HEAT TRANSFER ANALYSIS OF HORIZONTAL U-SHAPED HEAT EXCHANGER SUBMERGED IN A POOL USING MARS CODE

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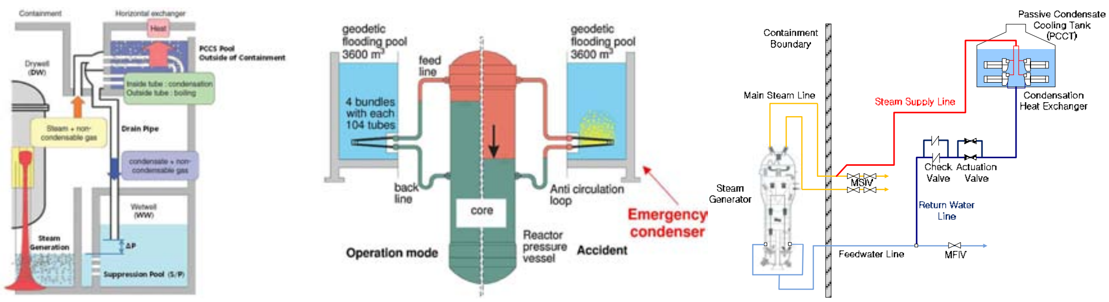
ABSTRACT

A horizontal U-shaped heat exchanger submerged in a pool is under development as a key equipment of a passive safety system. For the successful design of the heat exchanger and the safety analysis of the nuclear power plant, the reliable prediction of the heat transfer performance of the heat exchanger is important. At present, the design and the safety analysis of the passive safety systems are performed mainly using the best-estimate thermal-hydraulic analysis codes such as RELAP5 and MARS. However, those codes do not have the suitable models for both the condensation heat transfer in the horizontal tube and the natural convective and nucleate boiling heat transfer on the horizontal tube, both of which ultimately determining the heat transfer performance of the heat exchanger. This study developed the heat transfer model for the horizontal U-shaped heat exchanger submerged in a pool by improving the horizontal in-tube condensation model and developing the out-tube natural convective and nucleate boiling model. From the validation results, the proposed model provided the improved prediction of heat exchanger performance (condensation, natural convective and nucleate boiling, and heat removal rate of the heat exchanger) compared to the default model in MARS.

KEYWORDS
passive safety system, MARS, condensation, boiling, PAFS

1. INTRODUCTION

There have been many efforts to develop the passive safety systems in order to simplify a nuclear power plant (NPP) design and improve reliability of the performance of essential safety functions, and eliminate the costs of the installation, maintenance, and operation of active systems. Especially, recent research efforts have focused on the development of passive safety systems with a horizontal U-shaped heat exchanger (HX) submerged in a pool because it has some advantages over the vertical HX from the economical and structural standpoints. As notable examples, a passive containment cooling system (PCCS), an emergency condenser system (ECS) and a passive auxiliary feed-water system (PAFS) have been adopted in the advanced NPPs (see figure 1).



(a) PCCS [1] (b) ECS [2] (c) PAFS [3]

Figure 1. Passive Safety Systems.

Under an accident condition of a NPP, these passive safety systems mitigate decay heat by cooling the nuclear system effectively via the heat transfer through the steam condensation inside the U-shaped tube. By the transfer of the decay heat to the cold water in the pool passively, the integrity of a NPP can be ensured. Therefore, the accurate prediction of the heat transfer performance of the HX has been an important issue for the reliable design of the passive safety system and the safety analysis of a NPP.

At present, the design and the safety analysis of the passive safety systems are performed mainly using the best-estimate thermal-hydraulic analysis codes (BE codes) such as RELAP5 and MARS. However, those codes under-predict the heat removal performance of the HX significantly because the present BE codes do not have the suitable models for both the condensation heat transfer in the horizontal tube and the natural convective and nucleate boiling heat transfer on the horizontal tube, both of which ultimately determining the heat transfer performance of the HX (see figure 2). Therefore, for the accurate prediction of the heat transfer performance of the HX with the BE codes, it is required to develop and secure suitable models for both the condensation heat transfer in the horizontal tube and the natural convective and nucleate boiling heat transfer on the horizontal tubes.

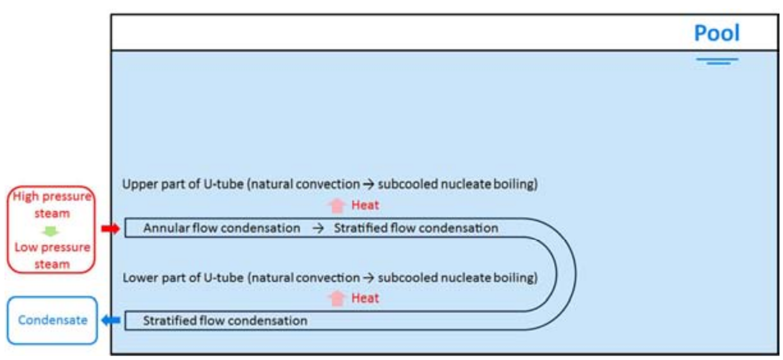


Figure 2. Main Heat Transfer Mode in Horizontal U-Shaped HX Submerged in a Pool.

The aim of this study is to develop the heat transfer model suitable to BE codes for the PAFS. To obtain a reliable prediction of the condensation heat transfer in horizontal tubes, the natural convective and nucleate boiling heat transfer on horizontal tubes, and the heat removal performance of the HX in the PAFS, this study performed the followings: 1) improvement of horizontal in-tube condensation heat transfer model, 2) development of natural convective and nucleate boiling heat transfer model for horizontal U-shaped HX submerged in a pool, 3) validation of proposed HX heat transfer model.

