Thermal hydraulic modeling needs for LWR-SMRs

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1. Introduction and main Characteristics of Small Modular Reactors

The Interest on development and deployment of Small Modular Reactors (SMR) has been increasing worldwide over the last years. Many studies have been carried out in many countries such as USA, China, United Kingdom, Canada or France about the technical and economic feasibility of SMR-deployment with an active role in the energy mix, together with large nuclear power plants and renewable energy facilities.

Several countries are arguing that SMRs must be part of the future energy-mix to achieve the low-carbon power generation goals with a low risk and cost in a competitive energy market. Other countries e.g. Finland or Poland, are also actively discussing the use of dedicated SMRs for district heating.

Many water-cooled SMR concepts are already in the certification and/or pre-licensing phase e.g. NuScale, SMART, CAREM, BWRX-100, ACP-100, RITM-200, etc. In Tables 1 and 2, the main features of the most promising SMR concepts are shown. It can also be observed that some of them are operated without active coolant pumps, using natural circulation instead and the majority have been designed as integrated primary system in a RPV.

To summarize, the following common features of water-cooled SMR-designs are highlighted hereafter:

- Integral concept for the RPV i.e. the RPV is housing many components such as helical SG (NuScale, SMART, CAREM), pumps (SMART, ACP100, mPower, W-SMR) or the pressurizer (SMART, NuScale, mPower)
- Some SMRs are based on forced convection for core heat removal (SMART, ACP-100, W-SMR, mPower, IRIS, UK-SMR) and others use natural circulation (SMR-160, NuScale, CAREM)
- Some concepts consider a boron free core design (CAREM, SMART with KSMOR core, SMR-160, mPower, UK-SMR, F-SMR) while other SMRs are operated with diluted boron in the primary system coolant (W-SMR, NuScale, SMART, ACP100)

One of the implications of the integrated SMR-concepts is the resulting three-dimensional mixed convection flow conditions prevailing during normal operation due to the presence of many components inside the reactor pressure vessel (RPV), which perturbs the main flow paths. In addition, the RPV-size, and the flow paths inside it determines the effectiveness of the heat removal in the SMR-concepts based on natural circulation.

From a safety point of view, the different LWR SMR-concepts are equipped with similar features to accomplish important safety functions such as core sub-criticality and core coolability under different accidental scenarios. The main step forward of these safety systems is that most of them relay on passive systems and natural circulation for the residual heat removal.

The ECCS mainly consists of core makeup tanks or hydro-accumulators, that rely for example on gravity drain to inject cold water and passive recirculation from sumps combined with an ADS. Given the small scale of the reactor, the containment wall can actuate as a heat sink in many SMR designs and then it acts as a safety system in several sequences (e.g. SBO and SBLOCA).

The short and long term residual heat removal mainly relies on natural circulation and passive residual heat removal systems that were already developed for Gen-III reactors such as, ESBWR, VVER-1200, HPR1000, AP-1000, APR+ or KERENA.

Additionally, due to the peculiar SMR-designs, some Events are considered as precluded:

- Large LOCA (for integral concepts)
- RIA due to rode ejection (For internal mechanisms designs) e.g. in NUWARD and CAREM
- LOFA, (precluded in designs with natural circulation, and minimized due to configurations more suitable for Natural Circulation)

	Name	Capacity	Type	Developer
In operation	KLT-40S	35 MWe	PWR	OKBM, Russia
	RITM-200	50 MWe	iPWR	OKBM, Russia
Under construction	CAREM-25	27 MWe	iPWR	CNEA & INVAP, Argentina
	ACPR50S	60 MWe	PWR	CGN, China
near-term deployment – development well advanced	NuScale	60 MWe	iPWR	NuScale Power + Fluor, USA
	SMR-160	160 MWe	PWR	Holtec, USA + SNC-Lavalin, Canada
	ACP100	125 MWe	iPWR	NPIC/CNPE/CNNC, China
	SMART	100 MWe	iPWR	KAERI, South Korea
	VBER-300	300 MWe	PWR	OKBM, Russia
	BWRX-300	300 MWe	BWR	GE Hitachi, USA
Small reactor designs at earlier stages or shelved (*Well-advanced designs understood to be on hold or abandoned.)	CAP200	220 MWe	PWR	SNERDI, China
	SNP350	350 MWe	PWR	SNERDI, China
	ACPR100	140 MWe	iPWR	CGN, China
	IRIS	335 MWe	iPWR	International Consortium
	Rolls-Royce SMR	220+ MWe	PWR	Rolls-Royce, UK
	VK-300	300 MWe	BWR	NIKIET, Russia
	Westinghouse SMR	225 MWe	iPWR	WEC, USA*
	mPower	195 MWe	iPWR	BWXT, USA*

