Innovative modelling approaches for Molten Salt Small Modular Reactors

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Nuclear Reactors Group

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Introduction

Objective:

Improvement of the multi-physics modelling of Small Modular Molten Salt Reactors.

The purpose is to provide a general description of the reactor dynamics behaviour, focusing in particular on the effect of the smaller size on the operation and safety of the reactor.

Motivation:

- Strong interest innovative nuclear systems, such as Molten Salt Reactors, with intrinsic characteristics of safety and sustainability (e.g., operation at atmospheric pressure).
- Strong interest in Small Modular Reactors (more flexible power generation for a larger basis of users and applications).
- Molten salt fuel can be an interesting option to achieve a higher modularity (thanks to plant simplification).
- The peculiarities of these new reactors and the lack of a wide knowledge of their dynamic behaviour require the development of new simulation tools, tailored on the specificities of these innovative systems.

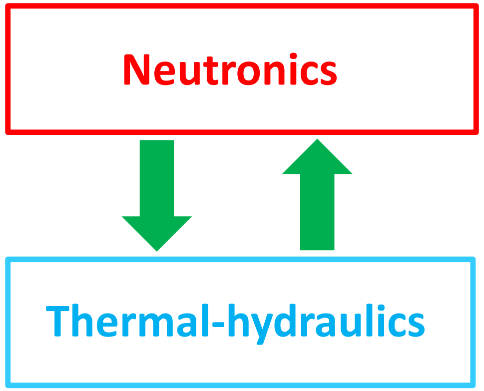
MSR specific issues

Differently from traditional solid fuel reactors, Molten Salt Reactors have some specific issues:

1. Due to the presence of a liquid fuel, the coupling between neutronics and thermal-hydraulics is stronger than in solid fuel reactors. New modelling approaches are needed to solve the coupling non linearities.

2. Gas (typically helium) bubbling systems are foreseen for the removal of gaseous fission products and as a possible option for reactivity control (exploiting the negative void coefficient of the bubbles).

3. Fuel compressibility may introduce delays in the thermal expansion feedbacks, affecting the system dynamics behavior.



Challenge:

- Different physics come into play (neutronics, two-phase fluid dynamics, nonlinear wave propagation, precursor transport).
- Each physics requires the development of a specific model.
- A coupling strategy is needed to describe the interactions among these physics.

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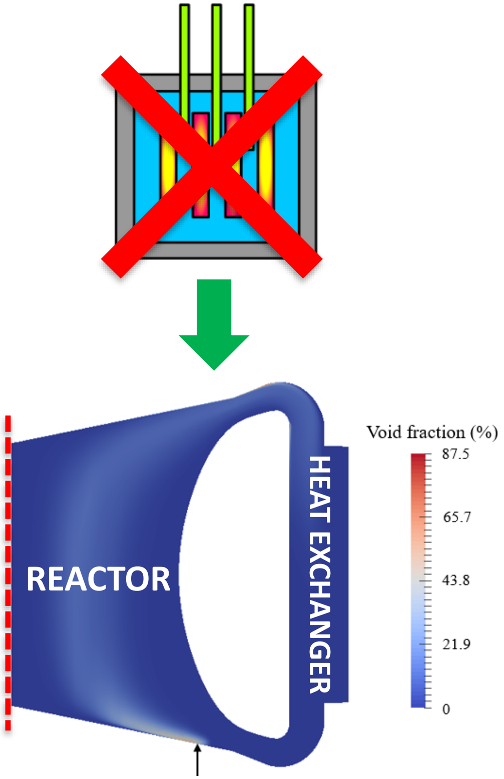

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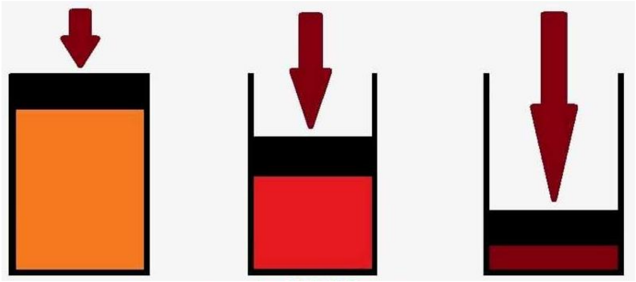

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MSR issues and reactor size

In the development of the SMR technology, it is relevant to investigate possible scaling effects and their impact on the operation and safety of the reactor.

Once these effects are well-defined, provisions and innovative solutions can be adopted in order to optimize the design and to fully exploit the benefits of the small modular concept.

In this view, the aim of this paper is analyzing the scaling effect on a molten salt reactor related to the presence of the bubbling system and to the compressibility.

Although these phenomena have been studied in larger-scale molten salt reactors [1, 2, 3], there is no detailed analysis of their impact in smaller reactors.

Compared to larger systems, these phenomena are expected to be particularly important in small modular reactors, in which thermal expansion and void reactivity effects are more significant due to the larger neutron leakages.