2. HORIZONTAL IN-TUBE CONDENSATION MODEL

In a horizontal condenser tube, the main flow regimes are the annular and stratified flows. As part of this research, Jeon et al. [4, 5] reviewed nineteen annular flow and eleven stratified flow condensation models and assessed the prediction capability of each model with experimental data obtained from Purdue-PCCS, JAEA-PCCS [1], PASCAL [3], and NOKO [6] experiments (see Table I) for the passive safety systems using MARS code. They proposed that the condensation models by Dobson and Chato (1998) for annular flow and Cavallini et al. (2006) for the stratified flow were the most applicable models to the HX of the passive safety system.

Table I. Passive safety system-related experiments

	Steady-state experiments				Transient experiment
	Purdue-PCCS (Wu, 2005)	JAEA-PCCS (Kondo, 2006)	PASCAL (Kang et al., 2012)	NOKO (Schaffrath, 1998)	ATLAS-PAFS (Kang et al., 2012)
No. of tube	1	1	1	4	3
Average tube length [m]	3	about 9	8.4	9.8	4.77
Tube ID [mm]	27.5	29	44.8	38.7	30.8
Tube thickness [mm]	2.1	1.4	3	2.9	3
Inclination of straight part of tube	0°	0°	3°	1.6° (upper) / 3.2° (lower)	3°
In-tube flow rate [kg/s]	0.006-0.023	about 0.046	0.15-0.43	0.08-0.52 (per tube)	about 0.1-0.4
In-tube pressure [bar]	1, 2, 4	7	about 13, 32, 67	about 10, 30, 70	about 20-80
Main flow regime in tube	Wavy/stratified	Annular/stratified flow			
Secondary-side cooling	Forced convection in cooling jacket		Natural convective and nucleate boiling in pool		

For the prediction of horizontal in-tube condensation heat transfer, the original MARS code employs Shah (1979) and Chato (1962) models for the annular and stratified flow regimes, respectively. MARS code determines the condensation HTC from the maximum of the values predicted by Shah (1979) and Chato (1962) models because the use of the maximum value ensures a smooth transition between models. To improve the horizontal in-tube condensation model, this study replaced the models by Shah (1979) and Chato (1962) with the annular flow condensation model by Dobson and Chato (1998) and the stratified flow condensation model by Cavallini et al. (2006), respectively. The validation results of the improved condensation model are described later in Sec. 4.

3. NATURAL CONVECTIVE AND NUCLEATE BOILING MODEL

3.1. Nucleate Boiling Model

As part of this research, Jeon et al. [7] reported the first systematic heat transfer analysis with the BE code for the nucleate boiling heat transfer on the horizontal U-shaped HX submerged in a pool of water with the multi-dimensional flow. To obtain a reliable prediction of the nucleate boiling heat transfer on the horizontal parts of the U-shaped tubes, following analyses were performed, namely: (1) a comprehensive review of the characteristics of the previous nucleate boiling correlations ranging from seven pool boiling correlations to eight forced convective boiling correlations on the horizontal tubes; (2) assessments of the prediction capability of the previous nucleate boiling correlations; (3) the investigation of the main heat transfer mechanisms on the horizontal U-shaped HX submerged in a pool; (4) the development of the nucleate boiling model; and (5) the validation of the proposed boiling model against the experimental data of PASCAL and ATLAS-PAFS.

According to the research by Jeon et al. [7], as a default model in MARS, the nucleate boiling model by Chen (1966) is not physically valid to be applied to the prediction of the nucleate boiling heat transfer on the horizontal tubes. Furthermore, there was no single correlation which could be universally applied to the prediction of the local HTCs on both upper and lower parts of the U-tube (see figure 2).

From the analysis of heat transfer mechanisms, Jeon et al. [7] proposed the prediction approaches to predict the nucleate boiling heat transfer on the U-shaped HX submerged in a pool: 1) Since the subcooling degree and the local flow velocity near the HX affects the local HTCs, for the reliable prediction of the local variables, it is recommended that the pool is modeled by using the multi-dimensional component in BE code such as MARS-MULTID. 2) In the upper and lower parts of U-tube, different heat transfer correlations should be applied because the phenomenological difference exists in the heat transfer mechanism on the upper and lower parts of the U-tube. 3) For the lower part of U-tube, it is reasonable to predict the heat transfer using the nucleate pool boiling correlation which considers the effect of subcooling since the lower part of U-tube experiences subcooled nucleate boiling. 4) For the upper part of U-tube, the base heat transfer mode is the subcooled nucleate pool boiling, but it is reasonable to predict the heat transfer using the forced convective boiling correlation because the effect of natural convection velocity from the lower part on the upper part of the U-tube should be considered. Moreover, in the correlation, it is required to consider the effect of void fraction around the upper part of U-tube because the effect of flow velocity induced from the lower part on the upper part increases due to the increase of turbulence and the liquid agitation by the bubble around the upper part.

Based on the heat transfer mechanism, Jeon et al. [7] developed a new boiling model. The proposed boiling model showed good agreement with the experimental data with a mean deviation of 8.1% by applying the new subcooled pool boiling correlation and the new forced convective boiling correlation to the lower and upper parts of the U-tube, respectively. Therefore, authors determined the nucleate boiling model by Jeon et al. [7] as the most applicable model to the HX of the passive safety system.

3.2. Natural Convection Model

The nucleate boiling model proposed by Jeon et al. [7] was validated at low subcooling conditions (up to around 30 K); however, when the passive safety system starts to operate, the water temperature in the HX pool is low at the room temperature, ~300 K, and the subcooling is significantly high (about 90 K for the PAFS). In order to complete the modeling of the heat transfer outside the horizontal HX tube, it is required to secure the heat transfer model to be applicable to a full time operation of the passive safety system including the high subcooling conditions. Therefore, this study assessed the prediction capability of the nucleate boiling models and the MARS default natural convection model using the HTC data at high subcooling conditions in the PASCAL experiment and developed the natural convection model on the horizontal U-shaped HX submerged in a pool suitable for high subcooling conditions.

