

Preliminary Design and Feasibility Assessment of a PCM-Based Passive Condenser for LOCA Mitigation in APR1400

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1. Introduction

In pressurized water reactors (PWRs), mass and energy discharge due to a loss of coolant accident (LOCA) rapidly increase the containment pressure and temperature. Removing part of this energy during the early blowdown period can moderate the pressure peak and support containment integrity. A passive condenser incorporating a phase change material (PCM) can operate without an external power supply and may provide prompt and reliable heat removal with a relatively simple system configuration. Moreover, owing to its high thermal storage capacity, it can effectively absorb part of the released energy and thereby help mitigate the pressure peak. However, the performance of a PCM-based passive condenser is governed by complex thermal-hydraulic phenomena, including condensation heat transfer in the presence of non-condensable gas, condensate drainage, natural circulation flow development, and PCM melting. These interactions make preliminary design optimization challenging.

This study investigates the feasibility of a PCM-based passive condenser as a means of containment pressure peak mitigation during the early blowdown stage of a LOCA in APR1400. The pressure and temperature transients during the early blowdown stage of LOCA, which are obtained from a containment analysis package (CAP) calculation, were imposed as time-dependent boundary conditions for a one-dimensional (1D) MARS-KS condenser model. A large number of randomly selected design options were then evaluated in terms of cumulative heat removal and PCM utilization to identify a favorable design.

Furthermore, the effects of geometric configuration and drain flow area were examined to identify the key parameters. Finally, the potential reduction in the containment peak pressure was estimated by iterative coupling of MARS-KS and CAP, in order to quantitatively assess the system-level feasibility of the PCM based passive condenser.

2. Preliminary Condenser Concept and MARS-KS Model

2.1. PCM-based passive condenser concept

In this study, a modular passive condenser mounted on the containment wall was considered as a preliminary

design concept. The proposed passive condenser design concept is illustrated in Figure 1.

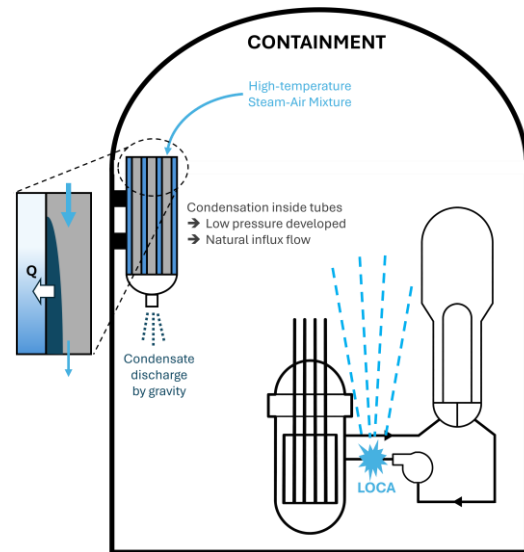


Figure 1. Design concept illustration of a PCM-based passive condenser

The overall dimensions of each module are assumed to be fixed by the available installation space. Within a module, multiple vertical heat transfer tubes are installed to provide condensation surfaces. The region outside the tubes is filled with PCM, and PureTemp 60 is selected as the reference PCM material. The tubes and fins were assumed to be made of aluminum because of its high thermal conductivity. The tube wall thickness was fixed at 1 mm. Under the constraint of a fixed module size, tube length, tube diameter, tube pitch, fin volume fraction, and drain flow area are treated as adjustable design variables. Examples of module geometries randomly generated from different design variable combinations are illustrated in Figure 2, including typical sparse and dense tube configurations.

