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REVISITING THE PIRT AND SCALING ANALYSIS WITHIN THE FRAME OF 3D SYSTEM CODE MODELLING

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ABSTRACT

A working Group of OECD-NEA-CSNI-WGAMA was created in 2016 to make a state of the art of existing 3D capabilities in TH system codes, to propose further activities to improve the modelling, and to complement the validation and verification of such tools. 3D modules use a two-fluid model in a porous body approach with a phase-time-space averaging procedure where terms related to diffusion and dispersion appear which were not present in the 1D models.

This paper presents a contribution to this work focusing on the revisiting of the process identification and ranking table (PIRT) including local 3D processes and on the scaling analysis to identify the order of magnitude of some terms of the equations depending on the flow situation. It is shown how the various components and flow situations may have specific dominant processes and may require specific additional modelling and validation efforts. The presence of internal structures, the porosity of the component and the space scales of the flow have a strong impact on the relative importance of wall transfers and diffusion-dispersion terms. Examples are given of flow situations in a pressurized water reactor (PWR) core in loss of coolant accidents (LOCAs), and in steam line breaks (SLB). This shows how such 3D tools used for pressure vessel require a specific analysis at the component level and for each transient phase.

KEYWORDS

PIRT, Scaling, 3D modelling

1. INTRODUCTION

A working Group of OECD-NEA-CSNI-WGAMA was created in 2016 to make a state of the art of existing 3D capabilities in TH system codes, to propose further activities to improve the modelling, and to complement the validation and verification of such tools [1]. The present work was partly done in this framework. However, it represents the opinion of the authors and was not yet endorsed by the working group.

The current generation of industrial system codes (CATHARE [2], RELAP-5 [3], TRACE [4], SPACE [5], ATHLET [6]) have 3D models in porous medium approach which were initially devoted to the prediction of very large scale 3D effects during large break loss of coolant accident (LBLOCA) and which were validated on the data of the 2D-3D experimental program performed in UPTF [7,8,9,10], SCTF [11] and CCTF [12] facilities. The PERICLES 2D program (see [13,14]) also investigated reflooding with radial power profile. The first applications used rather coarse 3D nodalization of the Pressure Vessel (PV) with only a few hundred meshes to keep a reasonable total CPU time. Today the computer power allows a much

finer 3D nodalization and many other transients may also use a 3D modeling for improving the code prediction accuracy [15]. A core modelling with one mesh per assembly may become a standard practice in near future with the CATHARE code for many accidental transient simulations including LOCAs. This allows to look at much finer multi-D physical processes and may provide a better accuracy of predictions. Specific requirements are necessary for such finer simulations. First, a more detailed PIRT exercise is needed to identify dominant phenomena at a smaller scale than for previous nodalizations. Based on porous body 3D equations, one can identify a list of new phenomena (compared to 1D approach) to model and to validate on specific separate effect tests. An order of magnitude analysis allows to neglect some of these processes or simplify some models, depending on the sub-component (core, lower plenum, annular downcomer, upper plenum) and depending on the physical situation encountered in accidental transients. Attention will be drawn on LOCA situations in PWRs and on the core component of the Pressure Vessel. The need to revisit the PIRT and scaling analyses is first presented. Then the identification of local phenomena is made on the basis of porous-3D set of equations. Some ways to estimate the relative impact of each basic phenomenon are presented. Attention is drawn on all diffusive and mixing processes. Considering the lack of large scale test facilities, a method to validate the 3D modelling is proposed using a new approach called “multiscale validation” where small scale separate effect tests are used together with several modeling scales to validate the system scale 3D models.

2. REVISITING PIRT AND SCALING ANALYSIS FOR A 3D MODELLING

2.1 The role of PIRT and scaling

In a reactor safety analysis the safety criteria are first defined which give limits to some parameters of interest or Figures of Merit (FoM), e.g. peak cladding temperature (PCT) in LOCAs, or liquid temperature field in a core in a main steam line break (MSLB), or boron concentration field in a core for a boron dilution transient.

Phenomena identification and ranking table (PIRT) and scaling analysis are used to investigate reactor accidental situations with the following objectives:

- Identify phenomena which have a dominant or significant effect on the FoMs and parameters of interest of the safety analysis.
- Identify all the phenomena which should be properly modelled and validated in the numerical tool to be used in the safety demonstration.
- Rank the phenomena to establish a hierarchy necessary to define scaling criteria for integral effect test (IET) facilities and separate effect test (SET) facilities which should be built and operated. The criteria are to preserve the dominant phenomena in the scaled experiment and to accept some distortion of the phenomena which have a lower influence on the parameters of interest.
- Establish a validation matrix which should be able to validate the numerical simulation tool on all dominant and influent phenomena in IETs and SETs.
- List and rank the phenomena and the related terms of the equations used in the simulation tool which should be included in the uncertainty analysis. The input uncertainty to be used for negligible terms may be neglected or better treated conservatively. The input uncertainty to be used for dominant terms must be treated with special care and possibly validated against SETs. The input uncertainty to be used for influent but not dominant phenomena should also be evaluated and preferably validated on SETs.