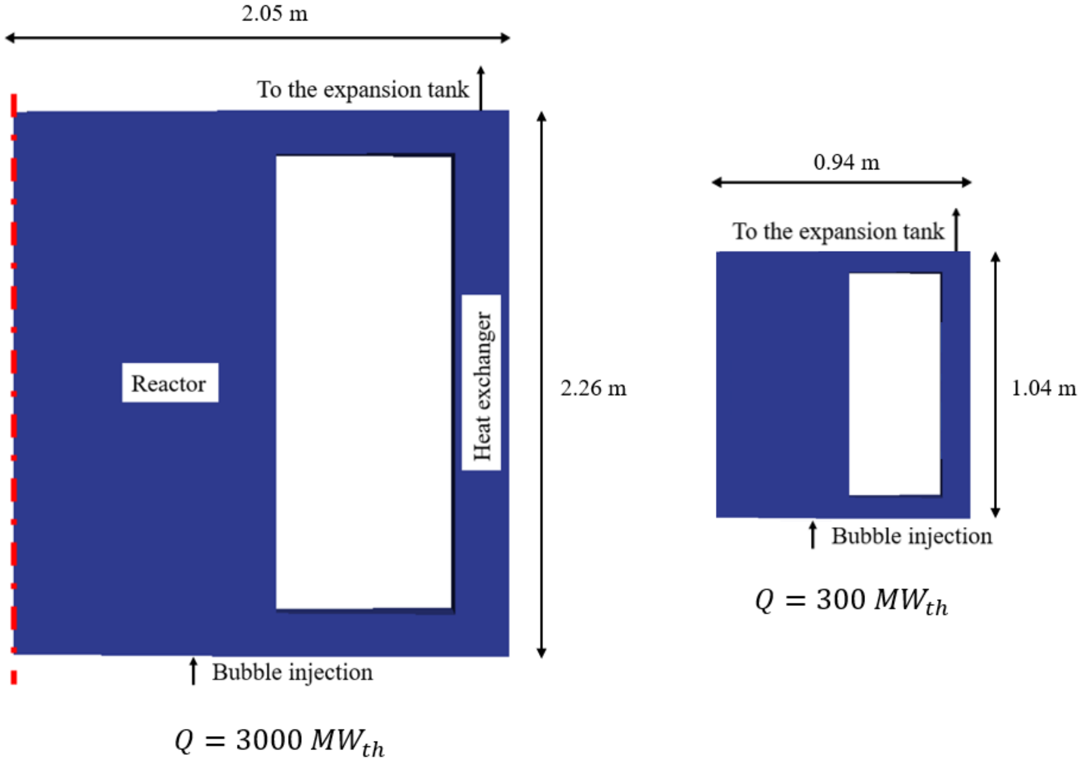
[1] Cervi et al., 2019. Development of a multiphysics model for the study of fuel compressibility effects in the Molten Salt Fast Reactor
[2] Cervi et al., 2019. Development of an SP3 neutron transport solver for the analysis of the Molten Salt Fast Reactor.
[3] Cervi et al., 2019. Multiphysics analysis of the MSFR helium bubbling system: a comparison between neutron diffusion, SP3 neutron transport and Monte Carlo approaches.

MSR issues and reactor size

To investigate these scaling effects, two reactors are considered:

- A 3000 MW Molten Salt Reactor;
- A downscaled 300 MW Small Modular Reactor.

Parameter	Value
Nominal power	3000 - 300 MW_{th}
Fuel inlet temperature	923 K
Fuel outlet temperature	1023 K
Total salt volume	18 m^3 - 1.8 m^3
Fuel composition (% mol.)	LiF (77.5) - ThF_4 (20.0) - $^{233}UF_4$ (2.5)
Static β_{eff}	300 pcm
Circulating β_{eff}	145 pcm



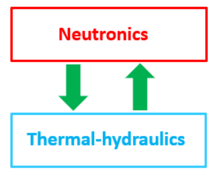
Overview

In the remaining part of the presentation, the following items will be discussed:

1) The modelling approach adopted in this work;

2) The impact of gas bubbling on reactivity;

3) Compressibility effects in fast transients.



MODELLING: state of the art

In the nuclear community, there is a strong interest on multiphysics for the analysis of innovative systems.

Multiphysics models for MSRs are available in literature [4,5]. However, these models

- Cannot handle the presence of bubbles inside the reactor;
- Treat the fuel mixture as an incompressible fluid.

For these reasons, they are not suitable for the analysis of (1) the bubbling system and (2) fuel compressibility effects.

New models have been developed to investigate these problems [1,2,3], but up to now they have never been applied to small modular systems. Scaling effects still need to be assessed.

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[3] Cervi et al., 2019. Multiphysics analysis of the MSFR helium bubbling system: a comparison between neutron diffusion, SP3 neutron transport and Monte Carlo approaches.
[4] Fiorina et al., 2014. Modelling and analysis of the MSFR transient behaviour.
[5] Aufiero et al., 2014. Development of an OpenFOAM model for the Molten Salt Fast Reactor transient analysis.