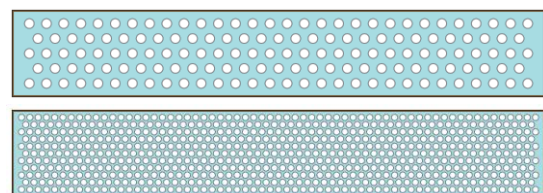


Figure 2. Examples of randomly generated tube configurations

Several trade-offs arise among these design variables. A dense tube configuration with small tube diameter and narrow pitch can increase the number of tubes and thereby increase the heat transfer area. However, it reduces the inventory of PCM and may increase hydraulic resistance. Conversely, a sparse tube configuration provides a larger PCM volume but reduces the heat transfer area. Similarly, increasing the volume fraction of fin outside the tubes can enhance the heat transfer into the PCM region but the corresponding displacement of PCM reduces the latent heat storage capacity. Another example is the effect of increasing tube length. Increasing the length of the tube directly increases the heat transfer area inside the condenser module. However, the additional tube length may not be as effective as the original tube length in terms of condensation heat transfer. Thus, extending the tube may be less effective than increasing the number of condenser modules. These competing effects are the main motivations for extensive design exploration to find the optimized design.

2.2. MARS-KS 1D Model Development

The MARS-KS one-dimensional model is illustrated in Figure 3. The condenser tube bundle, lower header for condensate collection, and drain for discharging condensate to the containment are represented by separate thermal-hydraulic components.

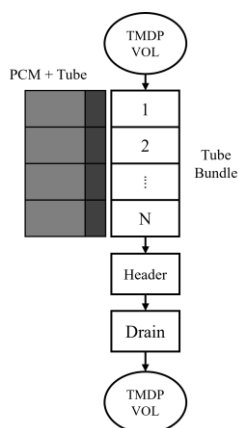


Figure 3. One-dimensional model of the PCM-based passive condenser

It is assumed that heat transfer occurs only inside the tube bundle and that the passive heat removal effect of other metal structures is not considered. Condensation heat transfer inside the tubes is modeled using the Colburn-Hougen correlation, which accounts for the degradation of condensation heat transfer caused by the non-condensable gas layer [1].

The PCM region is represented as a cylindrical heat structure with an equivalent radial thickness derived from a triangular tube-lattice arrangement. The effective thermal conductivity of the PCM-fin composite is calculated assuming parallel heat conduction according

to the fin volume fraction. Its volumetric heat capacity is similarly determined from the volume fractions and thermal properties of PCM and fin materials.

PCM melting is modeled using a narrow mushy region with a width of 0.5 K about the melting temperature. The effective volumetric heat capacity within the mushy region is defined such that its temperature integral preserves the prescribed PCM latent heat as shown in Figure 4. In Figure 4, the area of the shaded region under the graph inside the mushy region represents the volumetric latent heat of the PCM.

The fraction of molten PCM after the transient is subsequently evaluated from the temperature of each heat structure node and its volume. The reduction in latent heat caused by the volume occupied by the fins is also considered in the calculation. However, axial heat transfer inside the PCM region is not considered because of the limitation of 1D representation. Also, convective heat transfer within molten PCM is neglected in the present 1D model for simplicity.

The tube inlet and drain outlet are assumed to be directly connected to the containment atmosphere and thus modeled as time-dependent volumes to impose the containment environment during the accident. The transient behavior of the containment atmosphere from CAP analysis, which is described in section 2.3, was prescribed in tabular form as a time-dependent boundary condition.

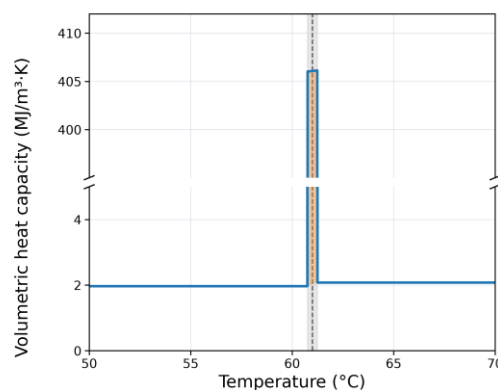


Figure 4. The effective volumetric heat capacity of the PCM including the melting latent heat

2.3. LOCA boundary condition

To evaluate the expected performance of the condenser under the accident conditions, the containment transient during the blowdown stage of a double-ended discharge line break for Saeul Units 3 and 4 was reproduced from the information provided in the public version of final safety analysis report (FSAR) using CAP and the resulting pressure, temperature, and gas composition were applied as a boundary condition for the condenser performance analyses.