2.2 Why and when revisiting PIRT and scaling analysis for 3D modelling?

Usual scaling methods such as H2TS (“Hierarchical Two Tiered Scaling”) [16] have two steps: a top - down, T-D, and a bottom - up (B-U). The T-D step uses non-dimensional form of mass (M), energy (E) and momentum (MM) conservation equations written at the system level to establish the scaling hierarchy i.e. what phenomena have priority in order to be scaled (e.g. in an IET), and to identify what phenomena must be included in the bottom-up analysis. The B-U step continues the analysis at the component or at the process level to scale SETs and both steps give requirements for the physical modelling in the simulation tool and of the validation of the tool. The scaling analysis is based on the PIRT but it can also help the PIRT by helping in the ranking of phenomena.

When 3D phenomena were identified in the LBLOCA (Large Break Loss of Coolant Accident) PIRT, they were investigated in specific large scale tests (UPTF, SCTF, CCTF). At that time, all the 3D local processes were not identified and that was the main reason for such very expensive tests. The downcomer refill at a reactor scale in UPTF was necessary since very complex countercurrent flow with high condensation rates and with azimuthal heterogeneity were encountered and no clear scaling criteria could be defined. In such complex cases the only way is to perform scale 1:1 tests in prototypical geometry and prototypical thermalhydraulic conditions. The 3D effects in the core during reflooding were also investigated with almost scale 1:1 tests in CCFT and SCTF. The vertical scale was preserved, the geometry of assemblies was prototypical and the radial transfers were well represented by using 8 full rod bundles (SCTF) with representative power differences between assemblies.

Reflooding models were first validated on 1D reflooding tests without radial power profile. When the models extrapolated from 1D were used in a 3D modelling of reflooding tests with radial power profile (SCTF, PERICLES-2D [17,18]) the predictions were rather satisfactory although no particular effort was spent to the specific 3D phenomena such as radial transfers which were observed in the experiments. This was possibly due to some compensating errors but since the tests were very close to reactor conditions, the same compensations are expected in reactor simulations. There was no need to investigate more deeply local 3D processes. Today 3D modeling is envisaged in other situations such as SLB, boron dilution, and SBLOCAS (Small Break LOCA) without any large scale test facility to validate the codes. Therefore, the only way is to identify each basic 3D phenomenon, to validate the model on existing small scale data in a separate effect way and to use existing IETs for a more global validation even if the relative weight of each process is not fully representative of the reactor geometry.

2.3 Identifying phenomena from basic 3D equations

The system of equations used in porous-3D two-fluid model is the basis for identification of all relevant 3D processes. The local instantaneous mass momentum and energy equations are time averaged and integrated over a domain of space characterized by a scale. For example, in a PWR core, the domain of integration can be a section of an assembly (assembly scale modelling) or a section of a sub-channel (sub-channel modelling). Equations can be written as follows (see Chandesris et al., [19,20]):

$$\frac{\partial \phi \alpha_k \rho_k}{\partial t} + \nabla \cdot (\phi \alpha_k \rho_k V_k) = \phi \Gamma_k \quad (1)$$

$$\alpha_k \rho_k \left(\frac{\partial V_k}{\partial t} + V_k \nabla \cdot V_k \right) + \alpha_k \nabla P = (p_i + f_i^{TD}) \nabla \alpha_k + \tau_i + \alpha_k \rho_k g + \tau_{wk} + \frac{1}{\phi} \nabla \cdot (\alpha_k \rho_k \tau_k^{l+t+d}) \quad (2)$$

$$\frac{\partial \phi \alpha_k \rho_k e_k}{\partial t} + \nabla \cdot (\phi \alpha_k \rho_k h_k V_k) = \phi q_{ki} + S_c q_{wk} + \phi \Gamma_k h_k + \nabla \cdot (\alpha_k q_k^{l+t+d}) \quad (3)$$

In these equations, $\alpha_k, \rho_k, V_k, e_k, h_k$ are the volume fraction, the density, the velocity, the internal energy and the enthalpy for the phase k, ϕ is the porosity, P the pressure, Γ_k the interfacial mass exchange, p_i

and f_i^{TD} are void dispersion terms due to space averaging of interfacial pressure forces, and time averaging of drag and added mass forces. They tend to homogenize void fraction. τ_i is the interfacial friction force, τ_{wk} the wall friction force, q_{ki} , q_{wk} the interfacial and the wall to phase k heat transfer, S_c the heating surface, τ_k^{l+t+d} the stress tensor which accounts for laminar turbulent and dispersive effects, and q_k^{l+t+d} the laminar turbulent and dispersive heat flux