MODELLING: the developed model

In this work, a multiphysics model is adopted [1,2,3], including:

- **Multi-group neutron diffusion equations;**
- A two-phase, compressible thermal-hydraulics model, based on a ''two-fluids'' (or Euler-Euler) approach;
- Transport equations for the moving precursors.

This model has been implemented into OpenFOAM, a CFD and multiphysics toolkit based on the Finite Volume Method to solve partial differential equations.

$$\frac{1}{v_i}\frac{\partial \varphi_i}{\partial t} = \nabla \cdot D_i \nabla \varphi_i + \bar{\nu}\Sigma_{f,i}(1-\beta)\chi_{p,i}\varphi_i - \Sigma_{a,i}\varphi_i + S_{n,i}(1-\beta)\chi_{p,i}\varphi_i + S_d\chi_{d,i} + S_{s,i}$$

Source terms:

$$S_{n,i} = \sum_{j\neq i} \bar{\nu}\Sigma_{f,j}\varphi_j$$ (fission neutrons from the other groups)

$$S_d = \sum_k \lambda_k c_k$$ (delayed neutrons)

$$S_{s,i} = \sum_{j\neq i} \Sigma_{j\rightarrow i}\varphi_j$$ (scattering neutron to/from other energy groups)

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Neutronics
Thermal-hydraulics

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Mass:

$$\frac{\partial(\rho_j\alpha_j)}{\partial t} + \nabla\cdot(\rho_j\alpha_j\boldsymbol{u}_j) = 0 \qquad j = phase$$

Momentum:

$$\frac{\partial\rho_j\alpha_j\boldsymbol{u}_j}{\partial t} + \nabla\cdot(\rho_j\alpha_j\boldsymbol{u}_j\boldsymbol{u}_j) = \nabla\cdot\alpha_j\left[-p\boldsymbol{I} + (\mu+\mu_t)(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T) - \frac{2}{3}\mu\boldsymbol{I}\,div\,\boldsymbol{u}\right] + M_j$$

Energy:

$$\frac{\partial\rho_j\alpha_j h_j}{\partial t} + \nabla\cdot(\rho_j\alpha_j\boldsymbol{u}_j h_j) + \frac{\partial\rho_j\alpha_j k_j}{\partial t} + \nabla\cdot(\rho_j\alpha_j\boldsymbol{u}_j k_j) = \alpha_j\frac{\partial p}{\partial t} + \frac{\alpha_j}{\rho_j C_{p,j}}\nabla\cdot\left((K+K_t)\nabla h_j\right) + L\Delta T + \rho_j\alpha_j\boldsymbol{g}\cdot\boldsymbol{u}_j + Q$$

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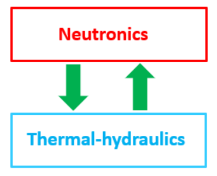

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Delayed neutron precursors:

$$\frac{\partial \rho_l \alpha_l c_k}{\partial t} + \nabla \cdot (\rho_l \alpha_l \boldsymbol{u}_l c_k) = \nabla \cdot \left(\rho_l \alpha_l \left(\frac{\nu}{Sc} + \frac{\nu_t}{Sc_t} \right) \nabla c_k \right) + \beta_k \sum_i \bar{\nu} \Sigma_{f,i} \varphi_i - \lambda_k \rho_l \alpha_l c_k$$

Decay heat precursors:

$$\frac{\partial \rho_l \alpha_l d_m}{\partial t} + \nabla \cdot (\rho_l \alpha_l \boldsymbol{u}_l d_m) = \nabla \cdot \left(\rho_l \alpha_l \left(\frac{\nu}{Sc} + \frac{\nu_t}{Sc_t} \right) \nabla d_m \right) + \beta_{h,l} \sum_i E_f \Sigma_{f,i} \varphi_i - \lambda_{h,l} \rho_l \alpha_l d_m$$

