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Improved Design of PECS to reduce Flow Instability for EU-APR1400

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1. Introduction

The design of EU-APR1400, which is modified and improved from its original design of APR1400, has been developed to comply with European Utility Requirements (EUR) and respective nuclear design requirements of the European countries [1].

For EU-APR1400, PECS (Passive Ex-vessel corium retaining and Cooling System), so-called core catcher, was adopted to keep the integrity of basemat in containment by preventing MCCI (Molten Core Concrete Interaction) through retaining core debris and cooling corium outside the reactor vessel.

In this paper, the improved design of PECS is presented to increase coolability by reducing flow instability in the region of cooling channel.

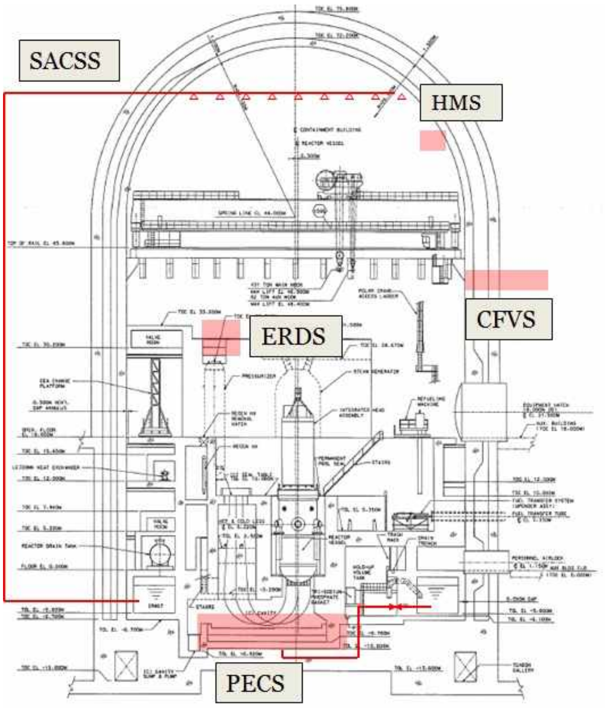

Fig.1 Diagram of Severe Accident Mitigation Systems in EU-APR1400

2. Outline for Flow Instability Analysis

2.1 PECS Cooling Process

For long term performance of the PECS cooling channel, the severe accident management sequence can be divided into two different phase based on time scale. First, the injection phase takes place during first few hours after severe accident occurs. Initially, the corium is released and it spreads out on PECS's body ablating the sacrificial material. It is flooded by injecting water from the IRWST (In-containment Refueling Water Storage Tank) so that its level rises continuously, passing the top of waterbox, the inclined channel and the vertical channel. Second, the recirculation phase involves a long-term steady-state period. The corium must be retained in PECS's body potentially for a long period of time. In this phase, water recirculates continuously through the downcomers and the coolant channel providing a stable cooling of the corium.

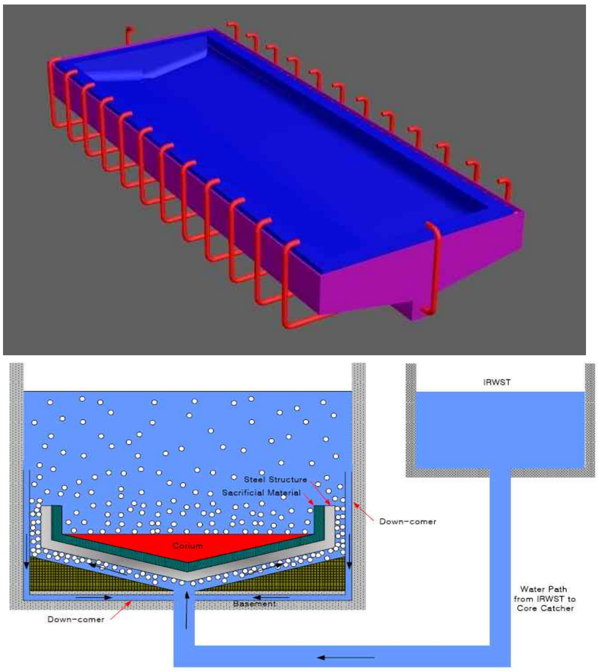

Fig.2 Diagram of PECS (above) and Schematic Diagram of PECS Cooling Process (below)

The design of the individual downcomer has been studied by employing a truncated domain called "Sector Model", which comprises a portion of the system containing only one downcomer.