Diffusion and dispersion terms

The momentum and energy dispersive and diffusive terms came out during the double (time and space) averaging process of the local convection terms:

$$\langle \bar{v}\bar{v} \rangle_f = \langle \bar{v} \rangle_f \langle \bar{v} \rangle_f + \langle \bar{v}'\bar{v}' \rangle_f + \langle \bar{\delta v} \bar{\delta v} \rangle_f \quad (4)$$

$$\langle \bar{v}\bar{h} \rangle_f = \langle \bar{v} \rangle_f \langle \bar{h} \rangle_f + \langle \bar{v}'\bar{h}' \rangle_f + \langle \bar{\delta v} \bar{\delta h} \rangle_f \quad (5)$$

\bar{x} is the time average of the quantity x and x' the deviation from this average:

$\langle x \rangle_f$ is the spatial average of the quantity x and δx the deviation from this average

The first rhs terms of equations (4) and (5) are the macroscopic convection of the mean velocity and enthalpy, the second rhs terms are the turbulent diffusion of momentum and energy, and the third rhs terms are momentum and energy dispersion terms (see Drouin et al, 2010, [21]).

3. LIST OF PHENOMENA FROM 3D EQUATIONS

3.1 List of phenomena

One may establish a list of phenomena based on these equations and see which phenomenon exists in 1D models and which are specific to 3D (see Table 1).

From this list there are several phenomena which are simply extrapolated from 1D models without any specific effort to take into account possible effects of the 3D geometry of the flow in the respective components of a pressure vessel, the downcomer, the lower plenum, the core, the upper plenum, the upper head. This is true for interfacial heat and mass transfers, interfacial friction, and wall friction. Depending on the local geometry there may be significant differences with typical 1D flows in pipes or axial flow in rod bundles. For example the impact of spacer grids in a PWR core is known to increase the turbulence intensity by a factor 4 or 5 and to improve wall heat transfers.

New phenomena appear that were not present in 1D models such as laminar and turbulent diffusion of momentum and energy and dispersion of momentum and energy.

The relative impact of each phenomenon depends on the component, the accidental sequence and the phase of the transient. Various modelling and validation needs are reported in the table but in many cases the absence of information is not dramatic since the phenomenon has a low or very low impact. Therefore some guidance is provided here below to help the evaluation of the order of magnitude of each term.

3.2 Ranking phenomena related to momentum

Let's consider first the relations between pressure and flowrate which may be described by the mixture momentum equation. One may consider one privileged flow direction (vertical upward in a core, vertical downward in a downcomer and consider mixture momentum balance in this direction integrated over a distance Δz .

In steady state, it reduces to:

$$\frac{\Delta P}{\Delta z} = \left(\frac{\Delta P}{\Delta z} \right)_{acc,z} + \left(\frac{\Delta P}{\Delta z} \right)_{acc,xy} + \left(\frac{\Delta P}{\Delta z} \right)_{gr} + \left(\frac{\Delta P}{\Delta z} \right)_{fr} + \left(\frac{\Delta P}{\Delta z} \right)_{form} + \left(\frac{\Delta P}{\Delta z} \right)_{diff} + \left(\frac{\Delta P}{\Delta z} \right)_{disp}$$

Table I. List of phenomena in a porous 3D model (M=mass equation, MM= momentum equation, E=energy equation)

Phenomenon	Equation (M, MM, E) Term	Present in 1D models	Validation in 1D	Models for 3D	Validation in 3D	Comments
Interfacial mass transfer	M $\phi \Gamma_k$	yes	yes	Taken from 1D	In some cases	
Space acceleration	MM $\alpha_k \rho_k V_k \nabla \cdot V_k$	yes	No need	No need	No need	Depends on porosity & density variations
Void dispersion	MM $(p_i + f_i^{TD}) \nabla \alpha_k$	yes	No	Yes for core geometry	Some data	
Interfacial friction	MM τ_i	yes	yes	Taken from 1D	No data	No model in complex geometry
Wall friction & P losses	MM $\alpha_k \rho_k g$	yes	yes	No	No	Needs for non-axial flow
Momentum diffusion (laminar)	MM $\frac{1}{\phi} \nabla \cdot (\alpha_k \rho_k \tau_k^l)$	No	No need	yes	No	Very often negligible
Momentum diffusion (turbulent)	MM $\frac{1}{\phi} \nabla \cdot (\alpha_k \rho_k \tau_k^t)$	No	No need	Yes for core	Some data for core	
Momentum dispersion	MM $\frac{1}{\phi} \nabla \cdot (\alpha_k \rho_k \tau_k^d)$	No	No need	Yes for core	Some data for core	geometry dependent
Energy transport	E $\nabla \cdot (\phi \alpha_k \rho_k h_k V_k)$	Yes	No need	Yes	No need	
Interfacial heat transfers	E ϕq_{ki}	Yes	Yes	Taken from 1D	In some cases	
Wall Heat transfers	E $S_c q_{wk}$	Yes	Yes	Taken from 1D	In some cases	
Energy interfacial transfer	E $\phi \Gamma_k h_k$	Yes	No need	Taken from 1D	No need	Derived from $\phi \Gamma_k$
Energy Diffusion (laminar)	E $\nabla \cdot (\alpha_k q_k^l)$	No	No need	yes	No	Very often negligible
Energy Diffusion (turbulent)	E $\nabla \cdot (\alpha_k q_k^t)$	No	No need	Yes for core	Some data for core	
Energy Dispersion	E $\nabla \cdot (\alpha_k q_k^d)$	No	No need	Yes for core	Some data for core	geometry dependent