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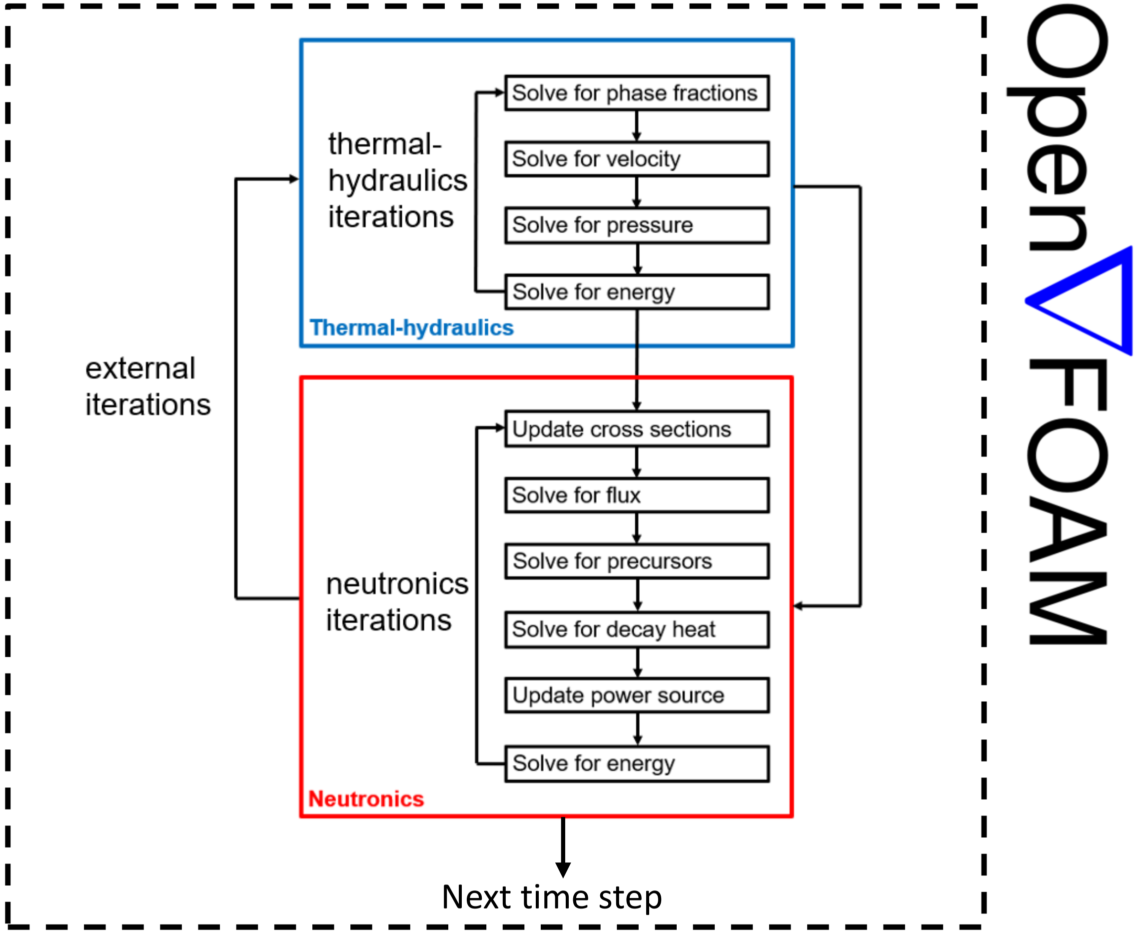
Solver structure and coupling strategy



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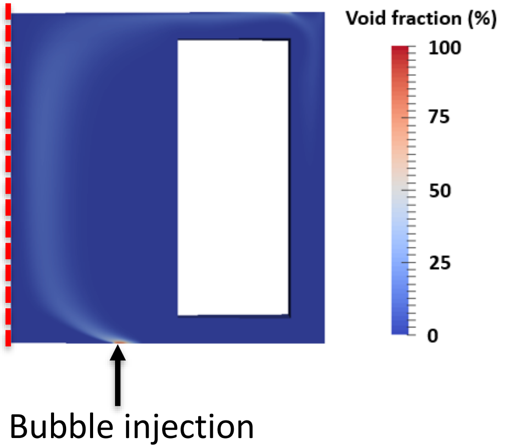
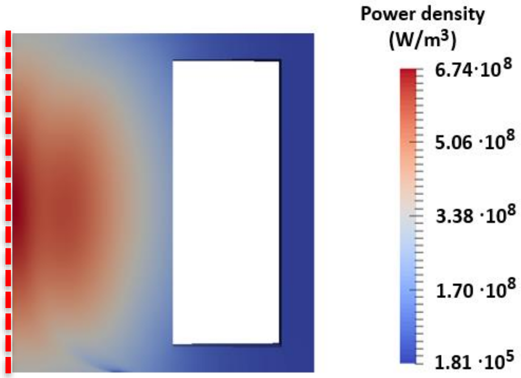
ANALYSIS OF THE GAS BUBBLING SYSTEM: Evaluation of the void reactivity coefficient





The void reactivity coefficient of the bubbles has been evaluated. Two approaches can be used [2,3]:

- Assuming a uniform bubble distribution (**green**);
- Calculating the bubble distribution with the multiphysics solver (**blue**).

Core average void fraction (%)	α_v (pcm/%) – 3000 MW system		Core average void fraction (%)	α_v (pcm/%) – 300 MW SMR	
	Uniform bubble distribution	*Real bubble distribution*		*Uniform bubble distribution*	*Real bubble distribution*
0.288	-154.2	-341.7	0.264	-363.6	-735.2
0.635	-155.0	-312.9	0.597	-361.8	-662.1
1.030	-155.7	-292.9	0.980	-364.9	-619.6
1.468	-156.5	-277.4	1.406	-365.7	-584.6

Visible differences arise between the two approaches. Spatial and neutron importance effects have a strong impact on the void reactivity feedback.

