TESIS DOCTORAL

DEVELOPMENT OF AN AP1000 3D FULL CONTAINMENT MODEL USING AN INNOVATIVE APPROACH

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Development of an AP1000 3D full containment model using an innovative approach

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ABSTRACT

In order to make the reactor accident management independent from alternating current supply, Generation III+ reactors utilize passive mechanisms for their safety systems. A prominent type is the Westinghouse AP1000® reactor which Passive Containment Cooling System (PCS) uses the atmosphere as the ultimate heat sink for evacuating thermal energy from the containment. Additionally, the AP1000 design includes an In-containment Refueling Water Storage Tank (IRWST) that acts as a heat sink of the Passive Reactor Heat Removal Heat Exchanger (PRHR-HX) and as the water source for the long-term cooling phase. The performance of these systems is not only dependent on the thermo-hydraulic state of the Reactor Coolant System (RCS), but also the containment. Under certain circumstances the core cooling, by means of the PRHR, would be determined by the heat transfer between the PRHR HX and the IRWST, being the IRWST thermo-hydraulic state dependent on the containment thermo-hydraulic state. The accurate simulation of this phenomenology is complex and demands 3D models that integrate all the AP1000 containment safety systems and spaces, which has not been the case in the state of the art.

Therefore, the goal of this thesis is the development of a detailed AP1000 3D full containment model that encompass the PCS and IRWST-PRHR detailed systems for its subsequent use on design basis accidents and severe accidents.

In a first step, the IRWST-PRHR model development is described. The best modeling strategy is obtained after modeling a down-scaled experiment. With the obtained insights, a full-scaled IRWST model is generated. The proper simulation of thermal stratification, which is a safety-relevant phenomenon for the containment integrity, is proven and its influence on containment pressure is evaluated. This model is used to study the ADS steam injection during an SBLOCA accident. The importance of a proper nodalization is presented.

Then, the PCS is modeled in GOTHIC taking the conservative hypothesis that no water is available from the Passive Containment Cooling Water Storage Tank (PCCWST). Due to its design characteristics different assumptions and simplifications were applied in this model. The model performance is tested against a steady state case and it was found that the modeling of natural convection of such complex geometry is not trivial. The modeling parameters should be studied carefully.

In a third step, the AP1000 containment (SCV) is also modeled in 3D. A methodology for its construction in GOTHIC is described: a detailed CAD model is constructed, then it is simplified into simple geometry forms and finally it is implemented in the GOTHIC code. The several modeling assumptions for the correct compartmentalization are discussed and presented.

Finally, the full containment model, containing all the previous developed models, is used for simulating two application cases: LBLOCA and SBLOCA. For each accident, different AP1000 approaches are used. In the case of the LBLOCA, only the SVC and the PCS are used as the IRWST does not play a significant role. In the case of the SBLOCA, the IRWST detailed model is implemented as the stratification of the pool may be relevant in the transient evolution.

The results obtained from the application cases show that the AP1000 containment GOTHIC model could be used for simulating these kinds of accidents giving enough resolution to see the evolution of the different containment compartments. For that purpose it was needed to develop different isolated models of the IRWST, SCV or PCS in detail, in order to understand and simulate all the complex phenomena that may occur. The computational competitiveness of the model, together with its accuracy allowed to understand phenomena that have not been seen in any other AP1000 models.

RESUMEN

Para hacer que la gestión de los accidentes se independiente del suministro de corriente alterna los reactores nucleares de Generación III+ utilizan mecanismos pasivos en sus sistemas de seguridad. Específicamente, el concepto de seguridad del reactor AP1000 se basa en el uso de estos sistemas. Entre estos se encuentra el PCS (Sistema de Refrigeración Pasiva de la contención), que usa la atmósfera exterior como sumidero último de calor de la contención. Además, entre otros sistemas, se encuentra el IRWST (tanque de agua de recarga en el interior de la contención) que funciona como sumidero de calor del intercambiador de calor PRHR HX, además de servir como fuente de agua para la refrigeración a largo plazo. El funcionamiento de estos sistemas es dependiente no sólo de su propio estado termo-hidráulico, sino además del estado termo-hidráulico de la contención. Bajo ciertas condiciones la refrigeración del núcleo, que se realizaría mediante el intercambiador de calor PRHR, va a depender de la transferencia de calor desde el PRHR hacia el IRWST; cuyo estado termo-hidráulico depende a su vez del estado termo-hidráulico de la contención. La simulación de este tipo de fenomenología es compleja y su correcto modelado exige el uso de herramientas 3D que integren los sistemas de seguridad de la contención además de sus diferentes partes, hecho que, por el momento, no se ha visto reflejado en el actual estado del arte.

El objetivo principal de esta tesis es la creación de un modelo en 3D de la contención del reactor AP1000 con el código GOTHIC, modelando el PCS e IRWST-PRHR de forma detallada para la simulación de accidentes base de diseño y accidentes severos.

En primer lugar, se describe la creación del modelo IRWST-PRHR. Su desarrollo se ha realizado a partir de la simulación con GOTHIC de un experimento a escala, a partir del cual se obtienen las mejores estrategias de simulación y se aplican a un modelo a escala real del IRWST. Después, se comprueba que es posible simular estratificación térmica en el tanque y su influencia en la presión de la contención. Finalmente, se implementa la inyección de vapor del ADS en el tanque destacando la relevancia de las hipótesis de modelado para representar correctamente su funcionamiento.

Seguidamente, el PCS es modelado en GOTHIC teniendo como la hipótesis conservadora que el agua del tanque de recarga de agua del sistema pasivo de refrigeración de la contención (PCCWST) no está disponible. Además, debido al diseño inherente del PCS distintas hipótesis y simplificaciones se han tenido que aplicar al modelo 3D. Finalmente, el funcionamiento del modelo creado es analizado ante condiciones estacionarias, pudiéndose comprobar que el modelado de la convección natural no es trivial, siendo necesario prestar especial atención a los parámetros que se usan para el modelado del PCS.

Más adelante, la metodología usada para la construcción de la contención tridimensional del AP1000 (SCV) se presenta: la contención del AP1000 se construye de manera detallada en

AutoCAD obteniendo un CAD de alto detalle. Este CAD es simplificado, pasando todas las partes que lo componen a geometrías simplificadas que sean aceptadas por GOTHIC. Finalmente, las coordenadas de estas geometrías se extraen y son implementadas en GOTHIC. Las diferentes hipótesis de simulación para la correcta compartimentalización de la contención en GOTHIC son descritas detalladamente.

Finalmente, el modelo de contención completa que incluye todos los modelos aislados creados previamente se usa para la ejecución de los casos de aplicación elegidos: un LBLOCA y un SBLOCA. Dependiendo del tipo de accidente las aproximaciones de modelización son distintas. En el caso del LBLOCA únicamente el PCS y el SCV se utilizan, ya que el IRWST no tiene ningún papel relevante durante este transitorio. En el caso del SBLOCA el modelo detallado del IRWST se incluye en la simulación, ya que la estratificación del tanque puede jugar un papel esencial en la evolución del transitorio.

Los resultados obtenidos de los casos de aplicación demuestran que el modelo de contención 3D de AP1000 creado en GOTHIC puede ser útil para la simulación de este tipo de accidentes, dando la suficiente resolución para poder observar el estado termo-hidráulico de los distintos compartimentos que forman parte de la contención. Para obtener este nivel de precisión y poder entender la compleja fenomenología que acontece en la contención del AP1000 se ha visto que es necesario el modelado en detalle del IRWST, SCV y PCS. La competitividad computacional del modelo creado junto con su precisión ha permitido entender cierta fenomenología dentro de la contención que no había sido vista antes en otros modelos de AP1000.

THESIS OUTCOMES

JOURNAL ARTICLES

- Samanta Estévez-Albuja, Ignacio Gallego-Marcos, Pavel Kudinov, Gonzalo Jiménez. Modelling of a Nordic BWR containment and suppression pool behavior during a LOCA with GOTHIC 8.1. Annals of Nuclear Energy. 2020. Vol 136. 107027.
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- Samanta Estévez, Gonzalo Jiménez, César Queral, Javier Montero-Mayorga. Simulation and thermal-hydraulic analysis in the In-containment Refueling Water Storage Tank (IRWST) and the PRHR Heat exchanger during a SBLOCA transient with the CFD code STAR-CCM+ and the thermal-hydraulic code GOTHIC 8.1. 42 Reunión Anual de La Sociedad Nuclear Española. 2016. Santander, Spain.

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NOMENCLATURE

AC	Alternating current	PCCWST	Passive Containment Cooling Water Storage Tank
ACC	Accumulators	PCS	Passive Containment Cooling System
ADS	Automatic Depressurization System	PIRT	Phenomena Identification and Ranking Table
APEX	Advanced Plant Experiment	PIV	Particle Image Velocimetry
BC	Boundary Condition	PRHR	Passive Residual Heat Removal Heat Exchanger
BWR	Boiling Water Reactor	HX	
CFD	Computational Fluid Dynamics	PSA	Probabilistic Safety Analysis
CMT	Core Makeup Tank	PSI	Paul Scherrer Institute
CPU	Central Processing Unit	PSP	Pressure Suppression Pool
CV	Control Volume	PWR	Pressurized Water Reactor
CVCS	Chemical and Volume Control System	PXS	Passive Core Cooling System
CVS	Chemical and Volume Control System	RCDT	Reactor Coolant Drain Tank
DBA	Design Basis Accident	RCS	Reactor Coolant System
DC	Direct current	RNS	Residual Heat Removal System
DCC	Direct Contact Condensation	RVC	Reactor Vessel Cavity
DCD	Design Control Document	SB	Shield Building
DLM-FM	Diffusion Layer Model with Film roughening and Mist formation	SBLOCA	Small break Loss of Coolant Accident
DVI	Direct Vessel Injection	SBO	Station Black Out
EPRI	Electric Power Research Institute	SCV	Steel Containment Vessel
FP	Flowpath	SNL	Sandia National Laboratories
FSAR	Final Safety Analysis Report	SG	Steam Generator
GOTHIC	Generator of Thermal Hydraulic Information in Containments	SotA	State of the Art
HTC	Heat Transfer Coefficient	SPES	Simulatore PWR per Esperienze di Sicurezza
IRWST	In-Containment Refueling Water Storage Tank	TC	Thermo Couples
JAEA	Japan Atomic Energy Agency	TH	Thermo-hydraulic
LOCA	Loss of Coolant Accident	THC	Thermal Conductor
LOOP	Loss of Offsite Power	UDF	User Defined Function
LP	Lumped Parameter	VA	Vertical Access
LSTF	Large-Scale Test Facility	VOF	Volume of Fluid
LUT	Lappeenranta-Lahti University of Technology		
NAI	Numerical Applications Inc.		
NCEPU	North China Electric Power University		
NPP	Nuclear Power Plant		

Part I

INTRODUCTION

Chapter 1

Motivation and objectives

The nuclear containment main purpose is to act as the final physical barrier for the defense in depth safety methodology controlling the release of radioactivity to the environment in case of an accident [1]. The containment is hence designed to withstand the demanding pressure and temperature conditions occurring after a postulated break in the primary/secondary circuit of the reactor.

To confirm that the containment structure meets its functional requirements under the conditions of the specific plant operating limits, containment analyses have been performed historically under the Final Safety Analysis Report (FSAR) and the level 2 of the Probabilistic Safety Analysis (PSA) [1]. These analyses have been conducted during the last decades using various codes following the Lumped Parameters (LP) approximation [2]. Examples include codes such as GOTHIC (using only LP capabilities) [3], COCOSYS [4], CONTAIN [5], MELCOR [6], MAAP [7], or ASTEC [5], which have been used for simulating design basis accidents (DBA) or Severe Accidents (SA) sequences for different containment types. In particular the GOTHIC code has been used extensively to perform licensing analysis following different methodologies [8]–[11] having all in common that LP approach was used.

Furthermore, 3D containment codes such as GOTHIC or GASFLOW [3][12] have been extensively used for performing three-dimensional containment analyses under DBAs or SA for the last twenty years. As an example, in the Nuclear Safety and Thermo-Hydraulics team at the

ETSII-UPM, the three-dimensional capabilities of GOTHIC have been tested for a wide range of containment types; such as BWR containments [13], [14], KWU containments [15], [16] and conventional PWR reactors [17], [18].

Contrary to these Generation II light water reactors (LWR), the AP1000® relies its safety systems performance on passive systems [19]. This fact has led the approximations and methodologies previously used for modeling NPPs to be reviewed and updated. For instance, the GOTHIC code had to be upgraded into WGOTHIC integrating the CLIME model to be able to simulate the AP1000 PCS for licensing purposes [20]. Furthermore, additional correlations were included in GASFLOW [21], MAAP [22] and COCOSYS [4] to be able to model the AP1000 containment phenomenology. However, there is not a 3D full containment AP1000 model that includes all containment safety systems and spaces in the literature.

Studies performed after the Fukushima accident revealed that the correct modeling of thermal stratification in the suppression pool (IRWST in the case of AP1000) is necessary to predict correctly the containment behavior [23]. Additionally, diverse studies about the AP1000 containment have demonstrated the importance of proper nodalization to capture the occurring phenomenology correctly [24], [25]. This fact, together with the experience with GOTHIC in a wide range of applications by the ETSII-UPM team, led to the decision of constructing the most detailed 3D containment model possible with GOTHIC in the framework of this PhD thesis.

Therefore, this PhD thesis main objective is the development of a detailed AP1000 3D full containment model. This model should include a detailed modeling of the PCS and IRWST-PRHR systems to allow the correct simulation and prediction of the AP1000 containment behavior with the GOTHIC code.

The strategy followed in this thesis is, in a first step, to create isolated models that simulate the different safety systems properly being validated with experimental data when possible. In a second step, to integrate the separate models in a full containment model. This full containment model will then allow to simulate and predict the AP1000 containment thermo-hydraulic behavior at design basis accidents and severe accidents adequately.

Chapter 2

Thesis structure

To pursue the previous stated objectives the thesis is structured into five parts. The main objective of this thesis, the setup and design of an AP1000 computational 3D model in GOTHIC is presented and discussed in Part III. The detailed outline of this thesis is as follows:

Part I (Introduction) is constituted by the general introduction of this thesis, detailing the main motivation and objectives, **Chapter 1**. The main objective and the thesis structure are also described in **Chapter 2**.

Part II (State of the Art) gives an introduction of the problem case, i.e. the AP1000 containment, and the GOTHIC code. The goal of this part is to briefly describe the main components this thesis talks about. This part is divided in two chapters:

In **Chapter 3**, the AP1000 reactor and passive safety system working principle during an accident phenomenology is presented. That includes a functional description of the Passive Core Cooling System (PXS) and the Passive Containment Cooling System (PCS). Likewise, the state of the art of relevant studies concerning these systems are presented. These studies set a precedent for the analyzes that have been carried out during this thesis.

In **Chapter 4** the GOTHIC code, the main tool for this thesis development, is briefly described. A general description of the code is given, as well as the different features it has for modeling containments. The models and components available in the code and used in this thesis are depicted.

Part III (Model Creation Methodology) describes the major work of this thesis: the methodology followed for the generation of an AP1000 containment 3D model in GOTHIC. Each chapter is used for the detail description of the methodology followed for the creation of the different systems that will compound the full containment model.

In **Chapter 5** the In-containment Refueling Water Storage Tank creation is described. First the validation against a down-scaled experiment is presented, and the insights obtained for its correct modeling are extrapolated into an IRWST full-scaled model. Moreover, the ADS injection modeling is extensively studied. The capability of GOTHIC for modeling such phenomena is tested against a down-scaled experiment and the lessons learnt are transferred and applied to the full-scaled IRWST model. Finally, the optimized model to be used in a full scaled AP1000 containment model is presented.

In **Chapter 6** the methodology followed for the Passive Containment Cooling System creation is described. The different tools used for the creation are presented. A steady state case is simulated to see if the natural circulation is being correctly modeled. Furthermore, a mesh sensitivity test is performed to obtain the optimum mesh.

In **Chapter 7** the SCV containment model creation methodology is presented. A CAD model is first created from information in the Design Control Document (DCD) and then translated into a GOTHIC SCV 3D model. The created model was tested against leakage to validate the inner-wall tightness. Finally, the coupling of the IRWST and PCS isolated models with the SCV containment model is described.

Part IV (Application Cases) presents the application of two different accident scenarios into the models created in the previous section. This part includes **Chapter 8**, where the boundary condition implementation in the models and the pressure and temperature results in the containment under the different scenarios tested are presented and discussed.

Part V (Conclusions) includes **Chapter 9** where the main achievements of this thesis are summarized, and the main conclusions and outlooks are discussed.

Part II

STATE OF THE ART

Chapter 3

AP1000 phenomenology

3.1. AP1000 description

The AP1000 is a Generation III+ nuclear reactor designed by Westinghouse Electric Company. It is a two-loop Pressurized Water Reactor (PWR) with a power output of 1200 MWe [26]. This reactor is characterized for the use of passive safety systems which enhances the plant simplification, safety, reliability and plant costs [19].

The AP1000 development started in the 00's with the objective of upgrading the previous Westinghouse design, the AP600. The AP1000 uses proven technology widely used in other PWR plants, such as the steam generators, 17x17 fuel, pressurizer, and reactor vessel. AP1000 is characterized for the simplicity of its systems and components. This makes the AP1000 easier and less expensive to build, operate and maintain.

One of the main characteristics of the reactor is its safety concept. Under a design basis accident, the reactor safety systems are not conditioned by the successful performance of active systems, for example, pumps and diesel generators. Instead, the performance is based on passive safety systems, which utilizes natural forces such as density differences, gravity or natural circulation. These systems are available during shutdown and power operation, maintaining the core cooling and containment integrity with no need of human actions or Alternating Current (AC) power. The only energy source these systems need to function are Direct Current (DC) batteries.

The passive safety systems can be grouped into:

- Passive Containment Cooling System (PCS)
- Containment Isolation System
- Passive Core Cooling System (PXS)
- Main Control Room Emergency Habitability System
- Fission Product Removal and Control System
- Spent Fuel Pool Cooling System

The PCS and the PXS are the target study systems on this thesis. Therefore, those will be explained in further detail in the following sections.

3.1.1. Passive Core Cooling System (PXS)

The main function of this system is to refrigerate the core in case of an emergency. The different functions of this system are [27]:

- Emergency core decay heat removal during transients, accidents, or any situation when the steam generators coolant capability is lost.
- Reactor coolant system emergency makeup and boration.
- Safety injection. It provides safety injection to the Reactor Coolant System (RCS) to maintain an effective core cooling in case of a Loss of Coolant Accident (LOCA) event.
- Containment pH control during post-accidental conditions for the radionuclide retention and equipment corrosion prevention during long-term reflood conditions.

The PXS is composed by different subsystems and components, Figure 3-1. The focus of this study is on the In-containment Water Storage Tank (IRWST), Passive Residual Heat Removal Heat Exchanger (PRHR HX) and the Automatic Depressurization System (ADS).

- **Core makeup tanks (CMTs):** Those are two cylindrical tanks with hemispherical upper and lower heads, located on the 107-foot floor elevation, just above the direct vessel injection line connections. During normal operation those are filled with borated water at containment temperature ($\sim 47^\circ\text{C}$) and RCS pressure (by means of the cold leg pressure balance line). The CMTs inject the borated water gravity into the RCS upon a Safety injection signal or/and a Loss of Offsite Power (LOOP) signal.
- **Accumulators (ACCs):** those are two spherical tanks located inside the containment on the floor just below the CMTs. Those are filled with borated water and pressurized at 49 bar with nitrogen gas (N_2), at containment temperature ($\sim 47^\circ\text{C}$). Each accumulator is connected to one of the direct vessel injection lines. When the RCS pressure falls below ACC pressure, check valves, which usually isolate the ACC from the RCS, open and the ACCs discharge into the RCS.

Figure 3-1. AP1000 Passive core cooling system scheme [28]

- **In-Containment Water Storage Tank (IRWST):** it is a large concrete tank with a stainless-steel liner. It is located behind the operating deck in the containment, and over the RCS loops elevation, to inject by gravity borated water when the RCS is depressurized through two redundant direct vessel injection lines. Submerged inside the tank there are located different components: the PRHR HX, two spargers from the ADS and two sump screens.

The tank is covered with a slab with normally closed vents (flappers) to prevent debris from entering the tank from the containment operating deck. These vents open when there is a slight pressurization in the tank, providing a path to vent steam/non-condensable gases released from the spargers or steam produced by the water evaporation due to the PRHR actuation. Overflow from the IRWST to the refueling cavity to accommodate volume and mass increases during PRHR or ADS operation is provided, to minimize the flooding of the containment.

IRWST volume is designed to provide enough water to refill the refueling cavity during normal refueling, to flood the containment during RCS long-term cooling mode and to withstand the PRHR HX heat transfer during its operation. Furthermore, it supplies the necessary injection until the containment sump floods up enough so recirculation flow can be initiated.

The sump screens are designed to reduce the chance of debris reaching the RCS in the safety injection during LOCA accidents. These screens are oriented vertically and made of trash rack and a fine screen. PRHR and ADS components are further described next. The components are presented in Figure 3-2. On the right is located the PRHR HX next to one vertical sump screen. On the other side, the left, the two spargers are located next to the other sump screen.

Figure 3-2. IRWST elevation. PRHR HX, sump screen and ADS positions [27].

- **Passive Residual Heat Removal Heat Exchanger (PRHR HX):** it is a heat exchanger composed by 689 C-shaped tubes, connected to inlet and outlet channel heads. It is located on one side of the IRWST near the outside top of the tank.

The inlet channel head is located in the upper part and it is connected to one of the hot legs. The inlet channel head and the tubesheet are attached to the tank wall via an extension flange, designed to accommodate thermal expansion. The heat exchanger is supported by a frame attached to the IRWST floor and ceiling.

The outlet channel head is located at the bottom of the tank and it is connected to steam generator chamber cold leg. The structural configuration is the same as the inlet channel head. The schematic of the PRHR and the IRWST connection is shown in Figure 3-3, and the main parameters are listed in Table 3-1.

Table 3-1. IRWST and PRHR HX main parameters [27]

IRWST		PRHR HX	
Minimum volume [m ³]	2092	Power [MW]	58.9
Nominal pressure [kPa]	34	Nominal flow [kg/s]	63.3
Nominal temperature [°C]	66	Inlet temperature [°C]	297
Initial temperature [°C]	49	Outlet temperature [°C]	93
Nominal water level [m]	8.7	Nominal pressure [kPa]	17.1
Material	Stainless steel	Number of tubes	689
		Tube diameter [mm]	19.05
		Tube thickness [mm]	1.65
		Tube pitch [mm]	38

Figure 3-3. AP1000 PRHR HX scheme [27]

- Automatic Depressurization System (ADS):** This system allows the RCS depressurization to permit the low pressure safety injection actuation (IRWST injection). The system consists of four different stage of valves. The first three stages are composed by two lines each, where each line has two valves in series. These valves belong to the pressurizer valves module, that discharge inside the IRWST with two lines with spargers at the end.

Each sparger has four branch arms inclined downwards, located around 7 m above the tank floor. Each branch has 174 holes, where high temperature and pressure steam is injected. Figure 3-4 represents one scaled sparger used for the APEX experiments [29].

The fourth stage has four lines, where each line has two valves in series connected to the hot legs and discharge directly to the containment.

Figure 3-4. Experimental scaled-down sparger at APEX facility [29]

During a LOCA, the CMTs drain down, the ADS valves are sequentially actuated. The depressurization sequence establishes reactor coolant pressure conditions that allow injection from the ACCs, and then from the IRWST and the containment recirculation path. Therefore, an injection source is continually available.

3.1.2. Passive Containment Cooling System (PCS)

The purpose of this system is to prevent the containment temperature and pressure from exceeding design values after a Design Basis Accident (DBA), transferring heat directly from the containment vessel to the environment. It could also help to withstand the extreme pressure and temperature conditions during a severe accident.

It is composed by: a steel containment vessel (SCV) surrounded by a concrete shield building (SB); the passive containment cooling water storage tank (PCCWST) located above the SB; an air baffle located between the SCV and the concrete SB, air inlets and air exhaust incorporated into the SB structure; and a water distribution system, mounted on the outside surface of the SCV. An illustration of these components arrangement is provided in Figure 3-5.

- **Passive Containment Cooling Water Storage Tank:** this tank is integrated into the SB structure, above the SCV. It has a volume of 2860 m³ and it is filled with demineralized water. The outlet piping is equipped with three sets of redundant isolation valves. In two sets, at Hi-2 containment pressure signal (155 kPa) air-operated butterfly valves open. The third set is equipped with motor-operated gate valves. The tank has four outlet pipes located at different elevations inside the tank, allowing to control the flow of water as a function of water level.
- **Water distribution bucket:** it is used to deliver water from the PCCWST pipes to the outer surface of the containment dome. The bucket is hung from the SB roof and suspended just above the containment dome. A set of circumferentially spaced distribution slots are included around the top of the bucket.
- **Water distribution weir system:** this system optimizes the wetted coverage of the containment shell during the PCS operation. It consists of two different set of weirs, located at different dome radius to collect and distribute the cooling water from the water distribution bucket. At the first distribution weir set, the water in that sector is collected and then redistributed onto the containment using channeling walls and collection troughs equipped with distribution weirs. A second set of weirs are installed on the containment dome at a larger radius to again collect and then redistribute the cooling water to enhance shell coverage.
- **Air flow path:** this path includes a screened shield building inlet, a metallic air baffle that divides the inner and outer flow annuli, and a chimney located at the upper part of the SB to increase buoyancy. This flow path provides a direct air along the containment shell to provide containment cooling.

The air flow path for natural circulation of air upward along the outside walls of the SCV is always open. The atmospheric air enters horizontally from the SB inlet through several inclined openings distributed along the SB wall. The air turns 90 degrees and flows downwards into an outer annulus, which is encompassed by the concrete SB and the air baffle. This space is called downcomer. At the bottom of the downcomer the air baffle, with the help of curved vanes, turns

the flow upwards 180 degrees into the inner containment annulus, which is encompassed by the air baffle and the SCV. This space is called riser. While the SCV is cooled by the air, it is heated and flows up through the riser to the top of the containment vessel and then exhausts through the SB chimney. A representation of these phenomena is presented in Figure 3-5.

Figure 3-5. PCS components: Baffle, liner and Shield building [30].

The density difference between the inlet cold air and the outlet heated air because of its contact with the liner, together with the riser reduced transversal section, higher air velocities could be reached, around 8.5 m/s [31]. In spite of that, the natural convection mechanism could not be sufficient to refrigerate enough the SCV after a DBA [32]. For that reason, an additional system to refrigerate the SCV liner was incorporated in the PCS: the PCCWST.

When Hi-2 containment pressure signal inside the SCV is reached, the isolation valves inside the PCCWST open. This allows the water flowing through the pipes, provided only by the force of gravity, reaching the top of the liner. The distribution bucket, together with the two rings from the weir distribution system, allow the homogeneous water film distribution over the dome and side walls of the containment structure.

The water film in contact with the liner surface is partially evaporated, removing latent heat from the SCV and being the principal cooling mechanism of the PCS [33]. The water film evaporation and the air natural convection allows the containment depressurization after an accident and reactor residual heat removal in the long-term.

As the containment liner heats up due to high containment temperature, heat is removed from inside the containment via conduction through the SCV, convection from the containment surface to the water film, convection and evaporation from the water film to the air, and radiation from the water film to the air baffle. As heat and water vapor are transferred to the riser, the air becomes less dense than the air in the outer annulus, resulting in a density difference that causes an increase in the natural circulation of the air upward. The heat transfer mechanisms are presented in a scheme in Figure 3-6. Heat from the containment is transferred by conduction (through the metallic liner and the metallic baffle), radiation (from the liner to the baffle, from the baffle to the SB and from the SB to the external atmosphere) and convection. Film evaporation plays an important role in the containment cooling.

The cooling water that is not evaporated from the SCV walls, flows down to the bottom of the riser, where it is drained. The drains are on the SB walls, slightly above the floor to avoid clogging of the drains by debris. These drains are always open and dimensioned to withstand the maximum water flow from the PCS.

Figure 3-6. Heat transfer mechanisms presented during PCS actuation [34]

3.2. Passive safety systems modelling state of the Art

Since the AP600 design several experiments have been carried out. The objective of those were to get to know and study the innovative passive safety system behavior.

The AP600 passive systems performance was evaluated within the AP600 testing program run by Westinghouse. These AP600 validation tests were also used to validate the AP1000 [20], although additional test carried out in APEX-AP1000 facility were performed to account for potential deficiencies in the supporting database [35]. Moreover, some of the experimental tests were repeated or complemented later on for the CAP1400 [36], [37]. The goals of the AP600/AP1000 testing program were: (1) to simulate the thermo-hydraulic phenomena and behavior of the passive safety systems; (2) to provide quality data for code validation used in safety analysis; and (3) to provide information for the verification of the components design and performance [35].