The r.h.s terms are 1: axial acceleration 2: contribution from radial flow, 3: gravity, 4: wall friction, 5: form losses, 6: viscous and turbulent momentum diffusion, and momentum. The gravity wall friction and form loss terms are very often dominant terms. The form pressure losses (5th) is related to singular geometries such as spacer grid, perforated plate, Only the first third and fourth r.h.s terms exist in a 1D model. The axial acceleration term may be due to variations of the porosity or to density differences. Density differences are likely to occur in case of heating, e.g. in a core. It is relatively small in single phase liquid since $\partial\rho_l/\partial h_l$ is rather small but may be significant in two phase with boiling and in single phase vapour since $\partial\rho_v/\partial h_v$ is rather high. The radial acceleration term exists in case of radial flow and may result from several reasons. In the case of the core geometry, both buoyancy driven crossflows and friction driven crossflows were already identified [22,23,24]. A radial power profile creates radial density gradients which decrease the axial gravity term (3rd term) and increase the axial acceleration (1st term) and the friction (4th term) and form losses (5th term).

A first analysis [22] proposed a non-dimensional number F_1 , to characterize the limit between both types of crossflows. From the simplified axial momentum equation:

$$\frac{\partial P}{\partial z} = \rho g - \rho \left(\frac{K_{SGz}}{\Delta z_{SG}} + \frac{4}{D_{hz}} C_{fz} \right) \frac{V^2}{2}$$

K_{SGz} is the form loss coefficient of a spacer grid, Δz_{SG} is the distance between grids, and C_{fz} the friction coefficient along rods.

One can see if it increases or decreases with heating and density change:

$$\left(\frac{\partial \frac{\partial P}{\partial z}}{\partial \rho} \right)_G = -g + \left(\frac{K_{SGz}}{\Delta z_{SG}} + \frac{4}{D_{hz}} C_{fz} \right) \frac{V^2}{2}$$

For a given mass flux G , the pressure gradient decreases with heating (decreasing ρ) for $F_1 < 1$ and there will be crossflows from low power (high ρ) to higher power (high ρ) creating the chimney effect. For $F_1 > 1$ there will be crossflows from high power to low power. A low F_1 creates buoyancy driven crossflow and a high F_1 creates friction driven crossflow.

$$F_1 = \frac{\left(\frac{K_{SGz}}{\Delta z_{SG}} + \frac{4}{D_{hz}} C_{fz} \right) V^2}{2g};$$

It was found that the momentum diffusion and dispersion effects related to the radial gradient of axial velocity (due to radial density gradients) were small and negligible compared to gravity and friction in a pure vapour flow. More recent investigations have found that in vapour flow, the acceleration may not be negligible in the balance and that a modified number F'_1 should be considered:

$$F'_1 = \frac{\left[\frac{K_{effz}}{L_z} + \frac{8\alpha\phi}{G C_p D_h} \right] V^2}{2g} \text{ with } \frac{K_{effz}}{L_z} = \frac{K_{SGz}}{\Delta z_{SG}} + \frac{4}{D_{hz}} C_{fz}$$

$$\alpha = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} \quad \text{Thermal expansion coefficient} \quad \phi: \text{ wall heat flux}$$

Laminar and turbulent momentum diffusion and momentum dispersion were modeled and validated for a PWR core geometry on the basis of small rod bundle data [20]. It was found that radial dispersion is usually larger than radial diffusion and depends significantly on the type and geometry of spacer grids. There may be a factor 30 between simple spacer grids and mixing grids.