3.2.1. Analysis code

In order to predict the HTCs outside the HX tube, the MARS-KS1.2 was used as a BE code. The code has been developed at Korea Atomic Energy Research Institute (KAERI) with the objective of producing a state-of-art realistic TH systems analysis code with multi-dimensional analysis capability. The main structures of MARS are based on the consolidated version of RELAP5/MOD3.2 and COBRA-TF codes. In addition to them, for a 3D simulation, MARS incorporates a multi-dimensional component named MULTID. MARS adopts a non-homogeneous, non-equilibrium two-fluid model for a two-phase flow and it has been used in many key areas of the nuclear industry, including PWR safety analysis and advanced reactor design. For the prediction of natural convection and nucleate boiling heat transfer, MARS employs the models by Churchill and Chu (1975) and Chen (1966), respectively [8].

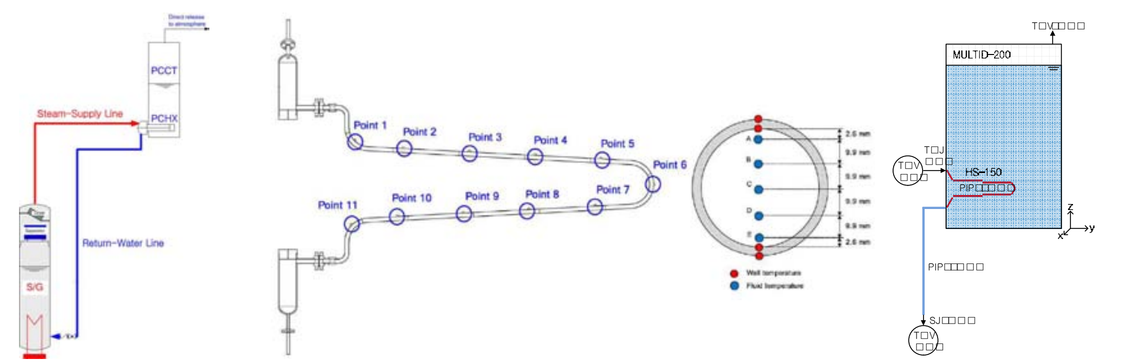
3.2.2. Description of PASCAL

To validate the cooling and operational performance of the PAFS and to investigate the local TH behavior in the PCHX (Passive Condensation Heat Exchanger) and the characteristics of the natural convection with pool boiling in the PCCT (Passive Condensate Cooling Tank), KAERI performed the separate effect test using the PASCAL (PAFS Condensing Heat Removal Assessment Loop). Figure 3(a) shows the schematic diagram of the PASCAL [9]. The main components of the PASCAL are a SG, steam-supply line, single U-tube called as PCHX, return-water line, and PCCT. The steam injected into the PCHX is condensed by the heat exchange with the cold water in the PCCT.

Geometrical data of the test section is as follows (see Table I). The PCHX is 8.4 m long tube with the inner diameter of 44.8 mm and the wall thickness of 3 mm. The U-tube is composed of two 3.22 m straight parts and a U-bend whose radius is 0.2667 m. The inclination is 3.0° in both upper and lower straight parts. The PCCT is the main heat sink of the SG. The dimensions of the PCCT are: length 6.7 m, width 0.112 m, and height ~11.5 m.

In the experiment, the tube inner/outer wall temperatures were measured at 11 different axial locations along the tube length and the fluid temperature profile inside the tube was obtained in a radial direction (see figure 3(b)). In addition, the local water temperatures were measured at 133 positions in the PCCT.

Three quasi-steady state cases were performed with three given SG thermal power conditions, 300 kW, 540 kW, and 750 kW. The PASCAL experiment provides the quasi-steady state data with the slow decrease of PCCT water level. Furthermore, it provides the detailed local heat transfer data at the high subcoling conditions of the PCCT. Therefore, it can be used to investigate the prediction capability of the nucleate boiling model and the natural convection model. For the heat transfer analysis on the horizontal tubes, this study used the experimental HTCs in 8 measured positions (points 2 to 5 and 7 to 10), which correspond to the nearly horizontal part of the condenser tube (see figure 3(b)).



(a) PASCAL (b) Measurement of wall and fluid temperature (c) MARS nodalization

Figure 3. PASCAL Facility and MARS Nodalization.

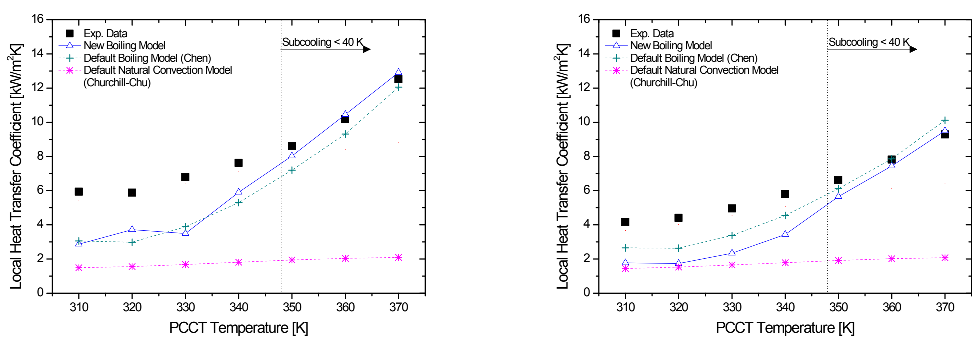
3.2.3. MARS modeling

Figure 3(c) shows the MARS nodalization for the simulation of the PASCAL experiment. The time-dependent volume, TDV-100, was used to provide the inlet boundary conditions for the saturated steam. The inlet flow rate of the steam was controlled by the time-dependent junction, TDJ-125. The pipe component, PIPE-150, was used to model the condenser tube, PCHX. The time-dependent volumes, TDV-190, was used to provide the boundary conditions for the pressure outlet. The condensate water is drained into the TDV-190 through the PIPE-180. The heat structure, HS-150, was used to calculate the heat transferred from the steam to the cold water in the PCCT hrough the condenser tube wall. The PCCT was modeled using the multi-dimensional component, MULTID-200, to effectively simulate the multi-dimensional natural convection flow and heat transfer phenomena in the PCCT. The number of cell is 1, 16 and 29 for x, y and z-directions, respectively. A time-dependent volume, TDV-210, was used to provide the pressure boundary condition where the steam produced in the PCCT flows out.