Table 1. Light water SMR under development

SMR	Country # Designer	Status	Configuration # Vessel (diameter (m)/ height (m))	Thermal / electric capacity (MWt/e)	Primary circulation	RCS pressure (bar)	Inlet / outlet Temperature °C	Fuel (enr. %)	Reactivity control	SGs (number / pressure (bar))
CAREM-25	Argentina # CNEA	Demostration plant. Construction started in Feb. 2014	iPWR # 3.2 /11	100 / 27	Natural Cir. 410 kg/s	122.5; PZR in-vessel. Self-pressurization	284 / 326 (void fraction: 0.12)	61 Hex. FA; 1.4 m; 108 fuel rods; UO_2 (~1.8-3.1 %)	ICRDM AIC; Gd_2O_3; boron free	Helical OTSG (12/ 47)
ACP-100	China # CNNC / NPIC	Project began by the end of 2019	iPWR # 3.35 /10	385/ 125	4 canned pumps	150; PZR outside vessel	286.5 / 319.5	57 FA; 2.15 m; 17x17; UO_2 (~4,2%)	C. Rods; Gd_2O_3; soluble boron	OTSG (16/40)
SMART	S. Korea # KAERI	First design Licensed and certified in S.Korea. New passive design under development	iPWR # 6.5 / 18.5	330/ 100	4 canned pumps	150; PZR in-vessel	296 / 323	57 FA; 2 m; 17x17; UO_2 < 5%	ICRDM; soluble boron	Helical OTSG (8/ 52)
NuScale	USA # NuScale Power / LLC	under NRC regulatory review	iPWR # 3 / 17.8	160/ 50	Natural Cir.	87.2; PZR in-vessel. Heaters + spray	258 / 314	37 FA; 2 m; 17x17; e<4.95%	C rods; soluble boron	Helical OTSG (2/ 34.5)
SMR-160	USA # SMR/LLC	Pre-Application licensing in NRC. MoU Ukraine 6 SMR	Compact Loop (1) # 3 / 15	525/ 160	Natural Cir.	155; PZR on top SG outside vessel	209 / 321	112 FA; 3.7 m	C. rods; boron free	OTSG (1/ 23)
mPower	USA # Power BMX Tech.	Pre-Application licensing in NRC. New developments are on hold	iPWR # 4.15 / 27.4	575/ 195	8 pumps	148; PZR in-vessel. Heaters + spray	290.5 / 318.9	69 FA; 2.4 m; 17x17; e< 5%	ICDRM AIC; Gd_2O_3; boron free	Integral Economizer OTSG (IEOTSG; 1/57)
IRIS	International Consortium. Originally USA # WEC	Concept design finished	iPWR # 6.2 / 21.3	1000 / 335	8 pumps	155; PZR in-vessel. Heaters	292 / 330	89 FA; 4.27 m; 17x17 ; e<5%	ICRDM; burnable absorber; limited soluble B	Helical OTSG (8)
W-SMR	USA # WEC	Concept design finished. New developments are on hold	iPWR # 3.7 / 28	800/ 225	8 pumps sealless	155; PZR in-vessel	294 / 324	89 FA; 2.4 m; 17x17	Black/gray control rods; soluble boron	OTSG straight tubes
CAP-200	China # SNPTC/ SNERDI	Concept design finished	Compact Loops (2) # 3.28/ 8.845	660/ >200	Forced, no shaft seals	155, PZR outside vessel	289 / 313	37 FA; 17x17	Black/gray control rods; solubre boron	U-tube SG (2 / 60.6); 3861 tubes.
UK-SMR	UK # Rolls Royce	Mature concept	PWR (3 loop) # 4.5 / 11.3	1200-1350 / 400-450	3 canned pumps	155, PZR outside vessel	296/ 327	121 FA; 2.8 m; 17x17; e<4.95 %	C. Rods; Gd_2O_3; boron free	3 U-tube SG
Nuward	France # CEA, EDF, Naval Group & TechnicAtome	Concept design under development	iPWR # N/A / 13.5	540 / 170	6 canned pumps	PZR in-vessel. Heaters + spray	N/A	76 FA 17x17	ICDRM; boron free	6 single plate SG + 2 independent safety SG with passive cooling

