FURTHER DEVELOPMENT OF A THERMAL-HYDRAULICS TWO-PHASE FLOW TOOL

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Abstract

The numerical simulation tool TWOPORFLOW is under development at the Institute for Neutron Physics and Reactor Technology (INR) of the Karlsruhe Institute of Technology (KIT). TWOPORFLOW is a thermal-hydraulics code that is able to simulate single- and two-phase flow in a structured or unstructured porous medium using a flexible 3-D Cartesian geometry. It has the capability to simulate simple 1-D geometries (like heated pipes), fuel assemblies resolving the sub-channel flow between rods or a whole nuclear core using a coarse mesh. The code uses six conservation equations in order to describe the coupled flow of steam and liquid. Several closure correlations are implemented to model the heat transfer between solid and coolant, phase change, wall friction as well as the liquid-vapor momentum coupling. Originally, TWOPORFLOW was used to calculate the flow and heat transfer in micro-channel heat exchangers. The main purpose of this work is the extension, improvement and validation of TWOPORFLOW in order to simulate the thermal-hydraulic behavior of Boiling Water Reactor (BWR) cores. For that aim, the code needs some additional empirical models. In particular, a turbulent lateral mixing model, and a void drift model have been implemented, tested and validated, adopting relevant tests found in the literature. Regarding reactor conditions, the BFBT critical power bundle experiments were selected for the validation.

1. Introduction

TWOPORFLOW is a thermal-hydraulic code based on a porous media approach to simulate single and two-phase flow in 3D Cartesian coordinates. The time dependent mass, momentum and energy conservation equations for each fluid are solved with a semi-implicit continuous Eulerian type method. TWOPORFLOW was originally developed for the simulation of thermal-hydraulic phenomena inside micro-channels [1] [2]. However, the code has been recently modernized and adapted to be able to describe thermal-hydraulic phenomena occurring in Light Water Reactors (LWRs), specifically BWRs [3].

2. TWOPORFLOW capabilities and main features

TWOPORFLOW is capable to solve transient or steady state problems in reactor cores or RPV with a flexible 3D Cartesian geometry which can be used to represent sub-channels, fuel assemblies, or even the whole core. The rod centered and the coolant centered approaches are available for sub-channel simulations.

TWOPORFLOW uses a system of six conservation equations. The mass conservation equations of the two phases are given by the following equations:

$$\frac{\partial(\alpha_L \rho_L \varphi)}{\partial t} + \nabla \cdot \left(\alpha_L \rho_L \varphi \vec{V}_L\right) = -\Gamma_I \tag{1}$$

$$\frac{\partial(\alpha_v \rho_v \varphi)}{\partial t} + \nabla \cdot \left(\alpha_v \rho_v \varphi \vec{V}_v\right) = \Gamma_I \tag{2}$$

$$\alpha_l + \alpha_v = 1 \tag{3}$$

The source term Γ_I describes the rate of evaporation or condensation at the liquid-vapor interface.
The momentum equations are used in non-conservative form as follows:

$$\alpha_L \rho_L \frac{\partial \vec{V}_L}{\partial t} + \alpha_L \rho_L \vec{V}_L \nabla\left(\vec{V}_L\right) + \alpha_L \nabla(P) = -\vec{F}_{wL} + \vec{F}_I + \alpha_L \rho_L \vec{g} + \alpha_L \nabla \mu \nabla \vec{V}_L \tag{4}$$

$$\alpha_v \rho_v \frac{\partial \vec{V}_v}{\partial t} + \alpha_v \rho_v \vec{V}_v \nabla\left(\vec{V}_v\right) + \alpha_v \nabla(P) = -\vec{F}_{wv} - \vec{F}_I + \alpha_v \rho_v \vec{g} + \alpha_v \nabla \mu \nabla \vec{V}_v \tag{5}$$

For energy conservation equations, the internal energy (e) is used as the main variable:

$$\frac{\partial(\alpha_L \rho_L \varphi e_L)}{\partial t} + \nabla \cdot \left(\alpha_L \rho_L e_L \varphi \vec{V}_L\right) + P\nabla \cdot \left(\varphi \alpha_L \vec{V}_L\right) + P\varphi \frac{\partial \alpha_L}{\partial t} + \nabla \lambda_L \varphi \alpha_L \nabla T_L = Q_{wL} - Q_I \tag{6}$$

$$\frac{\partial(\alpha_v \rho_v \varphi e_v)}{\partial t} + \nabla \cdot \left(\alpha_v \rho_v e_v \varphi \vec{V}_v\right) + P\nabla \cdot \left(\varphi \alpha_v \vec{V}_v\right) + P\varphi \frac{\partial \alpha_v}{\partial t} + \nabla \lambda_v \varphi \alpha_v \nabla T_v = Q_{wv} + Q_I \tag{7}$$

