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TWOPORFLOW: A two-phase flow porous media code, main features and validation with BWR-relevant bundle experiments

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ABSTRACT

TWOPORFLOW is a thermal hydraulics code under development, which simulates two-phase flow in a structured or unstructured porous medium using a flexible 3-Dimensional 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 complete nuclear reactor core using a coarse mesh. It solves the time-dependent system of six conservation equations i.e. the mass, momentum and energy conservation equations for liquid and vapor in 3-D geometry. This paper describes the conservation equations and the empirical closure correlations of TWOPORFLOW that are relevant to describe the BWR (Boiling Water Reactor) core thermal hydraulics conditions which may occur under normal or off-normal conditions. Afterwards, the code is validated using selected experiments such as the BWR Full-size Fine-mesh Bundle Test (BFBT) benchmark with emphasis on the prediction of the void fraction and the pressure drop along the core for stationary and transient test conditions. Based on the results of the validation work, TWOPORFLOW is able to predict the BWR-thermal hydraulic behavior with satisfactory accuracy compared to other well-known thermal-hydraulic codes.

1. Introduction

The simulation of the multidimensional two-phase flow phenomena within a BWR core is complex and very challenging for any kind of simulation tool. Historically, system thermal hydraulic codes together with sub-channel codes, e.g. 1D or 3D coarse mesh system codes like TRACE (USNRC, 2009) and quasi 3D sub-channel codes (Salko and Avramova, 2015), have been applied to describe all the BWR core phenomena under normal and accidental operation conditions in order to predict the safety-relevant parameters such as maximal cladding, temperature, critical power, pressure drops, void fraction etc.

Both approaches have good two-phase flow models and are capable of providing results with small computational efforts. In the last years, Computational Fluid Dynamics tools (CFD) are increasingly being applied for reactor safety problems, mainly for single-phase flow situations. The two-phase flow models are still under development and the high spatial resolution is CPU-intensive despite the parallelization. Hence, the porous media approach as implemented in some codes such as PORFLO (Hovi et al., 2014), CUPID (Yoon et al., 2014) and TWOPORFLOW (Imke, 2004) appears as a promising alternative option which is more accurate than 1D or 3D coarse mesh codes and at the same time it requires much less computational resources than CFD-tools.

KIT started the development of TWOPORFLOW as a porous media two-phase flow code to simulate mainly BWR-cores. Initially, it was developed to simulate single- and two-phase flow heat transfer in micro-channel heat exchangers (Imke, 2004).

Consequently, the code has to be validated for the new application field. In the first chapter, the main features of TWOPORFLOW are outlined, followed by the description of the conservation equations combined with empirical correlations and the code numerical implementation. The validation of several code models using different representative BFBT-tests is presented: 1) the void drift models using the data obtained in the steady-state sub-channel grade BFBT-benchmark; 2) void and pressure drop models adopting data obtained from transient BFBT tests reproducing the conditions of a turbine and a pump trip scenario. The present work is part of the validation process for

Abbreviations: ADI, Alternating Direction Implicit solver; ATHLET, Analysis of Thermal Hydraulics of Leaks and Transient; BFBT, BWR Full-size Fine-mesh Bundle Test benchmark; BICGSTAB, Biconjugate Gradient Stabilized solver; BWR, Boiling Water Reactor; CFD, Computational Fluid Dynamics; CHF, Critical Heat Flux; COBRA-TF, Coolant Boiling in Rod Arrays-Two Fluids; CPU, Central Processing Unit; FAVOR, Fractional Area Volume Obstacle Representation; ICE, Implicit Continuous Eulerian; INR, Institute for Neutron Physics and Reactor Technology; MSFBT, Minimum Stable Film Boiling Temperature; PWR, Pressurized Water Reactor; RPV, Reactor Pressure Vessel; TRACE, TRAC/RELAP Advanced Computational Engine

