A porosity method to model the internal structures of a reactor vessel

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A Porosity Method to Model the Internal Structures of a Reactor Vessel

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Abstract

To take into account the influence of a structure net among a fluid flow, without modelling exactly the structure shape, a concept of "equivalent porosity method" was developped. The structures are considered as solid pores inside the fluid. The method was studied for HCDA in LMFBR, but it can be applied to any problem involving fluid flow getting through a solid net.

1 Introduction

In case of a Hypothetical Core Disruptive Accident (HCDA) in a Liquid Metal Reactor, the interaction between fuel and liquid sodium creates a high pressure gas bubble in the core. The violent expansion of this bubble loads the vessel and the internal structures, whose deformation is important.

During the 70s and 80s, the LMFBR integrity was studied with codes specially devoted to the analysis of transient loads resulting from a HCDA : SURBOUM, PISCES 2DELK, SEURBNUK/EURDYN, ASTARTE, CASSIOPEE, REXCO, SIRIUS... In order to validate these codes, experimental programmes and benchmarks were undertaken by several countries : COVA, APRICOT, WINCON, MARA, STROVA, CONT...

The SIRIUS french code [1] [2] was validated on the MARA experimental programme [3] [4]. Based on a 1/30 scale model of the SUPER-PHENIX reactor, this programme involves 10 tests of gradual complexity due to the addition of internal deformable structures :
- MARA 01/02 [5] consider a vessel partially filled with water and closed by a rigid roof,
- MARA 04 [6] represents the main core support structures,
- MARA 08/09 [7] are empty and closed by a flexible roof,
- MARA 10 [8] includes the core support structures and a simplified representation of the above core structure (ACS).

The MARS test [9] rests on a 1/20 scale mock-up including all the significant internal components.

As other codes using a Lagrangian approach, SIRIUS needed rezonings during calculation because the internal structure presence caused high distorsion of the fluid meshes. Finite differences were used for the sodium and the roof and finite elements for the thin vessel. As the argon and the bubble were not meshed, a law related volume to pressure.

At the end of the 80s, it was preferred to add a specific ADCR sodium-bubble-argon tricomponent constitutive law [10] to the general ALE fast dynamics finite element CASTEM-PLEXUS code [11]. The ADCR constitutive law was qualified on the CONT benchmark [12] [13].

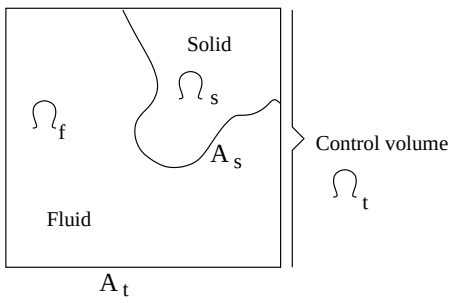
In order to demonstrate the CASTEM-PLEXUS capability to predict the behaviour of real reactors [14] [15], axisymmetrical computations of the MARA serie were confronted with the experimental results. Whereas the CASTEM-PLEXUS results and the MARA 08 and MARA 10 tests [16] were in a good agreement, the prediction of the MARS structure displacements and strains was overestimated [17].

This conservatism was mainly due to the fact that several MARS non axisymmetrical structures like core elements, pumps and heat exchangers were not represented in the CASTEM-PLEXUS model. These structures, acting as porous barriers, had a protective effect on the containment by absorbing energy and slowing down the fluid impacting the containment.

For these reasons, we developped in CASTEM-PLEXUS a new fluid constitutive law taking into account the presence of the internal structures (without meshing them) by means of an equivalent porosity method. This paper is focused on the theoretical bases of the method.

2 Definitions and hypothesises

Let us consider a fixed control volume Ω_t cut by an interface A_s. This interface divides the control volume into a fluid subvolume Ω_f and a solid subvolume Ω_s. Let us note A_t the surface bounding jointly the fluid volume and the control volume.