Table 2. In-land based light water cooled SMR

2. Thermal hydraulic phenomena challenging the thermal hydraulic codes

Most of LWR-SMR chose integral design concepts. The allocation of primary components within the RPV, and at the same time the elimination of pipelines (such as primary pipes, or SG tubes), lead to more “opened” geometries with no preferential flow direction for circulation or flow paths resulting in multidimensional flow conditions inside the RPV. Zones with different circulating characteristics may exist within the RPV, like recirculation or nearly stagnant zones, and the flow behavior there may impact the evolution of transients.

Helical coiled steam generators (hHX) are also incorporated in several designs (Table 2), with secondary systems within the tubes (e.g. eight and twelve hHXs are positioned within the RPV-upper part in case of the SMART and CAREM designs, respectively). The complicated geometry of the hHX-tubes and their arrangement is challenging for 1D system codes to correctly characterize the heat transfer and frictions. Here, detailed CFD-simulations of hHXs may help to predict form loss coefficients to be used later on in 1D system thermal hydraulic codes. Accuracy of those analyses may depend on the intended use of SG (only for operational modes or also to accomplish safety functions during accidents). On the primary side, the characterization of cross flow bundles (supported by CFD codes or experiments), the determination of the friction factors, which would be especially important for natural circulation cases, and the accurate prediction of the heat transfer coefficients (both for primary and secondary sides) is very important to assess the SG-efficiency.

Besides, natural circulation is also an issue to be well understood and evaluated for SMRs under normal and accidental operation conditions. Relatively complex flow paths may occur, e.g. with 3D characteristics, and eventually with competition of buoyancy forces. Moreover, parasitic circulations could determine renovation rates that could be important for example in determining characteristic times.

It is worth to note that SMR-systems working with natural circulation, including boiling and relatively large chimneys, are susceptible to oscillatory flow behaviors. It is known that numerical effects, or "numerical diffusion" in system thermal hydraulic codes, could highly influence the results, in particular to predict stability boundaries, (Shi et al., 2014). Normally, this is not a main problem for LOCAs or operational transients, because the dominant driving terms are due to well-defined transitions starting from operating conditions. However, for stability analysis, numerical diffusion may be an issue. In order to avoid this, it is usual to find simplified models, some of theme developed ad hoc, in order to avoid numerical problems, for example by solving balance equations analytically. These simplifications about safety relevant complex phenomena could also influence the results, like three-dimensional behavior, mixing promoted by turbulence and two-phase flow. Using system codes with stability analysis capability may be more convenient.

In addition, as it was previously pointed out, SMR are commonly more suitable for passive safety systems, because lower power is easier to manage, see IAEA-TECDOC-1624 for more details. Some challenges arise from those systems: Passive systems relies on relatively small driving forces, and small deviations on primary/containment conditions can cause relatively large deviations on systems performance: deeper comprehension of phenomena occurring on all interconnected systems is needed. Besides, as long as no control actions are taken into account, performance of systems should be evaluated within a relatively wide range of conditions (like temperatures and pressures).

Finally, the previous reviews and PIRTs related with different accidental sequences in LWR-SMRs need to be taken into account, see (International Atomic Energy Agency, 2012)**,** (Morin et al., 2020)**,** (NuScale Power LLC, 2013b) and (Westinghouse Electric Company LLC, 2012)**.** Considering all previous comments, the following thermal hydraulic issues are consider important for the overall assessment of SMRs:

- Specific heat transfer and friction factor models are needed for helical steam generators, for both primary and secondary sides, to be implemented in the system thermal hydraulic codes.
- Most of passive safety systems relies on natural circulation single and two-phase flow. In SMR, this could take place in relatively complex geometries (3D effects, no equilibrium).
- Most passive concepts relies on heat removal by means of condensation heat transfer. Correct prediction of this phenomenon becomes important; constitutive relations capture this, but these should be properly associated with flow regime maps. Normally, flow regime maps incorporated by default are suitable for boiling process. Proper flow

regime maps for condensation process should be also improved or incorporated. In addition, there is a lack of high-pressure (over 0.5 MPa) data for the condensation process in containments.

