Synopsis of Doctoral Thesis

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Degree for which submitted:	Doctorate of Philosophy
Thesis title:	Containment Thermal-Hydraulic Studies towards Understanding Post-Severe Nuclear Accident Scenarios
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Motivation and Objectives of Research:

The conventional resources of energy are almost 100 million years old, and they were first discovered 200 years ago. However, their usage is exponentially increased in the last 100 years (after industrialization). According to the current rate of consumption, the current available reserves of oil, gas and coal will not last more than a century. Additionally, the greenhouse gasses (such as CO_2) have been significantly increased in the past fifty years, with the use of these conventional energy sources. Significant progress in the production of energy from the non-conventional sources (solar, wind and geothermal) have been made; still, they are merely a part of current power requirements.

Alternatively, nuclear energy is a clean source in terms of greenhouse gas emission and a reliable replacement, which will last for a millennium. Nevertheless, some accidents in the past (such as Fukushima disaster, in March 2011 and Three Mile Island (TMI) accident, in March 1979) associated with the Nuclear Power Plant (NPP) have strongly changed the mind-set of the world, mainly due to the release of radioactivity in the environment. These accidents occurred primarily due to loss of coolant in the Reactor Pressure Vessel (RPV), which triggered the hydrogen production. The produced hydrogen and steam were eventually released in the containment. These gasses in the containment play a crucial role during a Severe Accident (SA). There are several interacting phenomena (related to heat transfer, mass transfer and concentration distribution) inside the containment that decides the outcome of the accident progression. A representative figure of few important phenomena occurring during a SA in a Boiling Water Reactor (BWR) containment are depicted in Figure 1 (a). Understanding these phenomena within the containment space is complex, but essential for deriving its safety requirements in critical situations. Thus, above-discussed points are the prime motivation for undertaking the study of containment thermal-hydraulics in a SA.

During a SA, the containment is cooled, internally and externally, to maintain safe thermodynamic conditions (temperature and pressure). The type of cooling systems varies depending on the design of the containment structure. Despite different cooling systems, the heat transfer process is mainly governed by heterogeneous wall condensation (on internal walls and structures). Apart from that, convection and bulk volumetric condensation mildly take part in removing the heat out of the containment building. The concentration distribution is another determining factor for maintaining containment integrity. Ideally, there is no chance of hydrogen combustion if all the released hydrogen from the RPV is uniformly distributed in the containment atmosphere. However, hydrogen can always accumulate in several regions of the containment building due to different interacting phenomena. Hence, stratified hydrogen forms a combustible mixture, which may deflagrate or detonate (according to the chart given in Figure 1(b)) and severely damages the containment structure. Finally, both the low heat and mass transfer, and hydrogen stratification can damage the containment, and are the focus of the current study.

