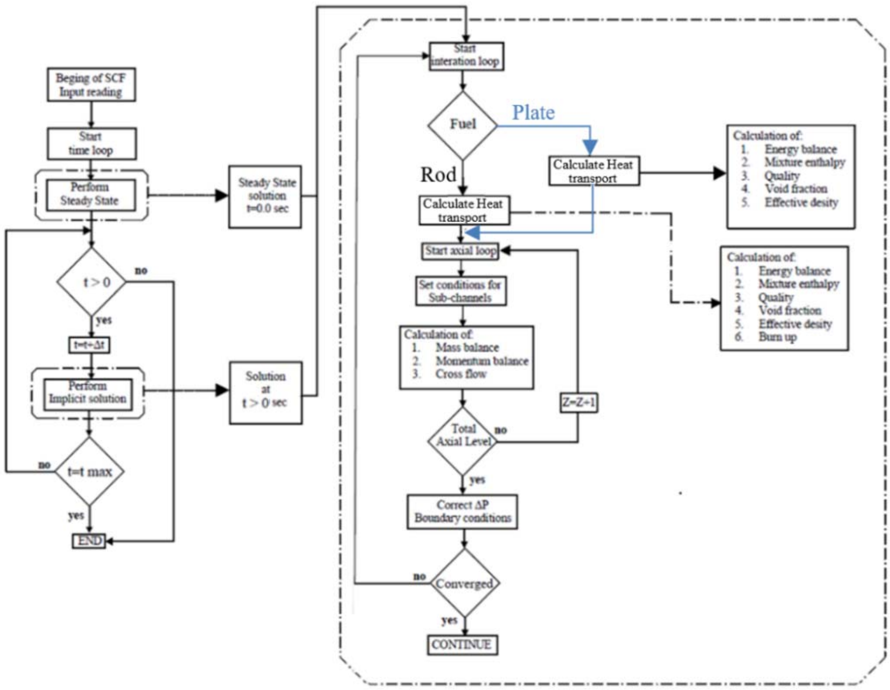

Fig. 5. SubChanFlow flow chart of solution procedure

4. Validation of SubChanFlow

For the validation of the SubChanFlow code, the experimental data of the test RA-6 done at the Centro Atómico de Bariloche and the Instituto Balseiro are used. The experimental device RA-6 is a 1:1 scale replica of the cooling channel inside the RA-6 reactor. The main parameters of the facility and the tests will be described below [7].

4.1 Description of the RA-6 test

The RA-6 experimental device consists of several circuits, Fig. 6. The pressure regulation circuit is responsible for maintaining a constant flow of pressurized refrigerant at 1.7 bar absolute, the pressure measurement is made of a Differential Pressure cell sensor (DP-cell) located at the entrance of the test section. Before reaching the test section, the coolant passes through 20 and 50 micron filters to deionise it and retain important particles to ensure electrical conductivity below $2\mu S$.

The test section consists of two TP-100 sensors and 10 K-type thermocouples located along the aluminium plates. The TP-100 sensors are used to collect fluid temperature values at the entrance and exit of the test section, and the thermocouples, located $2\ mm$ deep at the back of the aluminium plates, perform the coating temperature data collection.

The aluminium plates are heated using electrical energy provided by the Bruker model BMN 70-700 of $250\ Amp$. The aluminium plates are insulated to avoid heat loss to the outside [8] [7]. Finally, Table 3 summarizes the reference data of the RA-6 experimental device.