The hypothesises are:

H1 The issue is dealt with an Eulerian approach, so the control volume is constant and motionless.

H2 The solid is supposed inert, motionless, rigid, of any shape.

H3 The fluid is supposed homogeneous, isobar, adiabatic and Newtonian.

H4 The porosity is time independant.

H5 No material exchange between the fluid and the solid.

H6 No mass source.

H7 No heat source.

H8 The spatial fluctuations are much lower than the average values.

H9 The volumic viscosity is insignificant compared to the dynamic viscosity.

H10 The gradient of the viscosity (dynamic, volumic and turbulent) is negligible in comparison with the velocity Laplacian.

H11 The dynamic viscosity is negligible against the turbulent viscosity.

H12 The turbulent kinetic energy is insignificant against the (pressure/fluid density) ratio.

H13 The energy loss by solid-fluid viscous friction is inconsiderable, compared to the energy variation due to the pressure term.

H14 The average value of a variable on the solid surface is supposed equal to the fluid average value.

H15 The solid structures are supposed symetric enough to represent the fluid-solid friction by a diagonal isotropic tensor.

The porosity method aim consists in substituting an equivalent "porous" fluid for two different components (solid and fluid). The method is broken down into 3 steps:

• The fluid conservation laws are space-averaged on the control volume to consider the partial occupation of the control volume by the fluid. The fluid equations are written with both fluid, solid and control volume terms. As there is neither spatial nor temporal evolution of the solid (H2), it is pointless studying the solid conservation laws.

• The fluid equations are modified, by introducing a porosity coefficient, in order to replace the control volume terms by fluid ones. Except a fluid-solid force, the fluid conservation laws just depend on fluid variables.

• An equivalent "porous" fluid, with its own properties, is finally defined on the control volume. The conservation laws of this medium are matched up with the fluid equations previously defined.

Let $\Theta(x,y,z,t)$ be a function (scalar, vector or tensor) defined on the control volume Ω_t. $\overline{\Theta}(x,y,z,t)$ is the average value of Θ on the control volume Ω_t whereas $\underline{\Theta}(x,y,z,t)$ is the average value of Θ on the fluid volume Ω_f.

$$\overline{\Theta} = \frac{1}{\Omega_t}\int_{\Omega_f} \Theta \; d\Omega \qquad\qquad \underline{\Theta} = \frac{1}{\Omega_f}\int_{\Omega_f} \Theta \; d\Omega$$

Let β be the porosity, defined as the fluid presence fraction inside the control volume: $\beta = \Omega_f/\Omega_t$. The average values $\overline{\Theta}$ and $\underline{\Theta}$ are linked by: $\overline{\Theta} = \beta\,\underline{\Theta}$.

Consider a function ϕ defined on the fluid volume Ω_f. It can be separated into a fluid average term $\underline{\phi}$ and a fluctuating term ϕ', what leads to: $\phi = \underline{\phi} + \phi'$.

3 Fluid conservation laws homogenized on the control volume

The local conservation laws [18] of a fluid without source terms (H6) (H7) are:

$$\text{mass} \quad \frac{\partial}{\partial t}\,\rho_f + div\,(\rho_f\ \vec{v_f}) = 0$$

$$\text{momentum} \quad \frac{\partial}{\partial t}\,(\rho_f\ \vec{v_f}) + d\vec{i}v\,(\rho_f\ \vec{v_f}\otimes\vec{v_f}) - d\vec{i}v\,\overline{\overline{\sigma_f}} - \rho_f\ \vec{g} = \vec{0}$$

$$\text{total energy} \quad \frac{\partial}{\partial t}\left[\rho_f\left(u_f + \frac{1}{2}\,\vec{v_f}.\vec{v_f}\right)\right] + div\left[\rho_f\left(u_f + \frac{1}{2}\,\vec{v_f}.\vec{v_f}\right)\vec{v_f}\right] - div\,(\overline{\overline{\sigma_f}}.\vec{v_f}) - \rho_f\ \vec{g}.\vec{v_f} = 0$$