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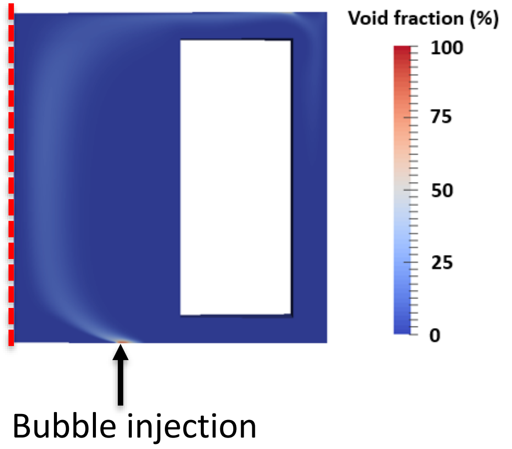
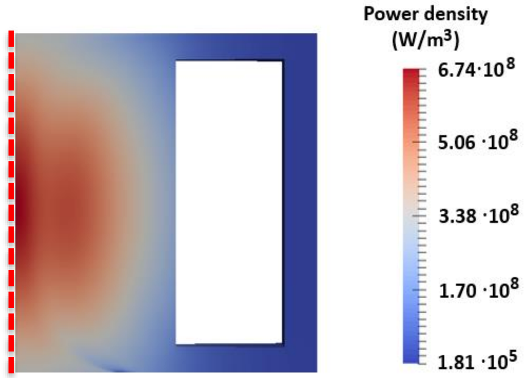
Evaluation of the void reactivity coefficient





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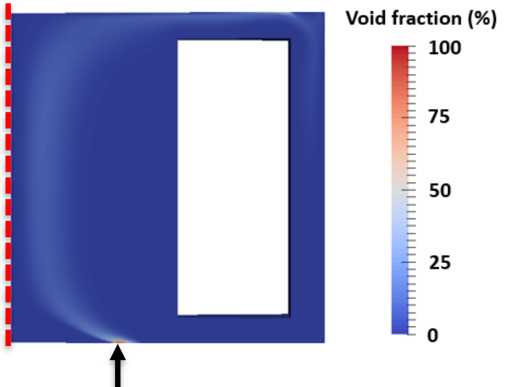
Uniform bubble distribution:

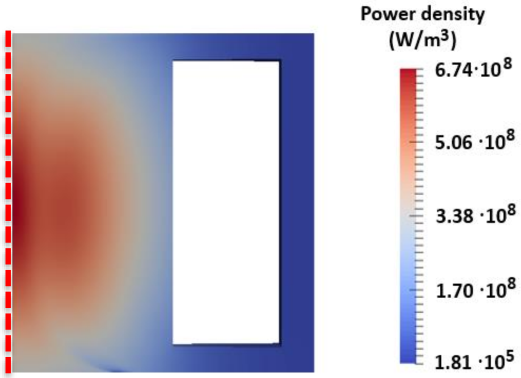
The void coefficient **slightly increases** at higher void fractions.

Higher void fraction → More neutron leakages → Stronger void feedback.

ANALYSIS OF THE GAS BUBBLING SYSTEM:
Evaluation of the void reactivity coefficient



Bubble injection



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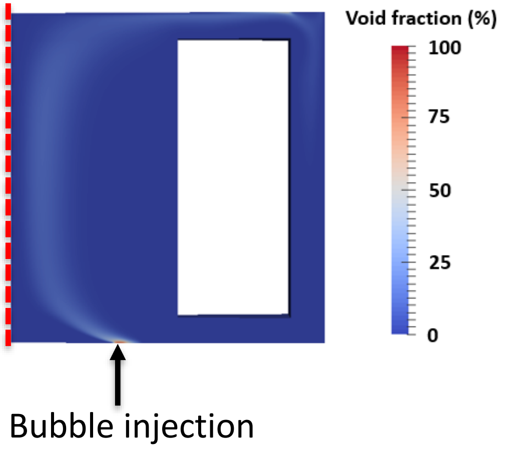
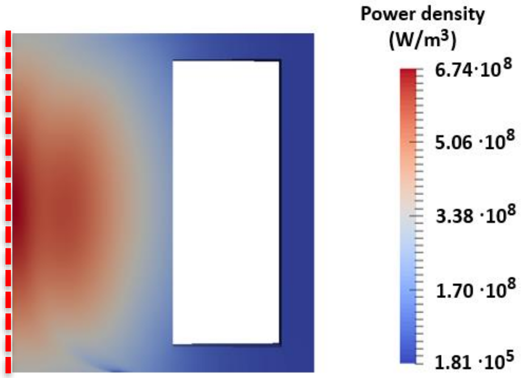
Calculated bubble distribution:

The void coefficient **decreases** at higher void fractions.

More bubbles in the reactor centre → Lower neutron importance in the centre → The marginal reactivity effect decreases.