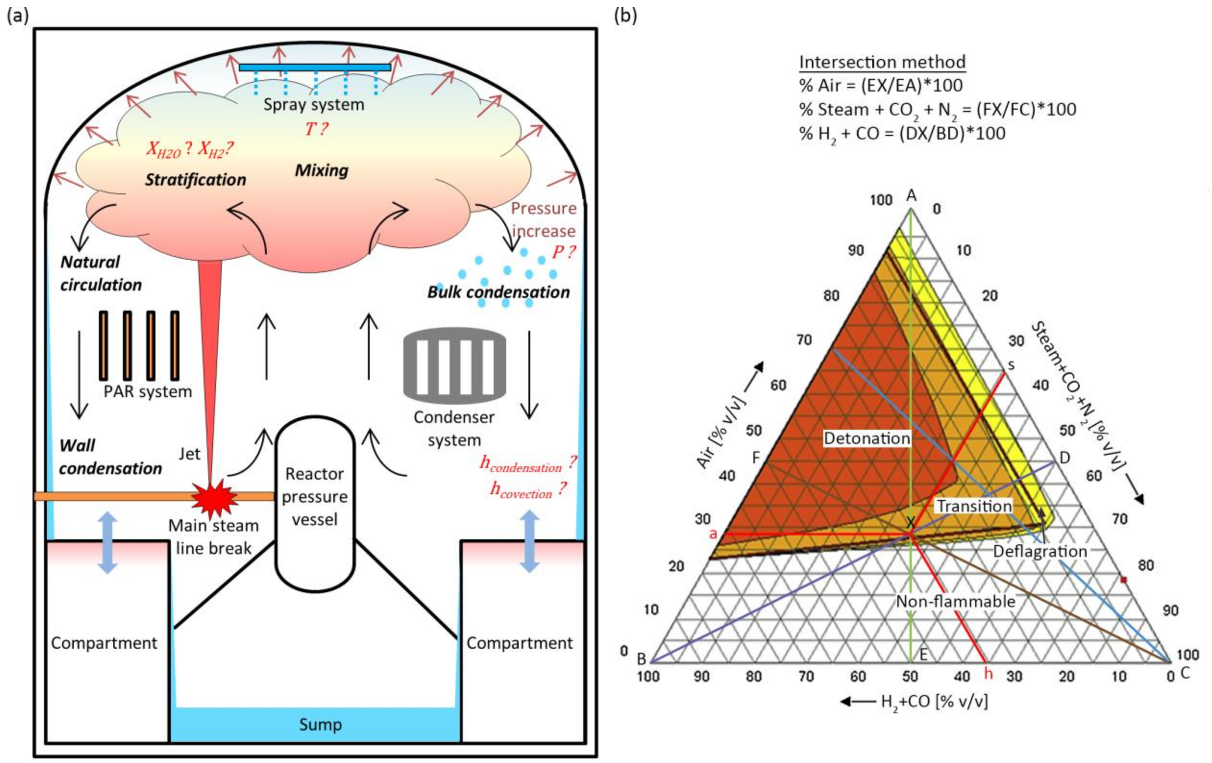

Figure 1: (a) Thermal-hydraulic behaviour with all important phenomena of a BWR containment during a severe accident, (b) modified Shapiro–Moffette ternary diagram

Containment has many interlinked phenomena, that needs detailed analysis through multiple small scale and large scale experiments, as it is impossible to do experiments on full-scale containment. The purpose of this study is to simulate the large-scale phenomena (such as buoyancy, natural circulation, turbulent natural convection and stratification), which are most prominent in containment for blowdown/injection and post-blowdown/post-injection phase of SA. A step by step process is followed here to judiciously simulate such experiments. At first, it was necessary to understand all the factors which affect the progression of a SA**.** Accordingly, the phenomenology of all the major factors which affect SA and related experimental and numerical studies are critically reviewed. Based on the research gap identified, the following objectives for this thesis work are accomplished.

(a) A preliminary work on steam condensation and hydrogen stratification is conducted. To simulate a SA in NPP containment, numerical models are developed and implemented to simulate multi-species flow and mixing, wall condensation and bulk condensation. These models are validated and benchmarked from the previous experimental work, which were conducted for different SA situations.

(b) A Thermal-HYdraulic test facility for CONtainment (THYCON) is designed, which can simulate different boundary conditions and initial conditions. An experimental test vessel and all the auxiliaries, required for the experimentation, are fabricated and installed at Southern Laboratories, IIT Kanpur. The design is based on the requirement of limiting pressure, wall conditions, initial condition, possible injection modes in the containment and the related phenomena to be replicated.

(c) The instrumentation is designed and installed such that all the necessary transient and steady-state phenomena can be experimentally simulated. An in-house inverse heat conduction based heat flux measurement, thermocouples, mass flow meters and online mass spectrometer system are incorporated.

(d) Study of different mixing mechanism of helium gas (as a replacement of the hydrogen gas) in injection and post-injection phase at different Richardson Numbers are needed to be explored. Richardson number (Ri) is the ratio of buoyancy and momentum, which signifies the flow characteristics of the interacting gasses. Stratification and mixing time scales are quantified in the THYCON vessel for a concentration range (obtained from the stipulated inlet jet velocity and amount of hydrogen leakage occurred) and injection locations. Since hydrogen has a broader range of combustion, this quantification is essential to get a broader picture of possible combustion in containments.