3.2.4. Assessment

The heat transfer analysis on the horizontal U-shaped HX submerged in a pool was performed using the MARS implemented with the improved condensation heat transfer model. In order to investigate the applicability of previous heat transfer models to the high subcooling conditions, authors used the nucleate boiling models by Chen (1966) and Jeon et al. [7], and the MARS default natural convection model by Churchill and Chu (1975) for a horizontal cylinder. Simulations of PASCAL experiment were performed under various PCCT water temperature conditions ranging from 310 to 370 K. Then, the comparison between experimental data and MARS predictions by each model was performed.

Figures 4(a) and 4(b) show the comparison between the experimental data and MARS calculation results for local HTCs at positions 3 and 7 (see figure 3(b)) under the SS-540-P1 (540 kW of the SG thermal power condition), respectively. The nucleate boiling models by Chen (1966) and Jeon et al. (2015) similarly-predicted the HTCs for the low subcooling conditions (ΔT_{sub} < ~40K), but significantly under-estimated the data for the high subcooling conditions (ΔT_{sub} > ~40K). Meanwhile, the natural convection model by Churchill and Chu (1975) considerably under-predicted the data for all test conditions. Considering the high heat flux from the HX tube surface, it was originally expected that the nucleate boiling model could be applicable to the high subcooling conditions. However, the nucleate boiling models were not valid to be applied to the high subcooling conditions. Furthermore, the application of the well-known natural convection model by Churchill and Chu (1975) to the operating conditions of the PAFS was also inadequate.



(a) Upper part of U-tube (b) Lower part of U-tube

Figure 4. Local HTCs on U-Tube (PASCAL) - Assessment.

To investigate the heat transfer regime, authors analyzed the PCCT water and PCHX outer wall temperatures in the PASCAL experiment and found that the PCHX wall temperature is below the saturation temperature in the initial phase of the HX operation (ΔT_{sub} > ~40K). This means that the heat transfer regime is governed by the natural convection in the high subcooling region. Therefore, it is obvious that a better heat transfer analysis with MARS requires a new natural convection heat transfer model to be applicable to the high subcooling conditions of the HX pool.

3.2.5. Development of natural convection model

According to Jeon et al. [7], different heat transfer correlations should be applied in the upper and lower parts of U-tube because the phenomenological difference exists in the heat transfer mechanism on the upper and lower parts of the U-tube. Therefore, this study developed the natural convection model by separating the upper and lower parts of the U-tube. Authors developed Morgan (1975)-type correlations for each horizontal part of U-tube using the PASCAL data for PCCT water temperature conditions of the high subcooling (310 to 350K) as shown in figure 5. All experimental HTCs on both upper and lower parts of U-shaped tubes were correlated satisfactorily by the developed natural convection model with a mean deviation of 12.9%.

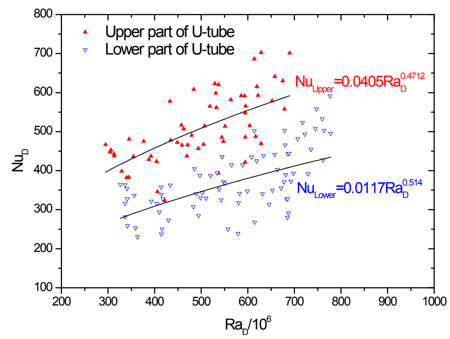
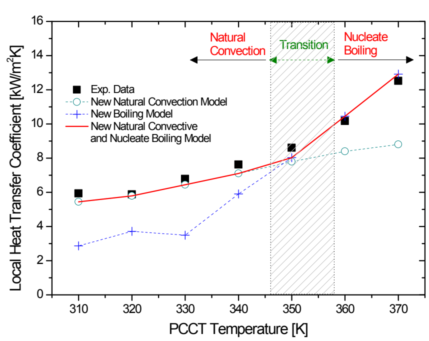


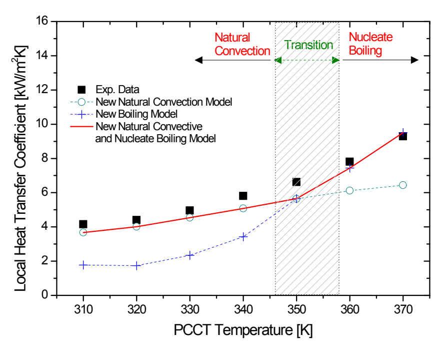
Figure 5. New Natural Convection Correlations.

3.3. Development of Natural Convective and Nucleate Boiling Model

Figure 6 shows the comparison between the experimental data and MARS predictions for local HTCs. The proposed natural convection model similarly-predicted HTCs for high subcooling conditions ($\Delta T_{sub} >$ ~40K), but significantly under-estimated the data for low subcooling ($\Delta T_{sub} <$ ~40K). On the other hand, the nucleate boiling models by Jeon et al. [7] similarly-predicted HTCs for low subcooling, but under-estimated the data for high subcooling. To combine the natural convection model and the nucleate boiling model exquisitely, authors determined HTCs from the maximum of the values predicted by the proposed natural convection model and nucleate boiling model by Jeon et al. [7]. As a result, HTCs calculated by the proposed natural convective nucleate boiling model shows good agreement with the data.



