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Development of a multiphysics model for the study of fuel compressibility effects in the Molten Salt Fast Reactor

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HIGHLIGHTS

- Investigation of fuel compressibility effects on the Molten Salt Fast Reactor (MSFR) dynamics.
- Modelling of the MSFR helium bubbling system.
- Development of a coupled neutronics and fluid dynamics model for the MSFR.
- Modelling of both liquid fuel and helium bubbles as compressible fluids.
- Effects on compressibility due to presence and distribution of helium bubbles are investigated.

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ABSTRACT

Compressible fluid dynamics is of great practical interest in many industrial applications, ranging from chemistry to aeronautical industry, and to nuclear field as well. At the same time, modelling and simulation of compressible flows is a very complex task, requiring the development of specific approaches, in order to describe the effect of pressure on the fluid velocity field. Compressibility effects become even more important in the study of two-phase flows, due to the presence of a gaseous phase. In addition, compressibility is also expected to have a significant impact on other physics, such as chemical or nuclear reactions occurring in the mixture. In this perspective, multiphysics represents a useful approach to address this complex problem, providing a way to catch all the different physics that come into play as well as the coupling between them.

In this work, a multiphysics model is developed for the analysis of the generation IV Molten Salt Fast Reactor (MSFR), with a specific focus on the compressibility effects of the fluid that acts as fuel in the reactor. The fuel mixture compressibility is expected to have an important effect on the system dynamics, especially in very rapid super-prompt-critical transients. In addition, the presence of a helium bubbling system used for online fission product removal could modify the fuel mixture compressibility, further affecting the system transient behaviour. Therefore, the MSFR represents an application of concrete interest, inherent to the analysis of compressibility effects and to the development of suitable modelling approaches. An OpenFOAM solver is developed to handle the fuel compressibility, the presence of gas bubbles in the reactor as well as the coupling between the system neutronics and fluid dynamics. The outcomes of this analysis point out that the fuel compressibility plays a crucial role in the evolution of fast transients, introducing delays in the expansion feedbacks that strongly affect the system dynamics. Moreover, it is found that the gas bubbles significantly alter the fuel compressibility, yielding even larger differences compared to the incompressible approximation usually adopted in the current MSFR solvers.

1. Introduction

Compressibility plays a crucial role in the propagation of waves within a fluid, since pressure and density perturbations travel at a finite velocity through the medium. The relative propagation velocity of the waves with respect to the fluid represents the local speed of sound. Although all the real fluids are compressible, this property can be often neglected, introducing the incompressibility assumption and assuming an infinite speed of sound (Thompson, 1972). However, there are many industrial applications, ranging from high-pressure chemistry to supersonic aerodynamics, in which the incompressible approximation is not suitable, since the fluid density is strongly affected by pressure. Compared to

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Nomenclature

Latin symbols

c	delayed neutron precursor density, m^{-3}
D	neutron diffusion coefficient, m
d	decay heat precursor density, W m^{-3}
$\mathbf{g}$	gravitational acceleration, m s^{-2}
h	specific enthalpy, J kg^{-1}
K	modified thermal diffusivity, J m^{-1} s^{-1} K^{-1}
k_{eff}	effective multiplication factor, –
K_{fuel}	pure salt bulk modulus, Pa
L	inter-phase heat transfer coefficient, W m^{-3} K
M	inter-phase momentum transfer, kg m^{-2} s^{-2}
Ma	Mach number, –
p	pressure, Pa
pcm	per cent mille (=10^{-5})
Q	power source density, W m^{-3}
S	mass source, kg m^{-3} s^{-1}
t	time, s
$\mathbf{u}$	velocity, m s^{-1}
v	neutron velocity, m s^{-1}

Greek symbols

α	gas fraction, –
β	delayed neutron precursor fraction, –
β_{heat}	decay heat energy fraction, –
β_{th}	thermal expansion coefficient, kg m^{-3} K^{-1}
ΔT	inter-phase temperature difference, K
κ	thermal conductivity, J s^{-1} m^{-1} K^{-1}
λ	delayed neutron precursor decay constant, s^{-1}
λ_h	decay heat precursor decay constant, s^{-1}
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2 s^{-1}
$\bar{\nu}$	mean neutrons per fission, –
ρ	density, kg m^{-3}
$\sum$	macroscopic cross section, m^{-2}
φ	neutron flux (diffusion equation), m^{-2} s^{-1}
χ	neutron yield, –
ψ	isothermal compressibility coefficient, m^{-2} s^{-2}