(e) A systematic study on containment thermal-hydraulics is also required for understanding the heat transfer during SAs. For that, two types of experiments are performed. In the first one, interaction of steam and air is considered, and heat transfer coefficients at different concentration of air, a range of pressure and wall temperature, are calculated. Later, in the second one, the effect of hydrogen (a surrogate, helium is used instead) along with steam and air are studied.

Summary of Experiments and Key Results

The first part of the work is on numerical model development and its implementation. The modelling of containment has been performed in two parts: isothermal modelling and heat transfer modelling. Isothermal modelling includes the mixing of multiple gasses (condensable and non-condensable gasses) in fixed environmental conditions. Important phenomena such as mass diffusion and buoyancy due to concentration difference are incorporated through separate abstraction in the Ansys® CFX code. The heat transfer modelling involves thermo-hydrodynamics of containment atmosphere in a severe accident situation. Convection and condensation are the primary modes of the heat transfer process. Wall and bulk condensation require separate models/abstractions, which are included as source terms in transport equations of energy and species. The buoyancy and stratification include the effect of both, concentration gradient and temperature variation. Other phenomena such as turbulence, diffusion and natural circulation are also incorporated in the latter part. The aforementioned modelling approach was implemented on different types of

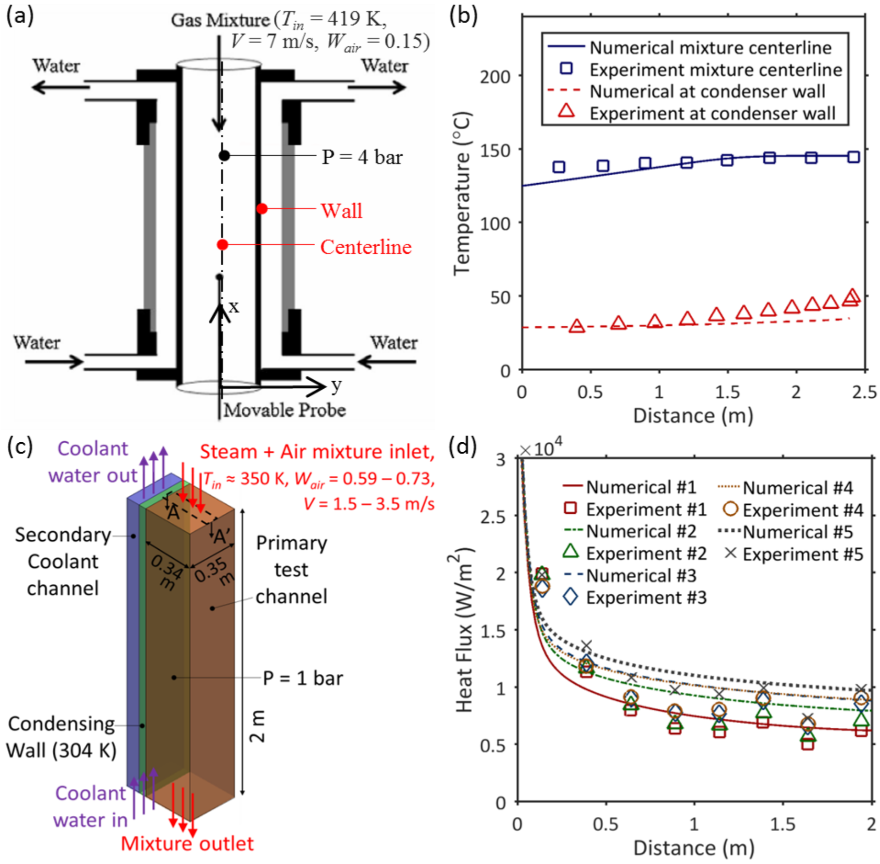

Figure 2: Schematic of the test section and validation of numerical models with Kuhn et al. experiments, 1997 ('a' and 'b', respectively) and CONAN tests, 2008 ('c' and 'd', respectively)