In this section the most relevant experiments and simulations developed by different institutions are presented and described. The studies have been separated into two main categories: PXS studies focused on the IRWST and PRHR performance; and the PCS studies.

3.2.1. In-containment Refueling Water Storage Tank (IRWST)

The thermal hydraulic characteristics of the PRHR HX in IRWST have been studied during the last decades through experimental and numerical studies. Integral test facilities, APEX (Advanced Plant Experiment) and SPES (Simulatore PWR per Esperienze di Sicurezza), were constructed by Westinghouse for the validation of its codes with experimental data [38]. The APEX facility experimental observations were used for the study of boiling heat transfer mechanisms, thermal stratification, and flow patterns in the IRWST for SBO transients. In addition to the experiments, single-phase CFX simulations were performed. The results showed thermal stratification, where the top layer of the liquid in the tank was at saturation temperature and the bottom layer was in subcooling conditions [39] [40]. Figure 3-7a shows the thermally stratified layers in the IRWST caused mainly by the buoyancy of the heated water.

(a) Experimental results at different elevations

(b) CFX simulation results

Figure 3-7. Thermal stratification in the IRWST in APEX (results in Kelvin) [39]

Furthermore, the AP1000 PRHR HX performance under different accidental conditions was studied in ROSA-V Large-Scale Test Facility (LSTF). The IRWST geometry (rectangular shape) and PRHR arrangement (forty-five tubes) was simplified. It was found that the heat from the

PRHR HX was removed through nucleate boiling and natural convection, causing an increase in the IRWST temperature [41]. ROSA-V PRHR HX was modeled with PRHRCFD code, and after concluding the heat transfer between the IRWST and the PRHR tubes was adequately simulated, the full AP1000 PRHR HX was modeled. In spite of a simplified IRWST geometry, the PRHR operational performance was verified [42].

Since that major experimental efforts, many other experimental and numerical analyses have been performed. Men et al. [43] built an experimental facility to study the applicability of different heat transfer correlations on the AP1000 PRHR HX design and the IRWST water mixing characteristics during PRHR operation. Using a cylindrical water tank where a C-shaped tube was located, they concluded the Dittus-Boelter and the McAdams correlations were suitable to model the heat transfer inside and outside the tubes, respectively. The IRWST thermo-hydraulic behavior was studied by the Harbin Engineering University (China) in a simplified-geometry Computational Fluid Dynamic (CFD) model in [44]. Considering a constant tubes temperature, the temperature and flow field distribution in the tank was analyzed, as well as the heat transfer mechanism on the 689 PRHR bent (non C-shaped) tubes. Wang et al. [45] modified this model using 60 C-shaped tubes. They concluded the horizontal sections of the PRHR tubes has a positive effect on the reactor safety as those enhanced the heat transfer.

Jia et al. [46] used a FLUENT CFD model to simulate the thermal stratification and natural circulation on a rectangular IRWST. The influence of the PRHR tubes number (eight or sixteen) and initial flow temperature was also considered. A rectangular shape IRWST was also used in [47] to model the tank using a porous media approach with FLUENT for simulating the PRHR tubes. The models were validated against experiments [48] and showed a good agreement for the axial temperature profiles. The early single-phase stage was simulated and the thermal-hydraulic characteristics of the IRWST was studied. They found out that thermal stratification is more prominent with time, and that a *dead zone* exists at the bottom of the tank, where the fluid does not exchange heat.

Also using FLUENT, Xia et al. [49] modeled a scaled-down IRWST and PRHR. The flow field and temperature distribution in the IRWST were studied applying a constant heat flux on twelve PRHR tubes. They found that vortices developed in different position of the IRWST which they addressed to the irregular shape of the tank. Xue et al. [50] developed in FLUENT a PRHR model with thirty-seven C-shaped tubes in a real shape IRWST. A linear decreasing inlet temperature was applied inside the tubes, and the outlet temperature agreed with the design values. Natural circulation and thermal stratification were found to occur in a prototypic shape IRWST. Also *dead zones*, mostly located at the tank bottom, were found. Again, these were addressed to the complex geometry of the IRWST.

Due to the lack of experimental data with adequate shape and arrangement of the IRWST and PRHR, researchers from North China Electric Power (NCEP) University and Nuclear Power Software Development Center created an experimental set up of a scaled IRWST/PRHR HX system in 2015 [51], Figure 3-8. Using the results from the experimental benchmark, a FLUENT

CFD model was validated under different turbulence models and meshes. Using the same experimental benchmark, Lu et al. [52] thoroughly analyzed the overall heat transfer performance in the IRWST. They found, that the PRHR system removes the heat mainly by natural convection, but forced convection plays a role too. The position of the thermocline location had a large influence on the thermal stratification. The details of the experimental setup are explained in section 6.3, as those have been used for the validation of the IRWST GOTHIC model. The experimental investigations also allowed to further study different strategies for enhancing the heat transfer from the PRHR to the tank. The use of baffles along the PRHR is one the strategies followed to reduce thermal stratification, however its existence also decreased the buoyancy lifting vertical velocity [53]. Furthermore, the experimental observations together with the available literature, allowed to create a Phenomena Identification and Ranking Table (PIRT) for the PRHR system in the IRWST [54]. Characteristics of the C-shaped tube geometry were analyzed, such as the tube orientation, the type (cylindrical, plane), the length, the bundle (heat flux and pitch), the surface roughness and the outside diameter. Moreover, the importance of the thermal status of the IRWST water was also studied, including the initial temperature, pressure, water level or thermal stratification as parameters.

Figure 3-8. Schematic of the experimental setup. Obtained from [51]

During the last years, the PRHR performance has been widely studied. Tian et al. [55] created an experimental set-up where a vertical tube is submerged into a cylindrical tank. The influence of being in a confined space in the heat transfer mechanism of saturated pool boiling is studied. After studying the different flow regimes and the heat transfer coefficient in detail, a correlation is proposed for calculating the Heat Transfer Coefficient (HTC) along the tube in a confined space. A Volume of Fluid (VOF) FLUENT model is validated against the experiments. They found that the HTC is higher in the upper parts and the large vapor slugs attached to the surface may deteriorate the heat transfer, whilst the wake of the large bubbles enhances the heat transfer [56]. Tao et al. [57] studied the PRHR heat transfer characteristics in an experimental facility. It was modeled as forty-two arranged C-shape bundle, located in the center of a

rectangular tank. The heat flux through the 7 m length tubes was studied for different conditions of inlet flow, temperature, and pressure. The results were compared to a theoretical model which allowed to predict the heat transfer along the tubes. This experimental set up was also used to study the transient thermo-hydraulic behavior of the PRHR. A FLUENT CFD porous media model was validated against the experiments, showing a good agreement. The single phase simulation showed a clear thermal stratification in the water tank, that was more prominent with time [58]. Du et al. [59] developed an IRWST-PRHR scaled-down experiment where the IRWST was modeled as a rectangular tank and the PRHR as five C-shape heating rods. Particle Image Velocimetry (PIV) measurement was conducted to obtain detailed information on velocity and the thermal-hydraulic behavior in the tank. They documented the tank is divided in three zones: high temperature (upper), natural convection (central) and *dead zone* (bottom), existing a thermal interface between the natural convection and *dead zone*, which had a big influence on the thermal stratification phenomenon.

Figure 3-9. FLUENT simulation results at 5000 s in Tao et al. experiment [58].

Ge et al. [60] used a FLUENT CFD porous media model to study the complete heat transfer mechanism in a full-scaled IRWST and PRHR. The PRHR was modeled as a porous media with the distributed resistance method. The heat transfer model was implemented as user defined function (UDF); and the primary side values were validated against ROSA-V experiments. The 3D thermal-hydraulic behavior in the pool was studied until saturation was reached. It was observed that thermal stratification was obvious along the tank and a *dead zone* existed at the bottom of the tank. This model was further enhanced to be able to model boiling and two phase flow regime [61]. The results showed that boiling and forced convection have a significant role in the heat transfer performance of the PRHR HX tube bundle, around 95 % of the total residual heat was removed by the upper horizontal and vertical tubes. Gui et al. [62] studied the heat transfer phenomena in an experimental facility where a full length PRHR tube was modeled. The influence of pressure and inlet mass flow on the condensation length and heat transfer was studied. They found that increasing inlet mass flow had a positive effect on the heat transfer. It was also observed that an increase in water temperature did not influence the heat transfer.

3.2.2. Passive containment safety system (PCS)

Experimental tests were carried out in a one-to-ten Large Scale Test facility (LST) to study the PCS behavior. The facility modeled the PCS with the riser and chimney sections, being the chimney outlet modeled in some experiments with an exhaust fan [63]. The results of these experiments were used to validate different Lumped Parameters (LP) codes. WGOTHIC was validated against these experiments under PCS dry conditions [63]. A 2D model for the containment was used, having enough resolution (168 nodes) to predict non-condensable stratification and flow fields. The applicability of WGOTHIC to analyze the PCS was demonstrated after studying the results. Moreover, the COCOSYS code used the LST experimental results to validate the CDW (Wall Condensation Model) model [25]. The simulation results of pressure, condensation and evaporation were in good agreement with the experimental ones.

Besides, the Westinghouse AP600 PCCS small-scale test facility data was also used to validate the COMMIX liquid-film tracking models [64]–[66]. The tracking models, meant to model the PCS spray actuation, computed the liquid-film thickness, velocity, and temperature on the containment sides. Simulation results showed good agreement with the experiment, Figure 3-10.

Figure 3-10. Westinghouse small-scale test COMMIX results comparison [64]

Later on, the PCS performance has been simulated with several codes, some of them developed or modified in order to simulate the key requirements identified by the Phenomena Identification and Ranking Table (PIRT) [34]. Some codes have used those simulation results to verify their models. The results of a modified version of CONTEMPT4/MOD5 were compared with WGOTHIC calculations with certain degree of similarity, [67]. Other codes such as PCCSAP-3D [68] have used COMMIX results to verify its capabilities, being able to predict

hydrogen, fission products or iodine behavior inside the AP1000 containment [69]. Additionally, Sandia National Laboratories (SNL) used the MELCOR code to assess the influence of the nodalization in the containment heat transfer, concluding that a multi-volume approach must be used to be able to simulate AP1000 natural convection phenomena. The results were compared with CONTAIN results [24]. Moreover, it was identified that the phenomena simulation inside the SCV and the PCS require the use of a multi-volume model. On another study, Dr. Broxtermann & Prof. Allelein., used the German code COCOSYS to study the AP1000 containment [25]. The model was validated with the LST experimental results, and the results from conservative and best-estimate approach were compared with WGOTHIC [20] and MELCOR [24] results

The 3D code GASFLOW-MPI has been modified to simulate the PCS water falling film in a more realistic way [70], [71]. Its results have been compared with COMMIX results and the model has been used to simulate AP1000 containment under different accident scenarios specially, for studying hydrogen risk under severe accident conditions [72]–[75].

CFD codes have been also used to simulate the PCS performance. Wang et al. [31] used ANSYS CFX to model 1/10 section of the PCS under dry conditions. The same software was used by Wright R. et al. [76] to model the Robust Containment Air Flow Tests (RAFT) 1/36th test facility that was constructed at Oregon State University. Under these studies the RAFT tests were proven to be representative of the full-scaled flow path. Moreover, Wang X. et al. [77] used the Eulerian Wall film model in ANSYS Fluent to study the falling film evaporation in the PCS. The film evaporation model was validated against the EFFE facility [78] results obtaining the simulation results agreed with the experimental data.

Regarding the studies with GOTHIC, as a first reference, Westinghouse adapted the commercial version of GOTHIC to simulate the AP600 PCS phenomenology, creating the above mentioned WGOTHIC code. Additionally, the WGOTHIC code was coupled with CLIME model to simulate relevant phenomena as water evaporation, heat removal or mixed convection and it has been validated with large and small scale tests [79].

Wang G. & Wang Z. used WGOTHIC to compare its results with GOTHIC 8.0 in an AP1000 containment model, and it was concluded that it is possible to use GOTHIC 8.0 code as a tool to analyze the AP1000 containment response [80]. Hung Z. et al. used GOTHIC 7.2a to create different AP1000 containment models (short-term model and long-term model) to simulate two accidents in order to study the containment integrity during a LOCA. The results agree with the DCD and the containment integrity was not compromised [81]. Lately, the GOTHIC code was used to model the containment safety verification via integral test (CERT), a 1/8-scale containment experimental facility [82]. The pressure and temperature results show the pressure is overestimated at blowdown phase and the temperature is slightly different.

Chapter 4

The GOTHIC code

4.1. General description

GOTHIC (Generator of Thermal Hydraulic Information in Containments) is an integrated, general purpose thermal-hydraulics computer program for design, licensing, safety and operating analysis of nuclear power plant containments, confinement buildings and system components [83]. It has been developed by Numerical Applications Inc (NAI). (which belongs to Zachry Nuclear Engineering) under the sponsorship of the US Electric Power Research Institute (EPRI).

GOTHIC has been successfully used by several plants to resolve technical issues in the areas of equipment qualification, accident analysis in support of probabilistic risk assessment, high energy line break analysis, room heat-up calculations, station blackout analysis, technical specification changes and other areas. Buoyancy dominated flow, condensation and evaporative heat transfer in the presence of noncondensing gases, stratification, hydrogen mixing, hydrogen burn (except detonation) and system controls can be model in GOTHIC [84]. The code has also the capabilities to analyze the thermal hydraulic response of passive containment designs.

The code solves the conservation of mass, momentum and energy equations for multiphase (vapor phase, continuous liquid phase, droplet phase) multicomponent (water, air, H₂, noble gases, etc.) compressible flow [85]. The vapor phase can be a mixture of steam and

noncondensing gases and a separate mass balance is maintained for each component of the vapor mixture. The phase balance equations are coupled by mechanistic models and correlations for interface mass, energy and momentum transfer that cover the entire flow regime from bubbly flow to film/drop flow as well as single phase flows. The interface models allow to have thermal non-equilibrium conditions among the phases and unequal phase velocities [84].

Navier-Stokes equations are solved in GOTHIC using a finite volume numerical method [86]. The conservation equations are presented in integral form for a specific volume V , limited by an area A . The volume V usually corresponds to one finite volume in the computational mesh.

- **Mass conservation equations** are solved for drops, liquid, ice and steam and the general form of the mass balance is given by [86]:

$$\begin{aligned} \frac{\partial}{\partial t} \int_V \alpha_\phi \rho_{\phi\zeta} dV = & - \int_A \alpha_\phi \rho_{\phi\zeta} \vec{U}_\phi \cdot \vec{n} dA + \int_{A_f} \alpha_\phi \epsilon_{\phi\zeta}^c \rho_\phi \nabla \left(\frac{\rho_{\phi\zeta}}{\rho_\phi} \right) \cdot \vec{n} dA \\ & + \int_{A_w} s_{\phi\zeta}^c dA + \int_{A_{I\phi}} S_{\phi\zeta}^c dA_{I\phi} + E_\phi^c \end{aligned} \quad [4.1]$$

Where the subscript ϕ refers to the phase, taking on values v (vapor), l (liquid), d (drops) and i (ice); and ζ refers to a component of the steam/gas mixture. α is the volume fraction, ρ the density, $\vec{U}$ velocity, $\vec{n}$ outward normal to dA , A_f portion of the total surface area, ϵ^c mass diffusion coefficient, s^c mass source per unit area through a bounding wall A_w , S^c mass source coming from the interfacial area A_I , and E^c is the source from engineering safety equipment.

- **Energy conservation equations** are solved for the fluid phases: drops, liquid and vapor, and for thermal conductors [86]:

$$\begin{aligned} \frac{\partial}{\partial t} \int_V \alpha_\phi \rho_\phi e_\phi dV = & - \int_A \alpha_\phi (e_\phi \rho_\phi + P) \vec{U}_\phi \cdot \vec{n} dA + \int_{A_f} \alpha_\phi \epsilon_{\phi\zeta}^e \nabla T_\phi \cdot \vec{n} dA \\ & + \sum_\zeta \int_{A_f} \alpha_\phi \epsilon_{\phi\zeta}^c \rho_\phi \nabla \left(\frac{\rho_{\phi\zeta} h_{\phi\zeta}}{\rho_\phi} \right) \cdot \vec{n} dA \\ & + \int_{A_w} s_\phi^e dA + \int_{A_{I\phi}} S_{\phi\zeta}^e dA_{I\phi} + E_\phi^e \end{aligned} \quad [4.2]$$

Where e is the internal energy, P is the static pressure, ϵ^e is the thermal diffusion coefficient, s^e is the energy source per unit wall area, S^e is the energy source per unit interfacial area, and E_ϕ^e is the equipment energy source.

- **Momentum conservation equations** are solved for drops, liquid, and vapor phases, being the general form of the equation [86]:

$$\begin{aligned} \frac{\partial}{\partial t} \int_V \alpha_\phi \rho_\phi \vec{U}_\phi dV = & - \int_A \alpha_\phi \rho_\phi \vec{U}_\phi (\vec{U}_\phi \cdot \vec{n}) dA \\ & + \int_{A_f} \alpha_\phi \vec{\sigma}_\phi \cdot \vec{n} dA + \int_{A_w} s_\phi^m dA + \int_{A_{I\phi}} S_{\phi\zeta}^m dA_{I\phi} + E_\phi^m \end{aligned} \quad [4.3]$$

Being the static pressure and the Reynolds stress term in $\vec{\sigma}$. s^m is the momentum source per unit wall area, S^m momentum per unit interfacial area and E^m the momentum from the equipment source. All components of the vapor are assumed to move at the same velocity.

The GOTHIC Technical Manual [87] gives additional information about the field equations and the detailed physical models. The differences when modeling subdivided or lumped parameters model in terms of field equations are also provided.

4.2. Nodalization and geometry approximation

GOTHIC can model the containment building as interconnected control volumes or even as a single control volume. Using the lumped-parameter model approach, GOTHIC treats each Control Volume (CV), which can be a containment, a compartment or a single cell, with volume averaged quantities. If a more detailed analysis is needed (where a large gradient of fluid conditions is expected, such temperature, density or gas concentration [88]), the lumped-parameter CV can be subdivided using a pre-processor which adds grid lines in the orthogonal coordinates, creating 1, 2 or 3-dimensional grids [89].

As mentioned before, a finite volume method is used. Mass and energy equations are solved for each cell in the subvolume obtaining the three-dimensional distribution of mass and energy. Momentum equations are solved at the boundaries of each cell to obtain the flow pattern within the subvolume.

To define the containment/compartment geometry GOTHIC does not follow the same approach as commercial CFD codes where a body fitted mesh is applied, but instead a porous approach and a Cartesian mesh are used. In that sense, cell volume and surface porosities are used to model complex geometries [90]. The containment geometry can be represented by blocking specific cells and cell faces. By using a combination of the different blockages available (block, cylinder, wedge, cone and cap) complex geometrical compartment shapes can be modeled maintaining fluid independence between different compartments [88].

GOTHIC can model hydraulic connections in different ways, such as: Flow Paths (FPs), network models, cell interface connections in subdivided volumes, and 3D connectors for subdivided volumes. The FPs model the hydraulic connections between any two computational cells and

might represent doorways, pipes, instrument penetrations, ductworks, etc. The 3D connectors define the hydraulic connection across the wall interfaces common to two separate subdivided volumes or between a subdivided volume and a lumped volume [89]. Figure 4-1 represents the possible connections between the different volumes and components in a containment model.

For each junction, one-dimensional momentum equations for the vapor, droplets and liquid are solved. The effects of viscous and turbulent shear are not included in the junction equations. Furthermore, there is no mass stored in the junctions and mass taken out of one volume via a junction is immediately placed in the connecting volume. It should be taken into account the flow through a junction is limited using analytic and semi-analytic critical models. Depending on the upstream conditions (subcooled region, two-phase region and single-phase vapor) different models are used.

Figure 4-1. Computational mesh in a containment. Adapted from [91]

4.3. Stress terms: turbulence modelling

GOTHIC includes the full-treatment of the momentum transport terms in multi-dimensional models, with optional models for turbulent shear, turbulent mass, and energy diffusion [88]. GOTHIC can use two different models to calculate the turbulent terms: the Prandtl mixing length model and the two-equation k- ϵ model. The mixing length model (MIX-L) provides reasonable results for situations involving uniform geometries and flow fields [92]. Variations of the k- ϵ model available in GOTHIC are:

- **k ϵ -STD**: solves partial differential equations that model the transport of effective parameters for calculating local turbulence, velocity scale and length scale. The standard k- ϵ turbulence model [93] is based on the best understanding of the relevant processes, and presents a set of equations which can be applied to a large number of turbulent applications.

For turbulent kinetic energy k :

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + 2\mu_t E_{ij} E_{ij} - \rho \epsilon \quad [4.4]$$

For dissipation ϵ :

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\frac{\mu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} 2\mu_t E_{ij} E_{ij} - c_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad [4.5]$$

Where u_i represents velocity component in corresponding direction, E_{ij} represents component of rate deformation, ρ density, μ_t represents eddy viscosity ($\mu_t = \rho C_\mu \frac{k^2}{\epsilon}$). $\sigma_k, \sigma_\epsilon, C_{1\epsilon}, C_{2\epsilon}, C_\mu$ are adjustable constants.

- **k ϵ -RG**: k- ϵ turbulence model with the Renormalized Group source term. This model includes an advance source term developed by Yakhot [94] in the dissipation transport equation in order to enhance capabilities to simulate mixing driven by highly buoyant discharges [95].
- **k ϵ -NL2**: k- ϵ turbulence model with a second order approximation for the Reynolds stress term. In this model the Reynolds stress tensor is complemented by an additional quadratic nonlinear term [96]. This model has been enhanced with the aim that the anisotropic eddy viscosity relationship can allow the application of the k- ϵ turbulence model to a wide range of three-dimensional turbulent flow [97].
- **K ϵ -NL3**: k- ϵ turbulence model with a third order approximation for the Reynolds stress term. In this model a cubic relationship between the strain and vorticity tensor, and the stress tensor is established. This model gives more flexibility that enabled the stress levels to be captured over a wide range of complex strain fields. Therefore, the effects of streamlines curvature over a range of flows are better captured [98].

4.4. Source terms

The closure relationships mentioned at the beginning of this section, are necessary to perform the global P-T analysis in the three-dimensional or lumped parameters approach. The closure relationships make use of correlations which describes different phenomena and couples this phenomenon between the fluid fields and the solid structures. Among those can be included the wall source terms (i.e. convection and radiation heat transfer, condensation, evaporation, and wall friction) [88].

When GOTHIC solves the conservation equations for mass, momentum and energy for multiphase flow for three fields (steam/gas mixture, continuous liquid and liquid droplets), a multiphase Eulerian-Eulerian modeling is applied.

For the aforementioned fluid fields, GOTHIC calculates the relative velocities between the separate but interacting fluid fields, including the effects of two-phase slip on pressure drop. The heat transfer between phases and contact surfaces is calculated as interface source terms [92].

4.4.1. Interface source terms

GOTHIC accounts for interfacial transitions between all four fields. For the interface source terms it is assumed there is no mass or energy storage at the interface. The different models require flow regime maps, heat transfer correlations, state relationships, and fluid and material properties for completeness [88].

The heat transfer from the vapor to the liquid interphase and from the liquid to the interphase is calculated considering the interphase temperature, the convective heat transfer coefficients (HTCs) on the vapor (v) and liquid (l) sides of the interphase, eq. [4.6] [4.7], and the interphase area. The phase change rate depends on the mass transfer coefficient (obtained from the mass transfer Nusselt (Nu) number, eq. [4.8]), the molecular weight of steam and the steam mole fraction at the interphase and the bulk vapor.

$$Nu_{ll}(d_b) = 2 + 0.74Re_{bl}^{1/2}Pr_l^{1/3} \quad [4.6]$$

$$Nu_{vl}(d_b) = 2 + 0.74Re_{bv}^{1/2}Pr_v^{1/3} \quad [4.7]$$

$$Nu_{ml}(d_b) = 2 + 0.74Re_{bv}^{1/2}Sc_v^{1/3} \quad [4.8]$$

Where d_b is the bubble diameter, Re_{bl} , Re_{bv} are the bubble Reynolds number for liquid and vapor respectively; Pr_l , Pr_v and Sc_v are the Prandtl number for liquid, vapor and the Schmidt number for vapor [83].

4.4.2. Wall source terms

As stated previously the wall source terms include convection and radiation heat transfer, condensation and boiling at the wall, and friction at wall and orifice drags in junctions. These source terms are included in GOTHIC as Thermal Conductors (THC) which model solid structures and its heat transfer to the fluid volumes [88].

The thermal conductors are modelled as one-dimensional slabs, which includes a general model for heat transfer between the thermal conductors and the steam/gas mixture or the liquid [89]. There are different heat transfer options available in GOTHIC [91] [99]: (1) **Convection**: natural and forced convection. Different correlations are available in GOTHIC to define the heat transfer coefficient on the surface of a THC. Those correlations depend on the surface geometry; (2) **Radiation**: Wall-Steam, Wall-Wall; and (3) **Condensation**: DIRECT, Tagami and specified condensation. For calculating the condensation HTC, different correlations are available, such as Uchida, Gido/Koestel (extensively explained in [84]) or the max between those two.

When condensation is modeled in GOTHIC, basically two options could be selected: DIRECT or FILM. Condensation and evaporation are relevant in the PCS performance (explained in detail in section 3.1.2). Hence, available options in GOTHIC for simulating these modes will be highlighted next.

With the DIRECT option, condensation occurs at the wall and it is calculated by a correlation (Uchida or Gido/Koestel) or by an advanced diffusion layer model (DLM-FM). The diffusion layer model calculates the condensation rate and sensible heat transfer rate using heat/mass transfer analogy. Further, the model considers the film roughening, the heat transfer between the wall and film and mist generation in the boundary layer [99].

In the case of the FILM option, a fully mechanistic treatment of heat/mass transfers, considering the film of liquid (wet-wall model) is applied. The wall is split into wet and dry portions based on the available water for film coverage. Convection to the vapor is calculated to the vapor phase for the dry portion and to the liquid for the wet portion. Also, if the wall is cold enough, condensation on the dry portion is calculated using Uchida or Guido/Koestel or, if it is hot enough boiling is calculated for the liquid portion. Otherwise all phase change occurs at the liquid/vapor interface using the convective heat transfer coefficients on either side of the interface and the analogous mass transfer coefficient on the vapor side.

Part III

MODEL CREATION
METHODOLOGY

Chapter 5

Subsystem modelling: IRWST + ADS

5.1. Introduction

The containment thermo-hydraulics is widely affected by the IRWST surface temperature, which determines the steam partial pressure of the gas space above it. At the same average pool temperature, higher surface temperatures of a stratified pool will lead to higher containment pressure compared to a mixed pool. Different simulation studies on Fukushima Daiichi Unit 3 accident development showed that when lumped parameters code used a mixed pool assumption the maximum pressure achieved was underestimated [100]. Moreover, in [23] was showed the pressure could be well predicted when the thermal stratification of the pool assumption was followed. Additionally, steam condensation is determined by the water temperature at the sparger outlet: if the water is close to saturation, condensation is reduced (or directly avoided), and steam bypass or flashing may occur. Therefore, thermal stratification within the IRWST is a safety issue of great significance and simulating properly the IRWST thermal-hydraulic behavior during transients is a key factor for determining the containment safety. For that reason, a 3D GOTHIC model has been chosen as a simulation tool.

In the following sections of this chapter the validation of the GOTHIC IRWST 3D model will be presented step by step. Firstly, a scaled-down model is validated against experimental data obtained from the public literature. This experiment is a scaled-down IRWST-PRHR facility constructed in the NCEP University (China), which main objective was to study the different phenomena that occurs inside the tank, such as natural convection and thermal stratification during the PRHR performance. Secondly, the insights learnt from the previously validated model, in particular the mesh and PRHR modeling, are applied into an AP1000 IRWST full scaled model. Finally, the ADS spargers are implemented in the IRWST and its performance and best modeling set up are studied.

5.2. North China Electric Power University IRWST experiment simulation

5.2.1. Introduction

As it was presented in Part II3.2.1, due to the lack of experimental data with adequate shape and arrangement of the IRWST and PRHR, researchers from NCEPU and Nuclear Power Software Development Center created an experimental set up of a scaled IRWST/PRHR HX system in 2015 [101]. Using the results from the experimental benchmark, a FLUENT CDF model was validated under different turbulence models and meshes.