2.2 Analysis Tool and Method

Flow instability analysis for PECS in EU-APR1400, STAR-CCM+ code [2] is used for the CFD (Computational Fluid Dynamics) simulation. For calculation method, EMP (Eulerian Multiphase Model) in place of HMP (Homogeneous Multiphase Model) is selected because it is judged that the characters and parameters are to be most suitable for the EMP calculation.

2.3 Existing design and Idealized design for PECS

The existing design to be used as a baseline design and idealized design are shown in Fig. 3 as a sector model to compare the degree of voids generated at downcomer in the region of cooling channel. The idealized configuration prevents vapor entrainment into the downcomer, maximizing the mixture density difference with the cooling channel and therefore maximizing the flow through the downcomer.

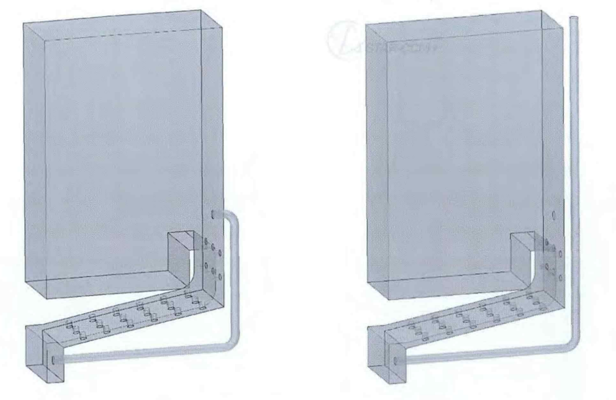

Fig.3 Baseline downcomer design (left side) and Idealized downcomer design (right side)

3. Flow Instability Analysis with Downcomer designs

Presented are several designs to reduce flow instability in PECS as follows. For each design, CFD simulation is carried out for parameters such as mass flow of liquid at downcomer outlet and gas holdup in downcomer as well as cooling channel.

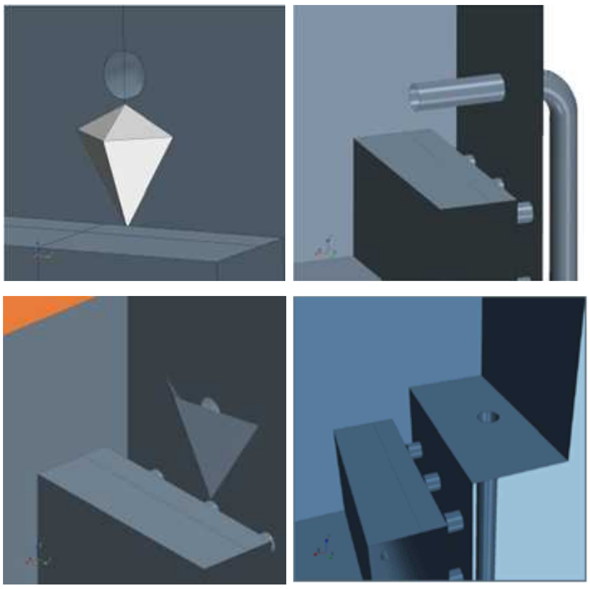

Fig.4 Suggested downcomer designs
Pyramid shaped wedge (left above),
Intruded downcomer (right above),
Pocket (left below) and Superstep (right below)

3.1 Pyramid shaped wedge

For pyramid shaped wedge, it is inserted below the downcomer inlet to divert vapor flow from the inlet.