problem that exist during an accident situation. The non-condensable gasses have a significant effect on wall condensation, which was studied separately by comparing the fundamental problem of pure steam condensation with steam condensation on a horizontal flat plate in the presence of air. The discussed models were validated over a range of thermal-hydraulic test facilities at different initial and boundary conditions. Few of such validations are depicted in Figure 2 (b and d). Figure 2 (b) compares the numerical and experimental data of temperature at centerline and condenser wall, respectively, of the condensation experiments given in Kuhn et al. (1997). Similarly, another validation of CONAN tests (by Ambrosini et al. (2009)) compares the wall heat flux data in Figure 2 (d). Unless the net non-condensable gas (NCG) concentration is very low (less than about 6%), the condensation models (wall and bulk), in tandem with multicomponent mixture model (MCM), works quite well for simulating the considered containment thermal-hydraulic situations. This provides the necessary confidence to be further able to reliably simulate post-accident thermal-hydraulics of large containment structures.

In the backdrop of the above numerical work, a Thermal-HYdraulic facility for CONtainment (THYCON) is designed, fabricated and erected. The schematic of the complete THYCON facility is shown in Figure 3. This facility has a test section (THYCON vessel of volume ~ 2.7 m^3, height ~ 3.6 m), auxiliaries and instrumentation. The auxiliaries have a supply system for helium gas, air, steam and coolant water. An in-house inverse heat conduction based system is installed, which can quantity the transient heat fluxes appearing in the wall of the containment. Apart from that, several measuring devices are installed in the main test section for estimating heat flux, temperature concentration and pressure; this includes heat flux sensors, thermocouples, helium sensors or online mass spectrometer and pressure transducers. This test facility is capable of simulating different injection locations, injection Richardson numbers, condenser temperatures and wall conditions with the help of the