ANALYSIS OF THE GAS BUBBLING SYSTEM:
Evaluation of the void reactivity coefficient





The reactor size strongly influences the void coefficient:

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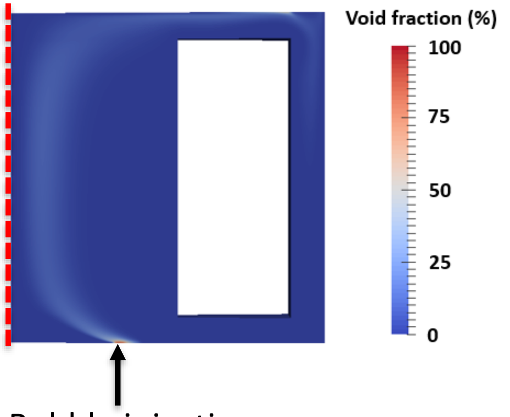
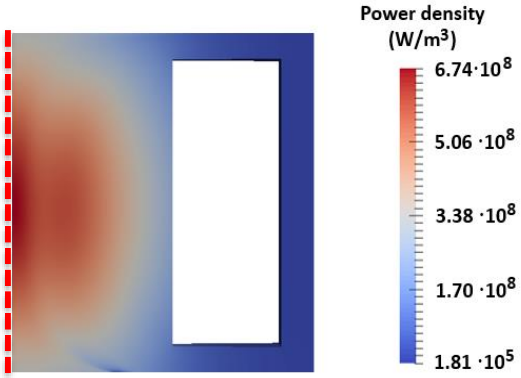
Uniform bubble distribution:

$\alpha_v \cong -150\ pcm/\%$ (3000 MW)

$\alpha_v \cong -360\ pcm/\%$ (300 MW)

ANALYSIS OF THE GAS BUBBLING SYSTEM:
Evaluation of the void reactivity coefficient





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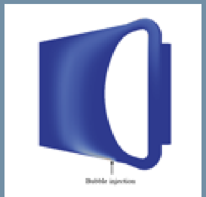
1.468	-156.5	-277.4	1.406	-365.7	-584.6

Calculated bubble distribution:

$\alpha_v \cong -300\ pcm/\%$ (3000 MW)

$\alpha_v \cong -600\ pcm/\%$ (300 MW)



ANALYSIS OF THE GAS BUBBLING SYSTEM: Discussion of results

- Due to higher neutron leakages, the void coefficient increases by a factor 2 in the 300 MW SMR.

- At 1% void fraction, a failure of the bubbling system would introduce about 600 pcm (POTENTIAL SAFETY CONCERN).

The void fraction should remain low to ensure safety. This may be feasible in a small modular reactor, due to the smaller quantity of gaseous fission products to be removed.

In any case, the adoption of a gas bubbling system constitutes a challenge in the design and development of a molten salt SMR.

Downscaling effects are an important aspect to be considered to design and optimize a gas bubbling system (and to evaluate its feasibility as well). Accurate multiphysics tools are required to fully investigate this challenging problem.

ANALYSIS OF FUEL COMPRESSIBILITY EFFECTS:
Pure salt compressibility

A 500 pcm reactivity insertion **(super-prompt-critical with the considered fuel composition)** at zero power conditions is simulated in two cases [1], using a simplified 2D geometry:

I-a) Compressible fuel: the fuel density depends on pressure and temperature as follows:

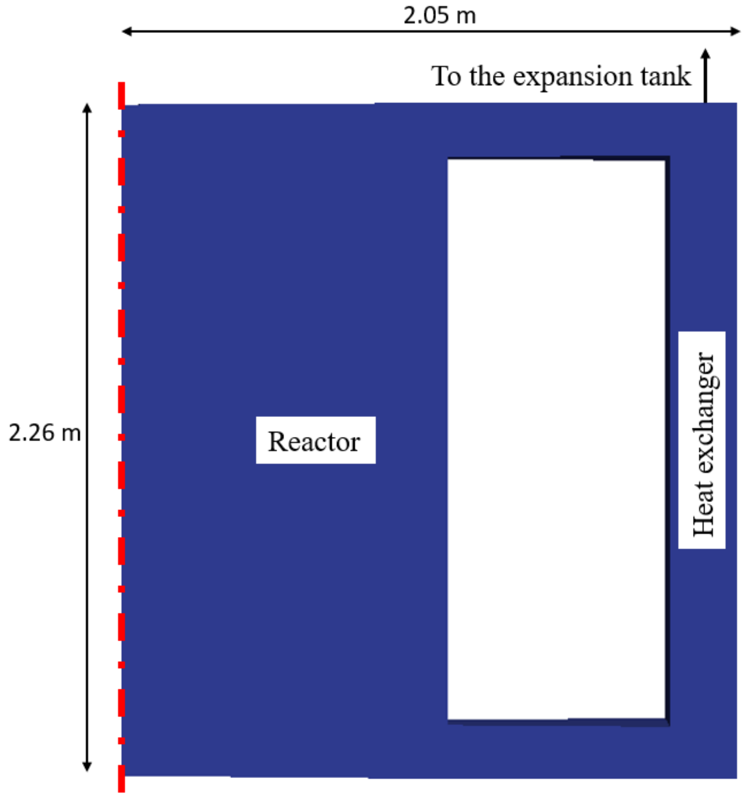
$$\rho_{fuel} = \rho_o - \beta(T - T_o) + \psi(p - p_o)$$

where ψ is the compressibility coefficient.