TWOPORFLOW has additional models to close the system of conservation equations, like solid-coolant heat transfer, interphase heat exchange, empirical correlations for wall friction, empirical correlations for interphase friction and liquid-vapor momentum coupling. However, some models need to be added or improved. For example, turbulent lateral mixing, void drift and critical heat flux (CHF) as well as the post-CHF models. In the next sections the addition of turbulent viscosity, void dispersion and turbulent conductivity, as well as the results of the validation of these models are presented.

3. Improvement of physical models

3.1 Turbulent viscosity

To describe the effect of the turbulent flow between sub-channels in the momentum equations a simple algebraic equation approach is chosen. According to this approximation, the turbulent flow can be simulated as a pseudo fluid having an effective viscosity (μ), which is the result from the addition of the molecular and the turbulent viscosities. This extension is based on a mixing coefficient (β) which was determined experimentally [4]. Such simple model does not account for the details of

turbulence, but it describes the general mixing behavior between sub-channels leading to the following equation for total viscosity.

$$\mu = \mu_{mol} + \mu_{tur} \tag{8}$$

$$\mu_{tur} = \beta \rho V l \tag{9}$$

3.2 Void dispersion

A void dispersion term (pi) is added to the vapor momentum equation for bubbly flow and is calculated from an assessment of the turbulent kinetic energy using the next equation [5]:

$$pi = 0.4\, \mu_{tur} \frac{V_L}{D_H} \tag{10}$$

This implementation affects directly the equation (5) adding a term, and thus gives the following equation:

$$\alpha_v \rho_v \frac{\partial \vec{V}_v}{\partial t} + \alpha_v \rho_v \vec{V}_v \nabla(\vec{V}_v) + \alpha_v \nabla(P) = -\vec{F}_{wv} - \vec{F}_I + \alpha_v \rho_v \vec{g} + \alpha_v \nabla \mu \nabla \vec{V}_v - pi \nabla \alpha_V \tag{11}$$

3.3 Turbulent conductivity

To describe the effect of the turbulent flow between channels in the energy equation, the turbulent conductivity between adjacent sub-channels is calculated using the turbulent Prandtl number [6]. This number is defined as the ratio between the momentum eddy diffusivity and the heat transfer eddy diffusivity. In this work the value of 0.9 is used [7].

$$\lambda_{tur} = \frac{\mu_{tur} C_p}{Pr_{tur}} \tag{12}$$

The turbulent conductivity is added to the thermal conductivity of the fluid and affects directly the conductivity terms in equations (6) and (7).

$$\lambda = \lambda_k + \lambda_{tur} \tag{13}$$

4. Validation

4.1 NUPEC PSBT stationary temperature tests (thermal mixing)

To validate the implementation of the turbulent-viscosity and conductivity, nine tests of the Exercise 1 Phase II “Steady State Fluid Temperature” from the NUPEC PSBT benchmark [8] have been used. The boundary conditions of the tests are:

- Outlet pressure: 4.92 – 16.58 MPa
- Inlet mass flow: 1.3 – 11.52 kg/s
- Inlet temperature : 86 – 289.2 °C
- Bundle power: 0.4 – 3.44 MW

The quoted measurement error for the outlet temperatures is 1°C [8].
The tests consist of a 5x5 rod assembly with constant axial power distribution. The PSBT benchmark uses the rod power map shown in **Figure 1**.

1.00	1.00	0.25	0.25	0.25
1.00	1.00	1.00	0.25	0.25
1.00	1.00	0.25	0.25	0.25
1.00	1.00	1.00	0.25	0.25
1.00	1.00	0.25	0.25	0.25

Figure 1 Lateral power distribution PSBT tests

The meshing in TWOPORFLOW is constructed by a coolant centered sub-channel approach, resulting in an arrangement of 6x6 sub-channels in directions X and Y respectively; and 27 axial cells in Z direction. The number of rods per channel is ¼, ½, or 1 depending on the location of the sub-channel as can be seen in **Figure 2**.