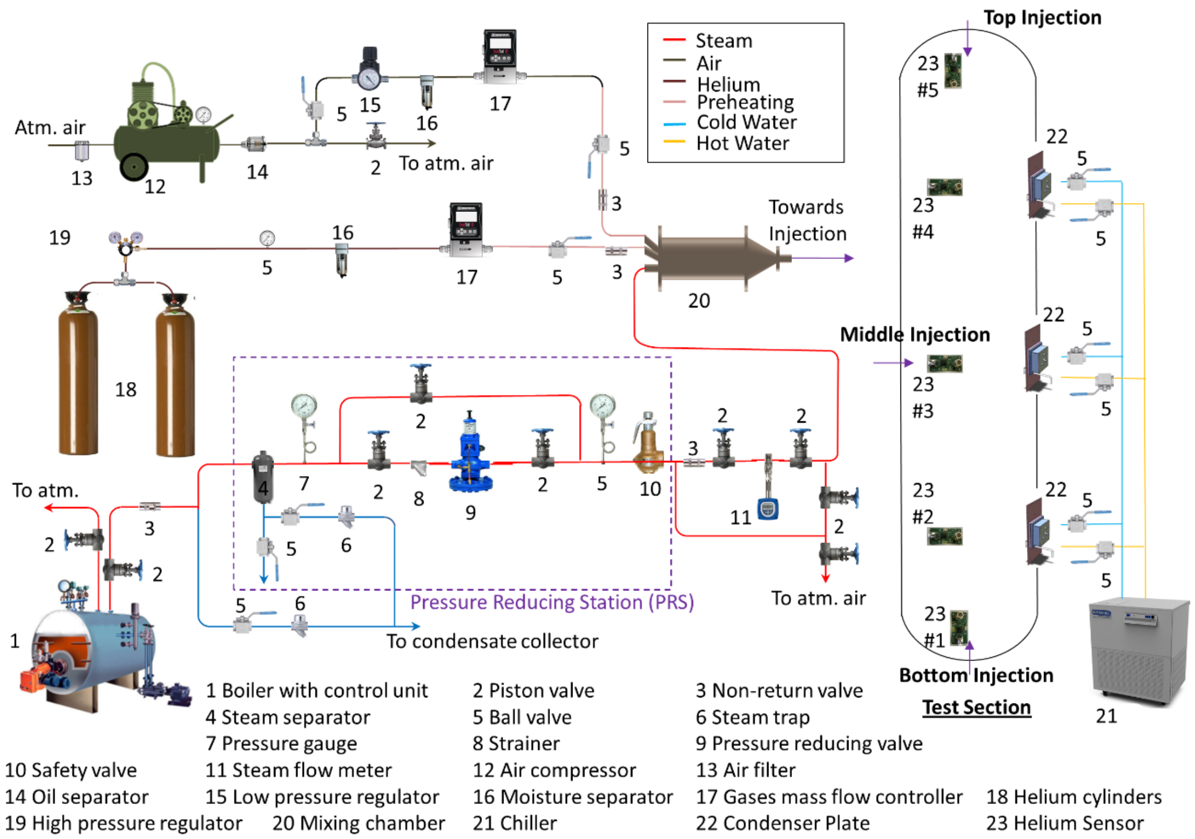

Figure 3: Full schematic of Thermal HYdraulic test facility for CONtainment (THYCON facility): test section, auxiliaries and instrumentation

Table 1: List of the experiments performed in THYCON facility.

Sets	Details of the experiments	Location and orientation of injection	Approximate parameters	No. of experiments (Total: 39)
A	Helium stratification and mixing study (Isothermal experiments)	Vertically upward from bottom, horizontal injection from middle, and vertically downward from top	Average helium concentration: 2%, 6% and 10%. Volumetric Richardson number: 0.1, 1 and 10 Steam flow rate: Nil	27
B	Condensation studies in the presence of air	Vertically upward from bottom	Final bulk pressure: 1.65, 2.5 and 3.4 bar absolute Condenser temperature: 293 K X_{H2O}: 0 - 49 %	6
C	Condensation studies with air and helium gases	Vertically upward from bottom	Final bulk pressure: 1.5, 2.5 and 3.5 bar abs. Condenser temperature: 293 K X_{H2O}: 0 - 40 %; X_{He}: 0 – 9.4 %	6

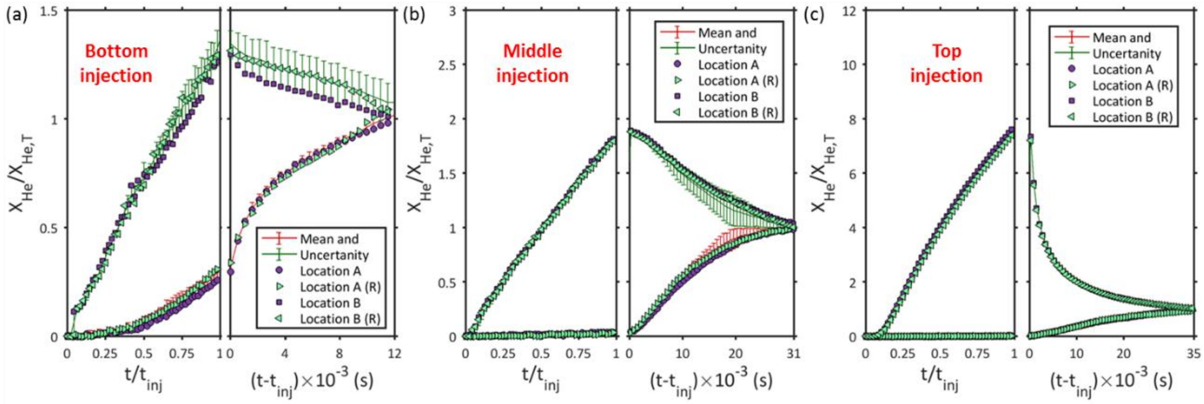

Figure 4: Concentration transient and uncertainty in measurement of helium-air mixing experiments at Ri_v = 1 and $V_{He,T}$ = 2% in THYCON vessel for (a) bottom, (b) middle and (c) top height of injection

auxiliary system. The THYCON vessel has a safe operating pressure up to 4 bar absolute. The experiments in the THYCON facility is also conducted into three parts, as given Table 1: (a) helium mixing experiments, (b) thermal-hydraulic experiments without helium and (c) thermal-hydraulic experiments with helium.