- Non-condensable gasses could influence the condensation process. Normally, only advection transport is modelled, but diffusion transport may affect localization of non-condensable gasses in cases with low flow conditions. Incorporation of diffusion transport would improve accuracy.
- Stability boundaries have to be analyzed in several LWR-SMR.
- A comprehensive experimental database is needed for validation of the thermal-hydraulics codes applied to SMRs analysis. Hence, SMR-designers and the research community built relevant experimental facilities to investigate safety-relevant phenomena needed for safety demonstration. Table 3 lists both numerical analysis codes and experimental facilities for selected SMR-designs used for code validation.
- Multiphysics tools may be needed for the accurate prediction of safety margins in case on non-symmetrical thermal behavior of SMRs .
- Multi-scale thermal hydraulic methods are required to describe the three-dimensional phenomena inside the RPV e.g. by a CFD code and the core behavior by a subchannel or 3D coarse mesh thermal hydraulic code coupled with 3D kinetic solvers.

For the description of the SMR-specific thermal hydraulic phenomena in the circuits and containment, the numerical tools (e.g. system thermal hydraulic, subchannel and containment codes) need to be extended and updated with the corresponding physical models and correlations, followed by an exhaustive validation. Hereafter, examples of such developments regarding different thermal hydraulic codes are summarized:

- TRACE code includes the following new models needed to simulate SMRs:
  - Heat transfer correlations for helical pipes in the inner surface.
  - Zukauskas heat transfer correlations for cross flow in the outer surface of the tube bank.
  - Dryout conditions inside the helical tubes.
  - Friction factor correlations inside the helical coiled pipe as a function of the Dean number.
  - Zukauskas friction factor correlations for cross flow through a tube bank.

- NRELAP5 code, (Houser et al., 2013), (Houser, 2015)**,** (Sawant et al., 2015):
  - Helical Coil Steam Generator testing at SIET. SIET TF-2 tests to validate inner and outer surface heat transfer and pressure drop models for helical steam generators
  - KAIST tube condensation. NRELAP5 with extended Shah correlation and KSP multiplier showed significant improvements compared to RELAP5-3D.
  - Critical heat-flux tests in order to obtain CHF data for developing the CHF correlation for the operating conditions. Specific NuScale CHF correlations were included in VIPRE-01.
  - NIST-1 facility. Large scale with integral-effects data for SBLOCAs, long-term core cooling, and high-pressure condensation data to validate the NRELAP5 code.

- MARS-KS, TASS/SMR and RELAP5-3D also include new models for helical SGs, (Anderson and Sabharwall, 2014), (Hoffer et al., 2011).

These and other system codes have been widely applied for LWR-SMR simulation, see Table 4.

As part of the international interest in the safety assessment of LWR-SMR, different projects are focus on the creation of an experimental database, the evaluation of the capability of thermal hydraulic codes and on the improvement of the safety analyses methodologies have been started in the EU in the frame of H2020, which are listed hereafter.

- McSafer (High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic Small Modular Reactors): This project is focused on multi-physics and multiscale methods for the analysis of LWR-SMR including the validation of system, subchannel and CFD-codes with data to be obtained at the experimental facilities:
    - KIT COSMOS-H facility focusing on investigation of flow boiling under forced convection up to the critical heat flux.
    - LUT MOTEL facility designed for SMR-specific experiments. With the essential components including the helical coil steam generator, the core and the pressurizer modules stacked on top of each other to form a compact test loop operating with natural circulation.
    - KTH HWAT facility for SMR. Several tests on two-phase heat transfer during forced circulation and transition from forced to natural circulation will be performed in conditions relevant for SMRs.

- ELSMOR (Towards European Licensing of Small Modular Reactors, http://www.elsmor.eu/): This project is mainly focused on developing systematic methods for the safety assurance of new and innovative reactors. Experimental investigations at SIET facility with a Heat exchanger design from TechnicAtome are also included in this project.
- PASTELS (PAssive Systems: Simulating the Thermal-hydraulics with Experimental Studies). This project aims to significantly increase the knowledge of innovative passive systems and the ability of several system and CFD computational codes to be able to accurately model key phenomena such as natural circulation loops and condensation. The project includes some experimental tests at PKL, PASI, PERSEO and HERO-2 facilities.