In this PhD thesis, a scaled IRWST-PRHR GOTHIC model is validated against the experimental benchmark presented in by the NCEP University [52]. The best modeling set up, which represents adequately the majority of the Thermo-Hydraulic (TH) phenomena, is extracted from the validation study and will be applied in a full IRWST-PRHR HX model. For that purpose, the experimental set-up and the benchmark experimental results are briefly described in section 5.2.2. Afterward, the model created in GOTHIC is described and validated against the experiments in section 5.2.3. Then, in section 5.2.4 the results of a parameter sensitivity analysis are presented. Finally, obtained conclusions are addressed and discussed.

5.2.2. Experimental facility description

Dimensions and data presented in this section have been all obtained from [51], [52], [102], where additional information about the experimental facility can be found.

The experimental facility constructed by NCEPU consists of four systems: a test section (which overall comprises the IRWST and PRHR HX), a water supply and purification system, the PRHR control system; and the data acquisition system.

The experimental model was scaled down in length (1/9.6) and height (1/3.72) after a scaling analysis [52]. The approximate data provided for the tank was: 3.75 m x 1.5 m x 2 m, Figure 5-1. The IRWST wall was 8 mm thick, 304 stainless steel, being the outside sidewalls insulated with a 500 mm thick layer of aluminum silicate wool. The IRWST shape is similar to the real AP1000 IRWST shape described in the AP1000 Design Control Document (DCD) from v14 to v19 [27].

The PRHR HX in the experimental set-up is located at one side of the IRWST at approximately 0.36 m above the tank bottom. It consists of 12 symmetrical arranged C-shape electrical heating rods, with an outside diameter of 19 mm, being the distance between two adjacent tubes 38 mm. Those 12 tubes represent the 689 tubes of the real AP1000 design. A scheme of the experimental set up is presented in Figure 5-1.

Figure 5-1. IRWST/PRHR HX experimental set up scheme. Adaptation from [52]

More than 150 calibrated T-type thermocouples (TC) have been used to monitor the temperature in the tank. Five key monitoring lines along the lateral direction are chosen for comparison, each line has eight TC at different heights (TC1: 2.1 m, TC2: 1.9 m, TC3: 1.77 m, TC4: 1.43 m, TC5: 1.1 m, TC6: 0.77 m, TC7: 0.43 m, TC8: 0.2 m). Two lines are in the PRHR tube bundle, Line 3 outside but close to the PRHR bundle, and Line 4 and Line 5 are located in the bulk water of the tank, far from the PRHR HX position. The approximate position of the different lines is presented in Figure 5-2.

Figure 5-2. IRWST/PRHR HX experimental setup dimensions. Adaptation from [52]

The conditions of the experimental benchmark test were an initial water level of 2.2 m at 48.9 °C, being the PRHR HX electrical power 176 kW. Besides, the laboratory ambient temperature was 19.85 °C.

The temperature results presented in [52] from the benchmark experiments have been digitalized with an estimated human error of ± 1 °C and ± 10 s, Figure 5-3 (the data included in this article were digitalized as it was the only public data available). In the experiment, the temperature increases steadily and, while transient advances, thermal stratification is being developed. The fluid close to the PRHR is heated, flowing upwards due to the buoyancy force. The less dense heated water flows up until it reaches the water surface, then it flows to the sidewalls, changing its direction downwards as it is reaching the wall, flowing back to the PRHR. Convective cells are formed and hot water is accumulated in the upper region, creating a “thermal interface”, also called thermocline. At the bottom of the tank, there is no apparent movement as the water is not exchanging heat with the PRHR, creating a so-called dead zone. The heat from the bottom and top zone is only transferred through the thermal interface by thermal diffusion, which is not sufficient to move the water from the *dead zone*. At the end of the transient, when the temperature in the upper part reaches saturation, the thermal interface propagates downwards, mixing the hot and cold fluids intensively, creating unsteady oscillations and increasing the temperature at the bottom. Moreover, at this point, when saturation is reached, thermal stratification is reduced.

Figure 5-3. Digitalized transient temperature variation along Line 3 taken from [52]

5.2.3. IRWST GOTHIC model validation

As the purpose of this work is to simulate the IRWST and PRHR HX behavior, only the test section of the full experimental facility is modeled with GOTHIC. The results are presented in a way that can be compared with the ones presented in [51], [52].

The model is composed of two Control Volumes (CVs) thermo-hydraulically connected. The tank is modeled with a 3D approach. The tank CV is created with the same dimensions of the experiment facility, being slightly taller in order to simulate correctly the water-air interface in the last numerical cell. Connected to the tank is the Laboratory atmosphere CV. The connection is made using a 3D connector component, which links all the tank CV upper cells to a lumped CV which represents the lab atmosphere (1000 m³). The lab atmosphere is connected to a pressure boundary condition (BC) of 101.35 kPa and 19.85 °C (to mimic lab conditions referenced in the experiment). A scheme of these connections is represented in Figure 5-4.

Figure 5-4. Scaled-down GOTHIC model control volume connections

The geometry of the tank is shaped using blockages. As commented in previous chapter, the blockages in GOTHIC are simple geometrical figures (cylinders, caps, blocks or wedges) used to partially or completely block cells of the computational domain. Those are represented in grey in Figure 5-5.

The PRHR geometry from the experimental test has been translated to GOTHIC and every tube has been modeled with cylindrical blockages. This approach allows modeling the real volume occupied by the tubes inside the tank, as well as has allowed modeling the friction between the tubes and the fluid surrounding it, using GOTHIC wall friction correlations. The PRHR heat power is modeled as a heat source to the pool using heater components. Those heaters are located in every cell occupied by the PRHR blockage tubes and all of them exchange 176 kW in total. The PRHR heat power modeling has been also tested using thermal conductors. These analyses are presented in section 5.2.4.3.

(a) GOTHIC interface

(b) 3D visualization obtained with AutoCAD

Figure 5-5. IRWST & PRHR blockages geometry and mesh.

The heat transfer through the IRWST lateral walls is modeled with thermal conductors taking the material and the thickness from the experimental test description, see the previous section. The insulation wool properties have been obtained from different suppliers [103], [104] and are presented in Table 5-1. The 304 stainless steel properties have been obtained from a heat transfer reference book [105].

Table 5-1. IRWST wall material properties

	Temperature [°C]	Density [kg/m ³]	Thermal Conductivity [W/mK]	Heat Capacity [kJ/kg]
Aluminum silicate	100	128	0.05	0.084
Stainless steel	27	7900	14.9	0.477

The HTC used in [51] of 0.5 W/m²K was applied outside the IRWST wall. A sensitivity case was performed with a HTC of 3.36 W/m²K, which was obtained using natural convection empirical correlations [105]. Nevertheless, the influence of this parameter and the wall heat transfer performance had little effect on the results because of the effectiveness of the isolation material. The heat transfer at the conductor surfaces in the inner side is modelled using the Diffusion Layer Model with Film roughening and Mist formation (DLM-FM), explained in Part II4.4.2.

The mesh implemented in the model was obtained after a sensitivity study which is explained in section 5.2.4. A 3D hexahedral mesh was created consisting of 6500 cells. The cells are distributed in 26 axial levels along the Z-axis, 25 divisions along the X-axis and 10 divisions along the Y-axis. The cells size on the abscissa and the ordinate axes is nearly homogeneous, with a mean value of 0.15 m. The small deviations are caused by a geometry necessity, particular to GOTHIC Cartesian mesh, of crossing the tank walls blockages with a mesh division, to better represent the geometry and to minimize the discrepancies with the experiment.

The Z-axis is composed of heterogeneous cell lengths. The size of the cells at the bottom of the tank is around 0.05 m, and the rest of the tank cell lengths are around 0.1 m. The reason of mesh selection is explained in section 5.2.4.

5.2.4.Sensitivity analysis

The set-up of different simulation parameters has been studied in order to determine the more appropriate ones representing the phenomena occurring at the experiment. Firstly, a mesh sensitivity analysis has been done studying the influence of lateral, longitudinal, and axial mesh in the thermal stratification in the pool. Secondly, once a reference mesh was selected, parameters concerning the PRHR have been studied. The heat transfer from the tube bundle to the water has been modeled using different components: heaters or thermal conductors.

All the simulations were run with GOTHIC 8.1(QA), with a second-order discretization scheme in space and a semi-implicit discretization in time. The turbulence model selected was the k-ε standard and the molecular diffusion was enabled. The minimum porosity was set to 0.001. The minimum porosity is defined as the minimum cell volume or cell face porosity that will be allowed in the model. In each time step, the pressure equation was solved with the conjugate gradient method until a 1e-6 residual was reached. The minimum time step was set to 1e-6 s and the maximum to 1e-3 s.

5.2.4.1. Mesh sensitivity analysis

As has been stated in different studies, the mesh is of great importance when attempting to simulate water thermal stratification in GOTHIC [106], [107]. Thirty 3D-Cartesian meshes have been created to be tested under the conditions of the experiment. Some of them are homogeneous, where all cell lengths (X, Y, Z) have the same size, and the rest are sorted as heterogeneous as cell lengths are not equal. The mesh characteristics of every sensitivity case are presented in Table 5-2.

The test matrix selection has the objective to study the influence of the cell lateral sizes (width and length) on different cell heights. The different heights selected were 0.2, 0.15, 0.1 and 0.05 m. The minimum size was selected following the recommendations given in [107], [108]. The previously chosen heights were used for the lateral sizes. In the case of the width, Y-axis, due to blockage-mesh restrictions, the minimal applicable size was 0.15 m. The nomenclature given to the cases follows: the first number is the cell height size (0.2, 0.15, 0.1 or 0.05), it is followed by a version number (v####) which represents the combination of X and Y sizes.

Table 5-2. Mesh sensitivity cases

Case	X size [m]	Y size [m]	Z size [m]	N cells	Case	X size [m]	Y size [m]	Z size [m]	N cells
z0.2_v12	0.2	0.15	0.2	2340	z0.15_v12	0.2	0.15	0.15	2880
z0.2_v11	0.2	0.1	0.2	3510	z0.15_v11	0.2	0.1	0.15	4320
z0.2_v10	0.2	0.05	0.2	7020	z0.15_v10	0.2	0.05	0.15	8640
z0.2_v9	0.15	0.15	0.2	3250	z0.15_v9	0.15	0.15	0.15	4000
z0.2_v8	0.15	0.1	0.2	5460	z0.15_v8	0.15	0.1	0.15	6000
z0.2_v7	0.15	0.05	0.2	9750	z0.15_v7	0.15	0.05	0.15	12000
z0.2_v6	0.1	0.15	0.2	4810	z0.15_v6	0.1	0.15	0.15	5920
z0.2_v5	0.1	0.1	0.2	7215	z0.15_v5	0.1	0.1	0.15	8880
z0.2_v4	0.1	0.05	0.2	14430	z0.15_v4	0.1	0.05	0.15	17760
z0.1_v12	0.2	0.15	0.1	3960	z0.05_v9	0.15	0.15	0.05	12500
z0.1_v11	0.2	0.1	0.1	5940	z0.05_v8	0.15	0.1	0.05	18750
z0.1_v10	0.2	0.05	0.1	11880	z0.05_v6	0.15	0.05	0.05	18500
z0.1_v9	0.15	0.15	0.1	5500	Mix_Z	0.15	0.15	0.05-0.12	6500
z0.1_v8	0.15	0.1	0.1	9240					
z0.1_v7	0.15	0.05	0.1	16500					
z0.1_v6	0.1	0.15	0.1	8140					
z0.1_v5	0.1	0.1	0.1	12210					

In order to evaluate the thermal stratification of the water inside the tank, the Stratification Number (*Str*) was used [109]. It is defined as the ratio of the mean temperature gradients at any time to the maximum mean temperature gradient during the whole transient, according to eq. [5.1]. The mean of the transient temperature gradients at any time is given by eq. [5.2].

$$Str = \frac{\overline{(\partial T / \partial z)_t}}{\overline{(\partial T / \partial z)_{max}}} \quad [5.1]$$

$$\overline{\left(\frac{\partial T}{\partial z}\right)_t} \approx \overline{\left(\frac{\Delta T}{\Delta z}\right)_t} = \frac{1}{K-1} \left[\sum_{k=1}^{K-1} \left(\frac{T_{k+1} - T_k}{\Delta z} \right) \right] \quad [5.2]$$

$$\overline{\left(\frac{\partial T}{\partial z}\right)_{max}} \approx \overline{\left(\frac{\Delta T}{\Delta z}\right)_{max}} = \frac{T_{max} - T_{min}}{(K-1)\Delta z} \quad [5.3]$$

Δz is defined as the distance between two adjacent points, the distance between two TCs. K is the number of nodes in a monitoring line, which in this study will be eight as it is the number of TC in each monitoring line, L3 and L5. The T_{max} selected is the maximum temperature measured during the experiment, 100 °C. The minimum temperature T_{min} is the water initial temperature, 48.9 °C.

In Figure 5-6, a representation of the results along the monitoring line 3, obtained for all the cases studied is given. The dotted black line represents the experimental values, the other lines in each graph represent every case for the different Z lengths. It can be observed that none of the configurations with the Z lengths of 0.2 and 0.15 m are capable to reproduce the thermal stratification within the tank during the whole transient. In the case of the 0.1 m Z -length cases, the difference of the stratification number between the experiment and the simulations is slightly lower. As the transient advance in time, the difference is greater, however, always less than in the bigger meshes. The 0.05 m Z -length cases show a good agreement of the *Str* number between the experiment and the models since the beginning to almost the end of the transient. The last 2000 s in these cases could not be reproduced due to convergence problems.

(a) z0.2 cases

(b) z0.15 cases

(c) z0.1 cases

(d) z0.05 cases

Figure 5-6. Monitoring line 3 Str number for all the sensitivity cases during the transient.

After analyzing all cases a smaller difference between the simulation and the experiments was noticed for some X-Y configurations. For all Z lengths the v9 case (0.15 m, 0.15 m) gives the smaller difference to the experiment (red line in Figure 5-6).

The quantification of the deviation extent between the different simulations and the experimental stratification number is represented with a relative absolute error value ε_{Str} for each monitoring line in each sensitivity case, for every time step, defined as:

$$\varepsilon_{Str}(t) = \left| \frac{Str_s(t) - Str_e(t)}{Str_e(t)} \right| \quad [5.4]$$

$$\overline{\varepsilon_{Str}} = \frac{\sum_{t_i}^{t_f} \varepsilon_{Str}(t)}{n_{points}} \quad [5.5]$$

$$\varepsilon_T(t) = \frac{T_e(t) - T_s(t)}{T_e(t)} \quad [5.6]$$

Str_s is the calculated Str Number in the simulation and Str_e in the experiment, calculated with eq. [5.1]. The average error $\overline{\varepsilon_{Str}}$ during the transient, which follows the eq. [5.5], for all the sensitivity cases in the monitoring lines L3 and L5, is presented in Table 5-4. The smallest errors for all the Z lengths configurations are achieved with the v9 configuration. When comparing the $\overline{\varepsilon_{Str}}$ of 0.2_v9, 0.15_v9, 0.1_v9 and 0.05_v9 one can see the smallest values are obtained with 0.1 and 0.05, being the 0.05_v9 case the one which is most comparable to the experimental values.

In order to find the causes of the differences between 0.1_v9 and 0.05_v9 cases the TC temperature error (eq. [5.6]) at two different times was studied. The results are presented in Table 5-3. It can be noticed the errors are higher for TCs at lower positions, such as TC7 or TC8, increasing its value as the transient advances. The rest of the upper TC errors follow a similar behavior, being around $\pm 2\%$ in most of the cases. Concluding that the tank upper part temperature was properly modeled for every Z-meshes. Whereas the bottom part was not captured correctly, and the simulated temperature was higher than the temperature reported in the experiments.

Table 5-3. Temperature error ε_T (%) between the experiment and some simulation cases at 3000 and 5000s for every TC position.

	3000 s				5000 s			
	0.2_v9	0.15_v9	0.1_v9	0.05_v9	0.2_v9	0.15_v9	0.1_v9	0.05_v9
TC1	0.608	-1.597	1.170	0.323	1.310	-0.613	2.118	1.771
TC2	0.152	-1.949	-0.538	-0.584	1.087	-0.711	1.026	1.807
TC3	1.591	0.437	0.967	1.324	1.299	-0.412	1.464	0.762
TC4	-0.779	-2.660	0.229	-0.672	-0.469	-2.244	0.524	-0.060
TC5	-1.752	-0.333	0.354	-0.284	-2.416	-1.979	-0.252	-1.250
TC6	0.549	2.912	2.107	3.380	-1.155	0.643	1.728	2.890
TC7	3.588	5.985	2.561	4.774	0.146	1.193	-0.710	3.757
TC8	20.470	23.071	8.313	3.619	40.467	41.981	19.733	9.171

As previously mentioned, during the experiment, there was a dead zone at the bottom of the tank, where the fluid had no movement and there was not mixing. To capture this phenomenon, and to avoid false mixing due to the numerical diffusion, a finer mesh has to be chosen to discretize the tank bottom in direction of the stratification, i.e. the Z-axis. Coarse meshes cannot reproduce accurately the phenomenon as a false mixing is produced by a numerical diffusion in the calculation and hence the bottom dead zone is not modeled. This behavior influenced by the mesh width can be observed in Figure 5-7 where the 0.05 m mesh can reproduce the thermocline just behind the PRHR, while the others are not capable, producing the heat transfer between the lower and upper layers. Therefore, it could be stated that with finer meshes the numerical diffusion is reduced, as well as the fluid mixing with the upper cells, as also the thermocline is more accurately modeled. These results are in accordance with [107] where it is stated the mesh size needed to reproduce this phenomena is around the size of thermocline width, 50-100 mm.

Figure 5-7. Thermal stratification in 0.05_v9, 0.1_v9 and 0.2_v9 cases at 3000 s and 5000 s

In the light of these results a new case with heterogeneous mesh in the Z direction was created, having a finer mesh (0.05 m) at the bottom of the tank until the beginning of the PRHR (right above the thermocline averaged position), represented in Figure 5-5.

From the PRHR position until the top of the tank a 0.1 m homogeneous mesh is applied. This case is named MIX_Z and the average temperature error and average Str number error results are presented in Table 5-4. For all cases, the smallest deviation from experiment was obtained with MIX_Z mesh. The average *Str* error results for all the recording times at the two monitoring lines are around 13 %. The average temperature errors are around 1.5 % (TC8 is not included in the average). Based on these results, the MIX_Z case is selected as the most suitable case for simulating this experiment.

The temperature error during the transient in all the thermocouples is not remarkable, except in the TC8, located at the bottom of the tank. In the GOTHIC simulations, at 2000 s the temperature of the fluid at the bottom starts to slightly increase. This behavior is observed even

with smaller meshes below the PRHR, therefore mesh convergence failure is discarded. This pronounced difference with the experimental results may be influenced by the diffusivity induced by the numerical error, characteristic of discretized systems. Nevertheless, the biggest deviations appear at the end of the transient when upper layers reach saturation. This difference is explained in the following section.

Table 5-4. Parameters and results of each mesh sensitivity study case.

	X size [m]	Y size [m]	Z size [m]	N cells	$\epsilon_{Str\ L3}$	$\epsilon_{Str\ L5}$	ϵ_{T-L3}	ϵ_{T-L5}	CPU time [h] *3CPUs
z0.2_v12	0.2	0.15	0.2	2340	0.499	0.474	0.309	0.293	6.967
z0.2_v11	0.2	0.1	0.2	3510	0.518	0.513	0.367	0.356	5.371
z0.2_v10	0.2	0.05	0.2	7020	0.539	0.501	0.364	0.374	46.023
z0.2_v9	0.15	0.15	0.2	3250	0.460	0.488	0.278	0.295	9.705
z0.2_v8	0.15	0.1	0.2	5460	0.443	0.456	0.372	0.385	46.433
z0.2_v7	0.15	0.05	0.2	9750	0.468	0.549	0.339	0.375	50.085
z0.2_v6	0.1	0.15	0.2	4810	0.497	0.485	0.338	0.347	8.732
z0.2_v5	0.1	0.1	0.2	7215	0.468	0.463	0.401	0.409	17.205
z0.2_v4	0.1	0.05	0.2	14430	0.529	0.560	0.429	0.464	101.215
z0.15_v12	0.2	0.15	0.15	2880	0.550	0.559	0.455	0.470	4.107
z0.15_v11	0.2	0.1	0.15	4320	0.599	0.620	0.497	0.532	8.218
z0.15_v10	0.2	0.05	0.15	8640	0.598	0.607	0.492	0.508	35.491
z0.15_v9	0.15	0.15	0.15	4000	0.529	0.534	0.378	0.426	9.376
z0.15_v8	0.15	0.1	0.15	6000	0.679	0.733	0.614	0.683	27.753
z0.15_v7	0.15	0.05	0.15	12000	0.547	0.545	0.407	0.459	69.432
z0.15_v6	0.1	0.15	0.15	5920	0.686	0.693	0.624	0.643	44.601
z0.15_v5	0.1	0.1	0.15	8880	0.681	0.680	0.562	0.589	70.953
z0.15_v4	0.1	0.05	0.15	17760	0.621	0.632	0.563	0.634	107.213
z0.1_v12	0.2	0.15	0.1	3960	0.280	0.250	0.256	0.248	28.769
z0.1_v11	0.2	0.1	0.1	5940	0.389	0.399	0.322	0.299	16.141
z0.1_v10	0.2	0.05	0.1	11880	0.380	0.378	0.269	0.240	69.257
z0.1_v9	0.15	0.15	0.1	5500	0.245	0.215	0.260	0.251	21.234
z0.1_v8	0.15	0.1	0.1	9240	0.263	0.228	0.304	0.288	48.820
z0.1_v7	0.15	0.05	0.1	16500	0.373	0.390	0.208	0.194	62.552
z0.1_v6	0.1	0.15	0.1	8140	0.312	0.270	0.329	0.294	40.578
z0.1_v5	0.1	0.1	0.1	12210	0.312	0.257	0.362	0.348	79.828
z0.05_v9	0.15	0.15	0.05	12500	0.261	0.251	0.265	0.250	43.125
z0.05_v8	0.15	0.1	0.05	18750	0.362	0.381	0.406	0.401	130.733
z0.05_v6	0.15	0.05	0.05	18500	0.270	0.245	0.425	0.396	49.295
MIX_Z	0.15	0.15	0.05-0.12	6500	0.135	0.113	0.238	0.229	26.072

5.2.4.2. MIX_Z case results

In this section the reference model (MIX-Z case) results will be presented. First, the temperature results along the tank at different positions (Line 1-5 in Figure 5-2) are explained. Later, using the Str number the thermal stratification in the whole tank is analyzed. Finally, the velocity fields and streamlines are qualitatively compared with the experimental ones.

All the simulations were run with GOTHIC 8.1(QA), with a second order discretization scheme in space and a semi-implicit discretization in time. In each time step, the pressure equation was solved with the conjugate gradient method until a $1e-6$ residual was reached. The minimum time step was set to $1e-6$ s and the maximum to 0.009 s.

Figure 5-8 displays the fluid temperature distribution in the model at different times during the transient (500, 1000, 2000, 3000, 4000, 5000, 6000, 7000 and 7500 s). In general, it could be seen the water in the tank is gradually heated up by the PRHR HX during the transient. Similar to what happens in the experiment, the PRHR heat transfer produces a temperature increase in the surrounding water since the beginning of the transient. The heated water, less dense, flows up for buoyancy effects until it reaches the water surface where it flows to the sides until the tank walls are reached. At this point the water flows down and back to the PRHR position, creating convection cells driven by natural circulation. The water not heated by the PRHR, at the bottom of the tank, stays steady and at the initial temperature. A thermal interface is then created between the upper heated layers and this *dead zone*.

Figure 5-8. MIX_Z fluid temperature distribution at different times

The streamlines generated in the tank at 500 s are presented in Figure 5-9. The fluid trajectory, and the formed the convection cells can be observed. Fluid near the PRHR bundle is heated and flows upward, reaching its maximum velocity at the top (0.2 m/s). Once the fluid contacts with the water surface it flows to the sides until it reaches the tank walls being the velocity in that zones around 0.02 m/s. The fluid is then cooled at the surface through the heat exchange with the atmosphere and becomes less dense flowing downwards and moving again to the PRHR bundle, where it will be heated again. Fluid from the bottom zones is mostly stagnant, not exchanging neither mass nor energy to the upper zones (*dead zone*).

Figure 5-9. Streamlines and velocity vector 3D representation.

Temperature simulation results together with the experimental ones during the transient are presented in Figure 5-10 and Figure 5-11 for line 3 and line 5, respectively. The temperature increase is almost linear in all the positions through line 3 and line 5. A clear thermal stratification is observed to occur. After 6000 s the temperature trend changes, not increasing more on the upper positions as saturation temperature is reached.

Figure 5-10. TC temperatures during the transient at Line 3

Figure 5-11. TC temperatures during the transient at Line 5

The temperature of the tank at different positions is presented in Figure 5-12. In general, there is an adequate agreement between simulation and experimental results. Analyzing in detail the different positions, it could be seen at 500 s temperature at line 1 and 2 is underestimated. The nucleate boiling observed to occur during the experiments at the tube surfaces, cannot be modeled with precision in GOTHIC due to the porous media approach used for modelling the PRHR tubes. This fact is less obvious at 3000 s when the pool bulk temperature has increased. Temperature results at lines 3 and 5 agrees quite well with the experimental results at these times of the transient. The thermal distribution in the PRHR side is presented in Figure 5-13 for different moments in the transient.

Figure 5-12. Temperature at different heights for lines 1, 2, 3 and 5 at 500 and 3000 s

Figure 5-13. Vertical plane crossing line 1 temperature at different transient times

The stratification extent during the transient is presented in Figure 5-14 using the stratification number defined in eq. [5.1] for line 3. When the top water layers reach saturation, the thermal interface moves downwards. At that moment (around 6200 s in the simulation) the mixing flow pattern developed at the same time than the numerical oscillations bringing the hot water in contact with the cold water at the bottom. It produces a sudden heat transfer and warms up the bottom layers. The numerical oscillations are clear looking at the oscillatory behavior of the liquid temperature in TC7 and TC8 positions.

Figure 5-14. Monitoring line 3 Stratification number for Mix_Z case.

The temperature results obtained from the simulation have some differences with the experiment, however. In Table 5-5 the temperature error, calculated with eq. [5.6], for all the TC positions in some of the transient digitalized points is presented. In general, a qualitatively good agreement can be seen for almost all the thermocouples during the whole transient. It can be noticed that the middle area, the bundle vertical zone, is the one with less temperature difference amongst the simulation and the experiment. The bottom area, below the PRHR, is well predicted during the transient early stage. However, higher temperatures than in the experiment are obtained after 3000 s.

The temperature error increases with time, possibly due to the effect of diffusivity on the “thermal interface” modeling and the way it exchanges heat between the hot upper and cold bottom layers. Errors bigger than 30% can be found after saturation temperature is reached. After this moment, the strong mixing increases the differences between the experimental measurements and the simulation results in the whole tank. The most plausible reason is the appearance of small steam volume fractions with higher velocity than in the experiment in the area close to the PRHR. This high-velocity (around 5 m/s) vapor phase increases the momentum in the tank, what enhances thermal mixing. Therefore, the inferences of the IRWST thermal-hydraulic behavior should be carefully assessed after reaching the saturation conditions within the pool. Moreover, the lack of interface tracking models in GOTHIC when there is two-phase flow within the pool, complicates the calculation of the flow patterns when small steam fractions appears near the PRHR.

Table 5-5. Temperature error (%) between the experiment and the Mix_Z case for every TC position during the transient.

Time (s)	ϵ_{TC-3-1}	ϵ_{TC-3-2}	ϵ_{TC-3-3}	ϵ_{TC-3-4}	ϵ_{TC-3-5}	ϵ_{TC-3-6}	ϵ_{TC-3-7}	ϵ_{TC-3-8}
0	2.357	1.884	1.145	0.898	0.398	0.147	0.401	0.109
1000	-0.598	1.897	-0.113	0.963	-1.700	-2.297	-3.163	-0.003
2000	-0.661	1.468	-0.869	0.806	0.440	-1.844	-2.720	-1.351
3000	-1.060	0.712	-0.692	0.137	0.172	-2.061	-2.569	-3.158
4000	-1.429	0.294	-0.860	0.054	0.027	-2.055	-1.531	-6.201
5000	-1.965	-1.020	-1.123	-0.262	0.637	-1.560	-0.695	-9.989
6000	-2.443	-1.394	-0.125	-0.859	0.673	0.117	0.912	-14.689
7000	0.356	0.597	0.787	0.503	0.572	1.036	3.095	-33.697
7500	0.048	0.399	0.287	0.067	0.361	0.849	2.474	-47.299

Comparing the simulation and the experiment velocity results qualitatively it can be seen those are quite similar, although the maximum values measured during the experiment [52] are not predicted in the simulation. Mostly probably due to the porous media approach used for modeling the PRHR tubes and the relatively high mesh size.