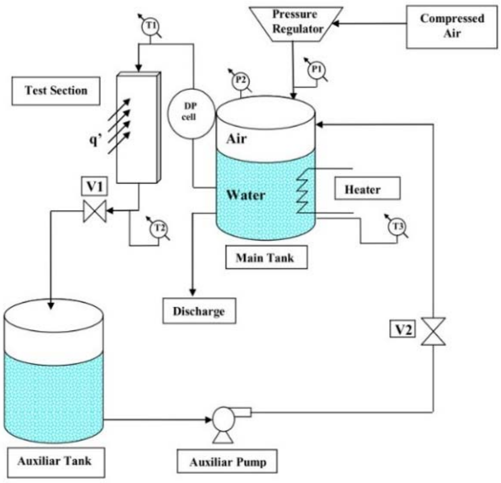

Fig. 6. Experimental setup scheme. **[8]**

Table 3: Main parameters of the RA-6 test

Boundary conditions	
Power (kW)	25
Pressure (MPa)	1.7
T inlet (°C)	38
Mass flow rate (kg/s)	0.1615
Flow direction	Downward
Reynolds range	$7 \times 10^3 < Re < 1.4 \times 10^4$
Channels flow dimensions	
Thickness (m)	0.0027
Width (m)	0.06
Height (m)	0.76
Plate dimension effective	
Width (m)	0.06
Height (m)	0.62
Thickness (m)	0.005

4.2 Test section

A top view of the test section can be seen in Fig. 7. The rectangular test section formed by the aluminium plates and separated by Teflon bands has a dimension of 2.7 mm thickness by 60 mm wide. The height of the experimental device is 76 cm of which only 62 cm are electrically heated, the rest is divided equally for the implementation of flow and temperature measurement devices.

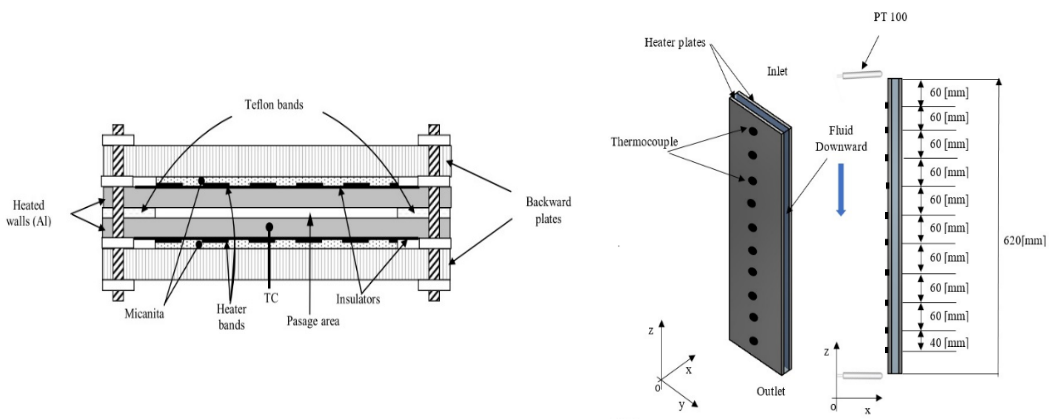

Fig. 7. Test section RA-6 [8]

4.3 SubChanFlow Modeling

The coolant channel is represented by one subchannel with 100 axial mesh cells. Each heating plate associated to the model has a total of 5 nodes at radial level and 100 axial mesh cells. The sum of the axial cells is equal to the effective height, Fig. 8. It can be observed that the heater and the plate are radially subdivided in two meshes, respectively.