SMR design	System and sub-channel licensing codes. References.	Validation: Experimental facilities
NuScale	NRELAP5 and VIPRE-01 (from RELAP5-3D). (Houser, 2014); (Reyes, 2010);	• Multi-Application Small Light Water Reactor (MASLWR) which was renamed NuScale Integral Scaled Test (NIST). • NIST-1 facility, upgraded version of NIST for the current design of NuScale reactor, located at Oregon State University. Large scale with integral-effects data

	(NEA/CSNI/R(2016)14, 2017)	for SBLOCAs, long-term core cooling, and high-pressure condensation data. • Helical Steam Generator testing at GEST Facility in SIET (Piacenza, Italy). • SIET TF-2 tests to validate inner and outer surface heat transfer and pressure drop models for helical steam generators • NuScale Critical Heat Flux testing at Stern Laboratories in Canada • Fuels testing at AREVA Richland Test Facility (RTF) in Richland, Washington • Critical Heat Flux testing at AREVA KATHY loop in Karlstein, Germany
CAREM-25	RELAP5 (Safety analysis) THERMIT/CITVAP: Support for calculation of thermal margins in the core (International Atomic Energy Agency, 2012)	• CAPCN: Natural Circulation and Self-pressurization facility constructed and operated to study the thermo-hydraulic dynamics in conditions similar to CAREM-25 operational states, 1:1 in height and pressure. • Low Pressure Facility: to characterize friction losses and flow induced vibration. Thermal Limits and CHF Tests • Tests performed at TH LAB IPPE (Obninsk-Russia): Low pressure Freon Loop Test (+250 tests) and High Pressure Water Loop Test (25 tests) • CNEA-CAB CHF Freon facility, 1MW: recently built, currently been used for Atuchall CHF test, 2021 for CAREM
SMART	TASS/SMR (NEA/CSNI/R(2016)14, 2017); (Yun et al., 2017); (Min et al., 2014)	Integral Effect Tests at VISTA-ITL (small-scale IEF) and SMART-ITL/FESTA (large-scale IEF). Separate Effects Tests: • ECC bypass flow at SWAT (SMART ECC Water Asymmetric Two-phase choking test) facility, • CHF tests at FTHEL (Freon Thermal Hydraulic Experimental Loop) facility. • Reactor internal flow and pressure distributions have been analyzed at SCOP (SMART COre flow distribution and Pressure drop test) facility
BWRX-300	TRACG, COBRG (or COBRAG), GOTHIC	TRACG code was qualified through a series of tests which covered important phenomena with parameter ranges that largely overlap the BWRX-300 parameter range, and was approved by USNRC for ESBWR safety analysis.
ACP100	RELAP5, MELCOR	Passive emergency core cooling system testing facility; fuel assembly critical heat flux; CMT and passive residual heat removal system; Passive containment heat removal testing facility
SMR WEC	WCOBRA/TRAC-TF2	Previous results from AP600 and AP1000 facility tests: ADS (Automatic Depressurization System) tests

	(NEA/CSNI/R(2016)14, 2017)	conducted in Milan, Italy; CMT (Core Makeup Tank) tests and PRHR (Passive Residual Heat Removal) tests conducted in Pittsburgh, USA; SPES-2 tests conducted in Piacenza, Italy, and APEX tests conducted in Corvallis, USA. UCB tube condensation facility; Westinghouse CMT test facility.
mPower	RELAP5, VIPRE, GOTHIC (NEA/CSNI/R(2016)14, 2017)	Multiloop Integral System Test (MIST) Integrated System Test (IST) facility, which is a scaled facility of the B&W mPower reactor