5.2.4.3. PRHR HX modeling sensitivity approach

Different approaches can be followed in GOTHIC for modeling the PRHR HX, geometrically and thermally speaking. In this section a sensitivity analysis has been performed to study the most suitable approach for simulating the thermal behavior observed in the experiment. Firstly, the manner the geometry is modeled is studied. Secondly, a sensitivity on how the PRHR is thermally modeled is performed. Finally, conclusions about the most suitable approach based on the results are presented.

- **PRHR geometry modeling approach**

The previous simulations were modeled following the same geometry than in the experiment. All the 12 tubes were modeled using cylindrical blockages. This porous media approach allows to model the real volume occupied by the tubes and to model the friction between the tubes and the fluid surrounding it. In these analyses two different approaches were used to see whether “less complex” simulation approach would give similar results.

These two alternative approaches were:

1. **“no PRHR geometry”**: Not modeling the PRHR geometry with blockages. Consequently, the volume occupied is not modeled, and the friction correlations between the tubes and the fluid is not calculated in the cells where the PRHR may be located.
2. **“PRHR volume”**: Not modeling the PRHR geometry with blockages but imposing the total volume directly on the cells that the PRHR may occupy. No friction is calculated.

These two approaches would give the possibility to see the influence of the PRHR volume and friction calculation on the general thermal-hydraulic results. The stratification number results are presented in Figure 5-15 and Figure 5-16 for Line 3 and Line 5, respectively. In general, there are little differences between the two sensitivities with the reference case (12 tubes) during the transient until the 6000 s. A higher Str number is observed for the 12 tubes case in the two lines studied, having the two sensitivities similar results until the 6000 s. After that moment, the Str number for each case follows a different behavior. When the PRHR geometry is not modeled, with volume or friction, the stratification is less pronounced. This may be caused because of the lack of obstacles that allows a free fluid movement, producing a more noticeable mixing. However, it should be considered, those are slight differences compared with the reference case.

The *Str* average error (eq. [5.5]) of these cases are presented in Table 5-6. It was found the temperature and *Str* number error is smaller, in average, when the PRHR geometry is modeled, considering volume and friction. However, the differences with the other cases is not remarkable, being around 1 % higher for the accumulated temperature root mean square error (eq. [5.7]) and 3 % for the *Str* average error.

$$\varepsilon_{Tsum} = \sum_{t=0}^{7500} \sqrt{\frac{(\sum_{i=1}^{n_{TC}} \varepsilon_T^2)_t}{n_{TC}}} \quad [5.7]$$

Table 5-6. Str number average error and accumulated temperature error for each PRHR geometry sensitivity case

Case	$\epsilon_{Str\ L3}$ [%]	$\epsilon_{Str\ L5}$ [%]	$\epsilon_{Tsum-L3}$ [%]	$\epsilon_{Tsum-L5}$ [%]
Base case: 12 tubes	12.02	13.76	19.34	17.57
no PRHR geometry	15.74	16.57	20.03	17.46
PRHR volume	15.54	14.49	20.14	17.38

Figure 5-15. PRHR geometry modeling sensitivity. Stratification number in Line 3 for the base case in green (12 tubes geometrically modeled), no PRHR geometry (yellow) and PRHR total volume (red).

Figure 5-16. PRHR geometry modeling sensitivity. Stratification number in Line 5 for the base case in green (12 tubes geometrically modeled), no PRHR geometry (yellow) and PRHR total volume (red).

It can be concluded that there is a slight difference for the PRHR occupied volume being modeled or not. If the tubes are modeled the agreement between the simulation and the experimental results is higher. However, if those are not modeled in volume/friction, the results can be also considered acceptable.

- **Heat modeling approach**

There are different options available in GOTHIC for introducing a heat source in a fluid. In the previous sections the *heaters approach* was used. A heater component is placed in every cell where the PRHR might be located. The heat applied in each heater is the total heat divided by the number of heaters used. It should be considered; the number of heaters vary depending on the number of cells in the tank. For the reference model, MIX_Z, 17 heaters were used to model the PRHR.

Other option available in GOTHIC are the THC, which can model heat sources associated with structures, in this case the PRHR tube bundle. There are different approaches that can be followed when using THC for simulating heat sources. In this work two of those options have been selected: (1) Imposing a volumetric heat when defining a conductor type, (2) imposing a heat flux when defining a surface option.

To model a thermal conductor the surface options and conductor types definition is needed. The surface options allow to specify the heat exchange from the conductor to the fluid (heat transfer models) and the surface condition of the conductor (thermal boundary conditions). The conductor types allow to specify the conductor nodding and its heat rate. Further information concerning thermal conductors modeling can be found in the User's manual [110].

To model the PRHR three different THC were used and positioned accordingly: upper horizontal tubes segment, vertical tubes segment, and lower horizontal tubes segment. The area of each THC was obtained as the sum of the area of the 12 tubes in that position. The area of each tube was calculated using its length (different for each tube, obtained from the CAD model) and radius (0.0095 m). The total area of each segment is 0.23 m² for the upper and lower horizontal section, and 0.96 m² for the vertical section. The material used is stainless steel 304. The heat transfer from the THC surface to the fluid is modeled using the DLM-FM. The rest of the parameters are selected depending on the approach used for the heat modeling: surface option (heat flux) or conductor type (volumetric heat).

When a **heat flux** (W/m²) is applied as the inner surface option, the heat is applied proportionally to the THC area, specified by the user. The conductor type does not include any inner volumetric heat. When a **volumetric heat** (W/m³) is applied in a conductor type the heat is applied proportionally to the volume. This volume is calculated with the specified area and the conductor radius (when the conductor type is selected as a rod type). The inner surface option in this case may be modeled as adiabatic.

An additional sensitivity study has been included, "**heaters volumetric**". Using heaters components, the heat is not evenly distributed among the heaters. The heat applied in each heater is proportional to the volume ratio that the segment occupies. Horizontal heaters correspond to the 16.2 % volume each, and vertical heaters a 48 %. This sensitivity is used to

compare the influence of modeling a heat source directly on the fluid with the influence of modeling using heat transfer correlations (as happens in a THC).

The stratification phenomena occurring in the different sensitivity cases are represented with the Stratification Number during the transient in Figure 5-17 and Figure 5-18 for Line 3 and 5, respectively. The differences between the cases are scarce until the 6000 s as can be seen in Figure 5-17 and Figure 5-18, where the different lines are overlapping. After the 6000 s all the cases have a similar trend, specially the heaters and heat flux approaches. A slight difference can be observed when the heat is applied as volumetric heat.

Figure 5-17. PRHR heat modeling approach. Stratification number in Line 3 for each PRHR heat modeling sensitivity case

Figure 5-18. PRHR heat modeling approach. Stratification number in Line 5 for each PRHR heat modeling sensitivity case.

The temperature error (eq. 5.6) is presented for all the THC at different times (3000, 5000 and 7000 s) in Table 5-7. The differences between the cases could be explained studying the way the heat is “deposit” in the different approaches. The volumetric heat approach applies heat in every region of the conductor type, so that the heat is distributed along the whole THC width. The surface flux approach applies the heat on the inner side of the THC, so that the heat has to be transferred from the THC center to the outer side in contact with the fluid. The material conductivity and specific heat plays a significant role in this process. The accumulated temperature quadratic error and the average Str number error are presented in Table 5-8. The differences among the different cases is not higher than 1.5 % for line 3 and around 3 % for line 5. The PRHR heat deposition, respectively heat source, can be reliably modeled by any of the presented models.

Table 5-7. Temperature error (%) between the experiment and the sensitivity cases for every TC position during the transient.

		TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8
3000 s	Heaters	1.01	-0.59	0.86	-0.09	-0.20	2.01	2.51	2.96
	Heaters volumetric	1.27	-0.49	0.86	0.19	0.57	1.67	1.73	2.77
	Volumetric heat DLM-FM	1.28	-0.58	1.06	0.16	0.49	1.80	1.69	2.96
	Heat flux DLM-FM	0.24	-1.38	-0.13	-0.92	-0.65	0.80	0.97	2.55
5000 s	Heaters	2.00	1.02	1.20	0.31	-0.54	1.57	0.70	9.15
	Heaters volumetric	2.26	1.06	1.33	0.55	-0.36	1.76	-0.29	8.49
	Volumetric heat DLM-FM	2.32	0.98	1.38	0.55	-0.42	1.82	-0.30	8.23
	Heat flux DLM-FM	0.91	-0.23	-0.03	-0.82	-1.74	0.43	-1.48	8.10
7000 s	Heaters	-0.19	-0.44	-0.59	-0.32	-0.51	-1.27	-2.28	35.32
	Heaters volumetric	-0.29	-0.58	-0.80	-0.52	-0.39	-1.42	-4.16	28.96
	Volumetric heat DLM-FM	-0.37	-0.78	-0.96	-0.48	-0.45	-1.18	-4.17	26.12
	Heat flux DLM-FM	-0.62	-0.96	-1.15	-0.69	-0.66	-2.00	-5.90	20.58

Table 5-8. Str number average error and accumulated temperature error for each PRHR heat modeling sensitivity case

Case	$\epsilon_{Str\ L3}$ [%]	$\epsilon_{Str\ L5}$ [%]	$\epsilon_{Tsum-L3}$ [%]	$\epsilon_{Tsum-L5}$ [%]	Computational time [h]
Heaters	12.02	13.76	19.34	17.57	26.94
Heaters volumetric	11.65	15.40	20.27	17.13	28.86
Volumetric heat DLM-FM	12.92	14.53	20.48	17.07	27.99
Heat flux DLM-FM	12.96	16.49	19.75	18.63	24.41

5.2.5. Conclusions

The IRWST-PRHR HX behavior has been extensively studied in the last decades due to its importance in the safety during an accident in the AP1000 reactor. Experimental facilities have been constructed to study the TH performance of the tank. Most of them were scaled-down with a simplified geometry, due to the huge cost of a full-scale experimental setup. Moreover, and for the aforementioned reasons, several simulation analyses were also performed in full-scaled geometry, using mostly the porous media approach due to the complexity of the problem and the large resources needed to model it accurately. In the work presented in this section, the GOTHIC code has been used to simulate a scaled-down IRWST, which data is available in the open literature.

In the first step, a mesh sensitivity analysis was performed to study the optimal mesh that models the phenomena that occurs in the IRWST. Several meshes were tested, and it was concluded that for the GOTHIC Cartesian mesh, the most important parameter was the height of the Z-axis grid levels. Meshes with a cell size of 50 mm were able to model the main phenomena, as thermal stratification, thermal interface, and bottom tank stagnation. Analyzing the different behavior along the tank, it was seen the most problematic part for modeling was the bottom of the tank, below the PRHR, where no heat exchange should occur (the so-called *dead zone*). However, due to numerical diffusion induced by the code when coarse meshes are used, the heat exchange between the lower and upper layers was overestimated. Using these insights, a “heterogeneous” mesh, with smaller cell size at the bottom and bigger cell size in the middle and upper part, was created and the most accurate results, in terms of temperature at the TC positions, were obtained. Using this heterogeneous mesh (Mix-Z) the IRWST performance was studied during a transient where constant heat is transferred from the PRHR. Natural convection was seen to occur during the early stage of the transient and thermal stratification was more pronounced with time, until saturation is reached. The simulation case reproduced the thermal stratification phase with acceptable precision, diverging from the experimental results once the mixing process is happening after 6000 s.

Different heat transfer modeling approaches have been studied in order to identify the most accurate method that models the heat transfer between the PRHR and the IRWST water. Different PRHR geometry configurations were tested. The analyses showed the most accurate approach was the PRHR tubes modeling as blockages with the pressure loss calculated by GOTHIC correlations. Moreover, different PRHR heat transfer configurations were tested. The sensitivity analysis showed all the configurations used gave similar results, with relatively little differences with the experiment. Any of those could be used to simulate the heat from the PRHR.

The modeling of this experiment has shown the capability of GOTHIC to simulate thermal stratification to certain extent. The temperature along different points in the tank was seen to be properly modeled. In addition, the difficulties related to the numerical diffusion and when saturated condition are locally reached at the pool were identified. The modelling hypotheses found an acceptable balance between accuracy and computational cost. However, the identified limitations should be studied in a full-scaled model and the full AP1000 containment. This work is presented in the next section.

5.3. IRWST FULL-SCALED MODEL

Following the validation of the modeling methodology in GOTHIC against a down-scaled experimental IRWST model, a full-scaled model was created in GOTHIC in a similar way. The objective was to understand if the lessons learnt from the experiment simulation can be applied in an IRWST full-scaled model, and the phenomena occurring could be properly modeled.

5.3.1. GOTHIC model

The IRWST shape and dimensions have been obtained from the public DCD [111]. Using Figure 3-2, together with drawings available in the DCD, the IRWST geometry was digitalized with AutoCAD (blue perimeter in Figure 5-19). The dimensions were extracted and implemented in GOTHIC. It should be noticed that the global dimensions perfectly agree with the scaled-up dimensions of the experimental test aforementioned.

Figure 5-19. AP1000 IRWST CAD scheme

In GOTHIC, a similar modeling strategy as in the experiment analysis was followed. The model is composed of two thermo-hydraulically connected CV. One represents the tank and the other the free volume space of the AP1000 containment, Figure 5-20.

The containment CV was modeled as lumped (one single node) with not thermal structures inside of it as it is only used as a steam sink. The free volume applied, after extraction of the IRWST volume, is about 59000 m³. Compartments, walls, or any other thermal structure are not modeled.

The geometry of the tank CV was shaped using blockages and openings. For this analysis, the PRHR tubes were not geometrically modeled in detail given the large number of tubes (689) and the increased discretization cost. Hence, the occupied volume and friction were not modeled. It was shown in the earlier sensitivity test for the scaled IRWST model, that this strategy had a negligible influence on the simulation results.

The PRHR HX power is modeled using heater components, which were located in every PRHR cell position (obtained from the CAD model), transferring 58.9 MW in total. The heat transfer

through the lateral walls was modeled with six thermal conductors. Following the DCD, the thickness of each wall was different depending on the pool side that was being represented. The materials used were stainless steel, epoxy painting, carbon steel, carbo zinc, and concrete of different thicknesses.

Once the geometry was created, different meshes were tested in the IRWST CV to see the influence and the plausible implementation of similar meshes in a full-scaled model.

Figure 5-20. Full-scaled GOTHIC model. IRWST-containment CV connections

5.3.2. Mesh sensitivity

The mesh selection in this model had to attend to different requirements to be selected:

1. To be able to represent thermal stratification in the tank
2. To accomplish with the number of cells restriction in GOTHIC 8.1 (<100k cells)
3. Consideration of its future implementation in a full AP1000 containment model (optimizing the balance between computational time - accuracy).

Following these requirements, a mesh sensitivity analysis was carried out.

The reference mesh selected for this analysis was the so-called “MIX_Z”, identified in the previous chapter for the experiment as the most suitable one. The MIX_Z mesh was scaled-up for the full-scaled IRWST, following the same scaling numbers in the different directions (9.6 in length, and 3.72 in height), has finally 7250 cells. Those are homogeneous on the X-Y direction (1.44 x 1.44 m), and heterogeneous in the axial direction (0.2 – 0.4 m).

Two different mesh sensitivity studies have been performed. In one study, the Z-axis mesh and its influence on thermal stratification was tested, and in the other study the X-Y axis mesh and its convergence with a prior selected Z-axis mesh was tested.

5.3.2.1. Z-axis mesh sensitivity study

The mesh schemes studied in this sensitivity analysis followed different criteria. In all of them the mesh on the X-Y axis was homogeneous (1.44 x 1.44 m), being the difference in the Z-axis cell dimension.

On the one side, in some of them, the cell dimension in the Z-axis was homogeneous: 0.2 m, 0.4 m, and 0.8 m being named Z-0.2 m, Z-0.4 m and Z-0.8 m, respectively. These cases aim to see the possible influence of the axial discretization overall and to find the mesh size where the stratification phenomenon is not properly modeled anymore. Figure 5-21 shows a representation of these schemes.

Figure 5-21. Full-scaled IRWST sensitivity analysis homogeneous mesh schemes

On the other side, heterogeneous meshes were created to evaluate the possible implementation of 0.05 m cell width (or even bigger sizes) below the PRHR, with 0.2 m or 0.4 m mesh width over the PRHR. These cases have the objective to see whether the finer mesh below the PRHR has a strong influence on the thermal stratification and to see if the mesh at the tank surface has an impact on the thermal state of the containment. The representation of these schemes is shown in Figure 5-22.

Figure 5-22. F Full-scaled IRWST sensitivity analysis heterogeneous mesh schemes

The initial temperature of the pool and the containment is 48.9 °C and the initial pressure in the containment is 108.25 kPa, following the AP1000 DCD [111]. The water level is 8.7 m. All the simulations were run with GOTHIC 8.1(QA), with a second-order discretization scheme in space and a semi-implicit discretization in time. In each time step, the pressure equation was solved with the conjugate gradient method until a 1e-6 residual was reached. The minimum time step was set to 1e-6 s and the maximum to 0.01 s.

The temperature results of the different run models in the sensitivity analysis are presented in Table 5-9 and Figure 5-23. The data were extracted in the similar positions as in the experiment TC , Line 3 (29.5 X, 9.4 Y), at 0.8, 2.4, 3.6, 4.8, 6, 7.2, 8 and 8.8 m in the Z axis.

Table 5-9. Temperature and *Str* number results for each TC for each case until 9000 s

		Z0.05-0.2	Z0.05-0.4	Z0.2-0.4	Z0.4	Z0.2	Z0.8
8.8 m	T _{max} [°C]	116.3	117.1	116.4	117.1	117.0	112.5
	T _{average} [°C]	85.2	83.1	83.0	83.4	85.2	76.4
8 m	T _{max} [°C]	116.1	116.9	115.9	116.8	116.7	112.5
	T _{average} [°C]	82.7	80.8	80.7	80.9	82.8	76.4
7.2 m	T _{max} [°C]	115.9	116.6	115.5	116.8	116.0	112.6
	T _{average} [°C]	77.6	77.9	77.8	77.9	77.7	75.4
6 m	T _{max} [°C]	115.5	116.4	115.6	116.3	115.8	111.7
	T _{average} [°C]	74.0	74.4	74.4	74.4	74.1	73.0
4.8 m	T _{max} [°C]	115.3	115.2	114.7	115.2	115.2	112.0
	T _{average} [°C]	71.5	72.0	71.9	71.9	71.7	70.8
3.6 m	T _{max} [°C]	113.9	113.6	113.4	113.8	113.8	111.3
	T _{average} [°C]	68.9	69.7	69.6	69.6	69.0	69.7
2.4 m	T _{max} [°C]	111.3	111.4	111.4	111.6	111.8	110.1
	T _{average} [°C]	66.7	66.9	66.9	66.8	66.7	68.5
0.8 m	T _{max} [°C]	67.9	63.9	65.7	66.7	70.8	98.7
	T _{average} [°C]	54.3	52.7	53.3	53.5	54.1	64.2
Str _{average}		0.493	0.533	0.495	0.515	0.519	0.2

Analyzing the results, general trends can be observed. In terms of maximum temperature there is an obvious similarity between all the cases at all the TC points, excepting for Z-0.8 case. In this case, the temperature is almost homogeneous along the tank. The temperature difference with the other cases is bigger at the bottom, where it is around 30 °C. The temperature differences are small in-between the other cases. The biggest deviations can be found at the bottom, where temperature differences go from 3 to 7 °C. In terms of average temperature during the transient the same tendency is observed. Z-0.8 case shows the most remarkable differences among all the cases, being the differences major at the top (around -9 °C) and at the bottom (around +9 °C) of the tank. Regarding the remaining cases, all the altitudes show a similar temperature. The most noticeable difference occurs at the bottom where the differences go from 1.5 to 0.2 °C. Furthermore, analyzing the average temperatures a similar tendency can be observed between the Z-0.05-0.2 and Z-0.2 cases, and between Z-0.05-0.4, Z-0.2-0.4 and Z-0.4 cases. The differences between those two groups are around 2 °C at the top, and 1 °C at the bottom.

Figure 5-23. Temperature at different elevations for the sensitivity cases

The importance of correctly modeling the thermal stratification in pools inside the containment due to the significant influence of the pool surface temperature in the containment pressure was studied in the assignment at the KTH of this PhD thesis, applied to a Nordic BWR [14]. This fact has also been extensively studied by other researchers [23], [100], [107].

Analyzing the pressure in the lumped CV that represents the AP1000 containment free volume, Figure 5-24, it can be seen the influence of the thermal stratification in the containment pressure. Having the same average temperature ($\sim 72^\circ\text{C}$), when the pool is mixed (low Stratification number of Z-0.8m case) the pressure in the containment is underestimated. However, when thermal stratification is properly modeled, the pressure in the containment is higher (around 180 kPa with a stratified pool and 160 kPa with mixed pool), reaching high values only having as source the evaporated steam from the pool.

The combined results of Figure 5-25 and Figure 5-24 demonstrate that the 0.05 m mesh needed below the PRHR to capture the experimental results is not required in a full-scale geometry.

The mesh refinement does not give significant details and the main phenomena could be modeled with coarse meshes, but not as coarser as they could not reproduce the thermal stratification (such as it happens in Z-0.8m). This may be explained with the decrease of the thermocline surface to pool volume ratio when scaling-up the pool dimensions. The larger surface to volume ratio the higher the effect of the numerical diffusion in the pool behavior. This fact explains why a likely overestimation of the numerical diffusion below the PRHR bottom using Z-0.2 m or Z-0.4 m meshes does not lead to a misprediction of the overall pool thermal-hydraulics.

Figure 5-24. Full-scaled IRWST cases AP1000 containment pressure.

Figure 5-25. Full-scaled IRWST cases stratification number

As stated at the beginning of this chapter, one of the main objectives is to find the most suitable mesh capable of predicting thermal stratification with an affordable computational cost. Omitting the Z-0.8m case, the containment pressure results are almost similar until the 3000 s. Afterwards, the difference is on average 4 kPa between Z#-0.2 and Z#-0.4 cases. Taking these results into account, it could be stated the one that could be used as a reference mesh would be the case which has a minor computational cost, since, in terms of thermal stratification and pressure, results are not much different.

Attending to the information presented in Table 5-10 and the previously commented results, the most suitable meshes could be Z-0.2-0.4 m and Z-0.4 m. Due to there are no experimental data of the full scaled model and the results cannot be compared with any experimental results, the mesh was selected attending to simulation parameters and taking as a reference the scaled-down IRWST experimental results. The homogeneity of the cells, and the low computational time made the Z-0.4 m case be the one selected as the reference mesh for its incorporation in the full containment model for the Z-axis.

Table 5-10. Computational time for the different Z mesh sensitivities

Case	N cells	Computational time [h] (1 CPU)
Z-0.05-0.2 m	18750	360
Z-0.05-0.4 m	13750	189
Z-0.2-0.4 m	7250	56
Z-0.4 m	6000	61
Z-0.2 m	12000	195
Z-0.8 m	3000	28

5.3.2.2. X-Y-axis mesh sensitivity study

Once the Z-axis mesh was selected, it is necessary to see if the mesh is also converged on the rest axes. For that purpose, different meshes have been created maintaining the Z-0.4 m at the Z-axis in all the cases.

Five difference schemes have been created. The nomenclature follows XY-## m where ## represents the cell size in the X and Y directions. The reference case is Z-0.4 m which will be renamed as XY-1.44 m. The different schemes created are presented in Figure 5-26, where the differences between the meshes can be appreciated, as well as the small modifications accomplished in order to maintain the walls geometry in the tank.

Figure 5-26. Mesh schemes representation for the mesh convergence analysis

The results of these cases will be presented in terms of stratification number and temperature at 4000 s in the transient. In the case of XY-0.5 m GOTHIC 8.1 was not capable to run this model for memory limitations due to high number of cells, so the second condition stated at the begging of this section could not be fulfilled. Therefore, no results of this case are presented. For the rest of the cases the results are showed in Table 5-11 for temperature at each experiment equivalent TC position at 4000 s. Figure 5-27 represents the stratification number at 4000 s of the different sensitivity cases. It can be noted that the mesh convergence is achieved with the XY-1m mesh due the differences with the next smaller mesh (XY-0.8) are small on the Str number and average temperature, around 0.006 and 0.6 °C, respectively.

Table 5-11. Temperature and Str number at 4000 s for all the XY sensitivity cases

	XY – 2	XY – 1.44	XY- 1.2	XY – 1	XY – 0.8
TC8	98.00	99.65	97.20	97.54	98.40
TC7	91.73	93.16	92.84	94.09	93.38
TC6	86.51	86.40	87.40	88.23	87.54
TC5	83.01	82.67	83.57	84.09	83.58
TC4	79.05	78.54	79.53	79.63	79.15
TC3	75.19	75.03	75.02	75.25	75.93
TC2	71.02	71.06	70.94	70.77	71.48
TC1	55.63	54.87	54.07	52.77	53.02
Str number	0.659	0.693	0.684	0.718	0.724

Figure 5-27. Str number representation at 4000 s for all the XY sensitivity cases

As presented for Z mesh sensitivity, the computational time and the number of cells of each case are summarized in Table 5-12. It can be observed the finer the mesh, the higher the computational cost is.

Table 5-12. Computational time for the different XY mesh sensitivities

Case	N cells	Computational time [h] (1 CPU)
XY-2 m	3456	20.53
XY-1.44 m	6000	60.92
XY-1.2 m	8352	76.24
XY-1 m	12096	106.8
XY-0.8 m	17952	156.36

5.3.3. IRWST GOTHIC full-scaled model results

Herein the temperature distribution and the velocity flow fields developed in the tank during a constant heat transfer from the PRHR will be presented. As previously commented, the selected mesh for this case is the Z-0.4m XY-1m, represented in Figure 5-28.

Figure 5-29 displays the fluid temperature distribution in the IRWST at different times during the transient (500, 1000, 3000, 4000, 5000, 6000, 8000 and 9000 s). In general, it could be seen the water in the tank is gradually heated up by the PRHR HX during the transient. As it has been presented before for this case in Figure 5-23d and Figure 5-25, there is a clear thermal stratification. At the beginning the fluid near the PRHR is heated and flows upwards under the buoyancy effect. When it arrives at the water surface, the fluid moves sideways, flowing transversely to the tank sides. The time it arrives to the side walls it flows downwards, going finally back to the PRHR, forming the so-called convection cells.

Figure 5-28. IRWST full scaled GOTHIC blockages geometry and mesh

The recirculation flow between the PRHR side and the other sides of the IRWST seems to mix the fluid at different temperatures in the tank. This recirculation flow is formed at the beginning of the transient in the upper zones, where the hot fluid is, and it develops to the bottom of the tank. The streams lines in the IRWST at 4000 s are presented in Figure 5-30.

This recirculation flow does not go below the PRHR in the whole tank, creating a low velocity and low temperature zone, so-called dead zone. The heat transfer at the thermocline, between the lower layers and upper layers, is almost inexistent. This zone can be clearly seen in Figure 5-29 at the bottom of the tank.

Figure 5-29. IRWST 3D Temperature distribution during the transient

Figure 5-30. Streamlines and velocity distribution in the IRWST at 4000 s

5.3.4. Conclusions

Following the insights obtained during the experiment simulation, the full-scaled IRWST model was created. The Z-Mix mesh from the experiment simulation was scaled-up and additional mesh sensitivities were performed. The optimal case was applied in the full-scaled IRWST model. Different conclusions can be extracted from the analysis:

(1) GOTHIC, as a containment code, can be used for simulating thermal stratification with reasonable accurate results.

(2) a refined heterogeneous mesh is not needed to properly model the *dead zone* at the bottom of the tank and,

(3) the minimum mesh size able to model thermal stratification was found to be 0.4 m. It is noteworthy to say that the thermal stratification modeling is important for the proper containment pressure prediction, as a mixed pool can lead to pressure underestimation.

5.4. ADS implementation

Once the mesh for the full-scaled model has been selected, the ADS spargers were implemented. However, it is necessary to understand the difficulties of such implementation in a containment code. Therefore, in the first part of this section, a short description of the studies related with steam injection in a pool is given. This brief introduction has the purpose to raise the reader awareness of the difficulties and problematic around the steam injection into a pool simulation.

After that, the GOTHIC validation and setup insights of a steam injection experiment carried out in collaboration with the Technical Munich University (TUM) are briefly described. Finally, different approaches are tested for the ADS implementation in the full-scaled IRWST GOTHIC model and the effect on the pool and simulation results are presented.