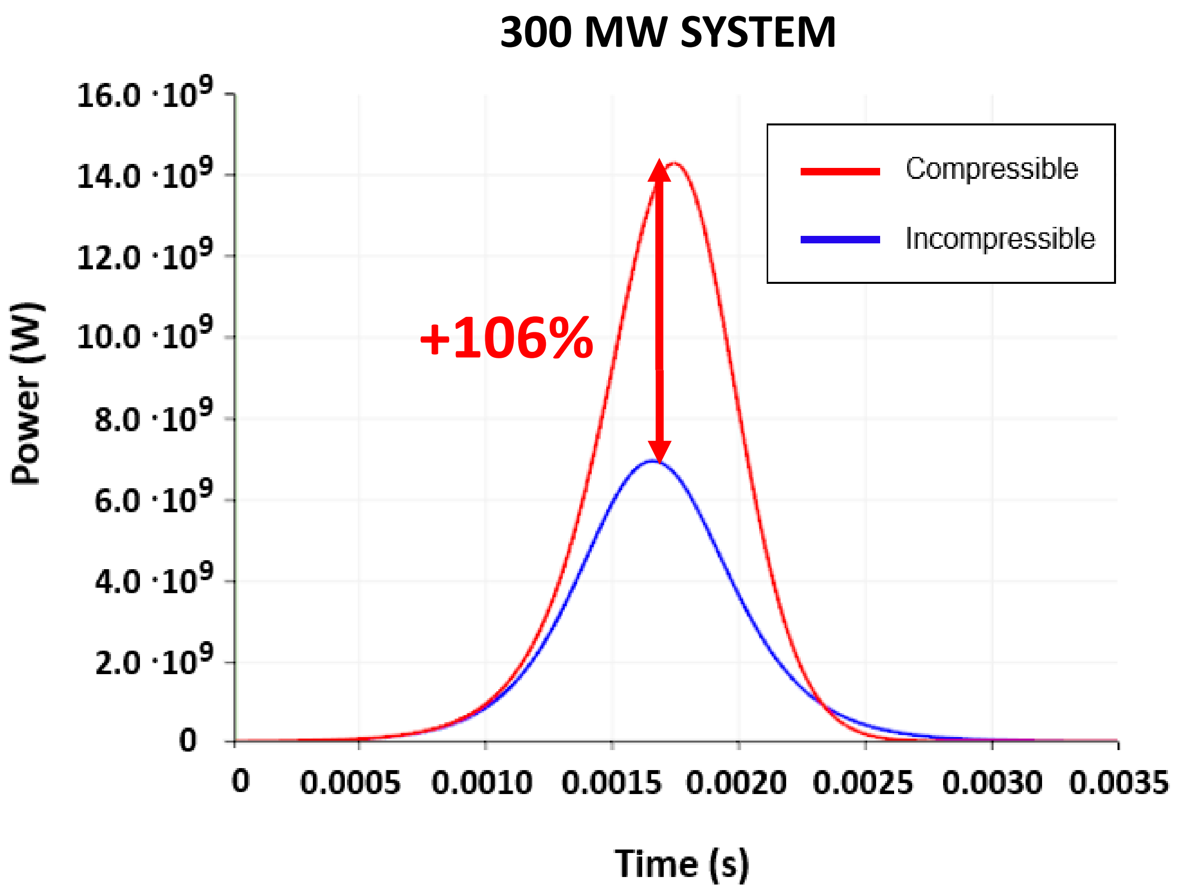
I-b) Incompressible fuel: the fuel density only depends on temperature.

$$\rho_{fuel} = \rho_o - \beta(T - T_o)$$

For simplicity, the helium bubbling system is not considered.



ANALYSIS OF FUEL COMPRESSIBILITY EFFECTS:
Pure salt compressibility



In the compressible case (**red**), the energy release is higher, compared to the incompressible one (**blue**).

In fact, compressibility introduces a delay in the thermal expansion feedback. The delay is not negligible because it is comparable to the transient characteristic times. Due to the delayed feedback, the energy release is higher.

On the other hand, in the incompressible case (**blue**), the expansion feedback is instantaneous and the energy release is lower.