Extending such order of magnitude analyses one may conclude that for a core geometry:

- High velocity liquid flow in a core with radial power differences does not create big density and velocity differences between high power and low power regions due to low thermal expansion and

induce small friction driven crossflows. In such case, radial momentum diffusion and dispersion will also be small. This is a situation encountered in high power high flowrate SLB

- Low velocity liquid flow in a core with radial power differences create higher density differences –than in previous case- between high power and low power regions and may induce buoyancy driven crossflows. In such case, radial momentum diffusion and dispersion may play a second order role. This is a situation encountered in low power low flowrate SLB.
- High velocity boiling flow in a core with radial power differences create density differences –due to boiling- between high power and low power regions and induces some friction driven crossflows. In such case, radial momentum diffusion and dispersion may play a lower role. This is encountered in a blowdown phase of a LBLOCA.
- Low velocity boiling flow in a core with radial power differences create high density differences – due to boiling- between high power and low power regions and induces very high buoyancy driven crossflows. In such case, radial momentum diffusion and dispersion may play a relatively minor role. This is encountered in a core uncover (SBLOCA, see figure 1, right) or in a LBLOCA reflooding situations (Figure 1, left) below the swell level or below the quench front.
- High velocity vapour flow in a core with radial power differences creates big density and velocity differences between high power and low power regions due to high thermal expansion and induce buoyancy driven crossflows. In such case, radial momentum diffusion and dispersion will may play a relatively minor role. This is a situation encountered in low pressure core uncover (SBLOCA, Figure 2, right).
- Low velocity vapour flow in a core with radial power differences create higher density differences –than in previous case- between high power and low power regions and induces high buoyancy driven crossflows. In such case, radial momentum diffusion and dispersion may play a second order role. This is a situation encountered in high pressure core uncover (SBLOCA).

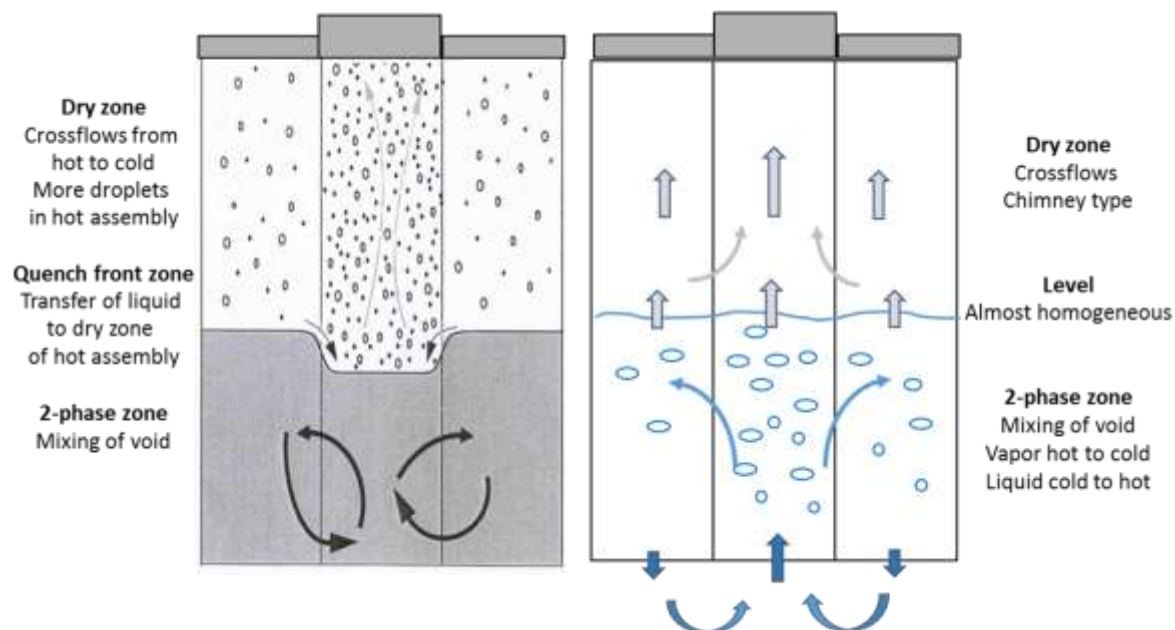


Figure 1: Radial transfers due to power profile. A high power assembly with two lower power neighbours. Left: low P LBLOCA reflooding; Right: high P SBLOCA core uncovering