The containment transient analysis focused on the period from accident initiation to the End Of Blowdown

(EOB) at 33 seconds. Since a significant portion of mass and energy release is concentrated in the blowdown phase and the first pressure peak usually occurs before EOB, the prompt heat removal capacity of the passive condenser is critically important.

The mass and energy release data before EOB are shown in Figure 5 [2]. A total mass of 336,664 kg and a total energy of 469.38 GJ were released into the containment atmosphere before EOB, and the first containment pressure peak of 424.1 kPa (abs) (46.82 psig) occurred a few seconds before EOB.

To reproduce the containment peak pressure, the passive heat sink in the CAP model was calibrated in the CAP calculation. The calculated pressure and temperature transients are shown in Figure 6. This transient behavior was then imposed on the time-dependent volumes at the tube inlet and drain outlet.

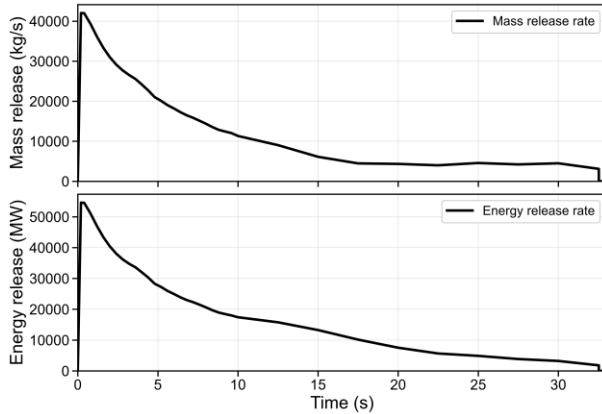


Figure 5. Mass and energy release before EOB

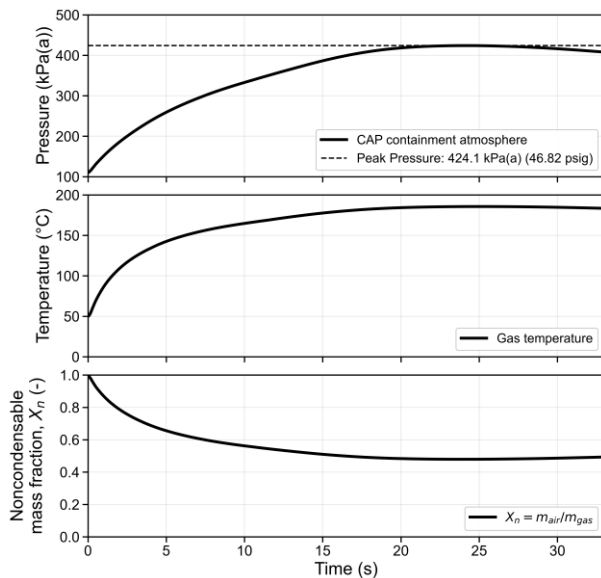


Figure 6. CAP analysis results for LOCA condition

3. Design Exploration and Optimization

3.1. Design variables and design exploration method

Five design variables were considered in the design space exploration: tube length, tube diameter, tube pitch, volume fraction of fin in PCM region, and drain flow area. All variables except tube length were treated as continuous variables, whereas the tube length was treated as a discrete variable in order to minimize the sensitivity to the 1D nodal scheme in the axial direction. The ranges of design variables considered in the design exploration are summarized in Table 1.

Table 1. Design variables and their ranges considered in the design exploration

Variable	Range
Tube length, cm	10, 20, 30
Tube inner diameter, mm	2 - 30
Tube pitch, mm	$1.25 \times D_o - 50$
Volume fraction of fin	0 - 0.3
Drain flow area, m ²	0.0025 - 0.03

In order to search for the optimized design option, a large number of random combinations of design variables were sampled, and their performance was directly calculated using the MARS-KS model.

Once the diameter and the pitch of the tube were determined, the total number of the tubes was calculated from the triangular configuration and the predefined module size. Therefore, by randomly sampling the diameter and the pitch, the trade-off relationship between heat transfer area and PCM inventory can be considered. Similarly, the competing effect of external fins can also be considered by randomly sampling the volume fraction of fins inside the PCM region.