The contour of vapor volume fraction for the pyramid shaped wedge at a plane section through the downcomer at 200 seconds is shown as below. The pyramid does not divert the vapor from the downcomer inlet as anticipated and vapor stratification is also seen in the downcomer.

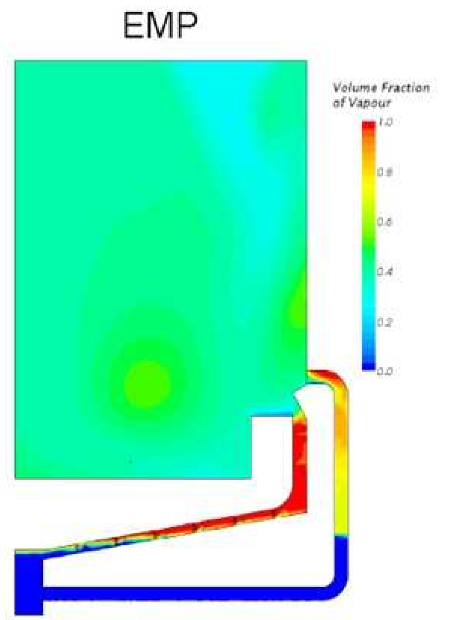

Fig.5 Contour of vapor volume fraction

As shown in the graphs of Fig. 6 below, the results of mass flow and gas holdup for pyramid shaped wedge in black are similar to the average values to those of the baseline downcomer design in red.

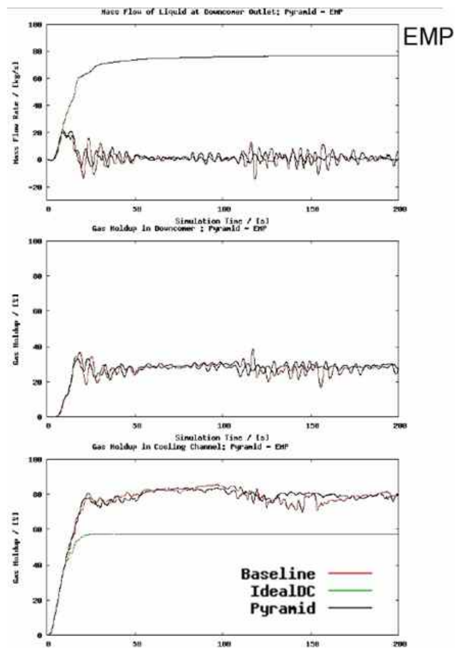

Fig.6 Mass flow at downcomer outlet (top),
Gas holdup in downcomer (middle),
Gas holdup in cooling channel (below)

3.2 Intruded Downcomer

For intruded downcomer, the inlet of downcomer is extended into the pool so that its opening is displaced from the vapor stream rising from the cooling channel.

The contour of vapor volume fraction for the intruded downcomer at a plane section through the downcomer at 200 seconds is shown as below. The vapor volume fraction in the downcomer is similar to that above the corium pool.

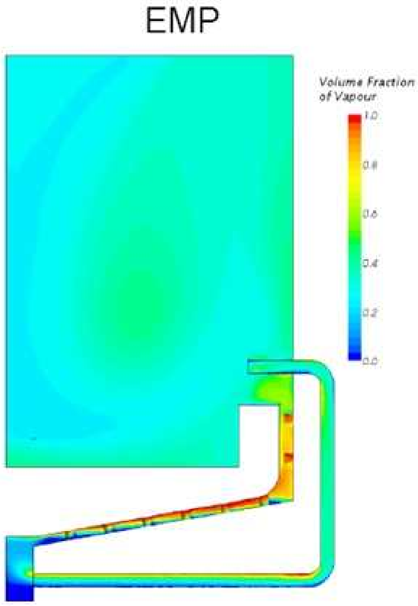

Fig.7 Contour of vapor volume fraction

As shown in the graphs of Fig. 8, the results of mass flow and gas holdup for the intruded downcomer in black show that higher mass flow rate results in reduced gas holdup in the cooling channel at the latter phase.