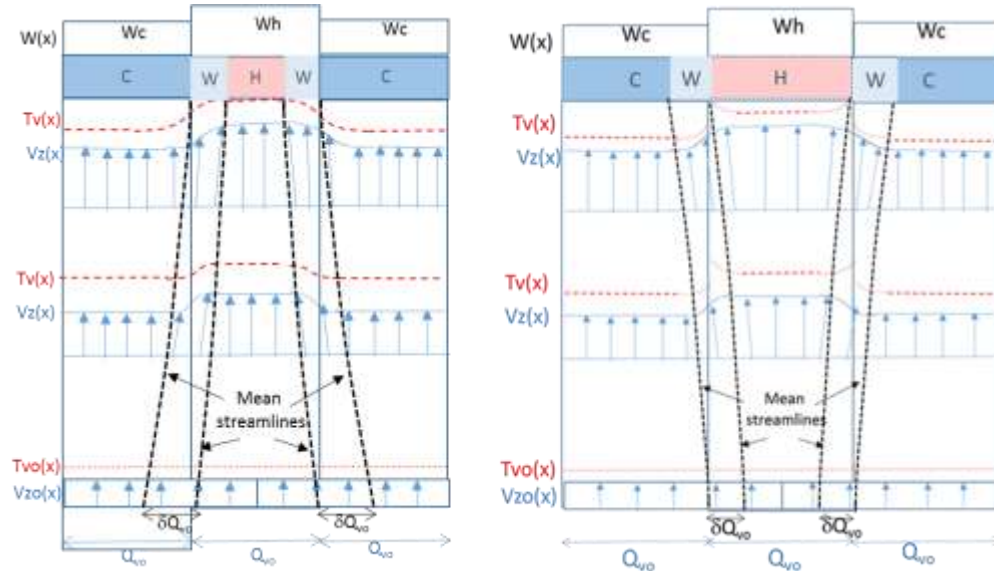


Figure 2: Chimney effect on the left and diverging crossflow on the right

3.3 Ranking phenomena related to energy

Let's now consider the mixture energy equation in the same case of a privileged flow direction (vertical upward in a core, vertical downward in a downcomer. In steady state, it reduces to:

$$\frac{\partial \phi G_{m,z} h_m}{\partial z} = - \left[\frac{\partial \phi G_{m,x} h_m}{\partial x} + \frac{\partial \phi G_{m,y} h_m}{\partial y} \right] + S_c q_w + \nabla \cdot (q^{l+t+d})$$

The first term is the axial convective term and the 2 first r.h.s. terms are the radial convection terms corresponding to crossflows.

The third term due to wall heating is clearly dominant in a core and the laminar diffusion, turbulent diffusion and dispersion terms can play a significant role only when crossflows are very small.

Crossflows are due to either buoyancy or friction and depend mainly on the friction and form losses for a radial flow. There is lack of information on such radial pressure losses and this is a weakness of current 3D core models. New experimental programs should provide information on wall friction for non-axial flow in a core (see the METERO program [25,26])

3.3 Ranking phenomena related to phase repartition

The core void fraction repartition may play a dominant role on the cooling capabilities particularly in the reactor core. In a SBLOCA when there is an uncovered zone, the swell level controls the PCT. It is mainly determined by the axial interfacial friction. Current models are satisfactory and extensively validated. However when 3D phenomena exist due to core radial power differences, (see figures 1 and 2). The interfacial friction for non-axial flow is very poorly known. It may affect to what extent the vapour axial flowrate is homogenized or not at the swell level. If the radial mixing below a swell level is perfect the void fraction and the vapour mass flux is homogeneous at the swell level and the highest power rods do not benefit from the large vapour production below the level. If the mixing is not perfect, the situation may be better for the high power rods.

The void dispersion term can also play a significant role in some conditions as shown by Valette in PSBT analysis [27]. From sensitivity tests, it appears that it can be dominant only in high speed two-phase flow and it is much lower than the buoyancy driven crossflow.

New experimental programs should provide information on interfacial friction for non-axial flow and on void dispersion force in a core (see the METERO program [25,26])

3.4 Ranking phenomena for PWR core thermalhydraulics

One can then propose a ranking of core 3D phenomena based on the impact on a good prediction of flowrate and temperature or steam quality repartition which have an impact on cooling capabilities and PCT. Only phenomena which require models are considered. Crossflows depend on gravity and affect convection or acceleration terms which are not listed here, since they do not require any models but they are influenced by friction and pressure losses which are listed. Ranking uses 3 categories: dominant (D), influent (I) and negligible (N). The favorable (f) or unfavorable (uf) effect on cooling are mentioned, and the availability of validation data (v) or the lack of data (nv) are also mentioned. The wall transfers are necessarily dominant in all conditions since they may include the onset of nucleate boiling (ONB) and net vapor generation point (NVG) which creates void and affects reactivity (SLB), CHF occurrence which decrease dramatically heat transfer coefficients (LBLOCA blowdown), quenching which recovers good cooling (reflooding), film boiling which controls post-CHF overheating in LOCA blowdown phase, and vapor convective heat transfer which controls PCT in core uncover (SBLOCA). 6 main conditions are considered characterized by either single phase liquid single phase vapor or two-phase, and by low or high velocity. High velocity here corresponds to $F'_1 > 1$ where friction crossflows may take place and low velocity corresponds to $F'_1 < 1$ where buoyancy driven chimney effects may occur. This ranking is made on the basis of some quantitative evaluations, on some sensitivity tests, on some experimental data analyses, and on some expert judgement. Further checking may be necessary.