The conservation laws are space-averaged [19] on the control volume. For instance, the mass conservation becomes :

$$\frac{1}{\Omega_t}\int_{\Omega_f}\left[\frac{\partial}{\partial t}\,\rho_f + div\,(\rho_f\ \vec{v_f})\right]d\Omega = 0$$

According to the Leibniz and Gauss theorems [20], the volume integral is split up into:

$$\frac{1}{\Omega_t}\left[\left(\frac{d}{dt}\int_{\Omega_f}\rho_f\,d\Omega - \int_{A_t}\rho_f\ \vec{n_f}.\vec{v_t}\,dA - \int_{A_s}\rho_f\ \vec{n_f}.\vec{v_s}\,dA\right) + \left(div\int_{\Omega_f}\rho_f\ \vec{v_f}\,d\Omega + \int_{A_s}\rho_f\ \vec{n_f}.\vec{v_f}\,dA\right)\right] = 0$$

The hypothesises (H1),(H2) and (H5) impose that: $\vec{v_t} = \vec{0}$, $\vec{v_s} = \vec{0}$,

$$\int_{A_s}\rho_f\ \vec{n_f}.\vec{v_f}\,dA = 0 \qquad \text{and} \qquad \int_{\Omega_f}\frac{\partial}{\partial t}\,\rho_f\,d\Omega = \frac{\partial}{\partial t}\int_{\Omega_f}\rho_f\,d\Omega = \frac{d}{dt}\int_{\Omega_f}\rho_f\,d\Omega$$

After simplifications, the mass equation becomes: $\frac{\partial}{\partial t}\,(\overline{\rho_f}) + div\left(\overline{\rho_f\ \vec{v_f}}\right) = 0$

On the same way, the momentum and total energy equations can be written:

$$\frac{\partial}{\partial t}\left(\overline{\rho_f\ \vec{v_f}}\right) + d\vec{i}v\left(\overline{\rho_f\ \vec{v_f}\otimes\vec{v_f}}\right) - d\vec{i}v\,\overline{\overline{\sigma_f}} - \overline{\rho_f\ \vec{g}} - \frac{1}{\Omega_t}\int_{A_s}\vec{n_f}.\overline{\overline{\sigma_f}}\,dA = 0$$

$$\frac{\partial}{\partial t}\left[\overline{\rho_f\left(u_f + \frac{1}{2}\,\vec{v_f}.\vec{v_f}\right)}\right] + div\left[\overline{\rho_f\left(u_f + \frac{1}{2}\,\vec{v_f}.\vec{v_f}\right)\vec{v_f}}\right] - div\left(\overline{\overline{\sigma_f}.\vec{v_f}}\right) - \overline{\rho_f\ \vec{g}.\vec{v_f}} - \frac{1}{\Omega_t}\int_{A_s}\vec{n_f}.(\overline{\overline{\sigma_f}}.\vec{v_f})dA = 0$$

4 Fluid conservation laws homogenized on the fluid volume

By introducing the porosity β, the control volume averaged values can be replaced by fluid averaged terms. The porosity is time independent (H4) but space dependent, so β can be put out of the time derivatives but not of the space derivatives. The conservation laws can be rewritten in the following form:

$$\text{mass} \quad \beta\frac{\partial}{\partial t}\,\underline{\rho_f} + div\left(\beta\ \underline{\rho_f\ \vec{v_f}}\right) = 0$$

$$\text{momentum} \quad \beta\frac{\partial}{\partial t}\left(\underline{\rho_f\ \vec{v_f}}\right) + d\vec{i}v\left(\beta\ \underline{\rho_f\ \vec{v_f}\otimes\vec{v_f}}\right) - d\vec{i}v\left(\beta\,\underline{\overline{\overline{\sigma_f}}}\right) - \beta\ \underline{\rho_f\ \vec{g}} - \frac{1}{\Omega_t}\int_{A_s}\vec{n_f}.\overline{\overline{\sigma_f}}\,dA = 0$$