3.2. Performance metrics and optimum design selection

Two performance metrics are used to evaluate each design: cumulative heat removal until EOB per module volume and PCM melt fraction at EOB. Cumulative heat removal until EOB per module volume is the primary performance metric which directly represents the capacity to remove energy promptly after the initiation of the accident under a limited installation volume.

The secondary performance metric, PCM melt fraction, is introduced to evaluate the spatial utilization of PCM thermal storage capacity. A melt fraction near unity indicates that most of the PCM inventory has participated in heat absorption. However, it may also indicate that the PCM inventory is insufficient to provide further thermal storage, which can limit the cumulative heat removal. Conversely, low PCM melt fraction may indicate that the PCM has not effectively absorbed heat and that the installation volume is underutilized. Therefore, desirable designs are expected to achieve both

high cumulative heat removal and high PCM melt fraction in the early phase of the accident.

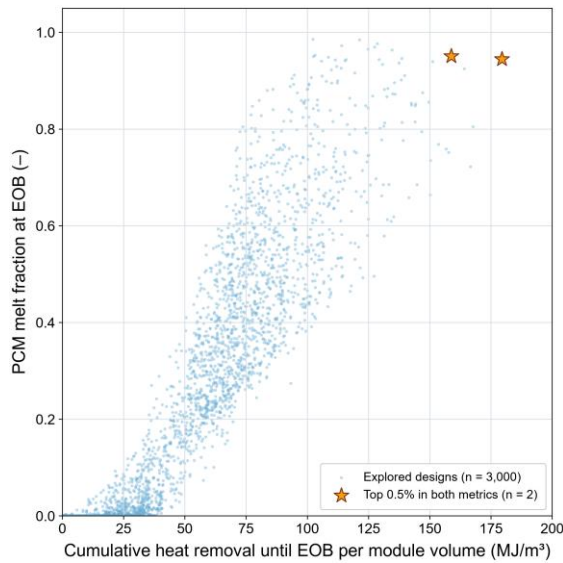


Figure 7. Performance metrics of 3,000 randomly sampled design options

Figure 7 shows the evaluation results of 3,000 randomly sampled designs in terms of two performance metrics. Two candidates were selected by screening the upper 0.5% for both performance metrics. The design parameters and the corresponding performance metrics are summarized in Table 2.

Two candidates provide preliminary insight into favorable design directions for the suggested passive condenser concept to reduce containment peak pressure. Both candidates employ relatively small diameter tubes with dense tube arrangements, which suggests that a greater heat transfer area is more favorable than retaining a larger PCM inventory. Both candidates also show that shorter tube length and a larger drainage area are favorable.

Candidate 2 has substantially higher fin volume fraction than Candidate 1, which could potentially be achieved using a dense fin configuration or a metal foam structure. The enhanced thermal conductivity enables a high PCM melt fraction despite a wider pitch. However, the PCM inventory is reduced due to the volume occupied by fins, and a lower cumulative heat removal is achieved with higher melt fraction. These observations are consistent with the qualitative description on the trade-off relationships in section 2.1.

Since Candidate 1 exhibits higher cumulative heat removal performance, it was selected as the representative optimized design and used in additional parametric analyses and system-level analyses. However, it should be noted that the selected design is not an actual global optimum, but a design with the highest performance identified among the evaluated random samples.

Table 2. High-performance design candidates

Parameter	Candidate 1	Candidate 2
Number of tubes	4,064	2,956
Tube inner diameter	3.023 mm	3.878 mm
Tube pitch	6.308 mm	7.407 mm
Tube length	10 cm	10 cm
Fin volume fraction	1.6%	15.2%
Drain flow area	0.0281 m ²	0.0214 m ²
Cumulative heat removal until EOB	179.52 MJ/m ³	158.78 MJ/m ³
PCM melt fraction at EOB	94.5%	95.0%

4. Numerical Analysis Results on the Selected Optimized Design

4.1. Effect of tube configuration

Parametric studies on the tube length, diameter, and pitch were conducted to evaluate the effect of the tube configuration on the performance metrics. First, the results from the tube length parametric studies are summarized in Figure 8.