(a) Upper part of U-tube



(b) Lower part of U-tube

Figure 6. Local HTCs on U-Tube (PASCAL) – New Model.

4. VALIDATION OF NEW HEAT TRANSFER MODEL FOR HORIZONTAL U-SHAPED HX SUBMERGED IN A POOL

This study developed the heat transfer model for the horizontal U-shaped HX submerged in the pool by combining the horizontal in-tube condensation model and the out-tube natural convective and nucleate boiling model. This heat transfer model is implemented to the MARS code. This modified version of MARS is renamed as MARS/PAFS. This section describes the validation results of the MARS/PAFS against three passive safety system-related experimental data of PASCAL [9, 10], ATLAS-PAFS [10, 11], and NOKO [6].

4.1. Simulation Results of PASCAL Experiment

For the PASCAL experiment, the validation of MARS/PAFS was performed through three items: (a) HX heat removal performance, (b) local HTCs, and (c) quasi-steady state system pressure. For the validation of each item, two nodalization schemes were used. In approach 1 (see figure 3(c)), the SG was not modeled to investigate the HX performance and the local HTCs. The inlet and outlet of the PCHX is modeled as boundary conditions to set the same conditions with the experiment. In approach 2 (see figure 8(a)), all systems with SG were modeled to investigate the quasi-steady state SG pressure.

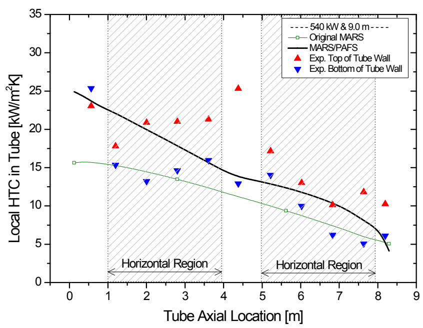
Table II shows the comparison between the experimental data and MARS calculation results for the HX heat removal rate under various test conditions. While the original MARS generally under-predicted the HX heat removal rate with a mean deviation of 10.9%, the MARS/PAFS slightly under-estimated the experimental data with a mean deviation of 1.4%. Compared to the default model in the original MARS, the proposed HX heat transfer model provided the improved prediction of the heat removal performance.

Table II. Test conditions and HX heat removal performance of PASCAL experiment

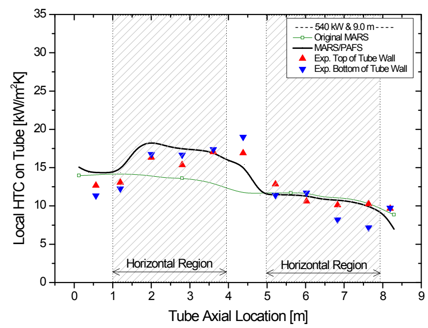
No.	Test conditions			Results				
	Tube inlet P [bar]	Tube inlet flow [kg/s]	PCCT Level [m]	Experiment Q [kW]	Original MARS Q [kW]	Original MARS Deviation [%]	MARS/PAFS Q [kW]	MARS/PAFS Deviation [%]
1	10.29	0.1455	4	292.9	249.8	-14.7	290.2	-0.9
2	11.57	0.1460	6	291.9	254.7	-12.8	292.5	0.2
3	13.29	0.1473	9	288.4	257.6	-10.7	292.1	1.3
4	26.20	0.2832	4	526.9	463.1	-12.1	516.3	-2.0
5	27.99	0.2885	6	523.2	467.4	-10.7	519.9	-0.6
6	31.92	0.2947	9	526.6	477.7	-9.3	524.1	-0.5
7	58.51	0.4136	4	730.4	654.3	-10.4	709.2	-2.9
8	62.37	0.4218	6	725.8	659.3	-9.2	711.0	-2.0
9	67.09	0.4305	9	727.1	664.3	-8.6	711.6	-2.1
Mean deviation [%]					-	10.9	-	1.4

Figure 7(a) shows the comparison between the experimental data and MARS calculation results for local HTCs of the horizontal in-tube condensation along the tube axial length under the SS-540-P1 test as a representative condition. While the original MARS code, based on the combination of condensation models by Shah (1979) and Chato (1962), generally under-predicted the local HTCs, the predictions by MARS/PAFS, based on the combination of condensation models by Dobson and Chato (1998) and Cavallini et al. (2006), were well located between experimental top and bottom HTCs.

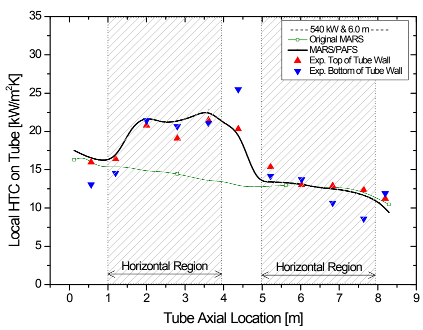
Figures 7(b) to 7(d) show the comparison between the experimental data and MARS calculation results for local HTCs of the nucleate boiling outside the HX tube according to the decrease of PCCT water level under the SS-540-P1 test condition. While the original MARS code, based on the nucleate boiling model by Chen (1966), generally under-predicted the local HTCs on the upper part of U-tube, the predictions by MARS/PAFS, based on the nucleate boiling model by Jeon et al. [7], show good agreement with the experimental data. The MARS/PAFS well traced the increase of local HTCs according to the decrease of the PCCT water level.