Table 2: Ranking of PWR core 3D phenomena with respect to cooling capabilities

PHENOMENON	THERMALHYDRAULIC CONDITIONS					
	High V liquid	Low V liquid	High V vapor	Low V vapor	high V 2-phase	Low V 2-phase
Wall friction axial	D..v	N..v	D..v	N..v	I..v	N..v
P losses axial	D u v	I.. u v	D.. u v	I.. u v	I.. u v	I.. u v
P losses radial	I uf nv	D f nv	I uf nv	D f nv	I uf nv	D nv
Void dispersion	-				D f v	I nv
Interfacial friction axial					I v	D uf v
Interfacial friction radial					I, uf nv	I uf nv
Momentum diffusion	I f nv	N	I f nv	N	I	N
Momentum dispersion	D	I	I	N	D	I
Wall Heat transfers	D v	D v	D v	D v	D v	D v
Energy diffusion	I. f nv	N	I f nv	N	I f nv	N
Energy dispersion	D f v	I f v	I f nv	N f nv	I nv	N nv

3.4 Impact of porosity and geometrical scales on mixing processes

The core geometry has a rather low porosity and a small hydraulic diameter compared to other components of a PV. Therefore, friction terms often play a dominant role and dispersion may be much larger than turbulent diffusion. Therefore a turbulence model is not required and dispersion may be modelled without any additional transport equation. In a more open medium like an annular downcomer or upper and lower plena, due to much lower wall friction, one may expect buoyancy driven rather than friction driven crossflows. If turbulent mixing is expected to play a dominant role (e.g. in downcomer and lower plenum during SLB or boron dilution transients) a turbulence model is needed and the 3D modules of system codes may not be well adapted to these components. A coupling of the system code with a CFD in open medium may be necessary. Also wall friction and wall heat transfers which are extrapolated from 1D to porous 3D models are not adapted to open media with small meshes, for which a wall function approach is needed. In such case a CFD simulation with fine meshing may be used as a reference for a coarse 3D modelling of system code to tune some models and/or evaluate the uncertainty (see [29]).

4. USING PIRT AND SCALING FOR 3D MODELLING AND VALIDATION

It was shown in chapter 2 and 3 how revisiting the PIRT and listing all local 3D effects could identify the modelling weaknesses and the lack of validation on some influent or dominant phenomena. The analysis was illustrated by the PWR core 3D. After the identification and ranking presented in table 2 the analysis may go farther by identifying more precisely the sensitivity of each process on some specific core situation, the influence of geometrical characteristics and the availability of validation data. This was made for SBLOCA and already presented [28]. Appendix 1 shows another Table which was used to determine the experimental needs. The METERO experimental program was defined to answer many of the identified needs which is also briefly presented in Appendix 1 by a Figure and a test matrix, more detail information being available in two recent papers [25,26]. A large scale test facility in prototypical steam-water conditions with full power full pressure is not available and would be extremely expensive without having measurement techniques able to provide the necessary information on each basic process. Therefore separate effect validation experiments may be used to provide information on mixing processes. Since some available data are performed in small rod bundles (5x5 to 8x8), they cannot investigate transfers between assemblies of different power. However, they can be used to model radial transfers at the sub-channel modelling scale and then may provide useful information for validation of a core modelling at the assembly scale. This uses the new concept of multiscale validation also recently presented in [29]. A validation of core 3D effects in SBLOCA may use IET which have radial power differences (Rabe & Prea, 2019, [30]) although the limited radial core size

5. CONCLUSIONS

The paper has shown how to analyze 3D processes occurring in a LWR PV at a basic level in view of providing a better modeling and identifying the validation needs. This is based on the porous 3D equations and on an order of magnitude analysis in order to rank phenomena. The paper illustrated the method on core thermalhydraulics for a range of situations including LOCAs, SLBs.

NOMENCLATURE

List of Acronyms

FoM	Figure of Merit
IET	Integral Effect test
LOCA:	Loss Of Coolant Accident
LBLOCA	Large Break Loss Of Coolant Accident

PCT	Peak Clad Temperature
PIRT	Phenomena identification and ranking table
PV:	Pressure Vessel
SBLOCA:	Small Break Loss Of Coolant Accident
SET	Separate effect test
SLB	Steam Line Break

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APPENDIX 1: ADDITIONAL INFORMATION ON CORE 3D VALIDATION NEEDS

The following Table 3 presents additional analysis made for a 3D approach for an uncovered core in a SBLOCA. for more information. This Table was used to define the METERO test program. The Figure 3 below shows the METERO test facility. Then the table 4 presents the test matrix and how each test series may answer some needs. It is not possible here to comment in detail these tables and the figure 3, the reader may go to reference [28] for more information.