In the first part, helium (a surrogate of hydrogen) mixes with atmospheric air in the isothermal environment. These experiments include different volumetric Richardson number (Ri_v = 0.1, 1 and 10), injection locations (bottom, middle and top) and amount of helium injected ($V_{He,T}$ = 2%, 6% and 10%) in the test section. Helium concentration transient in injection and post-injection phase of the experiment at 2% of $V_{He,T}$ and Ri_v = 1 for the three injection locations (bottom, middle and top) are shown in Figure 4. At Ri_v = 0.1, the stratification is more dominant as compared to other Ri_v. However, in all the cases, diffusion of stratified helium overcome buoyancy lately in the post-injection phase. Second and third part involve the bottom injection of high-temperature steam and steam-helium mixture, respectively, in the test section. Each of these two types of experiments is conducted in two

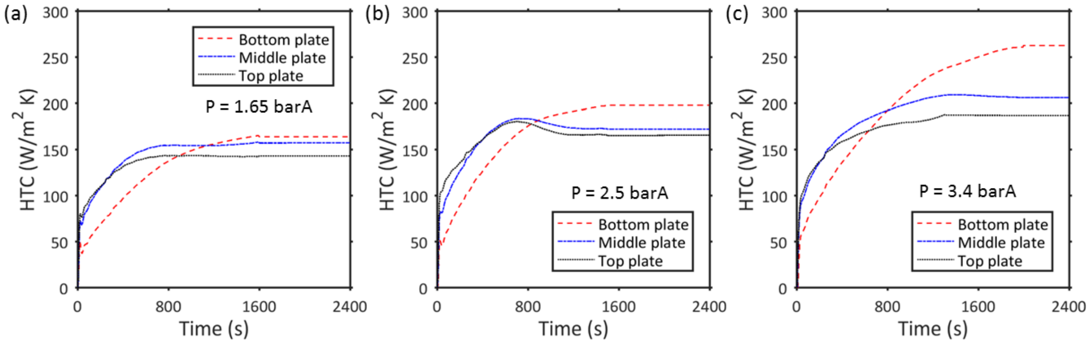

Figure 5: HTC during steam-air mixing at different heights (0.8 m, 1.8 m and 2.8 m) inside the THYCON vessel for three pressure cases: (a) 1.65 barA, (b) 2.5 barA, and (c) 3.4 barA, respectively

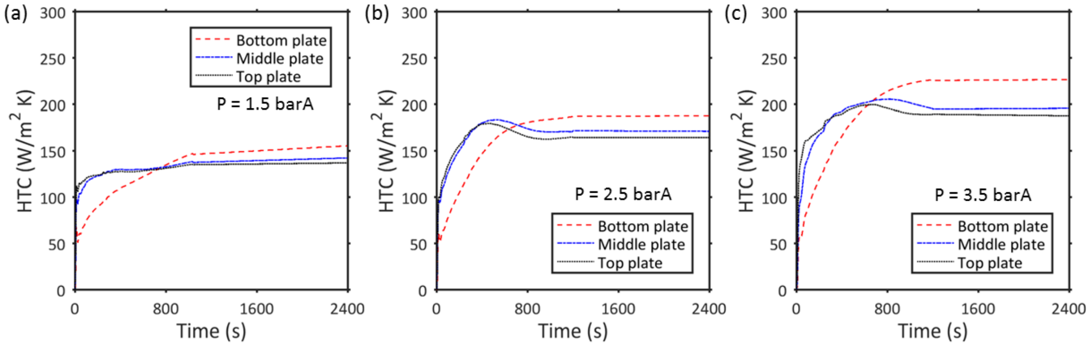

Figure 6: HTC during steam-air-helium mixing, at different heights (0.8 m, 1.8 m and 2.8 m) inside the THYCON vessel for three pressure cases: (a) 1.5 barA, (b) 2.5 barA, and (c) 3.5 barA, respectively