5.4.1. Introduction

Mentioned in section 3.1.1., in case of an ADS actuation in an AP1000, the steam is directly released into the IRWST from the pressurizer. The thermal-hydraulic behavior of the pool is quite complex under these conditions: the pool receives high temperature steam at high velocities from the RCS. At the same time, the IRWST serves as the heat sink of the PRHR, which is heating the pool, and its inventory is used as water reservoir for the low-pressure safety injection system.

Under these circumstances the water could reach saturation, losing the IRWST its steam condensing efficiency. Consequently, the containment pressure and temperature would increase. It could also happen the extraordinary case when saturation conditions are approached in the levels above the sparger that flashing might occur near the water surface, propagating downwards. It poses a risk of losing large amounts of the IRWST inventory, lowering the availability for core cooling.

During the last decades there have been several studies about thermal stratification, mixing, and Direct Contact Condensation (DCC) in the Pressure Suppression Pool (PSP), a component in BWR reactors equivalent to IRWST. Experimental studies about DCC have been performed for sonic and sub-sonic jets [112]–[114], as well as for pool behavior [115], [116]. The capability of Computational Fluid Dynamics (CFD) codes to evaluate the steam direct contact condensation and the thermal mixing in a pool has also been assessed by several research groups in the past [117], [118], [119], [120], [121].

Concerning the GOTHIC code, due to the lack of physical models in state-of-the-art approaches, it is not possible to simulate the effect of different condensation regimes. GOTHIC has heat transfer models for pipe flow regimes as film, churn or bubbly, but not regimes such as chugging or oscillatory bubble where the steam-water interface is displaced outside the pipe cannot be predicted by the code [122]. To forecast thermal stratification or mixing during steam injection into a PSP with the GOTHIC code, the KTH researchers (Sweden) [123] proposed two effective models: Effective Heat Source (EHS) and Effective Momentum Source (EMS) which have been validated and developed during the last years [106], [107], [124]. The idea of these models is to predict the overall PSP behavior, modeling the time-averaged effective heat and momentum

transferred from the steam to the pool circulation. These models have been validated for chugging and complete condensation inside of Blow Down Pipe (BDP) [106] with experimental data obtained from PPOOLEX facility located in LUT [125] and PANDA facility at PSI. Models for the oscillatory bubble regimes developing in spargers have also been proposed in [117], [126], [127] and applied to full-scale analysis in [128].

Alternatively, Ozdemir and George [129] also simulated POOLEX experiments with GOTHIC 8.0, without using effective models such as the KTH ones. They also performed a Fukushima Daiichi Unit 1 containment analysis using a GOTHIC 3D model, determining the influence of the thermal concentration in the pool on the containment pressurization and hydrogen release [130]. Finally, in a joint research project of Iberdrola and the UPM, several POOLEX experiments were simulated to decide the mesh and setting conditions of the PSP for the Cofrentes NPP full containment model with GOTHIC 8.0 [118].

5.4.2. Experimental TUM facility simulation

The prediction of the IRWST thermal hydraulic behavior is crucial for the correct simulation of the whole AP1000 containment under SBLOCA conditions. Therefore, more data on the IRWST thermal hydraulic behavior under these conditions was needed to determine the optimal modeling of the containment with GOTHIC. For this purpose, an experimental test rig was constructed in cooperation of the UPM with the two-phase flows laboratory of the Institute of Nuclear Engineering at the TUM university [84]. This experiment was modeled in GOTHIC using following different approaches and carrying several sensitivity analyses [44]. A short description of the experiment and the simulation results are given next.

The experimental test rig is composed by the test channel, the steam generator, and an automatic control unit to set the steam mass flow rate at a specific value, see Figure 5-31. The test section consists of a 2.5 m high, 0.15×0.15 m rectangular channel with 0.01 m wall thickness. A transparent polycarbonate material surrounds the channel allowing optical observation and a continuous operation. The top of channel is open and thus the excess of vapor is vented to the surrounding room atmosphere. Steam generated in the SG is degassed by boiling and injected through the injection nozzle to the channel.

The steam is injected via a vertical injection nozzle with a 4 mm diameter opening at 0.095 m from the bottom. The nozzle is installed at the center of the channel and the size of the opening was chosen so that it results in a steam output velocity close to the one occurring in realistic ADS sparger holes. A set of eight K-type TCs are installed into the test section to measure the time development of the axial temperature distribution. The TCs are built into a 1.5 mm stainless steel envelope, and they are inserted horizontally from the side so that the tip of each TC is located at the center of the test channel. The distances of the TCs from the injection nozzle tip were: 0.05, 0.15, 0.275, 0.4, 0.55, 0.8, 1.15 and 2 m, Figure 5-31. The steam mass flow rate and temperatures, are logged each 1 s during experiments. The accuracy of the k-type TCs class 1 plus the extension cables is ± 1.9 K. The steam mass flow rate was measured using a vortex flowmeter with a ± 2.55 % accuracy.

Figure 5-31. Left: ADS simulator experimental facility scheme. Right: Test section photography, thermocouples (TCs) appears at the right side and steam injection nozzle at the bottom.

A high-speed camera was used to obtain visual observations of steam condensation and qualitative 2D projection of the steam distribution inside the channel. A special image-processing procedure was developed [131] to extract the steam shape from raw images and deliver a time-average value of the obtained 2D-projection of the steam. It should be noted that the obtained images describe only qualitatively the existing steam distribution.

Experimental observations of steam injection into the channel show three stages of steam condensation: (1) Steam fully condensed at the nozzle where no steam plume is visible at the nozzle tip; (2) a steam plume is visible at the nozzle tip, and steam bubbles detach off the plume and condense while rising in subcooled liquid and; (3) steam bubbles rise and can reach the top of the channel, the channel condensation efficiency is reduced, and eventually flashing occurs. More information about the experimental set up can be found at [13].

5.4.2.1.GOTHIC model

The steam injection was modeled by using the mass flow Boundary Condition (BC) 2F (Figure 5-32). A mass flow rate equal to that measured in the experiment was applied, as well as the experimental values of temperature (104.2 °C) and pressure (117.117 kPa). The laboratory room CV is modeled with the pressure BC 1P with 96 kPa and 24.5 °C. CVs 1s and 2 represent the experimental test rig and the laboratory, respectively. To maintain nearly constant temperature (25.4 °C) and humidity (43 %) in the laboratory room CV, a second BC (3P) was used. This BC provide a natural circulation path in order to prevent the increase of temperature, or changes in humidity inside the laboratory room CV due to the released steam from the channel.

Initial conditions for the simulation were taken from the experimental data. An initial temperature of 25.4 °C was assigned to the channel's water and air, and also to the laboratory room, including the connected pressure BCs. The initial water level was set to 2.254 m. The channel walls are modeled with five thermal conductors. On the lab side a 4.51 W/m²K HTC was applied to represent natural convection.

The CV 1s was subdivided and it has a 2D hexahedral mesh with 400 nodes. The nodes are distributed in 57 divisions along the Z-axis and 7 divisions along the X-axis (Figure 5-32). The mesh elements are distributed with a size between 0.01 - 0.06 m in the Z-axis; and between 0.0163 - 0.03 m in the X-axis. Consequently, the aspect ratio varied from 0.23 to 1.69.

Figure 5-32. Geometry scheme and meshing. (left) Geometry scheme. (right) Meshing

As shown in Figure 5-33, the time development of all TCs in the GOTHIC simulation vs. the experimental data is represented. The fluctuations at 200, 1600 and 3800 s are result of the fluctuations in the imposed flow input. A gradual, and almost linear, increase of the temperature is observed in both the experiment and predictions. Near $t = 5450$ s, the lower sections of the channel start to reach the saturation temperature. However, due to the fact that the development of the steam fraction is quite different at final stages, the TC1 simulation results do not come into a direct and permanent contact with steam as in the experimental test. Therefore, the way the temperatures reach the saturation differs between simulation and experiment. Flashing occurs at 5458 s, about 500 s earlier than in experiment. In general, for each TC, there is a good agreement with the experimental data, except for TC1 when saturation temperature is approached, and in TC8, which is heavily affected by the occurrence of flashing. The decrease of temperature for TC6, TC7, and TC8 at the end of the transient is due to the loss of water/hydrostatic pressure after flashing.

Figure 5-33. Left: Temperature at every TCs. Right: Experimental results

In order to obtain 2D steam fraction distributions, and compare it with extracted experimental results, GOTHIC results were processed with the ParaView software [132]. Figure 5-34 shows a comparison between GOTHIC calculations and experimental data for all the cases. During cases 5-9, it can be observed that the plume size in simulations is similar to the experimental data and it grows as water temperature increases as in the experiments. However, distributions (shape, extension, steam fraction gradient within the flame) differs from experiments, due to the way GOTHIC calculates the steam condensation plume surface in the simulations. Plumes out of simulations continue to grow in size in cases 10-11 (at 5285 s, 5425 s respectively). However, starting from Case 11 (5425 s) to the end, distributions become very different due to early flashing in simulations; this is, the water suffers an instant evaporation and a considerable amount of inventory in the upper part is lost.

Figure 5-34. Comparison between 2D steam volume fraction distributions in the experiment (right) and reference simulation (left).

5.4.2.2. Sensitivity analysis

To analyze the influence of different model parameters and determine the optimal setting for the case presented, a sensibility analysis was performed. The effect of: (1) the mesh size, (2) discretization schemes, (3) turbulence model and, (4) heat transfer options for the channel wall, were evaluated upon the resulting accuracy in comparison with the experimental data.

Firstly, twelve mesh schemes were tested combining different cell sizes in Z and X axes direction. The four discretization schemes available in GOTHIC were tested using the reference mesh. The reference mesh was used also for the turbulence model sensitivity study where different k- ϵ models were tested. Finally, different approaches for modeling the wall heat transfer were tested. These sensitivity studies aforementioned are presented in Table 5-13.

To compare combinations of all sub-models and options studied in the sensitivity analysis, and to define an overall figure of merit; an indicator labelled as “**Simulation efficiency η** ” was proposed eq. [5.8]. This parameter takes into account the average temperature difference between TC1 and TC8 in the experiment (ΔT_{1-8}^{exp}) and in the simulation (ΔT_{1-8}^{sim}); the average

relative error of the total temperature ($\overline{\epsilon}_T$, eq. [5.9]); the difference between flashing time in the simulation (t_s^{sim}) and the experiment (t_s^{exp}); and the CPU computational time (t_{sim}):

$$\eta = \frac{10^9}{|\Delta T_{1-8}^{exp} - \Delta T_{1-8}^{sim}|^2 \cdot |t_s^{exp} - t_s^{sim}| \cdot \overline{\epsilon}_T \cdot t_{sim}} \quad [5.8]$$

$$\overline{\epsilon}_T = \frac{1}{8} \sum_{i=1}^8 \frac{1}{t_{max}} \sum_{t=t_0}^{t_{max}} \left| \frac{T_{i,exp}(t) - T_{i,sim}(t)}{T_{i,exp}(t)} \right| \quad [5.9]$$

The factor 10^9 is used to show the obtained results in a more convenient way. The temperature difference between TC1 and TC8 has been chosen in order to compare with the temperature results obtained from the experiment. The thermal stratification has been considered as the most relevant phenomenon in the simulations due to its influence in the operation of the IRWST, and therefore, it has been emphasized in the indicator to show its importance. The calculation of the simulation efficiency is shown in Table 5-13.

Table 5-13. Sensibility simulation results. Simulation efficiency scores

Case	Average ΔT [K]	Total average error [%]	Flashing time [s]	CPU required time [s]	Simulation Efficiency [η]
Experiment	10.26		6000		
ZaXa	1.67	4.800	5338	2707	1.576
ZaXb	3.74	3.602	5314	1660	5.735
ZaXc	4.09	3.349	5326	48200	0.241
ZbXa	1.56	4.503	5130	3567	0.946
ZbXb	5.24	4.416	5145	14130	0.744
ZbXc	4.65	3.087	5337	54810	0.283
ZcXa	6.147	3.924	5345	3230	7.120
ZcXb	7.16	3.302	5396	8844	5.899
ZcXc	5.78	3.207	5370	60400	0.408
ZdXa	15.72	6.064	5300	28900	0.273
ZdXb	16.49	6.637	5585	22450	0.417
ZdXc	12.66	4.423	5450	198000	0.360
FOUP	1.323	4.102	5330	4803	0.949
MFOUP	1.324	4.043	5323	15970	0.287
FLSOUP	2.65	4.288	5378	6085	1.064
k-e RG	7.89	3.039	5643	22080	7.432
MIX-L	4.55	3.610	5465	8318.8	1.909
k-e NL2	9.14	3.120	5344	7990	48.748
No turbulence model	7.11	3.960	5424	7517	5.878
Adiabatic	5.77	6.705	4705	6026	0.948
h GOTHIC	7.55	4.038	5183	12180	3.389
THC internal	8.43	3.499	5393	20887	6.731

After carrying out these analyses it was concluded the DCC that occurred when steam was injected in the tank full of water could be modeled in GOTHIC using a fine mesh and a specific set up. However, these insights and set-up (specifically the mesh because of its small size) cannot be extrapolated easily into a full-size containment model due to the excessive computational cost.

5.4.3. ADS implementation in a full scaled IRWST model

In this section the sparger implementation in the full IRWST model is going to be described. Firstly, geometrical specifications and boundary conditions are described. It is followed by the presentation of the results from different sensitivity analysis concerning the way the flow injection is modeled.

The same geometry and mesh presented in Figure 5-28 is used for the ADS spargers implementation. The two spargers position is obtained from the AP1000 DCD v14 [27] after the Figure 5-35a and Figure 5-35b vectorization. The center of both spargers is located at 5.6 m from the pool bottom. Using the X-Y axis reference presented in Figure 5-35, the sparger 1 is located at (5.4, 3) m and the sparger 2 at (8.4, 7.1) m. It is noteworthy that the locations given are approximate as those have been obtained after a vectorization and measurement, which have a small human error.

The spargers specifications are also given in the DCD. Each sparger has four downward inclined branches. Each branch has 174 holes. The total holes' flow area is ca. 0.177 m^2 and the hydraulic diameter of each hole is 0.0127 m.

Figure 5-35. AP1000 ADS spargers position. Obtained from [27]

These geometrical specifications have been used for the GOTHIC model creation. As stated previously the IRWST geometry is maintained. The ADS spargers framework is considered only as a 0.45 m diameter cylindrical tube 5.63 m height. Each sparger is modeled with flowpaths. The number of FPs used for modeling each sparger has been tested in a sensitivity analysis. The characteristics of the FPs depends on the number of FP used to model the injection. Thus, those are presented next in the sensitivity analysis.

The boundary conditions imposed in those spargers have been obtained from an UPM-ETSIME AP1000 TRACE model for a SBLOCA [133]. In particular, the temperature, pressure, liquid and steam mass flow have been obtained from this model. Those are presented in Figure 5-36a (liquid and steam temperature), Figure 5-36b (liquid and steam mass flow) and Figure 5-36c (pressure). Likewise, the PRHR heat was not maintained constant but it adapted to the SBLOCA transient, Figure 5-36c.

Figure 5-36. ADS injection SBLOCA boundary conditions.

The initial conditions are similar to the ones applied in section 5.3.2.1. The initial temperature of the pool and the containment is 48.9 °C and the initial pressure in the containment is 108.25 kPa. The water level is 8.7 m.

All the simulations were run with GOTHIC 8.3(QA), with a second-order discretization scheme in space and a semi-implicit discretization in time. In each time step, the pressure equation was solved with the conjugate gradient method until a 1e-6 residual was reached. The minimum time step was set to 1e-6 s and the maximum to 0.01 s.

The results for this SBLOCA transient are presented in Figure 5-37 for temperature distribution and Figure 5-38 for containment pressure and tank stratification number. As the PRHR heats the IRWST, the temperature within the tank increases. After 1000 s the heat transferred decreases (Figure 5-36d) and so occurs with the tank temperature. Until 4000 s, when the transient finishes, the tank temperature maintains constant and stratified.

The stratification extent can be observed in Figure 5-38, reaching a maximum of 0.73 at 1600 s. It should be clarified the T_{max} from [eq. 5.3] used for this analysis is 80 °C. After reaching the peak, the stratification slightly decreases maintaining almost constant until the end of the transient. The pressure in the containment increases around 2 kPa during the whole transient.

Figure 5-37. IRWST temperature during the SBLOCA transient without ADS

Figure 5-38. IRWST Str number and containment pressure during the SBLOCA transient

5.4.3.1. Spargers implementation sensitivity analysis

The spargers are modeled using BC and FP (where the BC is connected to the CV using the FP which models the injection). The number of BC-FP for simulating each sparger is studied in a sensitivity analysis. Four different scenarios have been studied:

- (1) **2 FP**: each sparger is modeled with 2 BC-FP, one BC-FP is used to model the liquid injection and one BC-FP is used to model the steam injection for each sparger. In total there are 4 BC-FP for the ADS sparger modeling. The flow area is set as 0.088 m^2 and the hydraulic diameter 0.0127 m .
- (2) **4 FP**: each sparger is modeled with 4 BC-FP, two BC-FP are used to model the liquid injection and two BC-FP are used to model the steam injection for each sparger. In total there are 8 BC-FP for the ADS sparger modeling. The flow area is set as 0.044 m^2 and the hydraulic diameter 0.0127 m .

(3) **6 FP**: each sparger is modeled with 6 BC-FP, three BC-FP are used to model the liquid injection and three BC-FP are used to model the steam injection for each sparger. In total there are 12 BC-FP for the ADS sparger modeling. The flow area is set as 0.059 m^2 and the hydraulic diameter 0.0127 m .

(4) **8 FP**: each sparger is modeled with 8 BC-FP, four BC-FP are used to model the liquid injection and four BC-FP are used to model the steam injection for each sparger. In total there are 16 BC-FP for the ADS sparger modeling. The flow area is set as 0.022 m^2 and the hydraulic diameter 0.0127 m .

During the different models' execution there were found some code limitations that did not allow the simulation of some cases. The limitation is related to the free volume of the cell where the injection is located. There is a volume limit that depends on the mass flow injected. For this particular case, with the ADS flow injection from a SBLOCA (Figure 5-36a-b), several simulations were run in a simplified model, to see where the boundary was.

Modeling each sparger with one FP for liquid and one FP for steam phase for each sparger is possible until a cell volume of around 3 m^3 is reached (the study started from 81 m^3). After this point, two FPs for each phase and each sparger are needed, until approximately a cell volume of 1.3 m^3 . It was seen after this point the injection could be modeled with three FP for each phase and each sparger. The mesh obtained in this model in the spargers position has a volume of approx. 0.4 m^3 . Thus, the injection could only be modeled with the 6FP and 8 FP scenarios. A scheme of the FP injection modeling of these different scenarios is presented in Figure 5-39.

Figure 5-39. BC-FPs sensitivity cases schemes

From these scenarios the influence of the injection direction was also studied. For the 6FP scenario, the incoming injection was directed to the sides of the cell: North and South directions (6FP_NS) and East-West direction (6FP_EW). For the 8FP scenario, the incoming injection is directed downwards, and to the sides of the cell; right, left, north and south directions following different approaches; 8FP_v1 and 8FP v2 respectively.

The temperature results at Line 3 for all the ADS sensitivity cases are presented in Figure 5-40. There is a similar trend in all the cases until the injection that starts at 1350 s. After this moment there are some differences between the cases, but in general, a similar behavior could be observed. The thermal stratification is lost as soon as the injection starts. This is due to the momentum induced by the steam and liquid injections. It creates a convective movement, producing the mixing of the different thermal layers in the tank. After 2000 s, the temperature stabilizes at around 60 °C in the upper layers in all the sensitivity cases. The temperature in the bottom of the tank at 0.8 m follows a slightly different behavior.

(a) 6FP_NS case axial temperature results

(b) 6FP_EW case axial temperature results

(c) 8FP_v1 case axial temperature results

(d) 8FP_v2 axial temperature results

Figure 5-40. ADS modeling sensitivity analysis temperature results.

The influence of the ADS injection on the IRWST thermal behavior during the SBLOCA can be also observed analyzing the Stratification Number, Figure 5-41. At the beginning, the steam/liquid injection at higher temperature than the IRWST water produces a local temperature increase in the area close to the injection. The water temperature first increases at around 6 m layer, and then it diffuses to the adjacent layers. The Str number peak at 1440 s could be explained with this phenomenon, where the bottom layer continues with the same temperature while the upper layers have already increased their temperature. Afterwards, the general phenomenology is practically similar for all the sensitivity cases. When the Str number peak is reached a sudden decrease is observed. This is caused by the water movement induced by the injection momentum at the first seconds, and then by the buoyancy momentum created which mixes the water pool. From 1500 to 2000 s some slight differences can be appreciated during the temperature fluctuation caused by the pool movement and mixing.

Finally, from 2000 s to 4000 s the Str reaches values close to 0.3 in all the simulations with lateral injections, and 0.1 in the one with a downward injection. As explained before, the injection not only induce momentum, but also increase the surrounding fluid temperature. The bottom layers would not exchange heat with the upper layer because of the thermocline in between those. However, the injection produces a movement of the fluid, elevating the thermocline position and heating up the bottom layers. These layers have a slightly different temperature compared with the upper layers. It is also observed the Str number for the 8FP_v1 case, where the injection is directed downwards, is slightly different than the other cases. This is because in this case, the steam reaches lower layers, breaking the thermocline and reaching a complete mixing.

Figure 5-41. ADS sensitivity cases results. Stratification Number

The smallest differences among the sensitivity cases can be found when studying the pressure change in the containment free volume, Figure 5-42. The pressure difference in the containment between the sensitivity cases is almost negligible, being around 0.005 kPa at 4000 s between 6FP and 8FP cases.

There is a higher difference when the sensitivity cases are compared with the SBLOCA with no ADS case. The tendency until the injection is the same for all cases. After this moment, the cases with injection develop a lower increase in pressure, reaching a pressure of 108.25 kPa at 4000 s. In contrast to the ADS injection cases, the SBLOCA with no ADS reaches a pressure of 110.71 kPa at 4000 s. This slight difference of 2.5 kPa is owing to the higher surface temperatures reached when there is a more marked thermal stratification. The ADS produced the mixing of the pool, reducing the surface temperature, and hence, producing a smaller pressure in the containment.

Figure 5-42. ADS sensitivity cases results. AP1000 containment CV pressure

To decide which case will be used as base case and considering there are not significant differences between the cases studied, the computational time is analyzed. The results, together with the averaged Str number, are presented in Table 5-14. It can be observed the computational time is similar for 6FP_EW, and 8FP cases. The Str number is similar for all the cases expect for the 8FP_v1 for the reasons explained previously. Due to those results cannot be compared with experimental results, it is difficult to determine the “most suitable one”. Therefore, it was arbitrarily decided, based on the computational time and the small differences with the other cases, to use the 8FP_v2 case as base case.

Table 5-14. ADS sensitivity cases. Average Str number and computational time

	Average Str number	CPTIME [h] (1 CPU)
6FP_NS	0.359	55.6
6FP_EW	0.370	47.5
8FP_v1	0.273	46.6
8FP_v2	0.363	44.0

5.4.3.2. Base case (8FP_v2) detailed results

In this section the results obtained from the selected as base case are presented. Temperature distribution and velocity fields are presented and used to explain the phenomenology occurring in the tank.

Temperature evolution in the tank during the SBLOCA transient is presented in Figure 5-43 at different times (500, 1000, 1500, 2000, 2500 and 4000 s). At the beginning of the transient the water in the tank is gradually heated up by the PRHR HX. As occurred with a constant heat source, the heated water with less density flows up for buoyancy effects until the water surface is reached. Then it flows to the tank sides until the tank walls are reached, there the water is

redirected flowing downwards to the bottom of the tank and then back to the PRHR position, creating convection cells driven by natural circulation. A thermal interface between the hot upper layers and the cold layers in the bottom is created.

When the ADS injection starts, the momentum injected breaks the thermal stratification, homogenizing the tank. This effect is first appreciated at the “left” corner of the pool (1500 s) and then it reaches the whole tank. The mixing effect of the ADS injection remains until the end of the transient, keeping a relatively constant temperature along the tank of around 60 °C. It is noteworthy to mention, the momentum injected by the FPs mixes the pool, although it does not reach the cold bottom layers, which remains colder than the rest of the tank.

Figure 5-43. IRWST temperature distribution during a SBLOCA with ADS injection

The velocity distribution in the tank before the injections start has been explained previously. It is represented in Figure 5-44 at 1300 s where velocity vectors at two different plane positions are showed. The arrows represent the fluid direction. The longitude of those is determined by the maximum velocity value (largest arrow).

The left picture corresponds to a vertical cut that crosses the Sparger 1 from South to North. The module of the Y and Z velocity components reaches a maximum value of 0.09 m/s. The fluid, depending on the layer, moves to different directions, begin part of the so-called convection cells. The right picture corresponds to a horizontal cut that crosses the spargers position (16.34 m altitude) from East to West. At this fluid layer the fluid moves from the center

to the IRWST left wall and from the center to the right going towards the PRHR. The module of the X-Y velocity components reaches a maximum value of 0.07 m/s at this time.

Figure 5-44. IRWST velocity distribution during SBLOCA before the ADS injection

The velocity field distribution at different times after the injection is presented in Figure 5-45. The arrangement is the same as the one presented in Figure 5-44, left picture presents a N-S vertical cut at the sparger 1 position, and the right picture an E-W horizontal cut at the spargers elevation. It can be seen that 10 s after the injection (~ 1360 s) the velocity distribution within the pool changes completely. The momentum injected from the FPs moves the water arounds it. Although the injection is directed to the sides, within seconds the buoyancy force plays a dominant role and the liquid is directed upwards forming convections cells around it. The water velocity increases significantly, going from 0.07 m/s to 0.199 m/s. At this time the convection cells created by the PRHR heating still exists and determines the fluid movement. Moreover, at the sparger positions new convection cells starts to be formed.

At around 200 s later of the injection (1500 s) the maximum liquid velocity is reached in the pool. The convection cells formed over the spargers reach a velocity of 2 m/s, directed upwards, inducing bigger convection cells and the mixing of the pool. At this moment, the sparger injection is dominant and the convection cells at the PRHR positions starts to disappear. The streamlines at this moment are presented in Figure 5-46 for a better understanding. As the transient continues, the liquid velocity at the sparger position decreases (0.735 m/s), albeit the convection cells are still dominant.

Finally, when the injection ends the flow field distribution remains stable, having a maximum velocity of 0.137 m/s in the sparger area (module of Y-Z components) and 0.142 m/s in the rest of the tank (module of X-Y components). Different whirlpools are formed along the tank and those promote the mixing.

Figure 5-45. IRWST velocity distribution during SBLOCA with ADS injection

Figure 5-46. IRWST velocity distribution at 1500 s during a SBLOCA with ADS injection

5.4.4. Conclusions

In some accidental sequences steam/liquid from the pressurized could be injected in the pool by the ADS spargers. The possible existence of steam bypass or flashing makes necessary a detail study of this system.

For this purpose, firstly, in collaboration with TUM university a scaled-down experiment was created to check if any of those circumstances could occur during the ADS performance. The steam injection produced a temperature increase in the test rig, which led to saturation conditions and finally to the occurrence of flashing. All these phenomena were simulated in a GOTHIC model. It was concluded it was possible to simulate the experiment with GOTHIC, however, the setup obtained after a sensitivity analysis could not be extrapolated and implemented in the full-scaled IRWST model. The most restrictive limitation was the mesh size needed (around 0.05 m).

Despite the setup from the experiment could not be extrapolated, the ADS spargers were implemented in the full-scaled IRWST model. Spargers dimensions and arrangement have been obtained from public data available on the AP1000 DCD. The effect of these spargers on the tank was tested during a SBLOCA accident. Different configurations have been tested to model the injection, being found a cell volume limitation for the mass flow injected. After carrying out different analysis it was concluded, for the liquid/steam of the SBLOCA studied and this mesh size, the injection could be modeled minimum with 6 FPs in different cells for each sparger.

The injection direction effect is tested with different FPs configurations. It was observed there are scarce differences when the injection is directed to the sides using 6 or 8 FPs (per sparger). When the injections are directed to the sides the momentum does not reach those bottom layers, thus the temperature of the water at the bottom of the tank does not change significantly. However, when the injection is directed downwards the differences are more visible. In this case the momentum induced reaches the bottom layers, mixing those with the rest of the pool. This fact has influence on the water surface temperature, and hence on the containment pressure, which decreases with the temperature.

The ADS injection, regardless of the direction, induces a mixing of the pool, homogenizing the different layers temperature. The water surface temperature decreases (compared with no ADS injection) and thereby, the containment pressure is smaller.