$$\text{total energy} \quad \beta\,\frac{\partial}{\partial t}\left[\underline{\rho_f\left(u_f + \frac{1}{2}\,\vec{v_f}.\vec{v_f}\right)}\right] + div\left[\beta\ \underline{\rho_f\left(u_f + \frac{1}{2}\,\vec{v_f}.\vec{v_f}\right)\vec{v_f}}\right] - div\left(\beta\,\underline{\overline{\overline{\sigma_f}}.\vec{v_f}}\right)$$
$$- \beta\ \underline{\rho_f\ \vec{g}.\vec{v_f}} - \frac{1}{\Omega_t}\int_{A_s}\vec{n_f}.\,(\overline{\overline{\sigma_f}}.\vec{v_f})\,dA = 0$$

Separating the average and fluctuating components of each variable, the mass equation can be transformed into: $$\beta \frac{\partial}{\partial t}\left(\underline{\underline{\rho_f + \rho_f{}'}}\right) + div\left[\beta \underline{\left(\underline{\rho_f} + \rho_f{}'\right)\left(\underline{\vec{v}_f} + \vec{v}_f{}'\right)}\right] = 0$$

Given ϕ and ψ some functions, we have: $\underline{\underline{\phi}} = \underline{\phi}$ $\quad \underline{\phi'} = 0$ $\quad$ and $\quad \underline{\phi + \psi} = \underline{\phi} + \underline{\psi}$

The average value of a product of an odd number of fluctuating terms is zero. Apart from the $\underline{\vec{v}_f{}' \otimes \vec{v}_f{}'}$ terms, the average value of a product of an even number of fluctuating terms can be disregarded (H8).

Applying these two rules to the mass conservation law, this one simplifies to [21] [22]:
$$\beta \frac{\partial}{\partial t}\underline{\rho_f} + div\left[\beta \underline{\rho_f}\,\underline{\vec{v}_f}\right] = 0$$

With the same method, we obtain the following expression for the momentum equation:
$$\beta\frac{\partial}{\partial t}\left(\underline{\rho_f}\,\underline{\vec{v}_f}\right)+\vec{div}\left(\beta\,\underline{\rho_f}\,\underline{\vec{v}_f}\otimes\underline{\vec{v}_f}\right)+\vec{div}\left(\beta\,\underline{\rho_f}\,\underline{\vec{v}_f{}'\otimes\vec{v}_f{}'}\right)-\vec{div}\left(\beta\,\underline{\overline{\overline{\sigma_f}}}\right)-\beta\,\underline{\rho_f}\,\vec{g}-\frac{1}{\Omega_t}\int_{A_s}\vec{n_f}.\overline{\overline{\sigma_f}}\,dA=\vec{0}$$

Using (H3)(H9)(H10), the stress tensor $\overline{\overline{\sigma_f}}$ can be expressed by [23]:
$$\overline{\overline{\sigma_f}} = \underbrace{-\,p_f\,\overline{\overline{I}}}_{\text{pressure}} \underbrace{-\frac{2}{3}\,\mu\,(div\,\vec{v}_f)\,\overline{\overline{I}} + \mu\left(\overline{\overline{grad}}\,\vec{v}_f + {}^t\overline{\overline{grad}}\,\vec{v}_f\right)}_{\text{viscous stresses}}$$

According to [21][24], the term $-\underline{\rho_f\,\vec{v}_f{}'\otimes\vec{v}_f{}'}$ is analogous to Reynolds stresses (turbulent stresses). Eliminating the negligible terms (H11)(H12) between $\overline{\overline{\sigma_f}}$ and $\overline{\overline{\sigma_{Re}}}$, we have:
$$\underline{\overline{\overline{\sigma_f}}} + \underline{\overline{\overline{\sigma_{Re}}}} = -\,\underline{p_f}\,\overline{\overline{I}} - \frac{2}{3}\,\mu_T\left(div\,\underline{\vec{v}_f}\right)\overline{\overline{I}} + \mu_T\left(\overline{\overline{grad}}\,\underline{\vec{v}_f} + {}^t\overline{\overline{grad}}\;\underline{\vec{v}_f}\right)$$