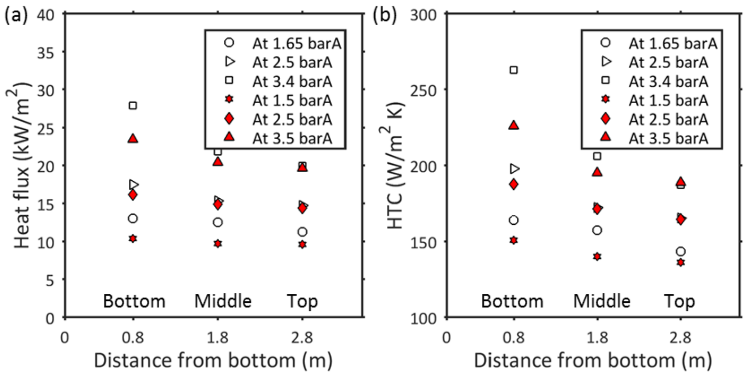

Figure 7: Effect of height on heat flux and Heat Transfer Coefficient (HTC) at different pressure condition of THYCON vessel

stages: (i) pressurisation by steam/steam-helium mixture injection up to stipulated pressures and concentrations, and thereafter (ii) continuous injection of steam only. In pressurisation mode, steam/steam-helium mixture is infused in the THYCON vessel, which was initially at atmospheric condition (1 barA, 300 K and 100 %vol air). Only the condensers were maintained at a constant temperature (at 293 K). The injection was highest at the start and eventually reached to a constant value (steady-state) when the imposed inlet pressure was almost equal to internal pressure of THYCON vessel. These experiments are conducted for three different imposed inlet pressures of ~1.5 bar, ~2.5 bar and ~3.5 bar absolute. The transient HTC for the two types of experiments i.e., steam-air mixing with condensation and steam-air-helium mixing with condensation, are shown in Figure 5 and Figure 6, respectively. Three condenser plates located at different heights (at 0.8 m, bottom, 1.8 m, middle, and 2.8 m, top, from the bottom centre) shows different time-dependent heat transfer behaviour. Initially, the heat flux order is $HF_{top} > HF_{middle} > HF_{bottom}$. This order later on changes to $HF_{bottom} > HF_{middle} > HF_{top}$ and remains same thereafter. Similar HTC trends are also observed. The second stage of study continues with steam injection at three different vessel pressure conditions (1.5 bar, 2.5 bar and 3.5 bar absolute), which was obtained at the end of the transient phase. In these experiments, the steam injection rate remains constant. Presence of helium in the vessel lowers the heat flux and HTC as compared to without helium experiments. At the later stage of transient injection part and steady-state injection, the difference between the heat flux and HTC at three locations (top, middle and bottom) increases with the vessel pressure (as shown in Figure 7).

Closure

In this work, an attempt has been made to address the complex transport processes, involving hydrogen stratification, its mixing and steam condensation along with other transport phenomena occurring in the containment atmosphere. The initial part of the work is on numerical model development and its implementation in the Ansys® CFX code to simulate different types of problem that exist during an accident situation. It involves the mixing of multiple gasses (condensable and non-condensable gasses), heat transfer, along with the most important phenomena, such as wall and bulk condensation. The non-condensable gasses showed a significant effect on wall condensation. In the backdrop of the above numerical work, a Thermal-HYdraulic test facility for CONtainment (THYCON) has been established. Both the mixing and thermal-hydraulic experiments were conducted in the THYCON facility. Helium, a surrogate of hydrogen was used for safety reasons. The stratification was studied in the first part and found to be highest for topmost injection and lowest volumetric Richardson number. The heat transfer in condenser plates, located at different heights of the THYCON vessel, shows different time-dependent behavior due to the circulation pattern initiated from injection.