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List of symbols

Symbols

A_T	Total area of sub-channel
A_F	Flow area of sub-channel
C_{LM}	Lockhart-Martinelli coefficient
Cp	Specific Heat
$\vec{D}$	Viscosity diffusion term
D_H	Hydraulic diameter
e	Internal energy
f_f	Friction factor
$\vec{F_I}$	Friction at vapor-liquid interface
F_I	Interfacial drag coefficient
F_s	Wall friction
G	Mass flux
$\vec{g}$, g	Gravity constant
h	Heat transfer coefficient
K	Thermal diffusion term
L	Characteristic length
P	Pressure
pi	Void dispersion term
P_{ls}	Pressure loss
Q	Heat exchange
Q_I	Heat exchange between phases
Q'''	Volumetric Heat generation rate
q''	Heat flux
Q_s	Heat exchange between structure and fluid
S	Suppression factor
T	Temperature
t	Time
$\ddot{U}$	Ünal coefficient
$\vec{V}$, V	Velocity of fluid
V_r	Relative velocity
V_T	Total volume in sub-channel
V_V	Void volume in sub-channel
w	Weighting factor
$\vec{w_L}$	Velocity vector related to volume porosity
X_{tt}^{-1}	Martinelli parameter
$x = \frac{G_v}{G_v + G_l}$	Quality
α	Volume fraction of fluid
Γ	Mass transfer rate
Γ_I	Rate of evaporation/condensation
Δ	Change in, denoting increment
ϵ_V	Volume porosity
λ	Thermal conductivity
μ	Effective viscosity
ρ	Density
σ	Surface tension
φ	Porosity

Non-dimensional numbers

$Nu = \frac{hL}{k}$	Nusselt number
$Pr = \frac{\mu Cp}{k}$	Prandtl number
$Re = \frac{\rho VDH}{\mu}$	Reynolds number

Subscripts

b	Bubble/bulk fluid
fc	Forced convection
i	Node in lateral direction x
j	Area boundary in fuel rod
k	Node in axial direction z or Fluid phase
l	Liquid phase
mol	Molecular
nb	Nucleate boiling
sat	Saturation
sub	Sub-cooled boiling
tur	Turbulent
v	Vapor phase
w	Wall surface
x	Cartesian direction x
y	Cartesian direction y
z	Cartesian direction z

TWOPORFLOW related to BWR.

Finally, a summary and an outlook are given.

2. Modeling features

Basically, TWOPORFLOW is a two-phase flow transient simulation code. A pseudo-transient calculates steady states. The TWOPORFLOW code solves a system of six balance equations for liquid and steam in a 3-D Cartesian geometry. It uses a porous media approach meaning that rods and solid structures are represented by blocking volumes and areas. TWOPORFLOW needs as input the area and the volume porosity for each 3D mesh cell. The volume porosity is the volume of void space divided by the total volume:

$$\epsilon_V = \frac{V_V}{V_T}. \tag{1}$$

The area porosity is the open flow area divided by the total area, and it is calculated for each direction (x, y, z) as:

$$\varphi_k = \frac{A_F}{A_T}. \tag{2}$$

The Cartesian discretization can be done in different ways e.g. centered rod, centered coolant, or assembly wise. Examples of the different discretization are shown in Fig. 1.

The balance equations for mass and energy are solved for each 3D cell using a staggered mesh for the momentum equation. In the next chapter, the formulation of those conservation equations is described.

The porosity is implemented by the Fractional Area Volume Obstacle Representation (FAVOR) technique (Hirt, 1993). A velocity vector related to the area porosity is defined and used in the formulation of the conservation equations:

$$\vec{w_k} = \begin{pmatrix} \varphi_x & V_x \\ \varphi_y & V_y \\ \varphi_z & V_z \end{pmatrix}. \tag{3}$$

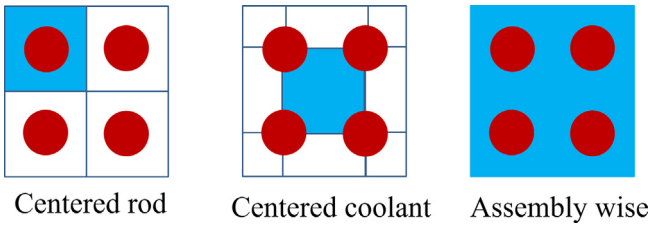

Fig. 1. Examples of Cartesian discretization at different spatial refinement (scales).

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