Table 3: PIRT analysis specific to a 3D approach for an uncovered core in a SBLOCA

3D EFFECTS IN AN UNCOVERED PWR CORE OF A SBLOCA				
Process	Sensitivity on FoM (<u>H</u>,<u>M</u>,<u>L</u>)	Model Uncertainty (H, M, L)	Geometry effect	SET or global validation
Flow regime identification	Possibly H	L in axial flow	possible effect of grids	No
Interfacial friction	H	M	probably low	Axial flow:OK Radial flow : no
Wall friction & form loss	M	axial flow: L radial flow: H	Spacer grids	Axial flow:OK Radial flow : no
Void dispersion	L	H	?	No
Interfacial H&M transfers	L (pure vapor in dry zone)			
Wall HT regime identification	H	L		Axial flow:OK
Convection to liquid	L	L	Spacer grids	Axial flow:OK
Nucleate boiling	L	M		Axial flow:OK
CHF (DNB or dry-out)	L to H	M	Spacer grids	OK
Convection to vapor	H	L	Spacer grids	Axial flow:OK
Heat diffusion-dispersion in liquid	L	M	Spacer grids	PSBT
Heat diffusion-dispersion in steam	L or M	M	Spacer grids	No
Specific 3D processes • Chimney effect • Diverging crossflow	M M	M M	Spacer grids Spacer grids	No PERICLES

H: high; M: medium; L: low

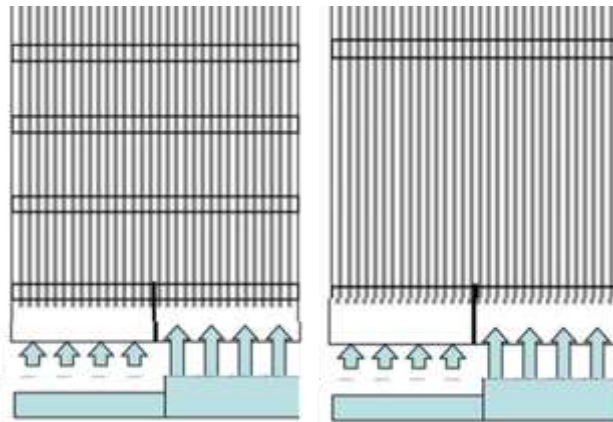


Figure 3: The METERO test facility with unbalanced feeding of two assemblies

Table 4: Test series in METERO test facility

Process	Term of equation	Test series	Test conditions
Wall friction	$\overrightarrow{\tau_{wk}}$	<ul style="list-style-type: none"> • P losses in axial flow • P losses in non-axial flow 	<ul style="list-style-type: none"> • Equal BC • UV
Momentum diffusion-dispersion	v_{tk}^ϕ	<ul style="list-style-type: none"> • Pressure losses with transverse flow 	<ul style="list-style-type: none"> • UV-UT-equal $\frac{\partial P}{\partial z}$ • With & without spacers
Scalar turbulent diffusion	d_{tk}^ϕ	<ul style="list-style-type: none"> • Mixing of a passive scalar in 1-phase flow 	<ul style="list-style-type: none"> • EV-US No spacers
Scalar dispersion	$\underline{\underline{D}}_{dk}^\phi$	<ul style="list-style-type: none"> • Mixing of a passive scalar in 1-phase flow 	<ul style="list-style-type: none"> • EV-US
Energy turbulent diffusion	α_{tk}^ϕ	<ul style="list-style-type: none"> • Energy mixing in 1-phase flow 	<ul style="list-style-type: none"> • UT No spacers
Energy dispersive tensor	$\underline{\underline{D}}_{dk}^\phi$	<ul style="list-style-type: none"> • Energy mixing in 1-phase flow 	<ul style="list-style-type: none"> • UT
Two-phase wall friction And two-phase interfacial friction	$\overrightarrow{\tau_{wk}}$ $\overrightarrow{\tau_i}$	<ul style="list-style-type: none"> • P losses and wall & interfacial friction in axial flow • P losses and wall & interfacial friction with transverse flows • P losses and wall & interfacial friction with buoyancy driven crossflows 	<ul style="list-style-type: none"> • EV-EX • UV-EX • UV-UX
Void dispersion	f_i^{TD}	<ul style="list-style-type: none"> • Void dispersion tests 	<ul style="list-style-type: none"> • UV-UX- equal $\frac{\partial P}{\partial z}$

UV: unequal velocity; EV equal velocity; ES equal scalar (tracer concentration); US unequal scalar concentration; UT: unequal temperature; UX: unequal quality; equal $\frac{\partial P}{\partial z}$ means that velocity differences and temperature or quality difference are such that the axial P gradient are equal to avoid crossflows and to measure scalar or temperature or void diffusion-dispersion