	Doppler feedback	**Expansion Feedback**	**Power increase**
Compressible	**Prompt**	**Delayed**	**Higher** ↑↑
Incompressible	**Prompt**	**Prompt**	**Lower** ↑

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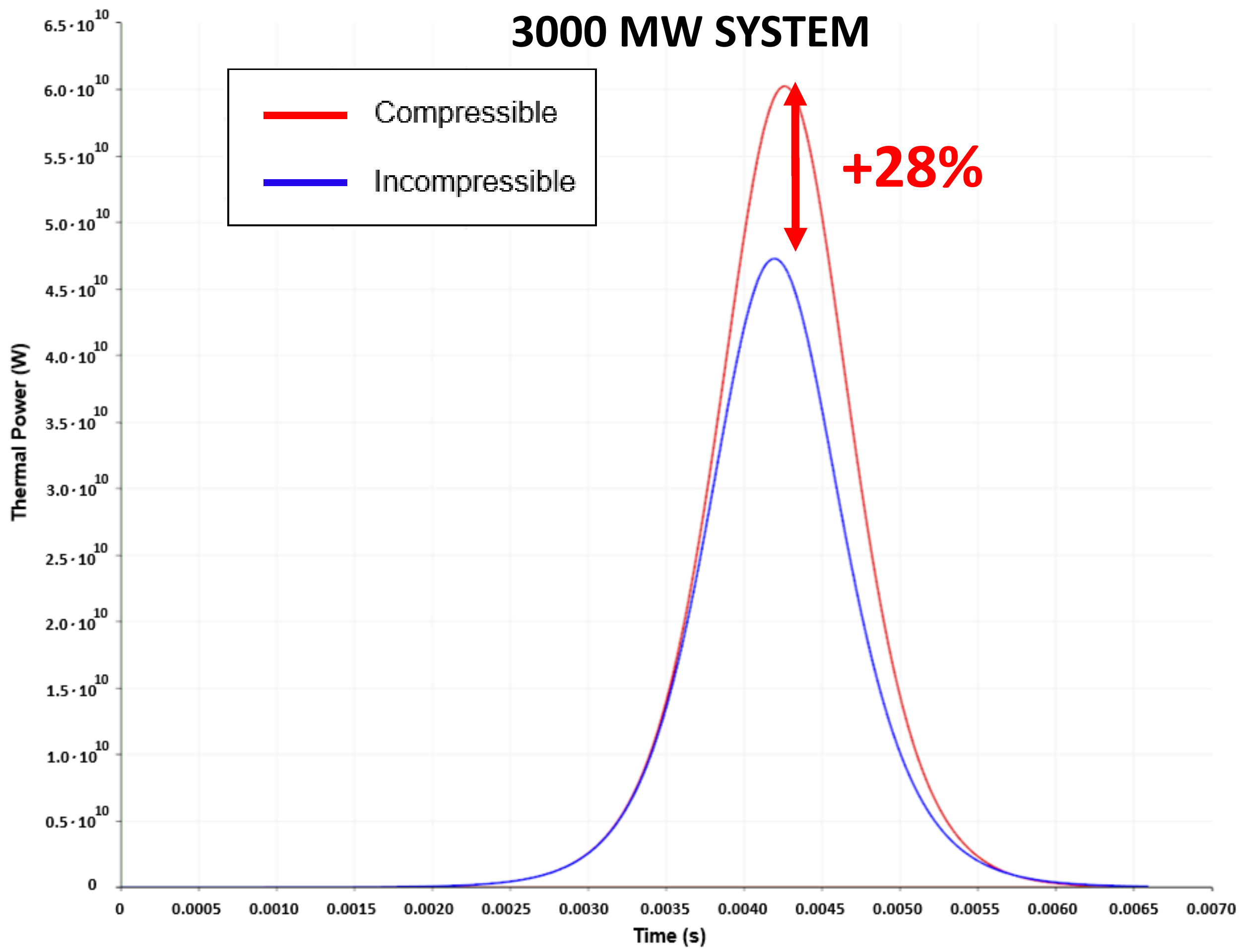
Pure salt compressibility



In the smaller system (strongly leakage dominated), the difference between the compressible and incompressible cases is higher (106% vs. 28%).

The incompressible approximation is non-conservative, because it underestimates the energy release.

This is especially true for small systems.

This constitutes a further example of how scaling effects are a challenging aspect that need to be considered in the development of Small Modular technology.

Conclusions

A multiphysics solver for the analysis of Small Modular Molten Salt Reactors has been presented. Thanks to this model, the following phenomena have been highlighted.

- The void reactivity feedback strongly depends on the bubble distribution through spatial and neutron importance effects.
- Compressibility has an important impact on super-prompt-critical transients, introducing delays in the thermal expansion feedback.
- **These effects are more evident in smaller systems, potentially raising safety concerns.**

The SMR technology has many advantages but also many challenges.

The increase of the void coefficient and of compressibility effects due to downscaling is an aspect that must be taken into account in the development of a Molten Salt SMR.

Suitable multiphysics tools are therefore required to investigate this problem, to optimize the reactor design and to fully exploit the benefit of the small modular concept.

THANKS FOR THE ATTENTION