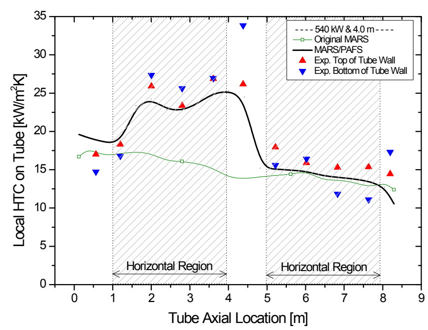
(a) HTCs in tube – condensation



(b) HTCs on tube – boiling (PCCT level: 9 m)



(c) HTCs on tube – boiling (PCCT level: 6 m)



(d) HTCs on tube – boiling (PCCT level: 4 m)

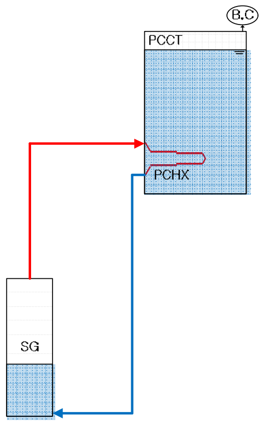
Figure 7. Local HTCs (PASCAL).

Figure 8(b) shows the comparison between the experimental data and MARS predictions the SG pressure at the quasi-steady state condition, according to a variation of the SG thermal power. The original MARS generally over-predicted the system pressure. The pressure difference between the data and predictions increased with the SG thermal power. On the other hand, the MARS/PAFS well traced the increase of the system pressure with the SG power. It is revealed that the proposed HX heat transfer model can provide the improved prediction of the heat transfer performance compared to the default model in MARS.

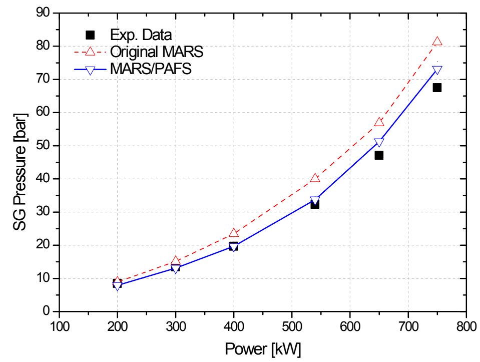
4.2. ATLAS-PAFS Experiment

4.2.1. Description of ATLAS-PAFS

To investigate the TH behavior in the primary and secondary systems of the APR+ during a transient when PAFS is actuated, KAERI performed the integral effect test using the ATLAS (Advanced Thermal-hydraulic test Loop for Accident Simulation)-PAFS facility [10].



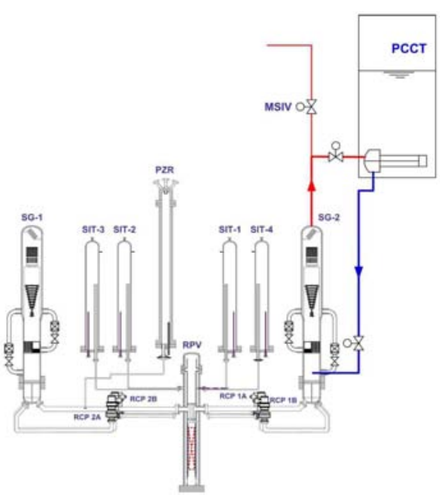
(a) MARS modeling of PASCAL



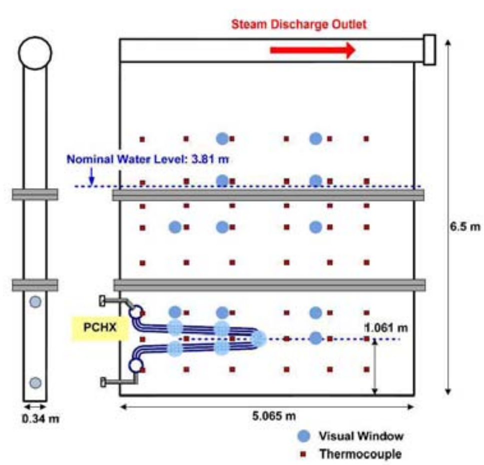
(b) Steady-state SG pressure of PASCAL

Figure 8. MARS Modeling and Result of PASCAL.

Figure 9(a) shows a schematic diagram of the ATLAS-PAFS facility. The ATLAS is a scaled-down facility of the APR+. The PAFS was connected to the SG-2 of ATLAS. Using this facility, the anticipated accident scenarios such as FLB (feedwater line break), MSLB (main steam line break), and SGTR (steam generator tube rupture) were simulated. Figure 9(b) shows a schematic diagram of the PCHX and the PCCT of the ATLAS-PAFS facility. Contrary to the use of a single tube in the PASCAL test, the PCHX in the ATLAS-PAFS has three tubes whose dimension was scaled-down to consider the scaling methodology applied to the ATLAS design. Geometrical data of the test section is as follows (see Table I). The PCHX is composed of three U-tubes. The average tube length is 4.77 m, the inner diameter is 30.8 mm, and the wall thickness is 3 mm. The U-tube is composed of two 1.806 m straight parts and the inclination is 3.0° in both upper and lower straight parts. The PCCT was designed as a rectangular pool whose dimensions are: length 5.065 m, width 0.34 m, and height 6.5 m. The ATLAS-PAFS data can be used to validate the prediction capability of MARS/PAFS for the transient-state. Since the FLB has been pointed out as the most important accident in evaluating the cooling capability of the PAFS among FLB, MSLB, and SGTR (Song et al., 2012), this study simulated the FLB accident scenario.



(a) ATLAS-PAFS facility



(b) PCHX and PCCT

Figure 9. Schematic Diagram of ATLAS-PAFS (KAERI, 2012).

