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Numerical modeling of an in-vessel flow limiter using an immersed boundary approach

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A B S T R A C T

This work is in the context of the mitigation of the consequences of a large-break loss of coolant accident in a pressurized water reactor. To minimize the flow leaving the vessel and prevent or delay the uncovering of the core, CEA has devised a device, named in-vessel flow limiter, limiting the flow of fluid from the vessel to the break. The goal is to interfere as little as possible with the nominal operation flow and maximize the fluid retained in the event of this kind of accident.

In order to quickly perform a series of 3D-CFD simulations to optimize this device, it is imperative to have a simulation tool that provides sufficiently accurate results in a reasonable time. For this goal, an immersed boundary condition approach is retained. The solid obstacles constituted by the fins of the device are not extruded from the fluid domain, but included in the calculation domain itself. Their presence is considered by a local forcing term.

Through 3D/1D up-scaling of CFD global quantities, local pressure-drop coefficients, induced by the in-vessel flow limiter, can be provided to thermal-hydraulic system safety codes. It allows safety studies of the thermal-hydraulic system taking into account the in-vessel flow limiter presence in a more realistic way.

1. Introduction – context

The context of this work is set in the domain of Generation II and III nuclear power plants. Generation II reactors are the class of commercial reactors that was built by the end of the 1990s and that includes several types of design: PWR, BWR, CANDU, AGR and VVER. Generation III reactors are the innovative designs that are under construction or still in design phase: EPR, ATMEA1, AP1000, APR1400, ESBWR, …(IAEA, 2013). More specifically, we focused on the light-water Pressurized Water Reactors (PWRs), which are the main type of reactors built and exploited in France. Nowadays passive safety systems are more and more included in the nuclear-reactor safety strategy to mitigate design basis accidents (for example AP600 and AP1000 (IAEA, 2013); see also (IAEA, 2009)). A passive safety system is a system that activates itself without the need of mechanical or electrical actuation. The passive systems are divided into four main categories (A to D), depending on the particular phenomena/device that is not used for the activation of the structure (IAEA, 1991):

1. No moving working fluid,
2. No moving mechanical part,
3. No input signal of “intelligence”,
4. No external power input or forces.

For instance, the fuel cladding belongs to the category A (1, 2, 3 and 4) and the pressurizer surge line or the hydraulic diode – one-way flow reduction through vortex effect – to the category B (2, 3 and 4). The accumulators belong to the category C (3 and 4) and the SCRAM to the category D (4 only).

The interest of these particular systems is given by the possibilities that derive from their employment. Some of the main benefits are: the simplification of the pipe networks for the safety injection (SI) systems, the potential disappearance of some active elements such as some specific pumps and the economical saving (less active systems to be placed and operated).

At CEA, some studies on passive safety systems have been done in the past years, notably for the in-vessel flow limiter (hydraulic diode) patented by the CEA (Gautier, 1988) designed to limit the amount of water lost during the short-term sequence of a Large-Break (LB) Loss Of Coolant Accident (LOCA), cf. Fig. 1. French 900 MWe CP1 and 1,300 MWe P4 PWRs and low-pressure PWRs have been the reference reactors for these investigations (Gautier et al., 1999). An other example is the advanced accumulator with passive hydraulic-diode device considered in the Generation III projects (ATMEA1, AP1000, APR1400, …) (Shiraishi, 2011; Chu et al., 2008). The goal of this device is to set up a two-step injection regime. The first one is a high-rate injection of the amount of water needed to fill the vessel lower plenum and down-

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Nomenclature

Latin symbols

a_S	Schlichting model dimensionless constant
A_e	obstacle area intercepted by the element e (m^2)
AGR	Advanced Gas-cooled Reactor
AP1000	Advanced Passive PWR
APR1400	Advanced Power Reactor
ATMEA1	High-performance medium-power reactor of the ATMEA company (a joint-venture of AREVA and MITSUBISHI companies)
BTD	Balancing Tensor Diffusivity method
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium Uranium reactor
C_d	drag coefficient
CFD	Computational Fluid Dynamic
CP1	900 MWe French PWR (*Palier CP1*)
EPR	Evolutionary Power Reactor
ESBWR	Economic Simplified Boiling Water Reactor
$\mathbf{g}$	gravity (m s^{-2})
$\mathbf{G}$	mixture mass flux ($=\rho\mathbf{V}$)
H	mixture specific enthalpy (J kg^{-1})
H_{ls}	saturated liquid specific enthalpy (J kg^{-1})
IB	Immersed Boundary
IBC	Immersed Boundary Condition
ISI	Immersed Spread Interface
L	latent heat (J kg^{-1})
L_T	typical vortex length (m)
L_w	recirculation length (m)
LB LOCA	Large Break Loss Of Coolant Accident
M_i	domain mesh
P	pressure (Pa)
P_R	Prandtl number $\left(=\frac{\mu_T}{\chi_T}\right)$
PWR	Pressurized Water Reactor
P4	1,300 MWe French PWR (*Palier P4*)
SCRAM	Safety Control Rod Axe Man
SI	Safety Injection
SUPG	Streamline Upwind Petrov–Galerkin method
t	time (s)
$\mathbf{V}$	mixture velocity (m s^{-1})
$\mathbf{v}_R$	relative velocity (gas minus liquid, m s^{-1})
VVER	Vodo-Vodiano Energuetitcheski Reaktor
x	static quality $\left(\equiv\frac{H-H_{ls}}{L}\right)$