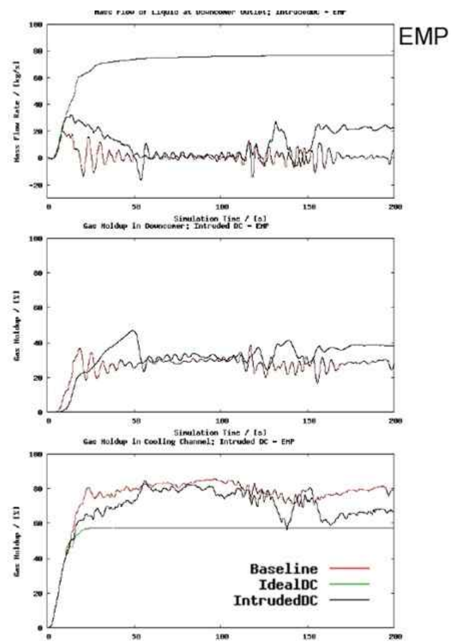

Fig.8 Mass flow at downcomer outlet (top),
Gas holdup in downcomer (middle),
Gas holdup in cooling channel (below)

3.3 Pocket

For pocket installed downcomer, a pocket covers over the downcomer inlet with a purpose to create a region around the downcomer inlet that is fully protected from vapor entrainment.

The contour of vapor volume fraction for the pocket installed downcomer at a plane section through the downcomer at 200 seconds is shown in Fig. 10. The pocket does not divert the vapor from the downcomer inlet and vapor stratification is also seen in the downcomer that these results are almost the same as those of pyramid shaped wedge. Additionally, a vortex is generated at the tip of pocket. This vortex penetrates into pocket, increasing the amount of entrained vapor.

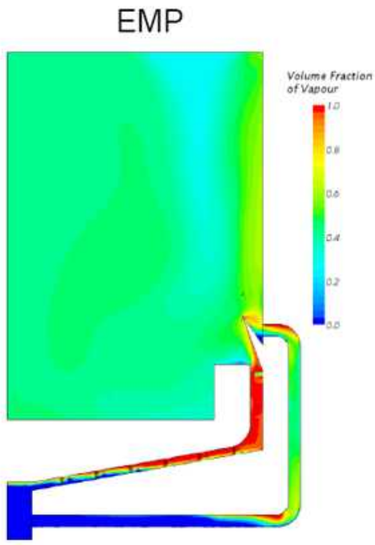

Fig.9 Contour of vapor volume fraction

As shown in Fig. 10, there is no effective difference in the performance between this design and baseline design.

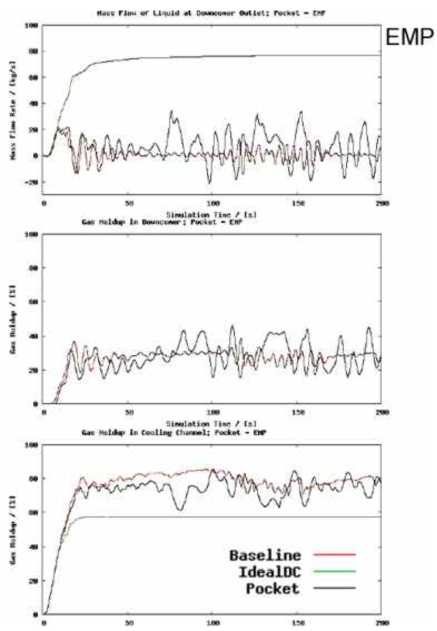

Fig.10 Mass flow at downcomer outlet (top),
Gas holdup in downcomer (middle),
Gas holdup in cooling channel (below)

3.4 Superstep

For superstep design, a horizontal step in the wall is created above the cooling channel exit and the horizontal inlet section of downcomer is removed. The downcomer inlet is not at the intersection between its vertical pipe and the new horizontal surface.