Table 3. Licensing codes and experimental facilities used in different LWR-SMRs

SMR Design	**System or Subchannel code**	**References**
ACP-100	RELAP/SCDAPSIM/Mod 4.0	(Deng et al., 2020); (Zhu et al., 2016); (CNNC, 2014)
NuScale	RELAP5	(Susyadi et al., 2017); (Susyadi, 2018); (NuScale Power LLC, 2013a); (Freitag, 2018); (Sadegh-Noedoost et al., 2020)
	NRELAP5	(NuScale Power LLC, 2019); (NuScale Power LLC, n.d.); (NuScale Power LLC, 2020)
	RELAP5/SCDAP; RELAP/SCDAPSIM/Mod3.4	(Fakhraei et al., 2020); (Trivedi et al., 2018)
	MELCOR	(Li et al., 2017); (Esmaili, 2019)
	APROS	(Leskinen et al., 2020)
	SCANR	(NuScale Power LLC, 2013a)
	VIPRE-01	(NuScale Power LLC, 2017); (NuScale Power LLC, 2020)
	Fluent	(Nejad and Ansarifar, 2020); (Liu et al., 2019)
IRIS	ASTEC	(Di Giuli, 2015)
	RELAP5	(Bajs et al., 2002); (Bajs et al., 2003); (Lian et al., 2020)
	RELAP5/GOTHIC	(Papini et al., 2011)
SMART	TRACE	(Sanchez-Espinoza et al., 2018); (Alzaben et al., 2019a)
	SUBCHANFLOW	(Alzaben et al., 2019b); (Alzaben et al., 2019c)
	TASS/SMR	(Chung et al., 2006); (Lee et al., 2009); (Chung et al., 2012); (Chung et al., 2013); (Kim et al., 2013); (Chun et al., 2013); (Chung et al., 2015); (Chung et al., 2003); (Yang et al., 2008)
	MARS/MARS-KS	(Park et al., 2014); (Kim et al., 2016)
MPOWER	RELAP5, VIPRE, GOTHIC	(Martin et al., 2013)
W-SMR	WCOBRA/TRAC TF2	(Liao et al., 2012); (Liao and Kucukboyaci, 2013); (Liao et al., 2016)
	RELAP5; MELCOR; SPECTRA	(Stempniewicz et al., 2017)

BWRX-300	TRACG; GOTHIC	(GE HITACHI, 2020)
MASLWR and NIST-1 facilities	NRELAP5	(Wolf et al., 2019)
	RELAP5; KORSAR/GP; RATEG (SOCRAT); TASS/SMR-S; MARS/KS-002; TRACE5.0 patch3; CATHARE mod2.1	(IAEA International Atomic Energy Agency, 2014);
	RELAP5/SCDAP	(Butt et al., 2016); (Deng et al., 2020)
	RELAP5-3D	(Hoover et al., 2017); (IAEA International Atomic Energy Agency, 2014); (Brigantic and Marcum, 2015) (Mascari et al., 2012)
	TRACE5	(Mascari et al., 2016); (Mascari et al., 2019); (Mascari et al., 2011)
	MELCOR 2.1	(Yoon et al., 2017)
	APROS	(Niemi, 2017)
SMART-ITL facility	MARS/MARS-KS	(Chung et al., 2020); (Jeon et al., 2017); (Bae et al., 2014); (Bae et al., 2017)
	TASS/SMR	(Chung et al., 2020)
VISTA-ITL facility	MARS/MARS-KS	(Park et al., 2014); (Park et al., 2017)
	TASS /SMR	(Chung et al., 2016b); (Chung et al., 2013a)
POSTECH and ITT facilities	TASS /SMR	(Chung et al., 2016a)
SPES3 facility	RELAP5; GOTHIC	(Carelli et al., 2009)
REX 10 facility	MARS/MARS-KS	(Jang et al., 2011)
	TASS/SMR	(Lee and Park, 2013)
Engineering Scaled Facility (ESF)	RELAP5	(Wang et al., 2018)

Table 4. LWR-SMR system code Models

3. Challenges found simulating the SMART plant behavior with system codes

As an example of the complexity developing integral thermal hydraulic models for a generic SMART-plant, the main challenges will be described hereafter.

3.1. Description of the generic SMART-plant

The System-integrated Modular Advanced Reactor (SMART) (Park, 2011) is an advanced small-sized integral pressurized water reactor developed by KAERI. The SMART's reactor core, pressurizer, steam generators (SGs), and reactor coolant pumps are all integrated into a single reactor pressure vessel (RPV). This feature enabled large-sized pipe connection to be removed; thus, eliminating the possibility of large breaks loss of coolant accidents. Fig. 1 shows the RPV internal components as well as the coolant flow path within the RPV.