Using (H14) and adapting [25], the surface integral becomes:
$$-\frac{1}{\Omega_t}\int_{A_s}\vec{n_f}.\overline{\overline{\sigma_f}}\;dA = -\,\underline{p_f}\,\vec{grad}\;\beta - \beta\,\vec{F}_s$$
where $\beta\vec{F}_s$ is the solid-fluid interaction force and contains all the stress terms other than this in average pressure.

According to [26] and with (H15), this force becomes: $\beta\,\vec{F}_s = -\beta\,\frac{1}{2}\left(\frac{A_s}{\Omega_t}\,{}^t\vec{\xi}\;\overline{\overline{I}}\right).\,\underline{\rho_f}\,\left|\underline{\vec{v}_f}\right|\underline{\vec{v}_f}$

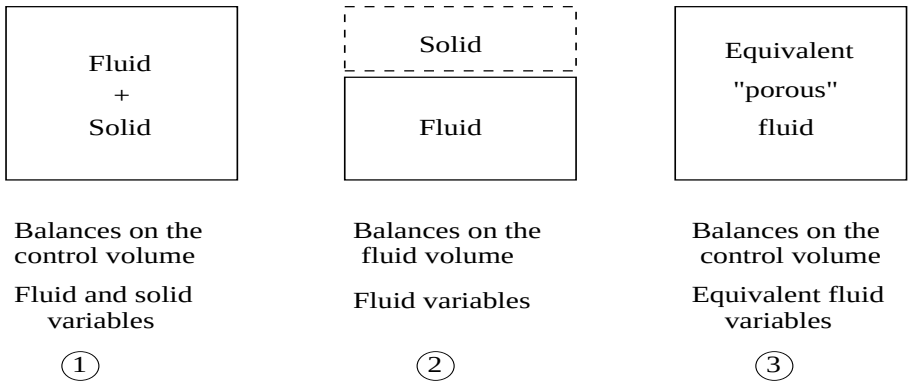
We then deduce the final expression of the momentum conservation law:
$$\beta\,\frac{\partial}{\partial t}\left(\underline{\rho_f}\,\underline{\vec{v}_f}\right)+\vec{div}\left(\beta\,\underline{\rho_f}\,\underline{\vec{v}_f}\otimes\underline{\vec{v}_f}\right)-\vec{div}\left[-\frac{2}{3}\,\beta\,\mu_T\left(div\,\underline{\vec{v}_f}\right)\overline{\overline{I}}+\beta\,\mu_T\left(\overline{\overline{grad}}\,\underline{\vec{v}_f}+{}^t\overline{\overline{grad}}\,\underline{\vec{v}_f}\right)\right]$$
$$+\,\beta\,\vec{grad}\,\underline{p_f}-\beta\,\underline{\rho_f}\,\underline{\vec{g}}+\beta\,\frac{1}{2}\,\frac{A_s}{\Omega_t}\,{}^t\vec{\xi}\;\overline{\overline{I}}\,.\,\underline{\rho_f}\;\left|\underline{\vec{v}_f}\right|\underline{\vec{v}_f}=\vec{0}$$

Let then deal with the total energy equation. Assuming (H2) and (H13), we have the following simplication:
$$\int_{A_s}\vec{n_f}.\left(\overline{\overline{\sigma_f}}.\vec{v}_f\right)dA = 0$$