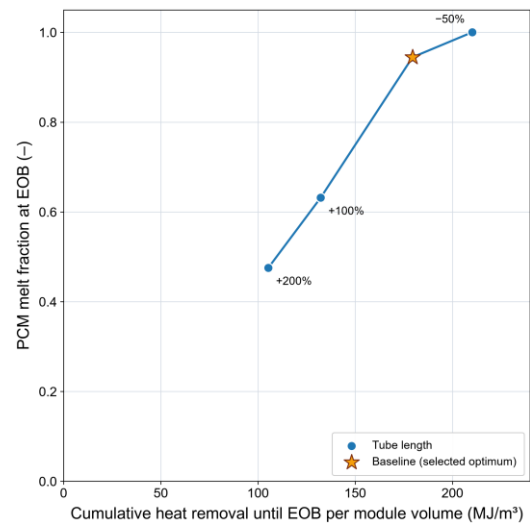


Figure 8. Parametric studies on tube length

The results show that the volumetric heat removal performance decreased as the tube length increased. This behavior can be attributed to the strongly nonuniform axial heat transfer inside the tubes. Figure 9 presents the temporal evolution of the axial heat removal rate distribution. As shown in the figure, heat removal occurs within a relatively localized region, and the region of active heat removal progressively shifts downwards. For the 10 cm tube, the active region reaches the lower part of the tube sufficiently early so that most of the PCM inventory contributes to heat absorption before EOB. As the tube length increases, the downstream PCM region is not effectively utilized within the blowdown period. This behavior can also be observed from the spatial distribution of the PCM melt fraction for the 10 cm and

30 cm tubes shown in Figures 10 and 11, respectively. Consequently, the increase in the prompt heat removal capacity obtained by extending the tubes was limited relative to the corresponding increase in the module volume. Therefore, the use of longer tubes can be unfavorable in terms of installation space utilization.

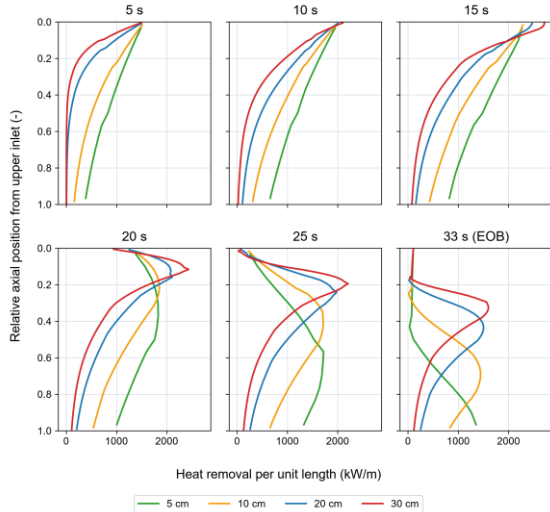


Figure 9. Axial distribution of heat removal rate for different tube lengths

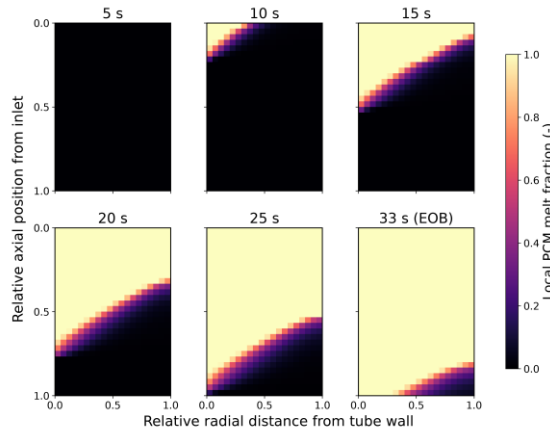


Figure 10. Distribution of the PCM melt fraction (10 cm tube case)