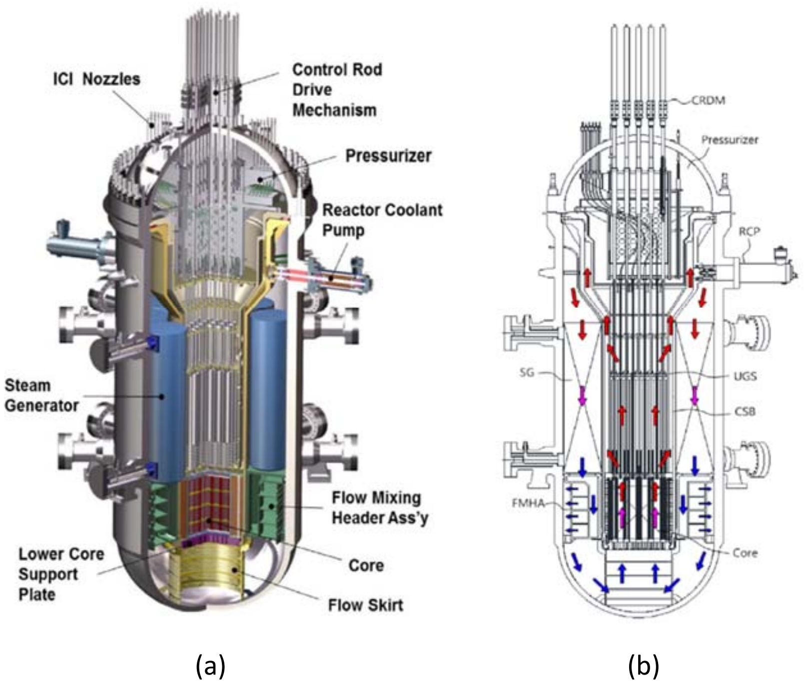

Fig. 1: An overview of SMART's (a) reactor pressure vessel, and (b) coolant flow diagram (Kim et al., 2015).

The SMART's RPV has four canned-motor pumps and eight helical-coiled SGs. These SGs are placed above the reactor core to provide enough coolant density gradients for establishing natural circulation inside the RPV in case of an accident. The working principle of the helical-coiled SGs is different from the conventional U-tube ones. In the helical-coiled SGs, the primary coolant flows downward outside the helical-coiled tubes, whereas the secondary coolant flows upward inside the helical-coiled tubes, which is the opposite of U-tube SGs. In addition, the coolant volume inside the helical-coiled tubes (i.e. coolant inventory of the SG's secondary-side) is much smaller than the U-tube SGs. Therefore, the peculiarity of thermal-hydraulic phenomena is different from those reactors with U-tube SGs. The RPV has also included a complex geometry following the coolant exit from the SGs in order to enforce coolant mixing and provide a uniform coolant flow and temperature distribution, at the core inlet, under normal and accidental conditions. That complex geometry is called flow mixing header assembly (FMHA) (see Fig. 2).

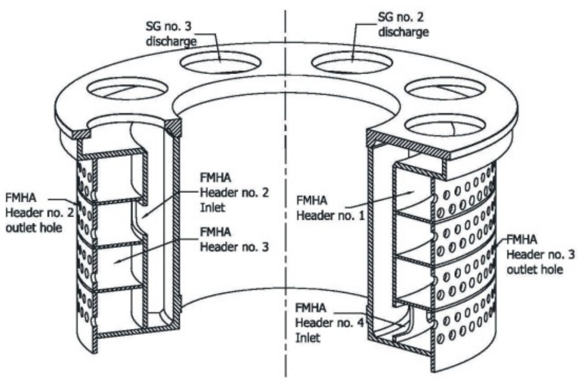

Fig. 2: Flow mixing header assembly configuration (Kim et al., 2015)

SMART has many safety systems; one of these is the passive residual heat removal system (PRHRS). This system is responsible for removing core decay heat through natural circulation in case of an emergency condition such as SLB-accident. The PRHRS consists of four independent trains with a 50% capacity for each train. Each train has a heat exchanger submerged in an emergency cooldown tank, a makeup tank, valves, and pipes. A schematic of PRHRS and its connection to the secondary-side is shown in Fig. 3.