5.5. Conclusions

The IRWST-PRHR HX behavior has been studied due to its importance in the safety during an accident in the AP1000 reactor. In the work presented in this section, the GOTHIC code has been used to simulate a scaled-down IRWST, which data is available in the open literature, and a full-scaled IRWST during a SBLOCA accident.

Firstly, the scaled-down model is validated against experimental data obtained from the public literature. The experiment constructed in the NCEP University has the main objective of studying the different phenomena that occurs inside the tank, such as natural convection and thermal stratification during the PRHR performance. The lessons learnt from the validation of this experiment are: (1) GOTHIC has the capability to simulate the phenomena occurring during the experiment to certain extent, (2) to be able to model the thermal stratification, the thermal interface and the bottom tank stagnation occurring in the experiment, meshes with a cell size of 50 mm at the thermocline position are needed, (3) heterogeneous meshes could be used to have a fine mesh at the bottom and a coarse one at the top, and (4) when saturation is reached the results obtained with GOTHIC slightly diverge to the experiment ones.

Following the insights obtained during the experiment simulation, the full-scaled IRWST model was created. The Z-Mix mesh from the experiment simulation was scaled-up and additional mesh sensitivities were performed. The optimal case was applied in the full-scaled IRWST model. Different conclusions can be extracted from the analysis: (1) GOTHIC, as a containment code, can be used for simulating thermal stratification with reasonable accurate result; (2) a refined heterogeneous mesh is not needed to properly model the *dead zone* at the bottom of the tank and, (3) the minimum mesh size able to model thermal stratification was found to be 0.4 m. It is noteworthy to say that the thermal stratification modeling is important for the proper containment pressure prediction, as a mixed pool can lead to pressure underestimation.

The ADS spargers were implemented in the full-scaled IRWST model during a SBLOCA accident. From the different sensitivities performed it has been extracted: (1) To model a steam/liquid injection in GOTHIC the cell volume where the injection is located and the mass flow should be compatible; (2) the FP injection direction has a slight influence on the stratification in the pool, having the downward injection more capacity of mixing the pool; (3) the slight differences on the stratification has a bare effect on the containment pressure; and (4) the ADS injection, regardless of the direction, induces a mixing of the pool, homogenizing the different layers temperature. In this situation the water surface temperature is smaller (compared with no ADS injection) and thereby, the containment pressure follows the same trend.

All in all, a full-scaled IRWST model has been created in the GOTHIC code. The model setup has been obtained after validating a down-scaled experiment and performing several sensitivity analyses. The model includes the PRHR heat transfer and the ADS sparger injection. The last step is to include this model in a full 3D containment model and see its influence in the general containment thermo-hydraulics.

Chapter 6

Subsystems modelling: Passive Containment Cooling System

6.1. Introduction

As it was mentioned previously, the PCS is an AP1000 passive safety system which allows to maintain the containment temperature during normal operation and to limit the pressure and temperature increase during accidental conditions.

The PCS uses natural phenomena such as gravity, natural convection, or density differences to transfer heat from the containment to the outside atmosphere. In detail, external air enters through inlets located in the SB, flowing downwards through the downcomer until it reaches a flow deflector, changing its direction and flowing upwards next to the SCV cooling it down. As the SCV has a higher temperature than the air that warms it up, it is always heat up, flowing out of the chimney to the atmosphere, establishing a natural circulation flow. During accidental conditions, water from the SB roof is released, creating a water film throughout the outer surface of the SCV liner, enhancing the liner refrigeration thanks to the evaporation process, and improving the cooling mechanism inside the containment [134]. Studies regarding the modeling of this system were presented in section 3.2.2.

Innovative modeling strategies in GOTHIC are necessary due to the geometrical characteristics and passive performance of the PCS. In this chapter the methodology for this purpose is detailed. Firstly, the CAD model creation of the main geometry is presented. Then, the simplification of this CAD model for its implementation in GOTHIC is explained. Finally, the GOTHIC model is showed, and the different sensitivity tests performed are presented.

6.2. PCS CAD model

Prior to this thesis, a PCS model had already been developed by the Nuclear Safety and Thermal-hydraulics team at ETSII-UPM [135]. This model was created following the DCD rev. 14 plant layouts. During the development of this thesis, the model was reviewed, and some discrepancies were found with the latest DCD versions, due to modifications in the design of the SB after 11S [136]. As new layouts and dimensions were found at DCD rev. 19 [137], those were used for the construction of a new model based on these plans. It is important to highlight that all the information used for the PCS containment model in GOTHIC was taken from the public versions of the DCD available at the NRC webpage (mainly, DCD, rev. 19 [137]).

The model was entirely created in AutoCAD following the plan dimensions of the Figures 3.8.4-1, 3.8.4-2 and 3.8.2-1 from [137]. In Figure 6-1 is presented a cross section of the SB upper part obtained from [137].

Figure 6-1. PCS general dimensions [137]

All the PCS geometrical parts were modeled. Firstly, the concrete SB was created. It was composed by a concrete lower part where the containment vessel is embedded up to elevation 100'. From this altitude until the air inlets location, the wall thickness is 3' (around 0.91 m). Air inlets design in the DCD rev.19 has some differences with previous versions. The initial design of fifteen large openings on the top of the SB was modified to 236 small inlet ducts. These inlets are 0.45 m ϕ circular steel tubes inclined upward from outside face to inside face (52°), located in a 4'-6" (1.4 m) thick wall [136]. The SB reinforced conical roof encloses the PCS tank and the air diffuser. A view section of the full SB is presented in Figure 6-3 in black lines. Also, a 3D view of the roof this structure is presented in Figure 6-2.

Within the upper annulus of the SB it is located the Air Baffle. Its upper portion is supported from the SB roof and the remainder is supported from the containment vessel. It is composed of metallic panels with a thickness of 0.057 m. This structure is presented in Figure 6-3 with blue lines. In Figure 6-2 a detail of the space between SB/ Air baffle and SCV is presented.

The last structure inside the SB is the SCV. It composed of a cylindrical steel vessel with ellipsoidal upper and lower heads, having a diameter of 130' (39.624 m). The wall thickness of this structure varies depending on the altitude, being in most of the cylinder 0,0445 m. Heads thickness is a bit smaller, 0.0413 m. However, in the CAD model all the SCV or liner has the same thickness, 0.045 m. This structure is represented with magenta lines in Figure 6-3.

Figure 6-2. PCS upper part. SB, Air Baffle and Liner

Figure 6-3. PCS structures. SB: black, Air baffle: blue, SCV: magenta

6.3. PCS GOTHIC model

6.3.1. Geometry simplification

The PCS structures dimensions and annular arrangement makes necessary to create a simplified CAD model. The downcomer width (space between SB and baffle) is 0.92 m, being almost 40 times smaller than its height. The same happens in the riser (space between baffle and SCV), which width is 0.35 m.

The problem lies in three main aspects:

- (1) Small downcomer and riser widths.
- (2) Cylindrical geometry of the structures (and annular arrangement of the free space), considering GOTHIC has a cartesian mesh.
- (3) Blocked spaces definition with GOTHIC (with blockages and openings).

Due to the way blocked spaces are defined in GOTHIC and its Cartesian mesh, it would be needed a fine mesh to be able to define the annular riser/downcomer spaces. Therefore, a really fine mesh would be created only for having geometrical definition and not for having spatial resolution. Figure 6-4 represents the prototype of a mesh needed to roughly model the annular space which connects the riser and the chimney. It should be considered mesh definition would be needed in X-Y and Z axes. This mesh would create the annular geometry approximation painted in yellow. If a more realistic representation would be desired, an even finer mesh would be needed.

Figure 6-4. The coarsest mesh needed for representing the riser-chimney annular space

Considering these circumstances, it is needed to find additional ways for modeling this system geometry with GOTHIC. On the basis of having a great cylinder radius/annulus width ratio (~ 24) the “Developed Volumes” technique was used. This technique was firstly used in the GOTHIC Fukushima PSP model published by NAI (Zachry Nuclear Engineering) [138].

With this technique the annular spaces are “opened” and “stretched” so the volume inside could be modeled as a parallelepiped of a determined length. Using this approximation some geometrical error is assumed, however, it is considered acceptable for the simplification it implies on the GOTHIC implementation.

The downcomer and riser spaces are modeled using this technique. Both maintain the profile section and are modeled in two different volumes. The length of each volume should be the same for a correct connection. It is calculated using as reference the downcomer inner radius, where the downcomer and riser volumes are connected to each other. Using this radius, the perimeter of a circumference of this radius is calculated. The perimeter should be equal to the length of these volumes. Considering that, the volumes length is 127 m.

Figure 6-5 represents the volumes definition for the downcomer (red rectangle) and riser (yellow rectangle). The 3D view of these new created volumes is also presented.

Figure 6-5. Downcomer and riser volume profiles

6.3.2. Geometry implementation in GOTHIC

The created model consists of three subdivided CVs, one comprised the downcomer, another the riser and the latter comprised the SB upper part and chimney. As explained before, the downcomer and riser have been created with a developed volume technique, meanwhile the chimney control volume maintained a real geometry in a conventional 3D volume.

Blockages and openings have been used in GOTHIC to define the flow pathways. Simple geometrical forms have been used to represent SB walls, air baffle curved panels and the metallic liner. Figure 6-6a represents the blockages used in the downcomer CV and Figure 6-6b the riser CV blockages. The free volume matches exactly with the free volume calculated in the annular spaces. The blockages used in the chimney CV are presented in Figure 6-7.

Figure 6-6. Blockages and openings used for downcomer (left) and riser (right) CVs

Figure 6-7. Blockages and openings used for chimney CV

Finally, 46 blockages were needed to define the PCS structures. Thirteen for the downcomer CV, eleven for riser CV and 22 for the chimney CV. As explained in Chapter 4, these blockages would only block the space if a grid line is completely crossing those. Therefore, a customized mesh was also needed to model properly this system.

The mesh of each volume was created to allow a proper connection between the different CVs. The mesh creation process follows three main steps: (1st) chimney CV mesh definition, (2nd) longitudinal mesh definition for riser and downcomer CVs, and (3rd) transversal mesh definition.

Therefore, the mesh creation process starts with the chimney CV mesh, as this one will determine the other CVs mesh. For this purpose, the CAD model is used.

To create the mesh for this CV, the annular gap between the riser and the chimney at the bottom is painted in AutoCAD. This area is used as reference for the mesh development. The grid lines are defined in such manner that this area only occupies one cell per level, and there are not unnecessary opened cells. The mesh obtained has 10 levels (around 3.5 m each) in the X-Y axes, and 20 levels in the Z-axis (of around 1 m height), Figure 6-8.

Figure 6-8. Chimney CV mesh

Studying the mesh-geometry generated, the number of non-blocked cells, where the fluid would flow, is obtained. The number of non-blocked cells determines the quantity of transversal levels the riser and downcomer CV have. This approach is used to be able to connect all these fluid cells with all the cells in the riser CV.

For the riser CV it was decided to define initially the air flow path with only one level in the Y-axis with the size of the riser gap (0.3501 m), and 36 cells in the X-axis (being in concordance with the number of fluid cells previously calculated), Figure 6-9. The downcomer CV has the same number of levels than the riser CV in the Y-axis (36). The downcomer gap (0.92 m) in this case is modeled with two levels. The level in which the connection to the riser CV is made, has the same size as the riser flow path grid level (0.3501 m), Figure 6-10.

Figure 6-9. Riser CV mesh

Figure 6-10. Downcomer CV mesh

6.3.3. Boundary Conditions and FPs specifications

The CVs are hydraulically connected using FP and/or 3D-connectors components. These connections are presented in Figure 6-11. The lateral side of the developed volumes was connected to its opposite side with a 3D connector. The riser CV is connected to the chimney CV through 36 FPs. Each FP from the riser CV connects the last upper cell along the X-axis to an open cell in the chimney CV. The downcomer CV is connected to the riser CV with a 3D-connector positioned in the last bottom cells along the X-axis in both CVs. Specific characteristics of these connections are explained next.

The correct election of the BCs is especially necessary in this model to simulate the passive mechanisms that happens during the PCS operation. As explained in Chapter 3, the PCS uses density/pressure differences to create natural convection driven flows. Therefore, inlet and outlet pressure values in the air inlets and chimney outlets, respectively, are key parameters in the model performance.

Air inlets are modeled with 17 pressure BCs to the downcomer CV cells by means of 17 FPs, BC 1 to 17 in Figure 6-11. Chimney outlet is modeled with four pressure BCs connected to the chimney CV through four FP, BC 18 to 21 in Figure 6-11. To calculate the BC values, it is necessary to fix reference pressure, temperature, and altitude. The reference altitude (h_{ref}) is fixed to 100 ft (~ 30 m), the position where the lower SB concrete basement ends. The reference

pressure (P_{ref}) selected is 101.235 kPa and temperature (T_{ref}) 26.85 °C (based on [139]). Using h_{ref} , P_{ref} , and T_{ref} a reference density (ρ_{ref}) is calculated: 1.177 kg/m³.

The pressure at the inlet and outlet is calculated following eq. [6.1] and eq. [6.2], respectively.

$$P_{inlet} = P_{ref} - \rho_{ref}gh_{inlet} \quad [6.1]$$

$$P_{outlet} = P_{ref} - \rho_{ref}gh_{outlet} \quad [6.2]$$

Where g is the gravity (9.89 m/s), h_{inlet} the altitude of the air inlets penetration middle point, and h_{outlet} the altitude of the chimney outlet. Making use of the CAD model, those altitudes are obtained: $h_{inlet} = 48.103$ m and $h_{outlet} = 69.723$ m. Applying these values to eq. [6.1] and eq. [6.2] the pressures at the entrance and the outlet are the following:

$$P_{inlet} = 100.766 \text{ kPa}$$

$$P_{outlet} = 100.519 \text{ kPa}$$

Figure 6-11. PCS Control Volumes connections in GOTHIC

The parameters that defines the FPs are also important to model properly natural convection. The main parameters to be studied are elevation, flow area, hydraulic diameter, inertial length, and loss coefficient. The elevation defines the gravitational head across the flow path, the gravitational head within volumes and the possible location above or below the liquid pool in the volume. Further detail of how gravitational head is calculated is explained in GOTHIC manuals [110]. The flow area is the minimum cross-sectional area of the flow path being the fluid velocities based on this area. The hydraulic diameter for cylindrical geometries is simply the diameter of the connection and it is used to calculate the wall friction head. The inertial length determines the inertia of the flow through the flow path and it is used to define an effective volume of the junction. Finally, the friction length is used to calculate the wall friction force.

All the above parameters are of great importance on the model correct performance. The values of these parameters for the FPs used in this model are presented in Table 6-1. Elevation, flow area, and hydraulic diameter have been obtained from the CAD model. Inertial length and loss coefficient have been calculated following the GOTHIC modeling best practices [110].

Table 6-1. PCS flow path parameters

	Air inlets-downcomer (37-58)	Riser-Chimney (1-36)	Chimney-outlet (54-57)
Elevation [m] (each)	58.12	59.348	79.438
Flow area [m²] (each)	2.277	4.258	18.679
Hydraulic diameter [m] (each)	0.457	0.635	9.754
Inertial length [m]	0.370	0.878	1
Loss coefficient [-]	1	0	0

The heat transfer between solid structures and fluid regions has been simulated through Thermal Conductor (THC). The surface area, the thickness and the material properties have been obtained from the CAD model and the DCD. The metallic baffle is modeled with two THCs that connect the downcomer with the riser, allowing natural convection in both sides of the conductor. The heat transfer at the conductor surfaces is modelled using the DLM-FM model. A single spanned THC represents the SB wall in contact with the atmosphere. The atmosphere heat transfer has been set with a HTC of 25 W/m²·C [140] and temperature boundary condition with a bulk temperature of 26.85 °C. The heat transfer by radiation was neglected.

6.4. PCS steady state results

In this section the steady state results obtained with the previously explained model are presented. Temperature and velocity field distribution along the different CV are presented. Nevertheless, during the execution of the steady state, it was noticed this model was sensitive to small set up changes. Therefore, a sensitivity analysis has been performed on the meshes.

6.4.1. PCS base case model results

This simulation was run with GOTHIC 8.3(QA), with a first-order discretization scheme in space and a semi-implicit discretization in time. The turbulence model selected was the $k-\epsilon$ standard and the molecular diffusion was enabled. The minimum porosity was set to 0.03. In each time step, the pressure equation was solved with the conjugate gradient method until a $1e-6$ residual was reached. The minimum time step was set to $1e-6$ s and the maximum to $1e-3$ s.

To simulate the bounding temperature conditions inside the SCV during a Large Break Loss of Coolant Accident (LBLOCA), the temperature has been fixed to $150\text{ }^{\circ}\text{C}$ in the liner through two THCs, which is the maximum temperature allowed in a containment design basis accident, [111]. The PCS tank water has been supposed to be unavailable. Both hypotheses create very conservative conditions for the PCS, as the energy released is maximum and the only heat transfer mechanism is the air natural convection.

To achieve a steady state in GOTHIC the BC should be maintained constant. For this simulation, the steady state is reached at around 150 s. In Figure 6-12 it could be observed the velocity steadiness reached at different positions in the different CVs of the model. The results presented next are the ones obtained at 300 s, to ensure the constant values.

Figure 6-12. PCS base case. Velocity evolution during the simulation time. D: downcomer CV, R: riser CV, C: Chimney CV

Velocity and temperature results are presented next in two main formats: (1) z-velocity component average values for each Z-axis level in each CV, (2) cell values represented with different colors. For the first format a MATLAB script was needed to post-process all the results obtained from GOTHIC. In this script the values of each level were averaged taking into account the volume and porosity of the level cells. For the second format, the Paraview software [132]

was used to postprocess the GOTHIC results. Paraview can work with VTK (Visualization toolkit) format and obtain the three-dimensional values in a CFD-like representation.

The obtained steady-state results show the PCS expected behavior. First, the air enters through the air inlets, flowing downwards the downcomer. When reaching the downcomer bottom, it is redirected 180° by the metallic baffle, going to the riser. In the riser the air is heated up by convection with the metallic SCV liner. At the chimney entrance from the riser, the air expands, it is heat up by the liner dome and finally flows towards the chimney outlet.

Figure 6-13a represents the velocity at the different elevations in the three CV. The downcomer air velocity is represented with blue rhomboids, the riser with purple squares and the chimney with green triangles. The downcomer velocity values are negative as the air flows downwards. An averaged maximum value of 1.35 m/s is reached, and it is maintained along the vertical section until the air baffle bottom. At this point, the velocity flows from the downcomer to the riser. In the riser the fluid is heated up, its density decreases and therefore, increases its velocity. The maximum average value reached is 3.83 m/s at around 55 m. When the air reaches the riser ending it can be seen a decrease in the air velocity: (1) because of the increase of the area in the chimney, (2) due to the slight curvature at the end of the riser that moves the velocity magnitude to the y-component not represented in Figure 6-13a. In Figure 6-13b this fact can be appreciated as all velocity components are represented.

Figure 6-13. PCS base case steady state. Velocity results

The velocity vectors are represented using GOTHIC in Figure 6-14. Each blue square represents a CV, not maintaining dimensions, but arrangement. In the downcomer CV it can be seen the air enters from the left of the CV, creates some vortices in the space between the upper SB and the baffle and then it is redirected downwards. It can be appreciated only two Y-levels are used to represent the downcomer space. At the bottom, the air is redirected to the right towards the riser. In this CV there is only one Y-level to represent the vertical section of this annular space. In the upper side, the liner curvature is followed, and the velocity has also a Y-component. When the air flows to the chimney CV its velocity reduces significantly at the beginning. Gaining momentum as it is heated up by the liner dome, having its maximum velocity at the chimney exit.

Figure 6-14. PCS base case. Velocity vectors

Temperature distribution along the CV is represented in Figure 6-15. At the steady state, the downcomer temperature reaches a constant value of 26.8 °C (like the initial temperature) and the chimney a constant value of 53 °C (increasing 26 ° from the initial conditions).

The air in the riser CV is warmed up by the liner, which has a constant temperature of 150 °C. The air as it flows through the riser increases its temperature, having a temperature difference from the bottom and the top of 26 °C. The air HTC in the vertical section is practically constant, going from 10.68 W/m²K to 11.05 W/m²K.

Figure 6-15. PCS base case steady state. Temperature results

6.4.2. PCS mesh sensitivity analysis

The strategy for analyzing the PCS mesh has followed different steps. First, the influence of the levels in the Z-axis has been analyzed. Then, the number of grid lines in the Y-axis influence is studied. Finally, the combinations of the most suitable Z and Y meshes are studied.

From now on the nomenclature used for describing the different sensitivity cases is the following: $Q_{\#p}$. Where Q is the volume studied in this case, and it could have the value of: D, R or C, being D: Downcomer CV, R: Riser CV, and C: Chimney CV. The # is number of grid lines the CV axis being studied has. The last digit refers to the axis studied, Z or Y. Therefore, the base case, which is called in the Z-axis sensitivity: D_16z R_15z C_20z, has 16 levels in the downcomer, 15 in the riser and 20 in the chimney CV. All referred to the Z axis. When the Y-axis is studied in the different CVs, the base case is named as D_6y R_4y C_10y. In this case, there are 6 levels in the downcomer, 4 in the riser and 10 levels in the chimney, all referred to the Y-axis.

6.4.2.1. Z-axis mesh sensitivity study

The cases created for the Z-axis grid lines number study are presented in Table 6-2. The figure of merit selected to compare the different cases is the maximum Z-component velocity. As mentioned before, the cell data obtained from GOTHIC are post-processed and the averaged velocity of each level is calculated. Thus, the maximum velocity of these averaged values by levels is the one showed next.

Table 6-2. PCS mesh sensitivity analysis. Z levels configurations

	Z downcomer	Z riser	Z chimney
Base case			
D_16z R_15z C_20z	16	15	20
C_40z	16	15	40
C_27z	16	15	27
R_27z	16	27	20
R_21z	16	21	20
D_30z	30	15	20
D_23z	23	15	20
D_30z R_27z C_40z	30	27	40
D_23z R_21z C_27z	23	21	27
D_30z R_27z C_27z	30	27	27

The meshes implemented in GOTHIC in each case are presented in Figure 6-16 and Figure 6-17. Figure 6-16 shows the schemes implemented in the downcomer and riser CV. Figure 6-17 depicts the mesh discretization in the chimney CV.

Figure 6-16. PCS Z-axis sensitivity. Riser and downcomer mesh configurations

Figure 6-17. PCS Z-axis sensitivity. Chimney mesh configurations

Figure 6-18 represents the maximum velocity reached in the different CVs for each case studied together with the simulation time. In general, it could be seen there is not a significant change between the different cases in terms on velocity. The maximum difference with the base case is around 0.18 m/s. The most notable difference among the cases is the simulation time, being almost twice higher for D_30z case than the base case. The mixed cases also use more computational time.

Figure 6-18. PCS mesh sensitivity analysis. Maximum velocity results for Z-axis cases.

The mesh cases previously depicted have been combined to study the effect of refining the Z-axis mesh in all the CVs. Three different type of combinations were tested:

- (1) Finest mesh. D_30z R_27z C_40z.
- (2) Intermediate mesh. D_23z R_21z C_27z.
- (3) Resolution-based mixed mesh. D_30z R_27z C_27z.

Maximum velocity results presented in Figure 6-18 show there are not significant differences comparing with the base case. However, when comparing the velocity and temperature at the different CV levels some differences can be observed, Figure 6-19. The downcomer mesh refinement only implies higher resolution at the CV upper section, not influencing downstream air velocity. The same fact occurs when the riser CV mesh is finer. The mesh in the liner curvature defines the channel geometry in GOTHIC, then it also defines the flow area and the air velocity. The grid lines in the chimney CV do not significantly affects the velocity and temperature results.

Figure 6-19. PCS CVs Z-axis mesh sensitivity. Velocity and temperature results

The inherent concept of this model produces that a difference in any CV causes an effect on the other CVs. Furthermore, analyzing the results obtained it was concluded the Z-axis mesh resolution has certain importance on the results but does not play a significant role. The Z-mesh in the upper section of the downcomer CV contributes to have higher spatial resolution on the results, being concluded C_27z is already converged as provides the same results as C_40z. In the chimney CV the mesh refinement gives similar results, therefore it can be said D_27z is already converged. The riser CV mesh is the one that presents a slight impact. The Z-mesh in the upper circumferential section in the riser CV scarcely influences the results as it defines the geometry and the flow area of the fluid. A further study on this CV together with the other axis would be necessary to completely understand its influence.

6.4.2.2. Y-axis mesh sensitivity study

The cases created for the Y-axis mesh study are presented in Table 6-3. The figure of merit selected to compare the different cases is the maximum Z-component velocity. As mentioned before, the cell data obtained from GOTHIC are post processed and the averaged velocity of each level is calculated. Thus, the maximum velocity of these averaged values by levels is the one showed next.

Table 6-3. PCS mesh sensitivity analysis. Y levels configurations

	Y downcomer	Y riser	Y chimney
Base Case			
D_6y R_4y C_10y	6	4	10
D_9y	9	4	10
D_11y	11	4	10
D_12y	12	4	10
R_5y	6	5	10
R_6y	6	6	10
D_12y R_6y C_10y	16	15	20
D_11y R_5y C_10y	16	15	20
D_11y R_6y C_10y	16	15	20

Two different meshes were tested for each CV. The chimney CV Y-axis mesh was not tested, as it defines the rest of the model configuration. Therefore, a study of this mesh will not give only results on the effect of the mesh, but the effect of all the configuration. Then, this case would not be comparable with the base case.

The downcomer CV cases are differentiated not only by the total number of grid lines, but some also by the number of grid lines that represents the downcomer annular space. The D_9y case models it with three grid lines, the same way as the D_11y case. The D_12y case follows the same mesh discretization than D_11y case including an additional grid line in the downcomer annular space. The mesh of these cases is presented in Figure 6-20.

Figure 6-20. PCS Y-axis sensitivity. Downcomer mesh configurations

For riser CV a different strategy was followed due to the small dimensions of the riser gap. In this CV only two meshes were tested. R_5y maintains only one grid line for the riser annular space, increasing the number of cells in the upper curvature. The R_6y case has two grid lines for representing the riser annular space. Figure 6-20 shows the mesh used for these two cases.

Figure 6-21. PCS Y-axis sensitivity. Riser mesh configurations

Figure 6-22 represents the maximum velocity reached in the all the CVs for each case studied. In general, it could be seen there is not a significant change between the different cases. The difference with the base case goes from maximum -0.11 m/s to 0.03 m/s in all the cases studied.

Figure 6-22. PCS mesh sensitivity analysis. Maximum velocity results for Y-axis cases.

The same approach followed in the previous section for Z-axis mesh was followed in the Y-axis mesh analysis. The mesh cases previously created have been combined to study the effect of refining the Y-axis mesh in all the CVs. Three different type of combinations have been tested:

- (1) Finest mesh. D_12y R_6y C_10y.
- (2) Intermediate mesh. D_11y R_5y C_10y.
- (3) Resolution-based mixed mesh. D_11y R_6y C_10y.

Maximum velocity results presented in Figure 6-22 shows there are not significant differences comparing with the base case. However, when comparing the velocity and temperature at the different CV levels some bare differences can be observed, Figure 6-23. The downcomer mesh refinement does not affect to the results, only increments the computational time. Something similar occurs when the riser CV mesh is finer. As observed previously, the mesh in the liner curvature defines the channel geometry in GOTHIC, then it also defines the flow area and the air velocity. Increasing the number of grid lines in the curvature section only has a resolution effect, not really having importance if the riser annulus is modeled with one or two levels.

Figure 6-23. PCS CVs Y-axis mesh sensitivity. Velocity and temperature results

As occurred in the previous section, the inherent concept of this model produces that a difference in any CV causes an effect on the other CVs. Moreover, analyzing the results obtained it is concluded the Y-axis mesh resolution has little importance on the results. The most prominent influence is the meshing in the upper circumferential section in the riser CV. As happened with the Z-axis mesh, the resolution defines the geometry, and hence, the flow area of the fluid. It produces that if a not correct nodalization was done in this area, the gap could be partially blocked (or inaccurately open), inducing less (or more) velocity.

6.4.2.3. Z-axis & Y-axis mesh combination study

Based on the results obtained in the previous section a Z/Y-axes combination study was decided to perform. The nature of this analysis is to further study the influence of riser CV nodalization on the results.