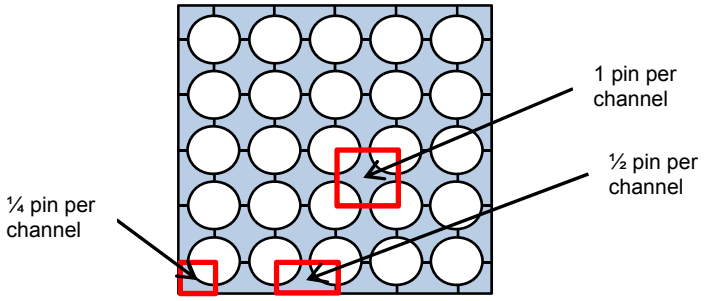

Figure 2 View from the top of the TWOPORFLOW’s model of the NUPEC PSBT

Six different mixing coefficients are tested for the validation, 0.03, 0.04, 0.05, 0.06, 0.07 and 0.08. **Figure 3** shows the difference between the average-calculated and –measured temperatures at the top of the sub-channels dependent on the mixing coefficients. With no mixing, most of the temperatures are outside the 10% scattering band, but an increasing mixing coefficient leads to temperatures closer to the measured values. However, starting at a mixing coefficient of 0.05 the temperatures disperse again. The minor deviation is found using coefficients of 0.05 and 0.06.

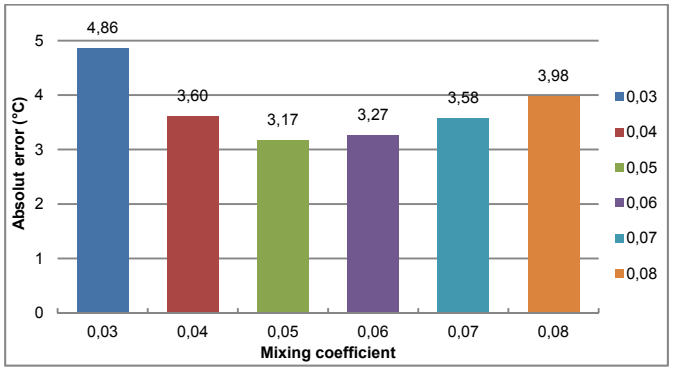

Figure 3 Difference between measured and calculated temperatures dependent on mixing coefficient

4.2 NUPEC BFBT stationary void fraction tests (void drift)

Fifteen tests of the Exercise 1 Phase I "steady-state sub-channel grade benchmark" from the BWR Full-size Fine-mesh Bundle Test (BFBT) Benchmark [9] were used to validate the implementation of the void dispersion. The tests have a geometry of 8x8 pin assembly , different lateral power distributions, (uniform for assembly 1; **Figure 5-A** for assemblies 01, 02, 03; and **Figure 5-B** for assembly 4), and different axial power distributions (constant for assemblies 01, 02, 03, and 4; and cosine for assembly 1).

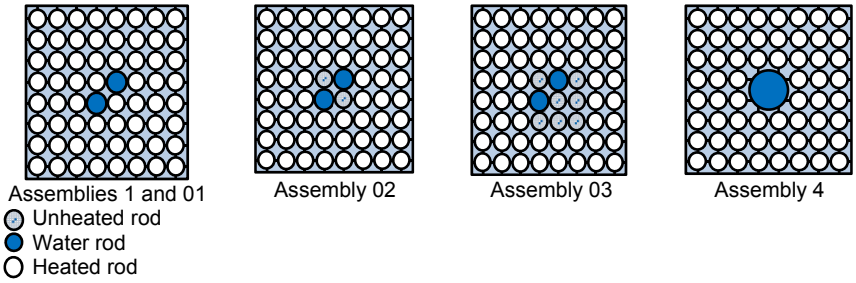

Figure 4 Geometry of test Assemblies 1, 01, 02, 03 and 04

1.15	1.30	1.15	1.30	1.30	1.15	1.30	1.15
1.30	0.45	0.89	0.89	0.89	0.45	1.15	1.30
1.15	0.89	0.89	0.89	0.89	0.89	0.45	1.15
1.30	0.89	0.89	0.89		0.89	0.89	1.15
1.30	0.89	0.89		0.89	0.89	0.89	1.15
1.15	0.45	0.89	0.89	0.89	0.89	0.45	1.15
1.30	1.15	0.45	0.89	0.89	0.45	1.15	1.30
1.15	1.30	1.15	1.15	1.15	1.15	1.30	1.15
A)							