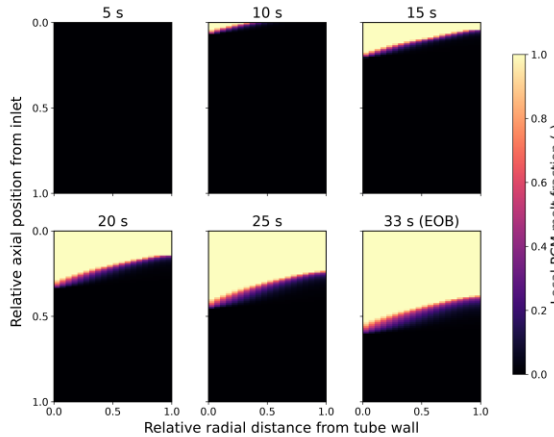


Figure 11. Distribution of the PCM melt fraction (30 cm tube case)

Figure 12 shows the sensitivity of the condenser performance to changes in the tube inner diameter and tube spacing. When the tube inner diameter was reduced by 30%, the number of tubes increased. However, the decrease in the diameter and the total flow area increased hydraulic resistance, thereby limiting the flow of the steam-air mixture and the condensate. Consequently, although the PCM inventory increased due to smaller tube diameter, it could not contribute effectively to heat absorption before EOB. Conversely, increasing the tube diameter reduced the hydraulic resistance but it also reduced the number of tubes and the total heat transfer area. Also, the PCM inventory was reduced because more volume was occupied by tubes. Therefore, the cumulative heat removal decreased while the PCM melt fraction approached unity.

The change of tube pitch has similar effects on the performance metrics. When the tube pitch increases, PCM inventory increases. However, the total number of tubes decreases, which leads to smaller flow area and smaller heat transfer area. Consequently, both the cumulative heat removal capacity and the PCM melt fraction decreased.

The tube pitch of the selected optimum design is close to the lower bound of $1.25D_o$ specified in Table 1. This indicates that a densely packed tube arrangement is favorable to the prompt heat removal capacity. As shown in Figure 12, a further reduction in the spacing between the tubes may provide additional performance improvement. However, its practical feasibility can be limited by other factors, such as structural integrity and manufacturability.

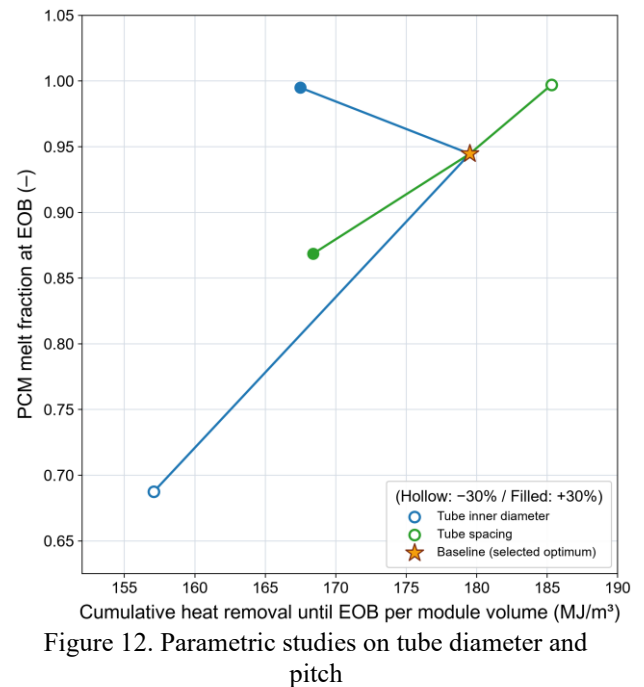


Figure 12. Parametric studies on tube diameter and pitch

4.2. Effect of drain flow area

The results from the parametric studies on the drain flow area are summarized in Figure 13. The drain flow area was identified as an influential design parameter directly affecting the performance of the passive condenser. Reducing the drain flow area resulted in clear decrease in the heat removal performance. However, once the drain flow area becomes sufficiently large, the performance becomes less sensitive to further increases in the drain area.