Applying the previous method, the total energy equation can be rewritten:
$$\beta\,\frac{\partial}{\partial t}\left[\underline{\rho_f}\left(\underline{u_f}+\frac{1}{2}\,\underline{\vec{v}_f}.\underline{\vec{v}_f}\right)\right]+div\left[\beta\,\underline{\rho_f}\,\underline{\vec{v}_f}\left(\underline{u_f}+\frac{1}{2}\,\underline{\vec{v}_f}.\underline{\vec{v}_f}\right)\right]+div\left[\beta\,\underline{p_f}\,\underline{\vec{v}_f}\right]$$
$$-\,div\left[\left(-\frac{2}{3}\left(div\,\underline{\vec{v}_f}\right)\overline{\overline{I}}+\overline{\overline{grad}}\,\underline{\vec{v}_f}+{}^t\overline{\overline{grad}}\,\underline{\vec{v}_f}\right).\,\beta\,\mu_T\,\underline{\vec{v}_f}\right]-\beta\,\underline{\rho_f}\,\underline{\vec{v}_f}\,.\,\underline{\vec{g}}=0$$

5 Equivalent "porous" fluid equations

The initial problem was formulated with conservation laws, defined on the control volume subdivided into a fluid zone and a solid zone, and using variables of both components. The conservation laws averaged on the fluid allowed to have only fluid equations defined on the fluid subvolume and with fluid variables. To return to the initial control volume, we have to consider an equivalent fluid defined on the control volume and whose properties have to be determined.



The equivalent "porous" fluid can be considered as a single substance taking the whole control volume up. It is governed by the classical conservation laws with an additional force term in the momentum equation. The conservation laws can be presented in the following form:

$$\text{mass } \frac{\partial}{\partial t}\,\rho_{eq} + div\,(\rho_{eq}\ \vec{v_{eq}}) = 0$$

$$\text{momentum } \frac{\partial}{\partial t}\,(\rho_{eq}\ \vec{v_{eq}}) + \vec{div}\,(\rho_{eq}\ \vec{v_{eq}} \otimes \vec{v_{eq}}) + \vec{grad}\ p_{eq}$$
$$- \vec{div}\left[-\frac{2}{3}\,\mu_{T_{eq}}\,(div\ \vec{v_{eq}})\,\overline{\overline{I}} + \mu_{T_{eq}}\left(\overline{\overline{grad}}\ \vec{v_{eq}} + {}^{t}\overline{\overline{grad}}\ \vec{v_{eq}}\right)\right] - \rho_{eq}\ \vec{g} + \vec{F_{eq}} = \vec{0}$$

$$\text{total energy } \frac{\partial}{\partial t}\left[\rho_{eq}\left(u_{eq} + \frac{1}{2}\,\vec{v_{eq}}.\vec{v_{eq}}\right)\right] + div\left[\rho_{eq}\left(u_{eq} + \frac{1}{2}\,\vec{v_{eq}}.\vec{v_{eq}}\right)\vec{v_{eq}}\right] + div\,(p_{eq}\ \vec{v_{eq}})$$
$$- div\left[\left(-\frac{2}{3}\,(div\ \vec{v_{eq}})\,\overline{\overline{I}} + \overline{\overline{grad}}\ \vec{v_{eq}} + {}^{t}\overline{\overline{grad}}\ \vec{v_{eq}}\right).\,\mu_{T_{eq}}\ \vec{v_{eq}}\right] - \rho_{eq}\ \vec{g}.\vec{v_{eq}} = 0$$

Comparing term by term these equations with the fluid conservation laws homogenized on the fluid volume, we obtain the value of each equivalent variable:

$$\rho_{eq} = \beta\ \underline{\rho_f} \qquad \vec{v_{eq}} = \underline{\vec{v_f}} \qquad p_{eq} = \beta\ \underline{p_f} \qquad u_{eq} = \underline{u_f} \qquad \mu_{T_{eq}} = \beta\ \mu_T$$
$$\vec{F_{eq}} = -\underline{p_f}\ \vec{grad}\ \beta + \beta\ \frac{1}{2}\ \frac{A_s}{\Omega_t}\ {}^{t}\vec{\xi}\ \overline{\overline{I}}.\ \underline{\rho_f}\ \underline{|\vec{v_f}|}\ \underline{\vec{v_f}}$$

6 Conclusion

The concept of "equivalent porosity method" consists in transforming the fluid conservation laws so that they become independent of the solid volume and the solid variables. These equations are then transposed to the whole control volume (containing fluid and solid), what leads to define an equivalent "porous" fluid.