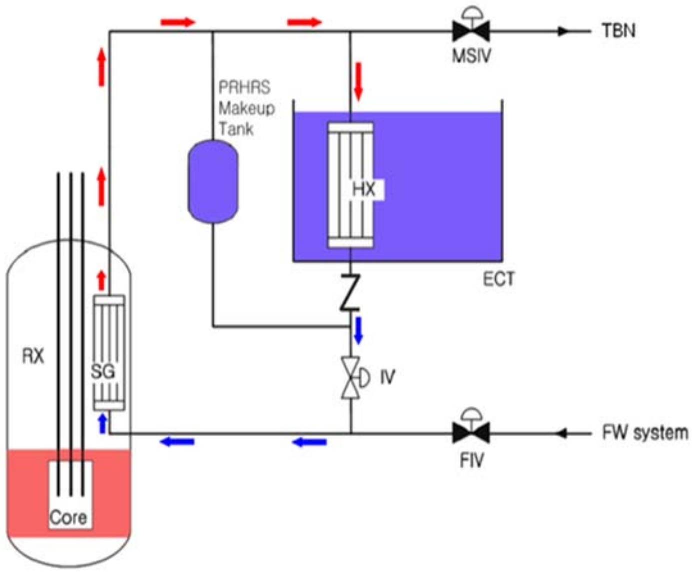

Fig. 3: A schematic of the passive residual heat removal system and its connections to the SG's secondary-side (Park, 2011)

3.2. Thermal-hydraulics modeling challenges of the SMART-plant

Due to the complex internal structure of the SMART's RPV, an exact flow representation is impossible with system thermal-hydraulics codes. CFD codes can simulate fluids flowing in complex geometry; however, its computational burden limits its applications in deterministic safety assessment

In (Alzaben et al., 2019a), the steam line break (SLB) accident in the SMART is analyzed using TRACE/PARCS. It has been reported that flow-mixing phenomena, due to the presence of FMHA in the downcomer, could be captured using coarse-mesh 3D modeling (i.e. TRACE CYLINDRICAL VESSEL component). However, an exact track of flow streamlines from the FMHA inlet toward core inlet requires 3D fine-meshes and turbulence modeling, which is out of the capability of system TH codes. Such kind of study would be beneficial to verify the capability of TRACE system code in capturing flow-mixing using coarse-meshes.

One of the quite challenges phenomena to capture is the pressure wave back propagation as a result of steam line break in the SMART. Such pressure wave could cause excessive fluid-dynamics load on the helical-tube steam generator; hence, lead to tube rupture. Therefore, the determination of excessive loads amount is interesting to decide whether there will be a SGTR associated with SLB-accident.

Mr. Alzaben has also studied the capability of the PRHRS of the SMART under the SLB-accident. A complicated two-phase natural circulation governs the PRHRS operation. In accident scenario, such as the SLB, the heat removed from the primary-side (through SG) in form of steam is being circulated through the PRHRS that has heat exchangers submerged in an emergency cooldown tank. A condensation process occurs inside these heat exchangers tubes causing liquid formation. The formed liquid-phase then goes back to the feedwater inlet pipes. Such a process is a gravity-driven and requires special validation and understanding of the associated thermal-hydraulics phenomena.

4. Conclusions

Considering the new design peculiarities of LWR-SMRs, the operation modes, and the thermal hydraulic conditions inside the reactor pressure vessel it can be stated that a physical sound simulation of the multidimensional flow (single, two-phase) requires 3D thermal hydraulic codes and/or multi-scale coupled codes(e.g. combination of CFD/system codes, system/subchannel codes) is required. Moreover, the physical phenomena on which the majority of passive safety system to remove the decay heat rely on, ask for an extensive re-evaluation and validation of the models of system codes, e.g.:

- Heat transfer correlations for helical pipes in the inner surfaces and tube-banks.
- Dryout conditions inside the helical tubes
- Condensation heat transfer correlations and flow-maps
- CHF correlations for the different SMR operating conditions.
- Friction factor correlations inside the helical coiled pipe and cross flow through a tube bank.

On the other hand, CFD codes also need to be validated/improved in SMR conditions:

- Flow mixing by means of turbulence
- Two-phase flow distribution, including bubbles drift by means of liquid recirculation; for example, bubbles drift from chimney to downcomer, during steady-state conditions.

Finally, new experimental data for key-SMR phenomena is needed for the validation of the different kinds of thermal hydraulic codes in order to increase the confidence on their prediction capability e.g. related to helical heat exchanger, PRHRS-effectiveness, transition from forced to natural circulation within the core, CHF, etc..

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