This behavior is attributed to the effect of the drain flow area on non-condensable gas discharge. A larger drain flow area facilitates the discharge of non-condensable gas through the lower outlet, thereby mitigating its accumulation inside the condenser tubes. Figure 14 shows the axial distributions of the non-condensable gas mass fraction for different drain flow areas. As the area decreases, the non-condensable gas mass fraction inside the tube remains higher throughout the transient. The resulting increase in the non-condensable gas concentration significantly degrades condensation heat transfer. As shown in Figure 15, the cases with a reduced drain flow area exhibited lower heat removal rate and thereby slower downward shift of the active heat removal region.

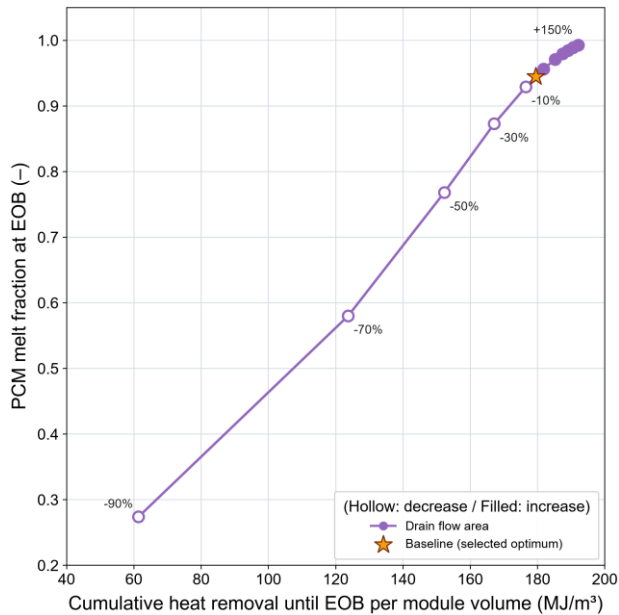


Figure 13. Parametric studies on drain flow area

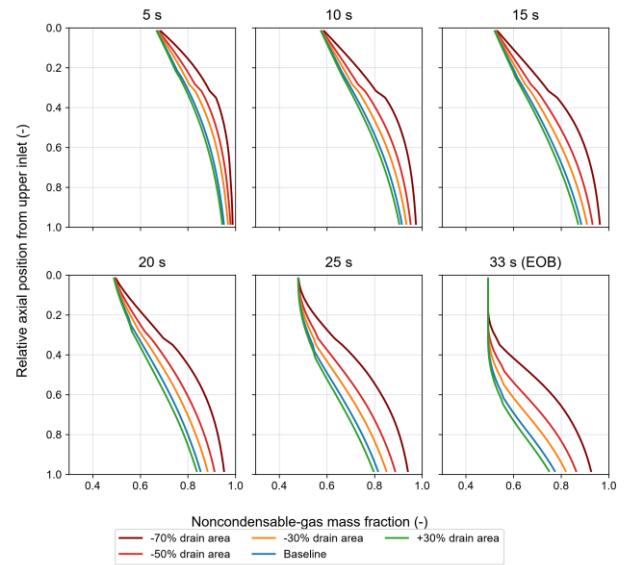


Figure 14. Effect of drain area on non-condensable gas concentration

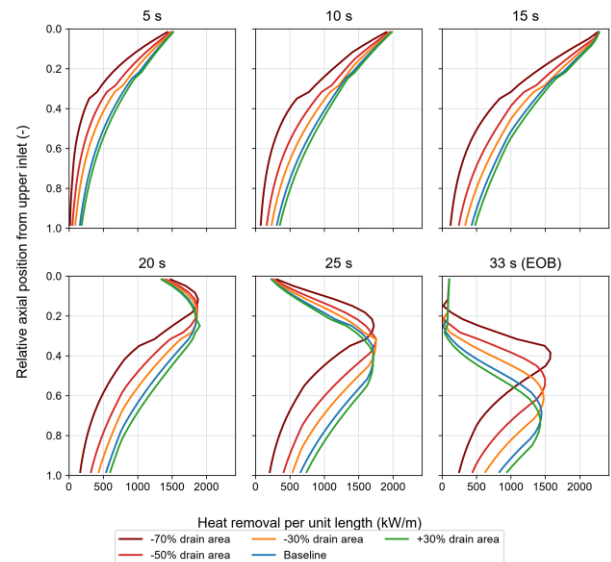


Figure 15. Effect of drain area on heat removal

4.3. System-level feasibility evaluation

To evaluate the system-level effect of the proposed PCM-based passive condenser, the MARS-KS condenser model and the CAP containment model were iteratively coupled to simulate the actual pressure peak mitigation effect during LOCA.