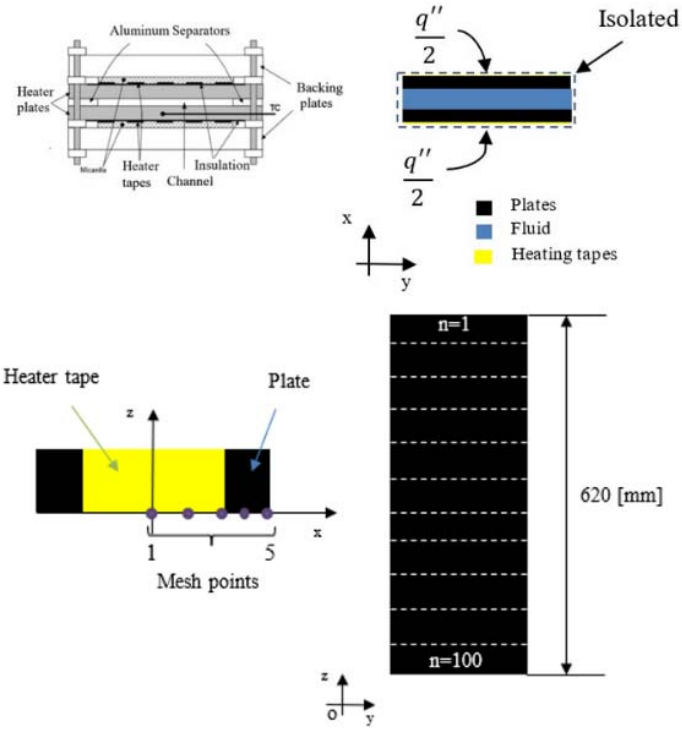

Fig. 8. Plate fuel and coolant axial and radial discretization

Using the described model of the RA-6 tests, SubChanFlow simulations of the test considering the boundary conditions (e.g. coolant mass flow rate, coolant temperature, system pressure, etc.) and using the five correlations listed in Tab 1 and
Tab. **2** are performed.

5. Results and discussions

For the validation of the extended SubChanFlow code, a comparison of the code predictions is performed with the measured data (cladding temperature of the plate) using different heat transfer correlations.
Fig. 9 shows 5 the comparison of the axial cladding temperature predicted by SubChanFlow with the experimental values reported by N. Silin and A. Vertullo [7]. Each temperature profile corresponds to the use of a specific heat transfer correlation summarized in Tab 1.
If Colburn's correlation is used the values predicted by SubChanFlow are closer to the experimental values than the ones calculated with the correlations of Dittus-Boelter, Gnielinski, and Sieder-Tate.
It is worth to note that the axial cladding temperature predicted by SubChanFlow with the Y-Sudo correlation is really out of range compared to the experimental values.

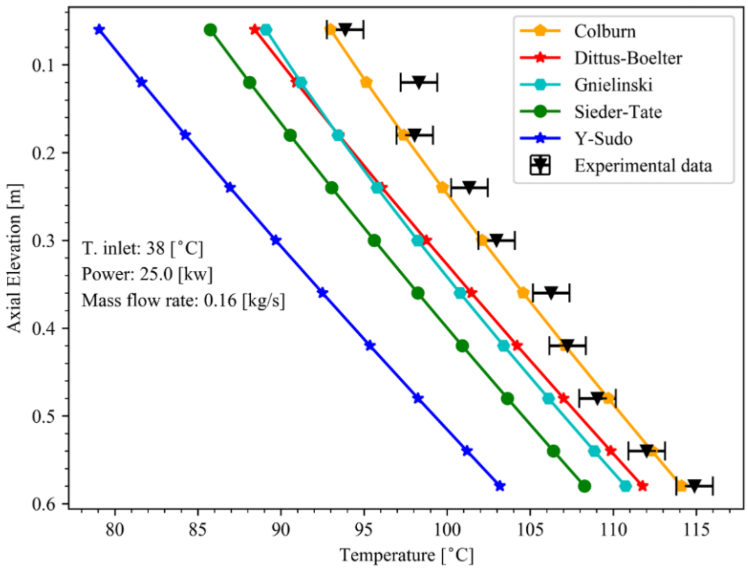

Fig. 9. Comparison of the cladding temperature distribution using different heat transfer correlation

In Fig. 10, the deviation of the axial temperature predicted by SubChanFlow with the different heat transfer correlations from the experimental data is shown. Deviations are between ±4 and ±18 °C. Based on these results, it can be stated that the Colburn correlation is the best one for MTR-cores under the conditions of the RA-6 test.