A set of cases called MIX_3.#, are created based on the conclusions extracted from the previous sections. The downcomer is modeled with an intermediate Z-axis mesh (D_23z) as it was the one converged. For the Y-axis, a same mesh as in the base case model was used (D_6y). The chimney uses the converged Z-axis mesh, C_27z. The riser CV mesh is then tested under different configurations, which characteristics are presented in Table 6-4. It is worth mentioning that all the presented cases maintain the same X-axis mesh: D_36x, R_36x, C_10x.

Table 6-4. PCS mesh sensitivity analysis. Z-Y mixed configurations

	Levels Z			Levels Y		
	Z downcomer	Z riser	Z chimney	Y downcomer	Y riser	Y chimney
MIX_3.1.1	23	15	27	6	4	10
MIX_3.1.2	23	15	27	6	5	10
MIX_3.1.3	23	15	27	6	6	10
MIX_3.2.1	23	21	27	6	4	10
MIX_3.2.2	23	21	27	6	5	10
MIX_3.2.3	23	21	27	6	6	10
MIX_3.3.1	23	27	27	6	4	10
MIX_3.3.2	23	27	27	6	5	10
MIX_3.3.3	23	27	27	6	6	10
MIX_4.1	23	28	27	6	7	10
MIX_4.2	23	24	27	6	6	10
MIX_4.3	23	30	27	6	12	10

MIX 3.# cases have been created using different combinations of the Z/Y-axis meshes previously used. In these cases, the first suffix refers to the Z-axis mesh in the riser. Being 3.1.# the ones that used the coarsest mesh, 3.2.# the intermediate and the 3.3 the finest mesh. The last suffix refers to the Y-axis mesh, having #.#.1 case the coarsest mesh, the #.#.2 the medium and the #.#.3 the finest. These Y-axis mesh configurations were presented in Figure 6-20 and Figure 6-21. The MIX4 cases are not created as a combination from previous meshes, but those are created based on specifically the riser upper curvature geometry. The meshes implemented in the riser CV in GOTHIC are presented in Figure 6-24. MIX_4.2/3 Z grid lines are similar until the curvature starts. After that the Z-axis mesh is optimized according to the Y-axis mesh. MIX_4.1 mesh is the same as R_27z mesh, including only one grid line at the top to adjust the geometry.

Figure 6-24. PCS Y/Z-axis sensitivity. Upper cells riser CV mesh

Max velocity general results together with the simulation time of each case are presented in Figure 6-25. Max velocity in the riser is the most influenced parameter with the different mesh configurations. Nevertheless, the difference between MIX_3 cases is not bigger than 0.21 m/s. MIX_4 presents slightly higher differences, where maximum temperatures are lower than the average for MIX_4.1 and MIX_4.2, and higher for MIX_4.3. Computational time is the most remarkable difference between MIX 3 and MIX 4 cases. Computational time used in MIX_3 cases is smaller.

Figure 6-25. PCS mesh sensitivity analysis. Maximum velocity results for Z/Y-axis cases.

Figure 6-26, Figure 6-27 and Figure 6-28 represent the velocity and temperature at the different elevations of the model. The cases using the same Y-axis mesh with different Z-axis mesh are represented. The tendency in all cases is similar. Increasing the mesh refinement produce an enhancement in the resolution in the upper curvature. The velocity at the chimney hardly change despite of the different meshes. However, some variations at riser velocity can be observed depending on the Z-Y configuration.

MIX_3.1# cases, where R_15z is maintained while Y-axis mesh is modified, suffer the most perceptible changes. The finer the mesh, the smaller the velocity at the same elevation is. The mesh impact on the geometry curvature is clear, leading to a scenario where the gap is more blocked than necessary. In MIX_3.2.# this fact is less significant, having similar values regardless of the Y-axis mesh. Lastly, it can be observed MIX_3.3.# maintains a similar tendency on the upper curvature independently of the Y-axis mesh. The velocity dropping at some elevations always occurs, being a phenomenon associated to the Z-axis mesh. It is worth mentioning the velocity at the chimney is kept to the same value.

The temperature distribution for all the MIX_3 cases studied barely changes. The temperature distribution at the riser CV suffers the highest differences. The smaller velocities reached with R_15z mesh at the riser exit leads to slightly higher temperatures. The differences between cases are about 1 °C. Despite riser temperature differences, temperature at the chimney exits remains practically constant.

Figure 6-26. PCS MIX_3.#.1 Z/Y-axis mesh sensitivity. Velocity and temperature results.

Figure 6-27. PCS MIX_3.#.2 Z/Y-axis mesh sensitivity. Velocity and temperature results

Figure 6-28. PCS MIX_3.#.3 Z/Y-axis mesh sensitivity. Velocity and temperature results

Figure 6-29 represents the velocity and temperature results of the MIX_4 cases. The different meshes tested have observable differences in the velocity reached in the CVs. MIX_4.1 and MIX_4.2 models the riser vertical gap with one level, and their results are considerable similar. The only difference is observed at the gap curvature in the riser CV. In this section, the MIX_4.1 case follows a similar trend, but smother, than MIX_3.3.# cases. The velocity is slowed down because of the Z/Y mesh configuration. This behavior is avoided in MIX_4.2 case. Velocities at same elevations have diverse values than the other cases, but similar to the base case. The velocity at the riser exit and at the chimney maintains equal for MIX_4.1, MIX_4.2 and the base case. The chimney exit velocity in MIX_4.3 is slightly higher (around 0.23 m/s). Moreover, the MIX_4.3 case velocity at riser CV and downcomer CV is also higher. On average around 0.4 m/s and around 0.13 m/s, respectively.

The temperature in all the MIX_4 cases is similar in all the CVs. The disparities observed on the riser with the base case are less than 1 °C.

Figure 6-29. PCS MIX_4 Z/Y-axis mesh sensitivity. Velocity and temperature results

Riser CV velocity vectors of MIX_3.1.3, MIX_3.2.3, MIX_3.3.3, and MIX_4.3 are presented in Figure 6-30. The discrepancies obtained between cases owing to the mesh refinement in the upper section can be clearly appreciated. Together with the previous results it is concluded the mesh refinement does apport resolution and better geometry modelling. However, this enhancement does not induce a significative modification on the results in terms of temperature and heat transfer, but it does increase the computational time.

Figure 6-30. PCS mesh sensitivity. Velocity vectors in riser CV

6.5. Conclusions

Using the available data from the public DCD of the AP1000, the PCS geometry has been created. A 3D CAD model is used to define a simplified model. In this simplified model three main sections are defined: downcomer section, riser section and chimney section.

To be able to model this system in GOTHIC, considering the thickness of the riser and downcomer annular space together with the mesh limitations in the program, the “developed volumes” technique has been used. Finally, a “base case” model is created in GOTHIC that consists of three CVs. Downcomer and Riser as developed volumes and Chimney as usual 3D volume.

Using constant BC, a steady state is simulated. It was possible to simulate the natural phenomena that may occur in a possible accidental condition (with no PCSWST actuation). To test the robustness of this model, a mesh sensitivity analysis was performed. After analyzing several mesh combinations for riser, downcomer and chimney CVs, it was concluded the mesh refinement has not remarkable influence on the thermal behavior of the system.

The selected mesh to be implemented in a full containment model is MIX_4.2 as in this case a compromise between computational time and resolution is reached.

Chapter 7

AP1000 GOTHIC full Containment model

7.1. Introduction

The nuclear power plants containment purpose is to control the release of radioactivity to the environment and to act as the final barrier in the defense in depth [1]. The containment is hence designed to withstand the pressure and temperature conditions occurring after a postulated break in the reactor. To confirm that the containment structure meets its functional requirements under the conditions of the specific plant operating limits, containment analyses have been performed [1]. These analyses have been conducted during the last decades using various codes following basically the LP approximation [2]

Contrary to other LWR, the AP1000 relies its safety systems performance on passive systems [19]. This fact has led the approximations and methodologies previously used for modeling NPPs to be updated to be able to model the AP1000 containment phenomenology [20][21][4]. Several codes and approximations have been used to model the AP1000 containment phenomenology during the last decades. However, possibly important phenomena might have been overlooked due to the simplifications in the mesh or system modeling (such as PCS or PXS) application.

The purpose of this chapter is to describe the construction process of an 3D AP1000 containment. Firstly, the 3D CAD model construction from plant drawings is presented. Using this model, the different compartments arrangement and communications are explained. Secondly, the GOTHIC model methodology implementation is explained. Beginning with the transfer from CAD to GOTHIC, followed by the different hypotheses assumed for its construction. Then, the airtightness analysis performed with this new complete model is presented. Finally, the implementation of the PCS and the IRWST isolated models in the 3D SCV model is described, reaching the AP1000 3D full containment model.

7.2. AP1000 SCV 3D CAD

An AP1000 SCV CAD model was previously constructed by the Nuclear Safety and Thermal-hydraulics team at the ETSII-UPM [141], [142]. However, it was discovered during this thesis that some model dimensions did not totally match with the DCD plans, Figure 7-1. Due to the difficulties of modifying that version, it was decided to create a new AP1000 3D CAD model again, from the public plans. The former model was then used as a reference for the new model creation.

Figure 7-1. AP1000 containment compartments drawings

The CAD model was created with Autodesk AutoCAD 2018 using the DCD public plant layouts from revision 14, [27]. This version was chosen as it was the most complete in civil engineering drawings. The post 11-S modifications were focus on the SB, therefore there were not seen significant differences in the SCV design between rev. 14 and later versions.

All the available floor layouts were imported, sized, and digitalized in AutoCAD in accordance with data included in the DCD. The 3D model was constructed from bottom to top, using the different structural modules (represented in Fig.3.8.3-1 (Sheets 1 to 7) from [27]) as reference for the different level's construction. Walls, floors, and ceilings thickness and altitude have not been digitalized, but obtained from DCD information (Tier 1 Table 3.3-1 from [27]).

Two different methods were used for the containment construction. The first method was applied until the design plant grade (at a 100' elevation), where the concrete hemisphere that embeds the bottom head containment liner ends. The second method was applied from this elevation, until the containment upper head.

The **first method** consists of the creation of a solid hemisphere, Figure 7-2b (representing concrete) from which the volumes of the compartments inside it are subtracted. The shape of these compartments is obtained from the plant layouts at 71', 83' and 94' elevations, Figure 7-2a. The remaining solid after the subtractions is the one that surrounds the compartments until the metallic liner, and the separation walls between these compartments, Figure 7-2d.

Figure 7-2. Concrete hemisphere inner compartments creation

The compartments in this lower section would be involved in a possible flooding event. In Figure 7-3 is represented a lateral section where the lower compartments in the containment are represented: the Reactor Vessel Cavity (RVC) and the Reactor Coolant Drain Tank compartment (RCDT). These compartments are connected by a door and an upper dumper, both are assumed to be open.

Figure 7-3. RVC and RCDT compartment connections

The RCDT compartment is connected to the so-called Vertical Access (VA) by a removable grating located at its ceiling. In turn, the VA connects the Steam Generator (SG) lower compartments. The above-mentioned rooms conform the “Reactor Coolant System Compartment”. The arrangement of these rooms is presented in Figure 7-4.

Figure 7-4. Reactor Coolant System Compartment

In the lower containment section, there are additional rooms: the passive core cooling system compartments (PXS A and PXS B) and the Chemical and Volume Control System Compartment (CVS compartment). The former ones are located in the southeast and northeast quadrants of the containment. Those are isolated one from the other. In case of a flooding, drain paths located at the bottom of those rooms redirect the water to the lower compartments of the containment (RCDT+RVC) These drain paths are assumed closed in this model. These rooms have the possibility to be connected over the Maintenance floor, which will be explained next.

The **second method** used is the vertical snap method [17], [143]. The digitalized layouts of the walls are distributed along the correspondent height, and then, extruded from bottom to top. In this case there is no need of subtracting the volume inside the compartments, as those are

simply defined by the wall's configuration. Unlike the first section, since 100' to the end of the dome, there are three different floors that separate the containment space along the Z axis. Those are located at 107'-2", 118'-6", and 135'-3", defining the Maintenance floor, the Mezzanine Maintenance floor and the Operation Deck, respectively. Figure 7-5a shows the Maintenance Floor, Mezzanine Maintenance Floor, and the compartment walls in this space. Figure 7-5b depicts the Operating Deck floor and the remaining compartment walls. From here to the top there are no floors or walls defined in the DCD.

Figure 7-5. Upper containment section creation

The compartments in the lower section (PXS A/B, and CVS) extend up to the top of the curbs through the openings in the Maintenance floor. The VA opening to the Maintenance floor does not have curbs to enhance the drainage of possible flooding. The curbs of the other openings have different elevations, so that the water flooding is first directed to the refueling canal (by means of a pipe located at 110'), then to the CVS compartment (curb elevation 110'-0") and finally to the PXS-B (100'-1") and PXS-A (100'-2"). The rest of openings observed in the Maintenance floor (mostly at the East quadrant) are for the stairs or elevator locations.

Over the Maintenance floor five different compartments are defined: SG I compartment, SG II compartment, PZR compartment, Refueling Cavity and IRWST. The location of each is presented in Figure 7-6. The Operating Deck floor is the last floor in the containment, and it covers the space not only of the previous maintenance floor, but also the IRWST. Thus, the IRWST compartment is only connected to the containment through this space, which is covered by flaps, which open when Hi-2 signal pressure is received from the containment. In this CAD model, the flaps are considered to be always opened.

Figure 7-6. Upper containment compartment distribution

Once all the walls, floors and compartments were created, the primary components (vessel, steam generators, pumps, hot and cold legs, etc.) and some safety components were included, Figure 7-7. Dimensions and position were obtained from DCD information. Shape and arrangement were extracted from the vectorization of DCD layouts of those components. Due to the incomplete information provided, these components have several simplifications.

With all the inner compartments and components included in the model, it is merged with the PCS CAD model, including first the liner, Figure 7-8 and then the rest of the PCS components, Figure 7-9. Representing the full 3D AP1000 CAD containment model.

(a) Lower compartment components (CMTs, pumps, vessel, hot and cold legs and SGs)

(b) Upper compartment components (IRWST pool, ACCs, SG lines, head package, pressurizer)

Figure 7-7. Primary and safety components incorporation

Figure 7-8. AP1000 SCV inner compartments and components 3D CAD model.

Figure 7-9. 3D CAD AP1000 containment model. SCV+PCS

7.3. AP1000 GOTHIC containment model methodology

To create the AP1000 3D GOTHIC containment model a methodology developed at the UPM has been followed and adapted to the AP1000 peculiarities [143]. First of all, using the detailed 3D CAD model previously created a process of *simplification* is carried out. The CAD is simplified in basic geometrical figures such as blocks, wedges, caps and cylinders, which are the ones that can be implemented in GOTHIC. Then, the 3D GOTHIC model is created from this geometrical input. Moreover, the airtightness of the inner compartments is tested. Finally, the IRWST-PRHR and PCS GOTHIC models created in Chapter 5 and Chapter 6, respectively, are implemented to the SCV 3D model.

7.3.1. SCV Simplified 3D CAD model

As commented previously in Chapter 4, GOTHIC only models specific geometries such as blocks, wedges, caps, and cylinders, treating them as a volume that block space. Due to this fact, the walls and components of the 3D CAD detailed model had to be modified into simple geometries. Having in mind that this model was going to be implemented in GOTHIC, the simplified model was composed by simple geometrical forms and represents blockages and openings.

As for the detailed model creation, the upper and lower sections had to follow different modeling approaches. Under the Maintenance floor, the solid hemisphere is modeled with a blockage cup geometry. The inside compartments are modeled using opening wedges. In Figure 7-10a this configuration is represented.

The containment upper section was modeled using blockages for the wall's modules and floors. Openings geometries were only used for modeling openings in the Maintenance floor (Figure 7-10b), Maintenance mezzanine floor and the Operating Deck. A side view crossing the SG compartments, Figure 7-11b, and the SCV-RCDT compartments, Figure 7-11a, is presented. It could be appreciated from the Maintenance floor to the top, only blockage wedges geometries are used.

The primary components such as the vessel, steam generators, pumps, pressurized, hot and cold legs, SG lines, ACCs and CMTs are included as simple geometric forms (cylinders, cones, and spheres).

Figure 7-12 represents the final arrangement of openings and blockages that forms the AP1000 SCV containment which is implemented in GOTHIC. A block shape blockage defines the space where the containment is. The SCV is then modeled using two cups. The upper cup is a trimmed object that will open the initial block. The lower cup is a blockage that only allows to have a reference. Between the cups an opening cylinder opens the space for the inner compartments in lower and upper sections.

Having all structures inside the containment simplified, the coordinates of each blockage were exported from CAD, and converted into a GOTHIC compatible format.

(a) Hemisphere concrete openings

(b) Maintenance floor openings

Figure 7-10. Concrete hemisphere simplified version using blockages and openings

(a) Side view RVC+RDCT room line

(b) Side view SGs compartments line

Figure 7-11. Openings and blockages lower and upper sections side view

Figure 7-12. Simplified 3D CAD model with blockages and openings

7.3.2. SCV 3D GOTHIC model

7.3.2.1. Geometry definition

The SCV model consists of a subdivided control volume. The volume of this CV is 131574.5 m³, which is the volume of the outer block (Figure 7-12) with dimensions: 42.75 x 42.75 x 72 m.

Once the CV is defined, the blockages and opening coordinates previously exported from the simplified CAD model are imported. For that purpose, 325 blockages/openings components are created. Among those, there are 39 cylinders, 11 caps, 270 wedges and 2 cones. In GOTHIC the blockages incorporation is an accumulative process, therefore any new blockage (that blocks or opens) will overlap the previous ones. For that reason, the blockages should follow a specific order to create the expected geometry. In addition, those blockages would only separate different fluid regions if those are entirely crossed by a grid line. For that reason, a mesh adapted to the different wall modules and floors was created using the simplified CAD model.

The grid lines on the X-Y axes were created firstly, followed by the Z axis. The simple geometry of the AP1000 containment allows to have relatively coarse meshes. Nevertheless, SG compartments which walls are not perpendicular, forced to have finer meshes in those areas. A representation of the wall blockages in the CAD model with the grid lines selected is presented in Figure 7-13. In addition, a detail of how the grid lines crossed the blockages is presented in Figure 7-14. Here it can be observed how the possible flow paths (dotted arrows) between adjacent cells are blocked (black line).

Figure 7-13. X-Y axes grid lines crossing containment blockages

Figure 7-14. X-Y axes grid lines detail on SG compartment

The grid lines in the Z axis should also cross the different blockages that represents floors and ceilings. The lower section below the Maintenance floor should have a finer mesh as several compartments are close and should not be hydraulically connected. Drainage connections between PXS A/B rooms with RCDT room are assumed closed. The mesh in the area between the Maintenance floor and the Operating Deck, is not meant to cross blockages, but is defined for IRWST water surface better simulation. However, it should be considered is not the optimized mesh size obtained from Chapter 5 for simulating thermal stratification. It is a testing mesh which could be refined when detailed IRWST simulation would be needed.

Figure 7-15. Z axis grid lines with blockages and lower section openings

The grid lines created in each axis are implemented in GOTHIC. Finally, the total number of cells in this SCV model are 23104 (where 12971 are not blocked active cells), with 32 grid lines in the X-axis, 19 in Y-axis and 38 in Z-axis, Figure 7-16.

Figure 7-16. AP1000 3D GOTHIC SCV model mesh

7.3.2.2. Leakage tests

The air tightness of the compartments defined in GOTHIC has to be tested to see if the mesh/blockage implementation has been done correctly. In these tests the lower section compartments connections are tested using H_2 as flowing material.

Firstly, the RCS compartments are tested (RVC, RCDT, VA and SG compartments). In Figure 7-17 it could be seen the initial flow, going from the RCDT to the RVC, VA and then SG. This H_2 flows to the upper containment section through the connection between the VA and the Maintenance floor, Figure 7-18. These figures demonstrate the proper mesh/blockage implementation for these compartments.

Secondly, the rest of lower section compartments are analyzed. It could be seen the walls surrounding these compartments are properly modeled for ACC, Figure 7-19, PXS-A, Figure 7-20, and PXS B, Figure 7-21. The small connections from these compartments to the Maintenance floor is also modeled.

Finally, the Refueling Cavity air tightness is tested. It could be observed the walls prevent the flowing of H_2 to the adjacent compartments, such as the IRWST or Maintenance mezzanine area, Figure 7-22.

Figure 7-17. Leakage test. RCS compartments. VA – SGs compartments

Figure 7-18. Leakage test. RCS compartments. VA– Maintenance floor connection

Figure 7-19. Leakage test. ACC compartment

Figure 7-20. Leakage test. PXS A compartment

Figure 7-21. Leakage test. PXS B compartment

Figure 7-22. Leakage test. Refueling Cavity

7.3.2.3. Thermal structures definition

Structures such as walls and floors that actuate as heat sinks/sources, are modelled with THCs. Each THC is modelled with specific materials and thickness according to the AP1000 DCD (Table 6.1-2, [27]). The position of each THC is obtained from the simplified CAD model together with the mesh. Each heat structure (wall or floor) is numbered, its area is calculated, and the different sides of the structure are delimited, Figure 7-23. When the walls are parallel to the grid, no difficulties are found. Nevertheless, the leaning walls (such as the SG ones) should be carefully divided into smaller heat structures to be properly represented. To include these heat structures delimitations in GOTHIC, the coordinates of each heat structure side are extracted from the CAD model and implemented in the GOTHIC model using a in-house script.

Figure 7-23. Heat structures sides definition in the CAD model

Finally, to model the containment walls and floors 50 THCs were used. Gratings and internal components as such as SGs or vessel were not thermally included (as heat sinks/sources) in the current GOTHIC model. A representation of the SCV CV and the THC distribution at 24 m is depicted in Figure 7-24.

(a) CV definition with THC (b) THC detail connections at 20 m

Figure 7-24. AP1000 SCV GOTHIC containment model.

7.3.3.Subsystem implementation

The isolated model's implementation has been a staggered process. Firstly, the PCS model is thermally connected to the SCV model. Then, using the previously created model, the IRWST full-scaled model is connected thermally and hydraulically to the PCS-SCV model. The methodology followed for a proper connection is explained in this subsection.

7.3.3.1. PCS implementation

The PCS GOTHIC model created explained in Chapter 6 and the SCV created in this chapter are connected. The coupling between the SVC and the PCS allowed to simulate the heat transfer with the atmosphere more realistically than imposing constant boundary conditions, as it has been the case for many AP1000 containment simulations that can be found in the literature.

The PCS model was thermally connected with the containment by means of the metallic liner: one THC connected the cylinder part of the metallic liner and other the spherical upper part. The coordinates of these THC's in the inner side (SCV) are not needed to be delimited as those are directly attached to the blockages that define the liner. On the outer side (PCS) the connection cells are spanned along the riser CV longitude, and associated to a cup blockage in the chimney CV. The thermal connections between the PCS and the SCV are presented in Figure 7-25, marked in red rectangles.

Figure 7-25. AP1000 SCV+PCS GOTHIC containment model.

7.3.3.2. IRWST-PRHR-ADS implementation

The full-scaled IRWST model explained in Chapter 5 is implemented in the 3D SCV model described in this chapter. The different steps followed for its correct implementation are explained next.

The IRWST model is connected to the full containment model thermally and hydraulically. It is connected hydraulically by the slaps situated over the tank and thermally by the walls that surrounds the tank. Before the connections are made the volume the IRWST occupied inside the SCV CV is completely blocked.

The slaps located over the IRWST are supposed to be always open as the Hi-2 set point is almost immediately reached in a LOCA. The connection in GOTHIC is made using a 3D-connector component which connects the last upper cells of the IRWST CV with the upper corresponding cells in the SCV CV. For the connection it is necessary the IRWST CV dimensions completely agree with the grid lines positions in the SCV CV. Moreover, the connection by a 3D-connector requires the grid lines lie in the same position for the group of cells that are going to be connected. In this case the grid lines of X and Y axes should match. The hydraulic connection is marked in a yellow square in Figure 7-26.

The thermal connection is made using THCs that connect the IRWST walls inner side (inside the IRWST CV) and the IRWST walls outer side (SCV CV). For this purpose, external THC already included in the SCV model are replaced from their last positions and located in the corresponding position in the IRWST CV. The THC represents the walls between IRWST and the Refueling Cavity north side, SG I cavity north walls, pressurizer north and east walls, and the north side of the maintenance floor. The THC used for this connection are marked in a red box in Figure 7-26. Walls materials and surface area are maintained according to the DCD information.

Figure 7-26. AP1000 SCV+PCS IRWST-PRHR GOTHIC containment model.

Due to the grid restrictions resulting from using the 3D-connector, the converged mesh obtained in Chapter 5 cannot be used completely as it is. The Z-axis definition is maintained (0.4 m mesh size). The X/Y axes definition is studied under different approaches to see its influence on the containment pressure. In all the cases studied the X-axis grid lines from the SCV CV are used. The cell sizes go from 2 m to 0.4 m, having a maximum aspect ratio of $\sqrt{2}$. The mesh discretization is presented in Figure 7-27a.

Then, the subject of study is the Y-axis discretization. Firstly, the same mesh used in the SCV CV is used (Mesh 1). There are 7 grid levels, and the cells sizes go from 2.6 m to 1.5 m, with a maximum aspect ratio of 1.3. Secondly, the Mesh 1 is partially changed, dividing by 2 the biggest cells (Mesh 2, Figure 7-27b). In this case there are 10 grid levels (1.3 to 1.9 m cell sizes).

Figure 7-27. SCV-IRWST mesh configurations

The mesh configurations are first tested in the IRWST isolated model (IRWST Mesh #). Then the same configurations are tested in the SCV-IRWST model (SVC Mesh #). The Str number and pressure results from these simulations are presented in Figure 7-28 and Figure 7-29. The results obtained in the IRWST isolated model with the XY-1m mesh is also presented, as well as the results obtained if the pool is modeled inside the SCV with five Z-axis levels (SCV initial).

From the Str results it is observed Mesh 1 and Mesh 2 in the isolated models have a similar behavior. The maximum Str reached is quite smaller than the one in IRWST XY-1m. When these mesh configurations are implemented in the coupled SCV-IRWST model the behavior is slightly different. Not until the peak is reached (around 1200 s) the tendency is similar. After this point the Str diverges, reaching the Mesh 1 a scarce higher stratification (approximately 0.04). The SCV initial case significantly diverges from the other cases. As expected, thermal stratification could not be achieved with the coarse mesh used in the Z-axis.

Analyzing the pressure results it is observed two clear trends. The pressure in the containment in the isolated models reaches higher values at the end of the transient (around 111 kPa). In contrast, the coupled models reach a smaller pressure. This fact is not only due to the difference in the Str number, but also due to the modeling approximations used in the two different approaches. In the isolated models the containment is modeled as a lumped CV with no THC.

However, in the coupled models the containment is modeled as a 3D subdivided CV where all the compartments walls inside are modeled with THC. The presence of THC is mainly the reason of the pressure difference between the models. The big difference appreciated with the SCV initial case is due to the way pressure values are averaged in the full containment model in ProTON, the tool used for post-processing the results. In this case the IRWST liquid water column is also included in the average, increasing considerably the pressure in the containment.

Figure 7-28. SCV-IRWST mesh configurations Str number results

Figure 7-29. SCV-IRWST mesh configurations containment pressure results

Despite the Str number differences, similar pressures are reached in each modeling approximation. The most remarkable difference is observed in the couple models with the SCV initial case. As thermal stratification is not reached, the water is mixed, leading to smaller temperatures in the water surface and then producing a smaller pressure in the containment.

After analyzing these results, it was decided the mesh configuration that will be used in the IRWST CV for modeling the SBLOCA is the SCV Mesh 1, as it can model thermal stratification and gives similar results compared with a finer mesh.

7.4. Conclusions

To create the AP1000 SCV containment model a methodology developed at the ETSII-UPM has been partially followed and updated [16]. First of all, a detailed 3D model was created in AutoCAD using public layout plans. Two methods were necessary to follow in order to model the different compartments in the containment. The compartments below the design plant grade were created after being subtracted from a solid hemisphere. The compartments over the design plant grade were created following the vertical snap method. A detailed view of the compartments distribution in the containment was obtained.

Secondly, the CAD model was simplified into basic geometrical figures (blocks, wedges, caps, and cylinders) that could be implemented in GOTHIC as blockages or openings. The lower compartments are defined as openings on a blocked space, and the upper compartments are defined by blockages that defines the walls. Finally, the 3D GOTHIC model was created from this geometrical input via an in-house script which exported the geometrical figures coordinates from AutoCAD and imported into GOTHIC. The compartments geometry is finally defined in GOTHIC when the mesh is implemented. A specific process was undertaken to assure the compartments airtightness using an optimized number of cells. At the end, a 3D GOTHIC SCV model was created.