Compared with the classical fluid conservation laws, these equations have three new parameters: a porosity β, a loss of pressure coefficient $\vec{\xi}$ due to the fluid-solid friction and a coefficient A_s/Ω_t describing the global solid shape.

Besides the fact the new equations (mass, momentum and total energy) are written with equivalent variables, the momentum equation contains two new forces: a fluid-solid interaction force $\beta \vec{F}_s$ and a force $\underline{p_f}\ \vec{grad}\ \beta$ at the interface between two equivalent media with different porosities.

This paper presents the mathematic formulation of the homogenization method for any dynamic problem, without high heat fluxes, involving a monophasic fluid flow through a structure net. This method was implemented in the CASTEM-PLEXUS software [27] to represent easily the LMFBR internal structures among a sodium-argon-bubble fluid melt. The model was used to compute a HCDA [28] and to compare the predictions of the new model taking into account the structure influence and the previous results computed by the model without structures.

7 Nomenclature

Suffixes

eq	equivalent "porous" fluid	f	fluid
s	solid	t	control volume

Variables

A	surface	$\vec{F}_s$	fluid-solid interaction force
$\vec{g}$	gravity	$\overline{\overline{I}}$	unit tensor
$\vec{n}$	normal to a surface unit vector	p	pressure
t	time	u	internal energy
$\vec{v}$	velocity	β	porosity
μ	dynamic viscosity	μ_T	turbulent viscosity
Ω	volume	ϕ, ψ, Θ	functions
ρ	density	$\overline{\overline{\sigma}}$	total stress
$\overline{\overline{\sigma_{Re}}}$	Reynolds stress	$\vec{\xi}$	coefficients of directional pressure loss

8 References

1. Y. Blanchet, P. Obry, J. Louvet. 1981. Treatment of fluid-structure interaction with the SIRIUS computer code. *Smirt 6. Section B 8/8.*

2. A. Daneri, G. Toselli, T. Trombetti, Y. Blanchet, J. Louvet, P. Obry. 1981. Influence of the representation models of the stress-strain law on the LMFBR structures in an HCDA. *Smirt 6. Section E 4/4.*

3. J. Louvet. 1989. Containment response to a core energy release. Main experimental and theorical issues. Future trends. *Smirt 10. Vol E. pp 305-310.*

4. C. Bour, M. Spérandio, J. Louvet, C. Rieg. 1989. LMFBR's core disruptive accident. Mechanical study of the reactor block. *Smirt 10. Vol E. pp 281-287.*

5. D. Acker, A. Benuzzi, A. Yerkess, J. Louvet. 1981. MARA 01/02 - Experimental validation of the SEURBNUK and SIRIUS containment codes. *Smirt 6. Section E 3/6.*

6. B.L. Smith, C. Fiche, J. Louvet, A. Zucchini. 1985. A code comparison exercise based on the LMFBR containment experiment MARA-04. *Smirt 8. Section E 4/7. pp 151-157.*

7. C. Fiche, J. Louvet, B.L. Smith, A. Zucchini. 1985. Theoretical experimental study of flexible roof effects in an HCDA's simulation. *Smirt 8. Section E 4/5. pp 139-144.*