The results of the iteratively coupled MARS-CAP calculations considering the installation of 1,000-5,000 proposed condenser modules are presented in Figure 16, while the reduction in the containment peak pressure as a function of the total installed condenser volume is shown in Figure 17. The installation of 5,000 modules requires a total module volume of 85 m³, corresponding to approximately 0.1% of the containment free volume of APR1400. Under this condition, the containment peak

pressure was reduced by 11.49 kPa, which corresponds to 3.66% of the pressure increase during the blowdown phase.

As described in the previous section, the optimum design was selected so as to maximize the utilization of the installation space. Consequently, a measurable reduction in the containment peak pressure can be achieved while occupying a relatively small fraction of the containment free volume.

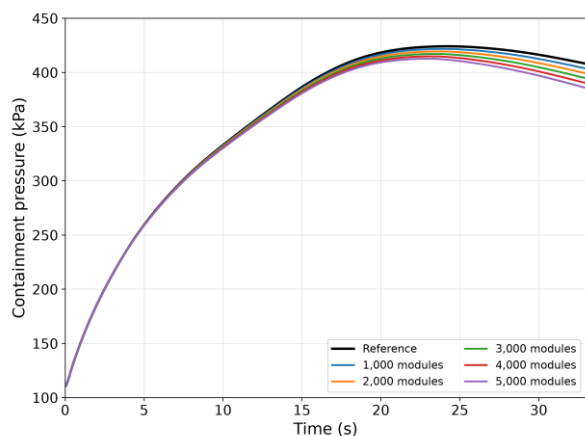


Figure 16. MARS-CAP analysis on passive condenser performance

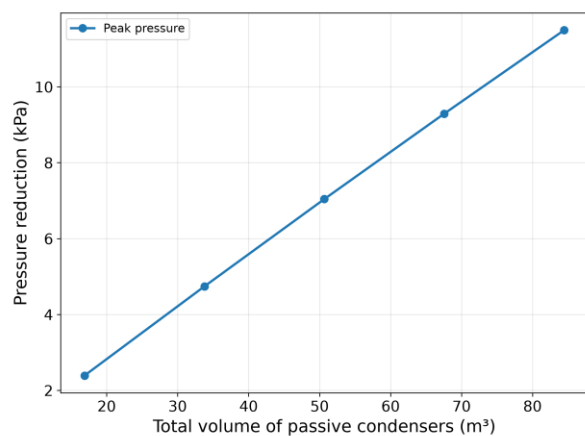


Figure 17. Peak pressure reduction

5. Conclusions and Future Work

This study evaluated the preliminary design and the feasibility of a PCM-based passive condenser for containment pressure peak reduction during the early blowdown phase of a LOCA in APR1400.

The preliminary design was optimized by 1D MARS-KS calculation on 3,000 randomly selected combinations of design parameters. In order to maximize the prompt heat removal performance under limited installation space, the optimization was based on two performance metrics: cumulative heat removal per volume during blowdown phase and PCM melt fraction at the end of the blowdown phase. Also, based on the selected optimum

design, parametric analyses of the design variables have been performed to identify the key parameters and the trade-off relationships among different variables.

Lastly, the system-level feasibility of the proposed PCM-based passive condenser has been evaluated by iteratively coupled MARS-CAP calculations. The calculation showed 3.66% reduction in the pressure increase during the early phase of LOCA by using approximately 0.1% of the containment free volume for the passive condenser installation. The results show the feasibility of achieving measurable containment pressure peak reduction while occupying a relatively small fraction of the containment free volume with a PCM-based passive condenser design.

Future work will focus on alternative geometries which can further maximize the prompt heat removal performance and minimize the installation space.

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