1.15	1.30	1.15	1.30	1.30	1.15	1.30	1.15
1.30	0.45	0.89	0.89	0.89	0.45	1.15	1.30
1.15	0.89	0.89	0.89	0.89	0.89	0.45	1.15
1.30	0.89	0.89			0.89	0.89	1.15
1.30	0.89	0.89			0.89	0.89	1.15
1.15	0.45	0.89	0.89	0.89	0.89	0.45	1.15
1.30	1.15	0.45	0.89	0.89	0.45	1.15	1.30
1.15	1.30	1.15	1.15	1.15	1.15	1.30	1.15
B)							

Figure 5 Lateral power distribution BFBT

The boundary conditions of the tests are:

- Outlet pressure: ~7.15 MPa
- Inlet mass flow: ~15.20 kg/s
- Inlet temperature: ~278 °C
- Bundle power: 1.9 – 6.48 MW

The error in the void measurement is given as 3% [9].The tests have been modeled in TWOPORFLOW using a coolant centered sub-channel approach, making an

arrangement of 9x9 sub-channels and 24 axial cells. A small mixing coefficient of 0.007 is set, because the assemblies do not have mixing vane spacers, as used in PSBT. The number of rods per channel is ¼, ½, or 1 depending on the location of the sub-channel (**Figure 2**).

The calculations were run with an old version of TWOPORFLOW without void drift, and with the new model. The average percentage error in void fraction per assembly of both simulations with respect to the experimental data shows a better approximation using the version of TWOPORFLOW with void drift (**Figure 6**).

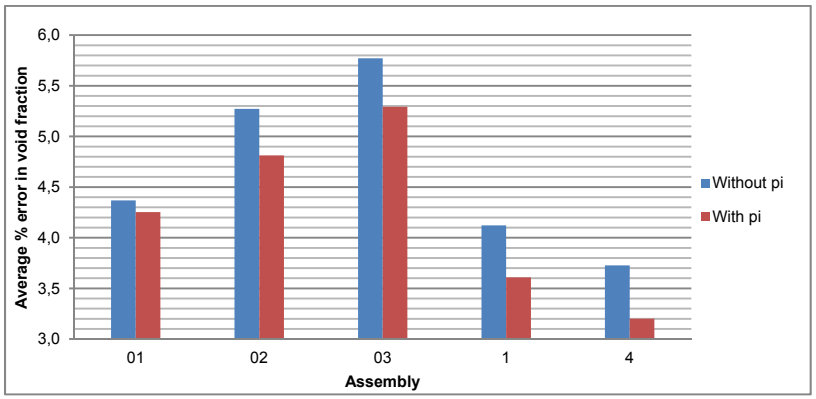

Figure 6 Average % error of simulations with- and without void dispersion term (pi)

5. Conclusions and outlook

The validation results obtained for the improved TWOPORFLOW code have shown that the code is capable to simulate in an appropriate way the most important thermos-hydraulic phenomena occurring in a BWR or in similar conditions.
The next step is to improve and validate critical heat flux (CHF), transition boiling, and subcooled boiling correlations of TWOPORFLOW.
In addition, post-CHF models like minimum film boiling temperature, annular film dry out, rewetting, and cool down of a superheated surface is needed in order to simulate the physical phenomena that may happen during accidental conditions in a BWR core.

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Nomenclature

C_p	Specific Heat (J/kg-K)
D_H	Hydraulic diameter (m)
e	Internal energy (J/kg)
$\vec{F}_I$	Friction at vapor-liquid interface (N/m^3)
$\vec{F}_{wk}$	Wall friction for phase k (N/m^3)
$\vec{g}$	Gravity (kg/m-s^2)
l	Characteristic mixing length (m)
P	Pressure (Pa)
pi	Void dispersion term (Pa/m)
Pr_{tur}	Turbulent Prandtl number (0.9)
Q_H	Internal heat source in porous structure (W/m^3)
Q_I	Heat exchange between phases (W/m^3)
Q_w	Heat exchange between structure and fluid (W/m^3)
t	Time (s)
$\vec{V}$, V	Velocity of fluid (m/s)

Greek letters

α	Volume fraction of vapor
β	Mixing coefficient
Γ_I	Rate of evaporation/condensation (kg/m^3-s)
λ	Total thermal conductivity (W/m-K)
λ_k	Turbulent conductivity of the fluid (W/m-K)
λ_{tur}	Turbulent conductivity (W/m-K)
μ	Effective viscosity (Pa-s)
μ_{mol}	Molecular viscosity (Pa-s)
μ_{tur}	Turbulent viscosity (Pa-s)
ρ	Fluid or clad density (kg/m^3)
φ	Porosity

Subscripts

L	Liquid Phase
v	Vapor phase

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