Greek symbols

ϵ	Penalty parameter ($0<\epsilon\ll 1$)
χ_T	turbulent diffusion coefficient for the enthalpy balance equation (kg m^{-1} s^{-1})
$\overline{\overline{\Lambda}}$	two-phase friction tensor (s^{-1})
μ_T	two-phase turbulent dynamic viscosity (N s m^{-2})
Ω_e	elementary volume of the element e (m^3)
ρ	mixture density (kg m^{-3})

comer. Then, the second step is a low-rate injection limited to just maintain the water level. The expected goal is a better use of the water injected by the SI accumulators and a bigger delay for the on-set of the SI pumps. Let us notice that it is important to assess the conjoint effect of these kind of passive devices. In fact, the effect of an elementary device can be increased or minimized in conjunction with other ones. For instance, In-vessel flow limiters and advanced accumulators contribute to strongly reduce the short-term primary-mass lost during LB-LOCA as demonstrated in Stratta and Belliard (2017) on a generic 3-loop middle-range electrical-power reactor of 1150 MWe, taking inspiration from the ATMEA1 reactor. In reference to the case without hydraulic diodes, the accumulator injection time is more than doubled (which means that the pumps can start with a bigger delay), the reflooding level is increased of almost +35% and the peak cladding temperatures are reduced of about −10% and −43% on the short and long term. These computations were done with the French reference thermal–hydraulic system safety code CATHARE (Barré and Bernard, 1990; Geffraye et al., 2009), originally devoted to the study of water-cooled reactor transients (standard operations or accidental transients from any kind of failures or size and location of breaks), that is based on 0D/1D and 3D modules using six-equation (mass, momentum and energy) two-fluid models. But, the relevance of these system-scale studies

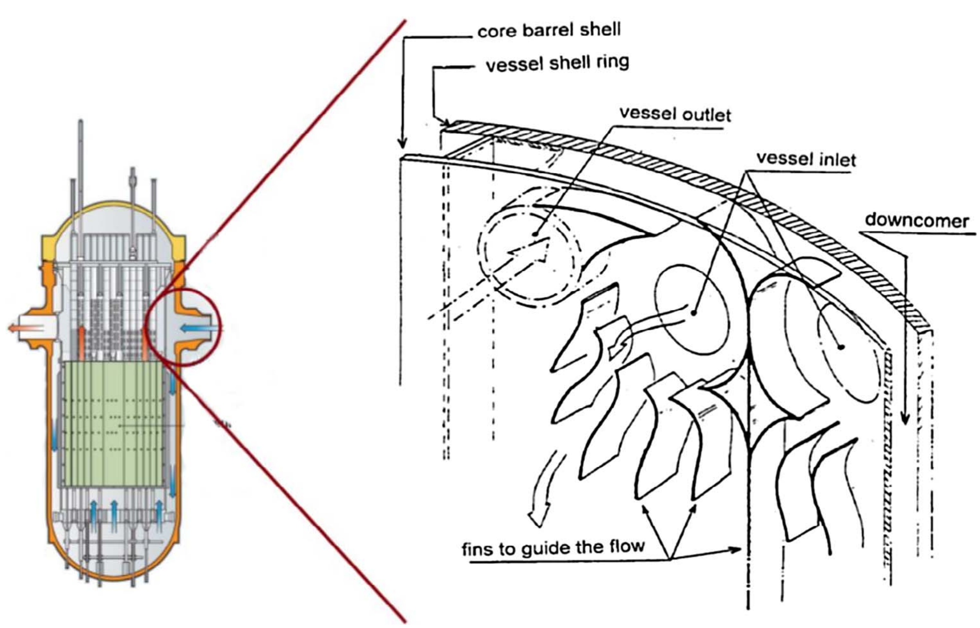

Fig. 1. Scheme of in-vessel flow limiters (hydraulic diode) located between the cold legs and the downcomer (Gautier et al., 1999).