In Fig. 11 below, the contour of vapor volume fraction for the superstep downcomer at a plane section through the downcomer at 200 seconds shows that the prevention of vapor entrainment into downcomer results in a greater density difference between the downcomer and the cooling channel.

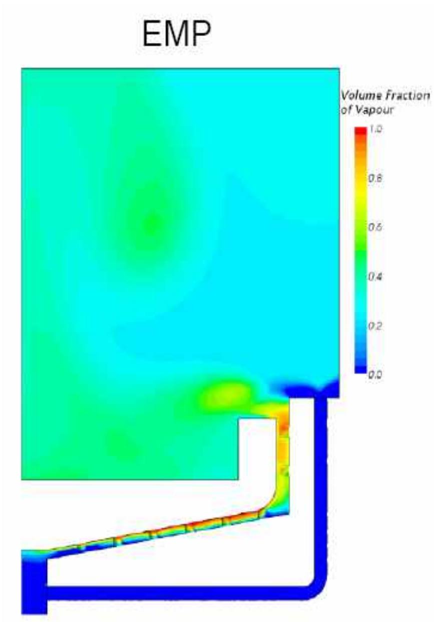

Fig.11 Contour of vapor volume fraction

As shown in the graphs of Fig. 12, the results of mass flow and gas holdup for the superstep downcomer in black show stable flow and significant improvement in performance that higher mass flow rate through the downcomer results in lower gas holdup in the cooling channel as well as the downcomer.

The superstep design avoids the entrainment of the rich vapor rising from the cooling channel. The reason for this is the liquid flow must follow a vertical downwards path to enter the downcomer. Since there is no spatial restriction, the liquid can follow this path at low velocity so that this allows the vapor to separate from the liquid flow due to buoyancy, resulting in the flow entering the downcomer with very low vapor ratio.

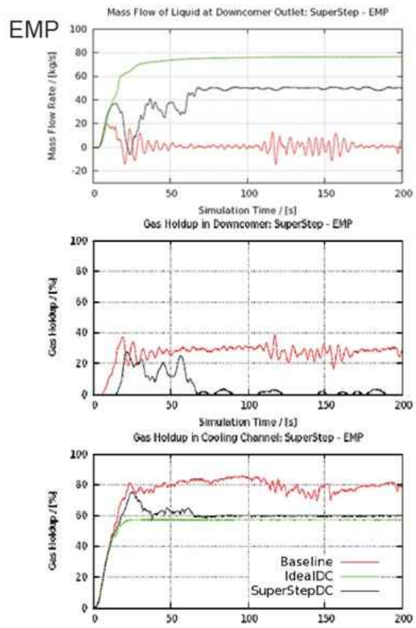

Fig.12 Mass flow at downcomer outlet (top),
Gas holdup in downcomer (middle),
Gas holdup in cooling channel (below)

4. Conclusions

In this paper, flow instability analysis was carried out using CFD code to find out the most improved design of PECS, which is to increase coolability by reducing bubble entrainment in the region of cooling channel. The reduction of bubble entrainment in the downcomer facilitates higher mass flow rates in the downcomer.

Among presented four designed for the downcomer of PECS, the superstep design shows the highest mass flow rate and the lowest gas holdup in the downcomer as well as in the cooling channel. Compared with the existing design, the elimination of the horizontal part and the addition of an extra space above the vertical entrance to the downcomer seem to help the separation of the vapor.

In the near future, the coolibility experiment is supposed to be performed for the PECS to which superstep design is applied.

Acknowledgement

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[1] D. H. Hwang, J. H. Na, Y. S. Kim, Criticality Analysis of Corium and Cooling Water Mixture for EU-APR1400, 5th ISFMFE, Oct. 24-27, 2012.

[2] CD-adapco., STAR-CCM+ v8.04 Documentation, 2013.