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Lappeenranta University of Technology
EXCOP and NUMPOOL projects

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EXCOP and NUMPOOL co-operation

- EXCOP and NUMPOOL projects are in close co-operation
  - Nordic co-operation through NORTHNET and NKS frameworks

- EXCOP = Experimental studies on containment phenomena
- NUMPOOL = Numerical modelling of condensation pool

- The research effort combines the thermal hydraulic experiments in the PPOOLEX test facility at LUT with the development work of numerical simulation models for nuclear safety analysis at VTT and KTH
Background

- In the reference BWR, 16 vent pipes connect the upper drywell compartment and the suppression pool.

- The vent pipes are submerged in the pool water by 6.5 m.

- In case of a pipe break inside the containment, gas/steam is blown through the vent pipes into the suppression pool.
PPOOLEX test facility

Model of BWR containment with drywell and wetwell compartments and withstanding prototypical system pressure

<table>
<thead>
<tr>
<th>Volume</th>
<th>Total</th>
<th>31.1 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry well compartment</td>
<td>13.3 m³</td>
<td></td>
</tr>
<tr>
<td>Wet well compartment</td>
<td>17.8 m³</td>
<td></td>
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| Test vessel outer diameter | 2.4 m |
| Height                    |       |
| Total                     | 7.45 m |
| Dry well compartment     | 3.18 m |
| Wet well compartment     | 4.27 m |

| Max. overpressure         | 0.4 MPa |
| Max. underpressure        | 0.05 MPa |
| Max pressure difference across the intermediate floor | 0.2 MPa |
| Max operating temperature | 190 °C |
| Wall thickness            |       |
| Vessel head               | 10 mm |
| Bottom end                | 10 mm |
| Lowest wall segment       | 10 mm |
| Other wall segments       | 8 mm  |

Construction material: Stainless steel (EN1.4301)

Steam from the nearby PACTEL facility (1 MW)

KHz range measurements and data acquisition

High-speed camera

PIV system
EXCOP summary 2011-2012

- In 2011-2012, experiments with the PPOOLEX facility have concentrated on thermal stratification/mixing, direct contact condensation (DCC) and on the effect of a blowdown pipe collar.

- A PIV measurement system has been acquired:
  - The idea is to get CFD grade measurement data of velocity fields in the vicinity of the blowdown pipe outlet.
  - First tests with the system have been done:
    - Rapid condensation processes are challenging for the system.

- A model of the Passive Containment Cooling System (PCCS) has been constructed and connected to PPOOLEX, which is acting as a host facility:
  - Thermal hydraulic tests in 2013 and aerosol studies in 2014 in a separate SAFIR2014 project (PCCS project).
NUMPOOL summary 2011-2012

- The CFD model for chugging has been further developed
  - The direct contact condensation model has been modified to obtain higher condensation rates at the outlets of the vent pipes and to obtain lower frequency of the chugging oscillations
  - Chugging phase of the earlier PPOOLEX experiment PAR-10 has been simulated and the recent MIX-03 experiment is being calculated

- In the Fluid-Structure Interaction subtask different approximations for the condensation rate have been tested and simulated collapse times and pressure loads near the bubble have been compared with high-speed video images and pressure measurements from the PPOOLEX experiments

- The structural response of BWR containment during multiple (100) chugging events has been computed using Abaqus explicit and simplified model geometry
Stratification and mixing experiments in PPOOLEX

- In case of small steam flow rates, thermal stratification could develop above the blowdown pipe exit elevation and impede the pressure suppression capacity of the condensation pool
  - Pressure of the containment is determined by the temperature of free surface of water pool in the wetwell

- Once steam flow increases significantly, momentum introduced by steam injection and periodic expansion and collapse of large steam bubbles can destroy stratified layers and lead to mixing of the pool water

- Accurate and computationally efficient prediction of thermal stratification, mixing, and transition between them, presents a computational challenge
  - DCC is not fully understood and cannot be modeled correctly
Stratification and mixing experiments in PPOOLEX

- VTT is improving CFD simulation models related to DCC in a suppression pool environment

- KTH is developing and implementing the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models in GOTHIC code

- To provide necessary data for the development and improvement of the models a series of stratification and mixing experiments in PPOOLEX was carried out by LUT in the framework of SAFIR2014 and NORTHNET RM3 programs
Stratification and mixing experiments in PPOOLEX

- Fine resolution both in space and time for detection of the dynamics of free water surface in the blowdown pipe is needed to get an accurate estimation of the frequency and amplitude of oscillations for the assessment of the effective momentum.