Publications/Conferences emanating from this thesis work

List of publications

1. Yadav M. K., Bhanawat A., **Punetha M.**, Khandekar S. and Sharma P. K., Experimental study of steam condensation in the presence of air on a small vertical flat surface under controlled conditions. ASME Journal of Thermal Science and Engineering Applications, April 2020. DOI: 10.1115/1.4046867
2. Yadav M. K., **Punetha M.**, Bhanawat A. Khandekar S. and Sharma P. K., Steam Condensation Heat Transfer during Initial Blow-down Period of a Severe Nuclear Accident, ASME Journal of Nuclear Engineering and Radiation Science, April 2020. DOI: 10.1115/1.4046910
3. **Punetha M.**, Yadav M. K., Khandekar S., Sharma P. K., Ganju S., Intrinsic Transport and Combustion Issues of Steam-Air-Hydrogen Mixtures in Nuclear Containments, International Journal of Hydrogen Energy, Vol. 45 (4), pp 3340-3371, 2020. DOI: 10.1016/j.ijhydene.2019.11.179
4. **Punetha M.**, Choudhary A., and Khandekar S., Stratification and Mixing Dynamics of Helium in an Air-Filled Confined Enclosure, International Journal of Hydrogen Energy, Vol. 43 (42), pp 19792-19809, 2018. DOI: 10.1016/j.ijhydene.2018.08.168
5. **Punetha M.** and Khandekar S., A CFD based Modeling Approach for Predicting Steam Condensation in the Presence of Non-condensable Gases, Nuclear Engineering and Design, Vol. 324, pp. 280-296, 2017. DOI: 10.1016/j.nucengdes.2017.09.007

Journal articles under preparation

6. **Punetha M.**, Jain S. and Khandekar S., Transient and Steady State Heat Transfer in Thermal HYdraulic Test facility for CONtainment (THYCON).
7. **Punetha M.** and Khandekar S., Hydrogen distribution and steam condensation modelling of Thermal HYdraulic Test facility for CONtainment (THYCON).

Peer reviewed conference proceedings (accepted/presented / published)

1. **Punetha M.**, Yadav M.K., Jain S., Khandekar, S., Design and Development of Thermal-Hydraulic Test Facility for Containment (THYCON), Advances in Thermal Hydraulics (ATH '20), EDF Paris-Saclay, France, presentation postponed for Oct 20-23, 2020.
2. **Punetha M.**, Kulkarni S., Yadav M.K., and Khandekar S., A CFD Study on Coupled Issues of Hydrogen Distribution and Steam Condensation Inside Thermal Hydraulic Test facility for Containment (THYCON), Proceedings of 25th National and 3rd International ISHMT-ASTFE Heat and Mass Transfer Conference, IIT Roorkee, Uttarakhand, India, 28-31st December 2019.
3. **Punetha M.**, Yadav M.K., Bhanawat A., Khandekar, S., Steam Condensation Heat Transfer inside Reactor Containment during the Initial Transient of a Severe Accident, Proc. 27th International Conference on Nuclear Engineering (ICONE27), Tsukuba, Ibaraki, Japan, May 18-24, 2019. DOI: 10.1299/jsmeicone.2019.27.2166
4. Bhanawat A., **Punetha M.**, Yadav M.K., Khandekar, S., Effect of Surface Inclination on Film Condensation Heat Transfer in the Presence of Air, Proc. 27th International Conference on Nuclear Engineering, (ICONE27), Tsukuba, Ibaraki, Japan, May 18-24, 2019. DOI: 10.1299/jsmeicone.2019.27.2133.
5. Kulkarni S., **Punetha M.**, Choudhary A., and Khandekar S., Effect of Stratification and Natural Circulation on Steam Condensation in Presence of Non-Condensable Gases, Proc. 5th International Conference on Computational Methods for Thermal Problems

(ThermaComp - 2018), pp. 480-483, IISc Bangalore, Karnataka, India, July 9-11, 2018. ISSN: 23055995.

6. **Punetha M.**, Choudhary A., Khandekar S. and Sharma P., Helium Stratification and Mixing Studies in a Fully Enclosed Chamber, Proc. 24th National Heat and Mass Transfer Conference and 2nd International ISHMT-ASTFE Heat and Mass Transfer Conference, Paper #IHMTC2017-08-1459, BITS Hyderabad, Telangana, India, December 27-30, 2017.
7. **Punetha M.**, and Khandekar S., Study of Film-wise Condensation inside Closed Containment using Wall Condensation Model (WCM), Proc. 6th International and 43th National Conference on Fluid Mechanics and Fluid Power (FMFP2016), Motilal Nehru National Institute of Technology, Allahabad, Uttar Pradesh, India, December 10-12, 2016.

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