4.2.2. MARS modeling

Figure 10 shows the MARS nodalization scheme for the simulation of the ATLAS-PAFS experiment. The primary- and secondary-sides of the ATLAS facility were modeled using one-dimensional volumes and junctions [11]. The break nozzle was placed on the SG-1. The PAFS was modeled similarly with the PASCAL nodalization (see figure 3(c)). However, three HX tubes were modeled as one pipe component (PIPE-200) and one heat structure (HS-200). The PCCT was modeled using the MULTID-200 where the number of cell is 1, 12 and 27 for x, y and z-directions, respectively. The initial and boundary conditions for the PAFS-FLB-EC-01 test (see Table 3 in the paper [11]) in the ATLAS-PAFS facility were equivalently simulated in this MARS simulation.

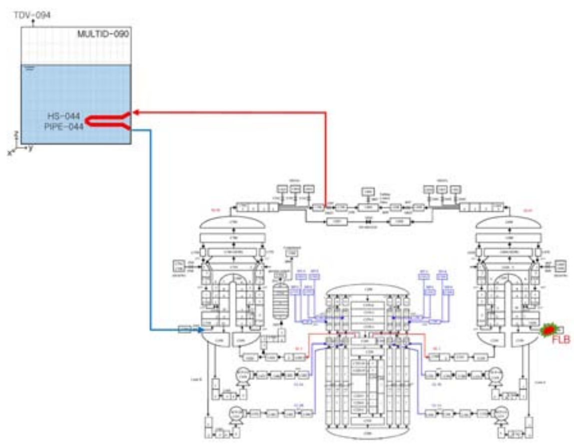
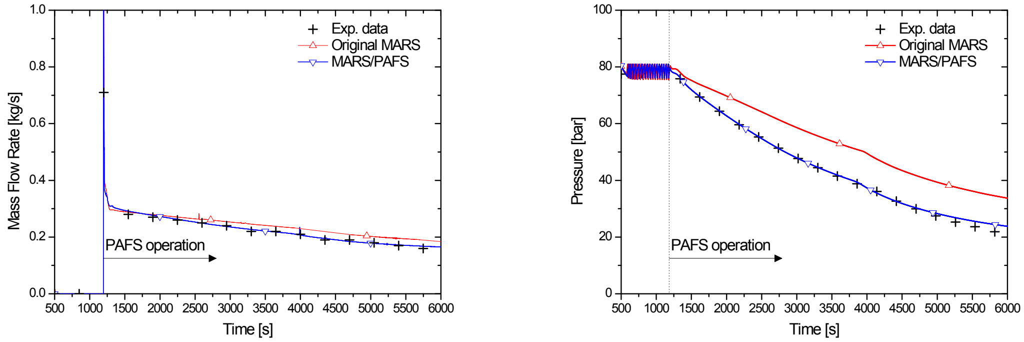


Figure 10. MARS Nodalization of ATLAS-PAFS).

4.2.3. Simulation results

According to Bae et al. [11], MARS code has a sufficient capability to quantitatively predict the FLB transient with the actuation of the PAFS; however, the authors mentioned that there was a difference between the data and the predictions for the mass flow rate because of the deficiency in predicting the heat transfer characteristics of the PCHX. Therefore, this study simulated the FLB accident focusing on the prediction capability of MARS/PAFS for the HX heat removal performance after the PAFS actuation.

Figure 11(a) shows the natural convection flow rate at the return water line of the PAFS. To focus on the heat removal performance of PAFS, this study slightly adjusted the PAFS actuation time to that of the experiment in the graph. As time passed, the natural convection flow rate gradually decreased due to the SG secondary side cooling by the PAFS. The original MARS generally over-predicted the natural convection flow rate because the SG cooling was progressed slowly compared to the experiment; however, the MARS/PAFS well estimated the data during the whole time of FLB accident. Figure 11(b) shows the comparison between the experimental data and MARS predictions for the SG secondary-side pressure. Initially, an oscillating behavior of the SG pressure is caused by the opening and closing of the main steam safety valve (MSSV). After the PAFS actuation, the SG pressure decreased rapidly owing to the SG secondary-side cooling by the PAFS. The original MARS significantly over-predicted the SG pressure. On the other hand, the MARS/PAFS considerably well predicted the system pressure with the natural convection flow rate similar to the experimental data. It means that the HX heat transfer model in MARS/PAFS well estimated the heat removal performance of the PAFS compared to the default model in MARS.



(a) PAFS flow rate (b) SG 2 pressure

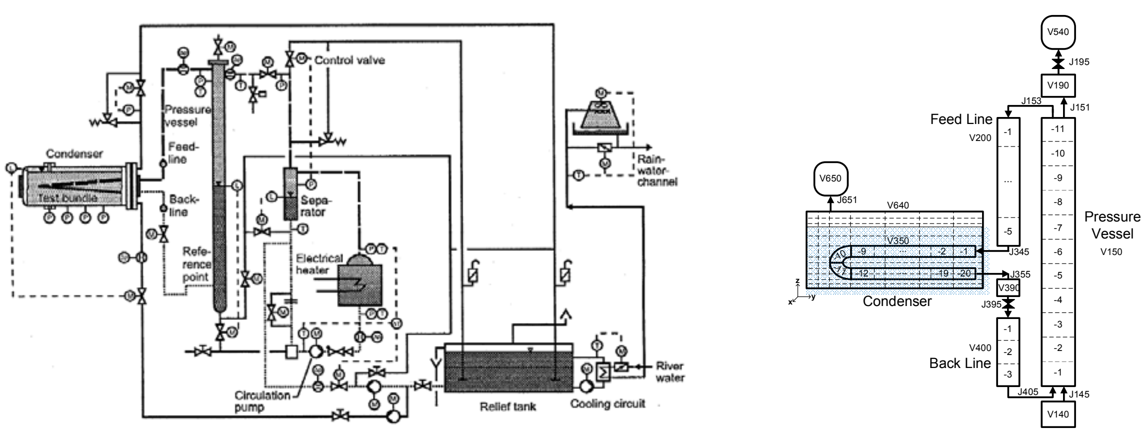
Figure 11. Simulation Results of ATLAS-PAFS.