Finally, the different isolated models were coupled to create the full detailed 3D AP1000 full containment model. On the one hand, the PCS model has been thermally connected to the SCV model, creating the SCV+PCS model, allowing to simulate the heat transfer with the atmosphere more realistically than imposing constant boundary conditions. On the other hand, the SCV+PCS model was coupled thermally and hydraulically with the full-scaled IRWST model. The thermal connection has been done connecting the THC that represents the surrounding walls. In order to assure a correct hydraulic connection specific steps had to be followed.

Overall, an AP1000 full containment GOTHIC model which represents in detail the different compartments in the containment and the PCS and IRWST systems, has been developed. This complete model is ready to be used for studying the containment behavior under different accidental scenarios.

Part IV

APPLICATION CASES

Chapter 8

LBLOCA & SBLOCA transients

8.1. Introduction

The Loss of Coolant Accidents (LOCA) together with the Main Steam Line Break (MSLB), are considered the most limiting events in the containment analysis. In those events, the Mass and Energy (M&E) release from the primary (LOCA) and secondary (MSLB) cooling systems is maximized and therefore, they create the most conservative conditions for the containment [144].

Both LOCA and MSLB accidents have been simulated in the AP600/AP1000 containment in the past. The LPs approach was used for modeling a double ended cold leg break (DECLB) LOCA in the AP600 containment with Contemp4/Mod5/PCCS [67], and the same transient has been simulated in a LPs WGOETHIC model [145]. Besides, a multidimensional code was used by Yan W. et al. [146] to model a LBLOCA. Three dimensional approaches have also been employed in simplified models for modeling DBA accidents. Codes such as PCCSAP-3D [146], COCOSYS [25] or GASFLOW [147] has been applied for this purpose, out of the FSAR framework.

In this chapter the performance of the AP1000 full containment 3D model created is studied under LBLOCA and SBLOCA accidents. Firstly, a LBLOCA is simulated to verify whether the containment is properly modeled. The purpose is to see the fluid distribution along the containment during this accident and to study the thermo-hydraulic state of the different compartments. The LBLOCA is chosen for that purpose as it is the accident in which more references are available in the state of the art. Secondly, the SBLOCA is simulated, which is more demanding since it implies the actuation of the PRHR and the ADS, and the IRWST as a heat sink of both systems. The averaged values of pressure and temperature in the containment compartments during this accident are presented.

8.2. LBLOCA transient

In this section a DECLB LBLOCA analysis with the AP1000 full containment model is presented. When this major break occurs, the fast RCS depressurization leads to the reactor trip and the safeguards actuation signal (S signal). During the blowdown phase the heat from the vessel, internals and core decay heat is transferred to the coolant, which is being released to the containment. The reactor coolant pumps trip occurs automatically after the S signal. The blowdown phase ends when the RCS pressure falls to a value approaching that of the containment atmosphere. The rapid RCS depressurization leads to reach both the CMTs and the ACCs set point, being the ACCs, which discharge first to the vessel. When the ACCs are empty, the CMTs begin to inject subcooled borated water into the reactor vessel through the direct vessel injection lines.

In the next sections the LBLOCA modeling set up in the containment model is described, followed by the presentation of the pressure and temperature averaged results in different containment compartments.

8.2.1. Transient boundary conditions

The boundary conditions for simulating the LBLOCA in the containment has been obtained from a TRACE model of the AP1000 developed at the ETSIME-UPM within the PYGAS national project framework. This model includes the primary and secondary systems, all the main components and the passive safety systems such as CMTs, ACCs, ADS and PRHR. Further information can be obtained from [148].

As has been previously stated, the postulated accident consists of a large break LOCA in the RCS cold leg. It is assumed it is a double ended guillotine break LOCA, therefore the M&E release is modeled with four BCs, two for each side of the break. Each side is modeled with one BC for liquid phase, and other for steam phase. The M&E release evolution after the break is presented as pressure, temperature, and mass flow for each break side (pump or vessel). Those are shown in Figure 8-1, Figure 8-2 and Figure 8-3, respectively.

Figure 8-1. LBLOCA M&E input. Pressure

Figure 8-2. LBLOCA M&E Input. Temperature

Figure 8-3. LBLOCA M&E Input. Mass Flow

8.2.2. LBLOCA results

The turbulence model selected was $k-\epsilon$ STD with the molecular diffusion enabled; the matrix resolution was solved by a conjugate method; the discretization scheme was a second order with the flux variables calculated upstream (FLSOUP) and the PCS tank water was supposed to be unavailable as a conservative hypothesis. The time step varied between $1e-05$ and 0.01 s.

The results for pressure and temperature were post-processed with ProTON, a software developed at the ETSII-UPM, which calculates each compartment properties considering the size and the porosity of each cell. The values obtained after postprocessing are the average pressure and temperature, maximum temperature, heat flux throughout walls, etc.. The SCV+PCS model required 18 hours of computation time with a 20 cores 2.10 GHz CPU cluster (Cesvima UPM) to run 2000 s of LBLOCA transient.

The containment average pressure is almost homogeneous in the whole containment during the transient, except in the IRWST, in which the water column creates a pressure gradient that increases the average pressure, see Figure 8-4. Due to the M&E release is in the SGI compartment, it has a slightly different behavior the first seconds of the transient. At the end of the transient, the pressure in RCV and RCDT compartments is observed to be higher than the rest of the containment. That is due to a water column that creates a pressure gradient that increases the average pressure. Those compartments are located at the lower positions in the containment and the condensed water and liquid from the break ends up there.

The pressure peak of 347 kPa is reached 29 s after the break. After that moment, the pressure in the containment decreases. The driving force is the steam condensation in the THC at the containment walls and the liner. At 260 s, the THC surfaces are as hot as the saturated steam and the released steam from the break is no longer condensed, producing a clear increase in the containment pressure. At the end of the transient a peak of 460 kPa is reached.

Figure 8-4. LBLOCA. Containment averaged pressure evolution

Contrary to the pressure, the containment temperature is heterogeneous (Figure 8-5), as the temperature evolution is governed by a slower convective-diffusive process depending on the geometry and the distance to the pipe break. Consequently, all the compartments present different temperature values during the transient.

The average temperature in different reactor coolant system compartments (RCV+RCDT+SGI+SGII+VA) is presented in Figure 8-6. It is observed the temperature follow a same trend as those compartments are connected. As occurred with the pressure, the temperature in the RCV+RCDT compartments at the end of the transient is lower due to the water collected in these compartments.

The highest temperatures are reached in the PXS-ACC A and RV nozzle area compartments. In the case of the PXS-ACC-A during the modeling the connection between this compartment and the Maintenance floor was supposed to be always open. From this connection is where the fluid is entering the compartment and hence increasing notably its temperature. The movement of the fluid 1 s after the break (6 s) could be observed in Figure 8-7.

Figure 8-5. LBLOCA. Containment averaged temperature evolution

Figure 8-6. LBLOCA. Containment compartments averaged temperature evolution

In Figure 8-7a it is depicted the streamlines starting from the SGI compartment, flowing through the VA and passing through the connection between the VA and the Maintenance floor, flowing upwards until the operating deck floor is reached. From here the fluid is redirected and surrounds the SGII compartment walls. At this point it has two ways out: the PXS-ACC-A/Maintenance floor connection and the Maintenance floor/operating deck connection, Figure 8-7b. The arrangement of the different compartments previously named could be checked in section 7.2.

Figure 8-7. LBLOCA. Initial streamlines (6 s)

In the case of the RV nozzle area the fluid follows a different path. From the break at the SGI, the fluid goes through the VA flowing down to the RCDT. From the RCDT it flows to the RCV, and from there to the RV nozzle area. The fluid path is shown in Figure 8-8. The temperature in this compartment remains high as the fluid does not have a way out rather than going back to the RCDT and VA.

Figure 8-8. LBLOCA. Initial streamlines (6 s) at the RCDT-RCV compartments

Following the streamlines from Figure 8-7 it can be observed how the release from the break flows upwards along the SG I compartment until it reaches the dome, where it is redirected, flowing downwards to the operating deck. The temperature along the SG I compartments (lower and operating deck) is slightly higher than the SGII ones.

The average temperature at the dome is comparable to the average temperature at the whole containment. The average temperature at this compartment reach a peak of 120 °C 29 s after the break, decreasing slightly (approximately 4° C) the next 200 s. The temperature increases again after this point due to the THC saturation, reaching a peak of 136 °C at 1560 s.

Despite different hypothesis and M&E releases, the results tendencies are similar to the ones observed in the current literature [25][67]. Moreover, the results obtained agree with the ones obtained by Wang et al. using a self-made multidimensional code [146] validated against WGOOTHIC results.

8.3. SBLOCA transient

When a SBLOCA occurs, the RCS depressurizes leading to the reactor trip and the safeguards actuation signal (S signal). In this transient four phases could be differentiated [149] [133]:

- **Blowdown:** just after the break the RCS depressurizes, triggering the reactor trip (at 12400 kPa). The RCS pressure keeps decreasing, and at 11700 kPa the safety injection signal is reached, establishing the natural circulation paths with the injection of the CMTs and the redirection of the RCS flow to the PRHR HX.
- **Natural circulation:** the RCS is cooled by means of the CMTs injection, the PRHR HX actuation and the SGs. When the CMTs level is lower than 67.5 % the ADS signal is activated, and this phase ends.
- **ADS blowdown:** The ADS valves open at different times, according to the ADS stages. First, the ADS-I valve opens, some seconds later it is followed by the ADS-II and ADS-III valves opening. When the CMT level is smaller than 20 % the ADS-IV valve opens. The ADS injections allow a depressurization so the ACCs could inject at 4900 kPa.
- **IRWST injection:** when the ADS-IV valve opens the RCS reaches the containment pressure and the IRWST could inject its water by gravity. From that moment on, the long-term cooling starts.

In the next sections, a 2-inch cold leg SBLOCA modeling set up in the containment model developed in this thesis is described. Finally, the pressure and temperature results obtained in the different compartments in the containment after the SBLOCA are presented.

8.3.1. Transient boundary conditions

The boundary conditions for simulating the SBLOCA in the containment has been obtained from the same TRACE model described in section 8.2.1. This model includes the primary and secondary systems, all the main components and the passive safety systems such as CMTs, ACCs, ADS and PRHR. Further information can be obtained from [133].

The accident studied is a 2-inch SBLOCA in the cold leg. The boundary conditions that are imposed in the containment model not only include the M&E release from the break, but also the different injections from the ADS stages, the PRHR actuation in the IRWST, and the IRWST injection for the long term cooling.

The boundary conditions imposed in the ADS spargers were described in section 5.4.3, and ADS mass flow, pressure and temperature of the injection could be found in Figure 5-36. Likewise, the PRHR heat can be found in Figure 5-36c. The break liquid temperature and pressure are presented in Figure 8-9. Analyzing the pressure, it could be observed the different phases previously mentioned: Blowdown (until around 40 s), Natural circulation (from 40 s to 1350 s), ADS blowdown (from 1350 to 2700 s) and the IRWST recirculation.

The liquid and steam mass flow from the break are shown in Figure 8-10. It is observed the M&E release from the break practically stops at around 1300 s, when the ADS blowdown phase

starts. In Figure 8-10 is also presented the ADS IV stage mass release to the containment. It starts at 2370 s and continues until the end of the transient. Finally, in Figure 8-11 the mass flow data regarding the IRWST are presented. The ADS I-III mass flow injected in the IRWST are presented again, together with the mass flow liquid flowing from the IRWST to the vessel.

Figure 8-9. SBLOCA M&E release. Pressure and temperature

Figure 8-10. SBLOCA M&E release. Break liquid and steam, and ADS4 mass flow

Figure 8-11. SBLOCA BC. ADS I-III liquid/steam and IRWST suction mass flow.

All the previously presented mass and energy releases from the SBLOCA has been implemented in the AP1000 GOTHIC model using different BCs and heaters.

Firstly, the break is modeled with two BC, one for each phase. The BCs are connected to the SCV using FPs, which injects the fluids at the cold leg position located in the SGI compartment. The set of BC-FPs using for the break are presented in Figure 8-12 inside a blue box.

The ADS injection to the IRWST is modeled with 16 BCs, eight for each sparger. Half of those inject steam and half liquid. The BCs are connected using FPs to the IRWST CV at the real sparger injection position. The set of BC-FP for the ADS I-III injection is marked in Figure 8-12 with a green dotted box. The ADS IV stage is modeled with two BCs, one for each side. The BC is connected to the SCV using FPs with the discharge at around 13.1 m at the SGI and SGII compartments. These BC-FPs are marked in Figure 8-12 in a red box.

The IRWST water suction for the long-term cooling is modeled using two BCs, one for each sump side. Those are connected to the IRWST CV using FPs. Contrary to the other BCs presented, these ones will absorb water from the IRWST instead of injecting to it. Those are presented in Figure 8-12 inside a magenta lined box.

Finally, the PRHR heat is modeled with 23 heaters components located in the IRWST CV at the PRHR-HX position.

Figure 8-12. SBLOCA Boundary Conditions scheme

8.3.2. SBLOCA results

The turbulence model selected was k- ϵ STD with the molecular diffusion enabled; the matrix resolution was solved by a conjugate method; the discretization scheme was FLSOUP and the PCCWST water was supposed to be unavailable as a conservative hypothesis. The time step varied between 1e-05 and 0.01 s.

As for the LBLOCA case, the results for pressure and temperature were post-processed with ProTON. The model required 49 hours of computation time using a 20 cores 2.10 GHz CPU cluster (Cesvima UPM) to run 4450 s of SBLOCA transient.

The containment average pressure in the compartments is almost homogeneous during the transient, Figure 8-13. Since the break occurs the pressure in the containment slowly increases, reaching a peak of 216 kPa at 1200 s short after the steam injection from the break starts. When the ADS-IV injection occurs a slight pressure peak can be observed at 2500 s. After this moment, the pressure decreases, reaching at the end of the transient a value of 195 kPa.

Figure 8-13. SBLOCA. Containment average pressure evolution

There are some compartments that do not follow the same pressure trend. The first one is the RCV-RDCT compartment after 900 s from the beginning of the transient. The pressure in this compartment after this moment is 22 kPa higher than the rest of the containment. This is due to water injected from the break, or condensed water from the containment walls end up in this compartment, as it is located at the lower elevation in the containment. Figure 8-14 represents the water flow distribution. Water starts to be storage in the SG I compartment (where the break is located), reaching the VA compartment, and then flowing from the VA to the RCV-RDCT compartment. Water is accumulated here, blocking completely the connection between the RCV and the RCDT rooms. The higher pressure calculated in this compartment is due to the water column creates a pressure gradient that increases the average pressure.

The second compartment which follows a bare different trend is the RV Nozzle Area compartment. Around 1500 s the pressure in this compartment starts to have a different trend, not increasing during the ADS-IV injection, and not decreasing at the same speed. It could be explained understanding the behavior of the RCDT-RCV compartment. The only exit way the RV nozzle room has is the RCDT-RCV compartment. If this compartment is filled with water the air cannot flow, and neither the changes from the full containment will reach this room, nor modifications in this room would affect the containment. Therefore, while in the full containment pressure is relieved by the condensation in the liner and the different compartment walls, the pressure in this room remains practically constant.

The flooding in the Reactor Coolant System compartment demonstrate the correct containment modeling. The water collected in these compartments is meant to be used for the containment recirculation phase which has the purpose to provide redundant flow paths from the containment to the reactor [111], [150]

Figure 8-14. Liquid distribution in the lower compartments

Contrary to the pressure, the average containment temperature among the compartments is heterogeneous, as the temperature evolution is governed by a slower convective-diffusive process depending on the geometry and the distance to the pipe break. Consequently, all the compartments present different temperature values during the transient, Figure 8-15.

Although the compartments temperature is heterogeneous, some similar trends are followed by mostly all of them. After the M&E release it is observed a rapid temperature increase (until 100 s) in all the compartments. From this moment on, two clear trends are observed in the containment. On the one side the lower compartments (PXS-ACC-A, CVS, PCS-ACC-B, Refueling Cavity and RV Nozzle area) are under lower temperatures, reaching a maximum peak at around 1200 s, and maintaining a practically constant temperature (around 65 °C). On the other side, the upper compartments (SG I, SG II, PZR, VA, RCV+RCDT and Dome) reach higher temperatures. After 100 s the temperature in these compartments increases, reaching a first peak of 144 °C at 1200 s and a second peak of 152.4 °C at 1350 s in the SG I compartment, where the break is located. The upper parts of this compartment (SG I Lower Manway area and SG I Operating Deck) follow a same trend. However, the temperature reached in these compartments is slightly lower. The rest of compartments of this group suffer a temperature

increase, reaching an average peak of 110 °C at 1200 s. After 2200 s when the ADS-IV discharges steam and liquid, the temperature which was decreasing, suffers an upturn increasing the temperature approximately 10 °C for 300 s. After this moment, the temperature constantly decreases, reaching a value of 90 °C at the end of the transient.

Figure 8-15. Containment average temperature evolution

As occurred with the pressure, the RCV+RCDT compartment follows a different tendency after 1000 s. The temperature in this compartment remains practically constant from this moment until the end of the transient. The stored water blocks the fluid trespassing from this compartment to the rest of the containment, maintaining its temperature constant.

The temperature distribution in different compartments from the beginning of the transient to the 1200 s is presented in Figure 8-16, and from 1200 s to the end of the transient in Figure 8-17. The temperature distribution in a vertical section of the SGI, SGII, RVC, the RV nozzle area and IRWST compartments is represented in the upper images. A horizontal section at 14 m is represented in the lower images. SGs, PZR, IRWST, Refueling Cavity and RV nozzle area compartments, together with the maintenance floor space are depicted.

The temperature increase in the SG I compartment due to the break and the plume formed over the SG I compartment can be observed in Figure 8-16. The plume, where the steam from the break flows across the SG compartment, is represented with streamlines and velocity vectors in Figure 8-18. The steam flows from the SG I compartment (which encompass the three subdivisions) towards the dome, where it is cooled down and redirected downwards. At 100 s the fluid flows over the Operating deck until it reaches penetrations where it can pass, and then flows over the Maintenance floor. Inside the SG I compartment velocities of around 10 m/s are reached.

The temperature at the end of the transient is less heterogeneous, reaching an averaged value of 100 °C in the upper compartments, Figure 8-17. At 2000 s the steam reaches higher velocities (15 m/s) at the bottom of the SG I compartment, where twirls are formed. At the end of the SG I compartment, the fluid flows towards the dome following a similar pattern as at the beginning of the transient.

Figure 8-16. SBLOCA. Temperature distribution in the containment from 100 s to 1200 s

Figure 8-17. SBLOCA. Temperature distribution in the containment from 2400 s to 4400 s

Figure 8-18. SBLOCA SCV streamlines at 100 s and 1000 s

Water temperature in the IRWST presented separately in Figure 8-19. It can be clearly observed the effect of the ADS injection and the water extraction from the sumps on the IRWST temperature. On the one side, as explained in section 5.4.3, the ADS injection enhances the mixing in the pool. This fact can be seen to occur at around 1500 s, when thermal stratification is partially lost. The water extraction also influences the pool state. When the leak starts, firstly water from the bottom layers of the tank flows to the BC producing the movement of the upper layers, which then flows downwards to the sumps. The temperature in the whole tank mixes and the water bottom layers increase their temperature. Finally, the tank is completely mixed with an average temperature of 65 °C.

Figure 8-19. SBLOCA IRWST temperature at different elevations

The water temperature distribution in the IRWST can be observed in Figure 8-16, Figure 8-17 and Figure 8-18. In Figure 8-16 it can be observed the thermal stratification reached in the IRWST before the ADS injection starts. Likewise, in Figure 8-18 at 2000 s the presence of thermal stratification in the PRHR area slightly after the ADS I-III initial discharge is observed.

Finally, the vector field distribution in the PCS CVs at 1000 s is presented in Figure 8-20. The behavior of the fluid, in this case air, is as expected. Fluid enters from the downcomer, is directed downwards and at the bottom, when the air baffle deflector is reached the fluid is redirected and flows upwards through the riser. In this CV the cold air is heated up by the hot liner (which has increased its temperature as it was in contact with hot steam from the break) whilst it refrigerates the liner. The warmed air flows from the riser to the chimney, where it stills exchange heat with the liner dome and flows to the chimney outlet. The maximum average velocities obtained in these CVs are: downcomer: 0.88 m/s, riser: 2.21 m/s, chimney: 1.84 m/s. The time selected for presenting these results is the one when constant conditions are achieved in the PCS.

Figure 8-20. SBLOCA. PCS velocity field distribution

8.4. Conclusions

In this final part of the thesis, the different AP1000 isolated models created throughout this thesis have been coupled to create a full detailed 3D AP1000 containment model.

Firstly, using the SCV+PCS model and the BC obtained from an AP1000 TRACE model, a DEGB-LOCA was simulated. With this model, and the use of tools as ProTON and ParaView it has been possible to analyze different regions inside and outside the containment.

The pressure in the containment was homogeneous along the compartments. The averaged containment pressure obtained reached a maximum peak of 420 kPa around at 1450 s. On the contrary the temperature is heterogeneous and depending on the compartment position and connections those develop different temperatures. The maximum average temperature reached in the dome is 122 °C. The compartments that reached the maximum averaged temperature were the PXS-ACC A compartment and the RV Nozzle area, both situated under the Operating Deck. Despite different hypothesis and M&E releases and the conservative hypothesis of no PCCWST actuation, the results tendencies are similar to the ones observed in the current literature for AP1000 [25][67][146] and CAP1400 [151][152].

Secondly, using the SCV+PCS model coupled with the full-scaled IRWST model, a SBLOCA sequence has been simulated. The BC for simulating the different phases of this accident are carefully implemented in the 3D model. Using this model, together with ProTON and Paraview the pressure and temperature results during the transient are obtained.

As occurred in the LBLOCA the pressure in the containment was homogeneous and followed a similar trend. It reached a peak of 212 kPa at 1200 s, decreasing afterwards, and having a final pressure of 195 kPa at the end of the transient. The temperature in the compartments during the transient was different and depending on the position, it followed different trends. “Upper-compartments”, e.g. SG I or dome, reached higher temperatures, reaching peak of about 150 °C at 1200 s. Meanwhile temperature in “lower compartments” was lower, not having such prominent peaks and keeping a practically constant temperature of 67°C until the end of the transient. The flooding in the lower compartments not only determines the thermal state of certain compartments, but also demonstrate the correct containment modeling.

The averaged pressure and temperature results are consistent with the M&E released from the break. The maximum average pressure obtained in the different containment compartments is as expected, and the temperature reaches values in accordance with the energy released from the break and from the systems that actuate during this accident. Nevertheless, these SBLOCA results cannot be compared with data available in the literature, as this scenario could not be found modeled for the AP1000 containment.

Part V

CONCLUSIONS

Chapter 9

Conclusions and outlook

The main objective of this thesis, the development of a detailed AP1000 3D containment model with GOTHIC that encompass the PCS and IRWST-PRHR detailed systems, has been achieved. For that purpose, the models of the IRWST-PRHR, the SCV, and the PCS had to be created and tested before joining them together in the full containment AP1000 model.

For creating the full-scaled IRWST model a scaled-down IRWST experiment was simulated using public data from the literature. Following the insights obtained during the experiment simulation (e.g. mesh limitation for modeling thermal stratification) the full-scaled IRWST model was created. Finally, the ADS spargers were implemented in this full-scaled IRWST model, emulating SBLOCA conditions. Different conclusions can be extracted from the analysis: (1) GOTHIC, as a containment code, can be used for simulating thermal stratification with reasonable accurate result; (2) a refined heterogeneous mesh is not needed to properly model the *dead zone* at the bottom of the tank, (3) the minimum mesh size able to model thermal stratification was found to be 0.4 m, and (4) thermal stratification modeling is important for the proper containment pressure prediction, as a mixed pool can lead to pressure underestimation.

Concerning the ADS injection in the IRWST several conclusions were obtained: (1) to model a steam/liquid injection in GOTHIC the cell volume where the injection is located and the mass flow should be compatible; (2) the FP injection direction has a minor impact on the stratification in the pool, having the downward injection more capacity of mixing the pool; (3) the slight differences on the stratification has a negligible effect on the containment pressure; and (4) the

ADS injection, regardless of the direction, induces a mixing of the pool, homogenizing the different layers temperature.

The PCS model has been created using the available public data from the AP1000 DCD. A 3D CAD model is used to create the complete model and afterwards define a simplified model. In this simplified model three main sections are defined: downcomer section, riser section and chimney section. To be able to model this system in GOTHIC, considering the thickness of the riser and downcomer annular space together with the mesh limitations in the program, the “developed volumes” technique has been used. Finally, a “base case” model is created in GOTHIC that consists of three CVs. Downcomer and riser as developed volumes and chimney as standard 3D volume.

Using constant BC, a steady state is simulated. It was possible to simulate the natural phenomena that may occur in a possible accidental condition (with no PCCWST actuation). To test the robustness of this model, a mesh sensitivity analysis was performed. After analyzing several mesh combinations for riser, downcomer and chimney CVs, it was concluded the mesh refinement did not have a significant influence on the thermal behavior of the system.

To create the AP1000 SCV containment model the methodology developed at the ETSII-UPM for previous containment models has been further developed [16]. First, a detailed 3D model was created in AutoCAD using public layout plans. Then, the CAD was simplified into basic geometrical figures (blocks, wedges, caps and cylinders) that could be implemented in GOTHIC. Finally, the 3D GOTHIC model was created from this geometrical input via an in-house script and consistent mesh study is performed to verify the airtightness of the different compartments in the containment.

Finally, the different isolated models created throughout this thesis have been coupled to create a full detailed 3D AP1000 containment model. Firstly, the PCS model has been thermally connected to the SCV model, allowing to simulate the heat transfer with the atmosphere more realistically than imposing constant boundary conditions. Using this model DEGB-LOCA was simulated. Secondly, the SCV+PCS model was coupled with the full-scaled IRWST model. The connection was done thermally (along the surrounding walls) and hydraulically (through the flaps space between the IRWST and the containment, which are assumed to be always open).

Using these models, a DEGB-LOCA and a 2-inch SBLOCA were simulated. Thanks to the spatial resolution provided by the created models, it has been possible to study the general behavior in the full containment, as well as the behavior in its different compartments. The results obtained for the DEGB-LOCA agree with the ones available in the literature in tendency and maximum values, demonstrating that this model has the necessary robustness for modeling correctly the phenomenology in the containment. The SBLOCA results are coherent taking the DEGB-LOCA ones as reference, albeit cannot be contrasted with other references in the public literature.

The computational competitiveness of the model, together with its accuracy, allowed to understand phenomena that have not been seen in any other AP1000 models, giving to this PhD thesis valuable outcomes:

- To understand the feedback between the IRWST water state and the pressure in the containment
- To be able to simulate the thermal stratification phenomena and the dead zone in the tank observed in the literature [58]-[61].
- To confirm the role of the lower compartments collecting water for the sumps that injects water in the core in the last phase of the SBLOCA during the containment recirculation phase.
- To see the detailed path of the steam from the break to the top of the containment and its way back downwards in both LBLOCA and SBLOCA scenarios.
- To check the differences in temperature behavior of the lower and the upper compartments in the SBLOCA compare to the LBLOCA.
- To understand the beauty of the thermo-hydraulics of the AP1000 containment, with the passive cooling thanks to the inner and outer natural circulation.

Finally, the innovative approach of modeling and studying different safety systems separately and then merging those in a full complete model has allowed to obtain a versatile model. It can alternate the use of these systems depending on the phenomena and scenario that wants to be simulated, including DBA and SA scenarios.

Future works

During this PhD thesis development certain restrictions were found, and due to time (this PhD period) and space (computational resources) limitations there are a wide range of applications that can be further improved in the future.

Concerning the full-scaled IRWST model, the lack of full-scaled experiments made not possible the its validation. The comparison code-to-code (GOTHIC vs a CFD code) would give a better consistency on the results and would provide insights for a more thorough model. Moreover, the ADS sparger injection could be validated against experimental test results and tested under different steam injection regimes.

Regarding the PCS model, the principal weakness of it is the conservative hypothesis of no PCCWST actuation. The lack of specific models in GOTHIC for modeling phenomena such as liquid film dynamics and evaporation, made necessary to find alternative ways for its modeling. Experiments available in the literature could be useful for validating scripts which could be implemented as a DLL in GOTHIC.

Although the AP1000 GOTHIC containment model was designed to be computationally efficient following the best modeling practices, the LBLOCA and SBLOCA scenarios needed a great quantity of time for being simulated in a 20 cores cluster (18 and 49 h, respectively). This fact creates the necessity of developing lighter models which allow a faster simulation of different transients, such as severe accidents with a much longer duration. However, it is important to highlight the already developed model lies between the bounds of accuracy and computational time.

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