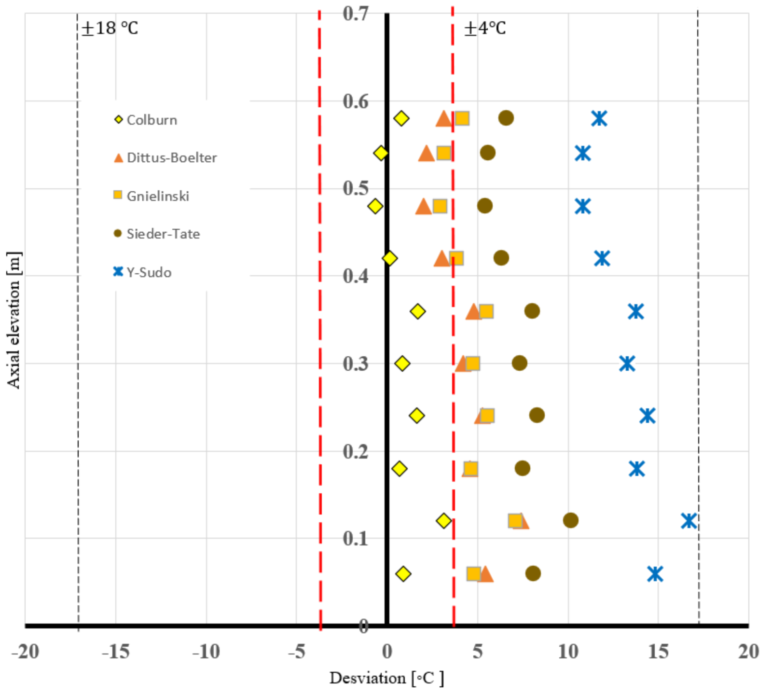

Fig. 10. Comparison of the deviation temperature using different correlations

6. Summary and Outlook

The SubChanFlow code has been extended for the thermo-hydraulic analysis of plate-type research reactors. The validation using data of the RA-6 test showed that SubChanFlow using the Colburn correlation predicts the thermal-hydraulic behaviour of the test with acceptable accuracy, the deviations being between ±4 and ±18 °C.

Additional validation will be performed using data obtained from other tests e.g. performed at the IEA-R1 reactor. Afterwards, the validated code version will be applied for the simulation of MTR-cores as stand-alone and coupled with the Monte Carlo code SERPENT2.

Acknowledgment

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Nomenclature

A:	Subchannel flow area (m^2)
C_k	Heat conductivity in lateral direction $(W/(mK))$
C_p	Specific heat (J/kgK)
D_h	Hydraulic diameter (m)
e	Direction of the lateral mixture
f	Single-phase friction coefficient (empirical correlation)
f_T	Factor for lateral turbulent momentum exchange
g	Gravity (m/s^2)
h	Specific mixture enthalpy (J/kg)
$h^*_{i,j}$	Enthalpy in axial direction
$h^*_{k,j}$	Enthalpy in gap
K	Axial pressure loss coefficient
K_p	Thermal conductivity for plate
K_G	Lateral gap pressure loss coefficient (empirical constant)
l_k	Distance of neighbouring subchannels
m	Mass flow rate axial cell boundary (kg/s)
Nu	Nusselt number
p	Pressure at axial cell boundary (Pa)
Δp	Pressure difference between neighbouring channels (Pa)
Pr	Prandtl number
P_r	Heater perimeter (m)
$\dot{q}$	Heat generation (W/m^3)
q''	Heat flux from fuel rod to coolant (W/m^2)
q'	Lineal fuel rod power (W/m)
Re	Reynolds number
r_Q	Total power directly deposited into the coolant
S_k	Gap width between two neighbouring (m)
T	Temperature (℃)
Δt	Time step (s)
v'^*	Specific volume for the momentum transport
w	Linear mass flow rate through the gap $(kg/(ms))$
w'	Turbulent cross-flow $(kg/(ms))$
ΔX	Length of axial cell (m)
x	Thickness of plate (m)
θ	Angle of the subchannel in vertical direction
ρ	Density (kg/m^3)
Φ^2	Two-phase friction multiplier (empirical correlation)
i	Channel i
j	Axial cell j
k	Gap k
n	Value at previous time step

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