Subscripts-superscripts

b	bubble
d	delayed
f	fission
g	gas
h	decay heat
i	neutron energy group
j	phase
k	delayed neutron precursor group
l	liquid
m	decay heat precursor group
p	prompt
r	removal
s	scattering
tr	transport

incompressible fluid dynamics, the study of compressible flows requires a specific treatment both from a theoretical and numerical point of view, calling for the coupled solution of the continuity, momentum and energy equations (Moukalled et al., 2016). In addition, the density variation may have important feedbacks on other physics involved in the problem, further complicating the analysis of many complex systems of industrial interest (e.g., chemical and nuclear reactors).

Compressibility effects become of particular interest in the analysis of two-phase liquid-gas flows. In this situation, the presence of gas bubbles may have a relevant impact on the average mixture compressibility. In addition, local effects may also arise in case of strongly heterogeneous spatial distributions of the gaseous phase, leading to phenomena that cannot be caught with single-phase or homogeneous-mixture approaches.

In this sense, the multiphysics approach constitutes a valuable tool to address the problem, providing an efficient way to describe all the different physical phenomena occurring in an industrial process (Cammi et al., 2011, 2012; Aufiero et al., 2014a, 2014b; Fiorina et al., 2014). In the present work, a multiphysics modelling approach is presented for the analysis of the impact of fuel compressibility during super-prompt-critical transients in the generation IV Molten Salt Fast Reactor (GIF, 2016).

The Molten Salt Fast Reactor (MSFR), developed in the framework of the H2020 SAMOFAR Project (http://samofar.eu/), is a circulating fuel nuclear reactor in which a mixture of molten thorium and uranium fluorides acts as fuel and coolant simultaneously (Serp et al., 2014; Dolan, 2017; Gerardin et al., 2017). From a computational point of view, the simulation of nuclear reactor dynamics is a complex multiphysics task, needing accurate solution for both neutronics and thermal hydraulics and considering the coupling between them. This is even more important in circulating fuel nuclear reactors, in which the velocity field of the fuel salt mixture has a significant impact on the distribution of the delayed neutron precursors, affecting the reactor kinetics (a brief description of the MSFR is provided in Section 2.1). Given this tight coupling between neutronics and fluid dynamics, the effect of the fuel mixture compressibility may play a relevant role on the dynamics of the system and on the transient behaviour of the reactor.

Due to the negative temperature feedback coefficient of the MSFR (Gerardin et al., 2017), temperature increases during power excursions lead to a reduction of the system reactivity. This feedback is partly due to the Doppler effect, related to the neutron captures by the fertile nuclides, and partly to the thermal expansion of the fuel, which increases neutron leakages. While the Doppler effect acts promptly to reduce the system reactivity, the expansion feedback is delayed, since a density perturbation takes a finite time to propagate through the reactor.

In the MSFR, the speed of sound in the fuel mixture is about 1200 m/s, hence sufficiently high to consider the pressure wave propagation connected to the fluid compressibility as “instantaneous” in most transient scenarios (Aufiero et al., 2017). On the other hand, this may not be the case for very rapid super-prompt-critical transients, which could be a reason of concern during the reactor start-up, due to unwanted fuel injections. In fact, the characteristic times of these transients are in the order of a few milliseconds, comparable to the propagation time of pressure waves in the reactor. This could lead to a delay of the expansion mechanism, resulting in an overall weaker feedback. For this reason, the adoption of incompressible approximation (Aufiero et al., 2014a, 2014b; Fiorina et al., 2014) may result in significant underestimations of the energy released in super-prompt-critical transients. The analysis of these strongly coupled transients provides meaningful information also from a safety point of view, as highlighted by Qiu et al. (2016) and Zhang et al. (2018).

In addition, a helium bubbling system is envisaged in the MSFR to efficiently remove the gaseous fission products in the salt, but also as a possible option for the reactivity control of the reactor, exploiting the void reactivity feedback of the air bubbles in the fuel