- This was achieved with an extensive net of measurements added into the blowdown pipe before the experiments.
Stratification and mixing experiments in PPOOLEX

- A series of six experiments was carried out in 2012

- Initially the wet well pool was filled with isothermal water (13–16 °C) to the level of 2.1 m i.e. the blowdown pipe was submerged by 1.0 m

- During the stratification phase the steam flow rate was small

- As the experiments proceeded to the mixing phase the steam flow rate was rapidly increased to get the steam/water-interface moving up and down inside the blowdown pipe and to totally mix the condensation pool water inventory
Stratification and mixing experiments in PPOOLEX

- The path of each experiment can be plotted on the condensation mode map of Lahey and Moody.
Stratification and mixing experiments in PPOOLEX

- During the small steam flow rate period, temperatures below the blowdown pipe outlet remained constant while increasing heat-up occurred towards the pool surface layers, indicating strong thermal stratification.
Stratification and mixing experiments in PPOOLEX

- Depending of the used steam flow rate and the degree of thermal stratification of the pool water it took 150–500 s to achieve total mixing of the pool volume.
Stratification and mixing experiments in PPOOLEX

- Temperature measurements with good spatial resolution in the vent pipe
- Movement of steam/water-interface can be tracked accurately
NUMPOOL: CFD modeling of experiments with two vent pipes

- Simulation of chugging phase of the experiment PAR-10
  - Chugging phase at time $t = 500$ s during the experiment is modeled
  - Drywell initially filled with vapor ($T = 140^\circ$ C, $p = 2.89$ bar)
  - Mass flow rate of vapor into the drywell ($m = 0.523$ kg/s, $T = 155$ C)
  - Vapor flowing into the dry well contains volume fraction of 0.01% of air
  - Pool temperature 43 C
  - Gas space of wetwell stratified, $T = 33...61$ C

- Enhanced heat transfer coefficient on the gas side
  - Earlier value of $h = 15$ MW/m$^2$K was too small
  - Larger value $h = 50$ MW/m$^2$K improves results somewhat
  - Higher values are also needed on the liquid side
NUMPOOL: Calculation of volume fraction of vapor

t = 6.04 s  6.09 s  6.14 s  6.19 s

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NUMPOOL: Iso-surface of void fraction $\alpha = 0.1$
NUMPOOL: FEM models for a BWR containment

- Detailed model
- Simplified model
NUMPOOL: Example loading for BWR containment

- Construction of desynchronized pressure loading
NUMPOOL: Maximum radial displacement

- Synchronized loading
- Desynchronized loading

Radial displacement at the nodes where the maximum displacement occurs.
Conclusions

- EXCOP and NUMPOOL projects have co-operated closely to combine experimental and calculational research of containment related issues
  - Close connection also to work done by KTH in modelling thermal stratification and mixing in a suppression pool

EXCOP:
- Instrumentation of the PPOOLEX facility has been improved to better track the movement of steam/water interface inside the blowdown pipe
- The acquired PIV measurement system is being tested
- The MIX experiment series in 2012 with PPOOLEX can be utilized in the improvement efforts of the DCC models of CFD codes as well as in the development work of the EHS and EMS models of GOTHIC code
- Characteristics of thermal stratification, mixing and chugging can be determined more accurately on the basis of the performed MIX experiments

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Conclusions

NUMPOOL:

- Some of the main features of blowing steam into pressure suppression pool can be reproduced in CFD simulations
- Clear differences are seen in CFD simulations of chugging compared to the PPOOLEX experiments
- The desynchronization of the pressure loads originating from different vent pipes decreases the pressure loads on the containment
- Scaling of the pressure loads from the laboratory experiments to BWRs has been studied but further investigations are still needed