8. J. Louvet, P. Hamon, B.L. Smith, A. Zucchini. 1987. MARA 10: an integral model experiment in support of LMFBR containment analysis. *Smirt 9. Section E. pp 331-337.*
9. M. Falgayrettes, C. Fiche, P. Granet, P. Hamon, P. Barrau, B. Magnon, J. Jalouneix, M. Nédélec. 1983. Response of a 1/20 scale mock up of the Superphenix breeder reactor to an HCDA loading simulation. *Smirt 7. Section E 4/1. pp 157-166.*
10. A. Hoffmann, M. Lepareux, B. Schwab, H. Bung. 1984. Plexus - A general computer program for fast dynamic analysis, *Conference on Structural Analysis and Design on Nuclear Power Plant, Porto Alegre, Bresil.*
11. M. Lepareux, H. Bung, A. Combescure, J. Aguilar. 1991. Analysis of a CDA in a LMFBR with a multiphasic and multicomponent behaviour law. *Smirt 11. Section E 13/1. pp 371-376.*
12. A. Benuzzi. 1987. Comparison of different LMFBR primary containment codes applied to a benchmark problem. *Nuclear Engineering and Design 100. pp 239-249.*
13. F. Casadei, A. Daneri, G. Toselli. 1989. Use of PLEXUS as a LMFBR primary containment code for the CONT benchmark problem. *Smirt 10. Section E 13/1. pp 299-304.*
14. M. Lepareux, H. Bung, A. Combescure, J. Aguilar, J.F. Flobert. 1993. Analysis of an HCDA in a fast reastor with a multiphase and multicomponent behavior law. *Smirt 12. Section E 7/2. pp 197-202.*
15. Y. Cariou, J.P. Pirus, C. Avallet. 1997. LMR large accident analysis method. *Smirt 14. Section P 3/7. pp 395-402.*
16. Y. Cariou, M. Spérandio, M.Lepareux, K. Christodoulou. 1993. LMFBR's whole core accident. Validation of the PLEXUS code by comparison with MARA tests. *Smirt 12. Section E 7/4.*
17. Y. Cariou, M. Lepareux, H. Noé. 1997. LMR's whole core accident. Validation of the PLEXUS code by comparison with MARS test. *Smirt 14. Section P 2/6. pp 339-346.*
18. S. Candel. 1995. Mécanique des fluides. Cours. *Dunod, Paris, 1995. pp 87-102.*
19. S. Banerjee and A.M.C. Chan. 1980. Analysis of the averaged and local instantaneaous formulations. *International Journal of Multiphase Flow. Vol 6. pp 1-24.*
20. J.M. Delhaye, M. Giot and M.L. Riethmuller. 1981. Thermohydraulics of two-phase systems for industrial design and nuclear engineering. *A von Karman Institute Book. Hemisphere Publishing Corporation. McGraw-Hill Book Company. New York. Chapters 5 and 7.* 21. M Grandotto and P. Obry. 1996. Calculs des écoulements diphasiques dans les échangeurs par une méthode aux éléments finis. *Revue européenne des éléments finis. Vol 5. $n^0 1$. pp 53-74.*
22. J.L. Cheissoux, T. Delorme, J.P. Gaillard, M. Grandotto, M. Bernard and E. de Langre. 1989. A 3D finite element code for solving two-phase flow problems in steam generators. *NURETH-4. Karlsruhe F.R.G..*
23. J. Bouttes. 1983. Cours de mécanique des fluides. *Ecole Polytchnique. Paris. France.*
24. B. Mohammadi and O. Pironneau. 1994. Analysis of the K-Epsilon turbulence model. Research in Applied Mathematics. Chapter 8. *John Wiley & Sons. Chichester.*
25. F. Gilbert. 1987. Descriptions thermo-mécaniques de milieux à plusieurs constituants et application aux milieux poreux saturés. Chapter 4. *PhD. Pierre and Marie Curie University. Paris. France.*
26. D. Butterworth. 1978. The development of a model for three-dimensional flow in tube bundles. *International Journal of Heat and Mass Transfer. Vol 1. pp 253-256.*
27. F. Bliard and M.F. Robbe. 1996. Programme PLEXUS. Introduction d'un modèle de porosité dans le matériau ADCR. *CEA Report. DMT/96-620.*
28. E. Treille and M. Lepareux. 1998. Qualification d'une loi de comportement de type

ADC avec porosité. *CEA Report. DMT/98-032.*