4.3. NOKO Experiment

4.3.1. Description of NOKO

The NOKO is a multipurpose thermal-hydraulic test facility to experimentally investigate the emergency condenser effectiveness of the SWR1000. A schematic diagram of the NOKO test facility is shown in figure 12(a). The main components of the facility are the pressure vessel (height 12.6 m, diameter 0.448 m), the laterally connected emergency condenser bundle and the condenser pool. The steam generated from the pressure vessel is injected into the emergency condenser bundle. Then, the steam becomes condensate by the heat exchange with the cold water in condenser pool.

Geometrical data of the HX test section is as follows (see Table I). The emergency condenser test bundle is composed of four U-tubes. The average tube length is ~9.8 m, the inner diameter is 38.7 mm, and the wall thickness is 2.9 mm. The inclination is 1.6 deg in the upper straight part and 3.2 deg in the lower straight part. The main dimensions of the condenser pool are: length 6 m, diameter 2 m, volume 20 m^3. In the NOKO tests, nine steady state cases were simulated to validate the cooling and operational performance of the emergency condenser. Table III gives an overview of the test matrix.



(a) NOKO facility (b) MARS nodalization

Figure 12. Experimental Facility and MARS Nodalization of NOKO.

4.3.2. MARS modeling

The MARS nodalization scheme of the NOKO test facility is shown in figure 12(b). It consists of the pressure vessel and the emergency condenser system including the bundle HX, the condenser pool, and the connecting line. The pressure vessel is composed of three regions (upper -, lower -, and middle plenum). The upper and lower plenums are modeled as single volume components of V190 and V140, respectively. The middle plenum is modeled as the pipe component of V150 where the electrical heater exits. The time-dependent volume, TDV-540, is connected with the upper plenum through the valve component, J195, to control the initial system pressure and the initial water level using the boundary condition. When the emergency condenser system starts to operate, the valve, J195, is closed.

The four HX tubes were modeled as a single pipe component, V350, which are divided into 20 control volumes, and one heat structure (HS-350), which was used to represent the heat transferred from the steam to the cold water in the condenser pool through the condenser tube wall. The steam produced from the pressure vessel is injected into this tube bundle through the steam line, V200. When the water level in the pressure vessel reaches the target level by the water boiling, the actuation valve, J395, at the feed line opens and then the natural circulation flow of the NOKO is formed. The condensate water is returned to the pressure vessel through the feed line, V400. The condenser pool was modeled using the MULTID-200 where the number of cell is 7, 7 and 11 for x, y and z-directions, respectively. TDV-650 is coupled to the pool for pressure control.

4.3.3. Simulation results

The code simulations of NOKO were performed by controlling the electrical heater power in the pressure vessel to investigate the electrical heater power which can maintain a constant system pressure through a balance between the heater power and the emergency condenser capacity. Table III presents the test conditions. A reference point of the water level is the connecting point of the emergency condenser outlet line at the pressure vessel. Since there is a fluctuation of the capacity during the measurement time period (see figure 13), authors used the average capacity. While the original MARS under-predicted the emergency condenser capacity with a mean deviation of 15.85%, the MARS/PAFS well-estimated it with a mean deviation of 4.26%. It is revealed that the proposed HX heat transfer model can provide the improved prediction of the heat removal performance compared to the default model in MARS.

Table III. Test conditions of NOKO

Test No.	Experimental Conditions			
	Pressure Vessel		Condenser Pool	
	P [bar]	Level above back line [m]	P [bar]	Level [m]
EU-1-3	9.8	3.66	1.1	1.33
EU-2-4	9.9	2.52	1.2	1.33
EU-1-5	9.8	1.31	1.1	1.36
EU-3-3	30.1	3.64	1.1	1.43
EU-3-4	30.1	2.47	1.4	1.37
EU-3-5	30.0	1.33	1.5	1.27
EU-5-4	70.7	3.58	1.4	1.39
EU-5-5	70.6	2.41	1.8	1.26
EU-5-6	70.6	1.29	1.7	1.34

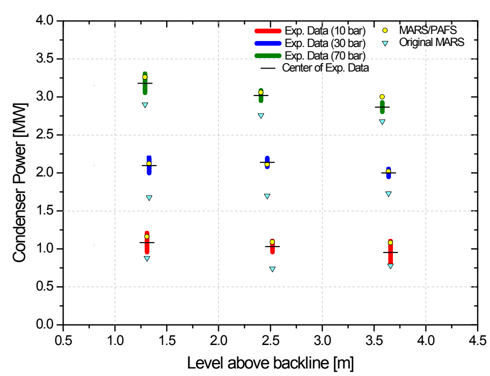


Figure 13. HX heat removal performance

5. CONCLUSIONS

The horizontal U-shaped heat exchanger submerged in a pool is under development as a key equipment of a passive safety system. For the successful design of the passive safety system and safety analysis of the

NPP, it is essential to predict the heat removal performance of the HX well. At present, BE codes such as RELAP5 and MARS do not have the suitable models for the heat transfer analysis of the HX. This study developed the heat transfer model of the horizontal U-shaped HX submerged in a pool in order to obtain a reliable prediction of the HX heat removal performance of the passive safety system using MARS.

For the horizontal in-tube condensation heat transfer, this study improved the condensation model in the original MARS by replacing the models by Shah (1979) and Chato (1962) with the annular flow condensation model by Dobson and Chato (1998) and the stratified flow condensation model by Cavallini et al. (2006), respectively. For the heat transfer outside the horizontal tube, authors developed the natural convective and nucleate boiling heat transfer model. The MARS/PAFS implemented with the proposed new HX model was validated with the passive safety system-related experiments of the PASCAL, ATLAS-PAFS, and NOKO. From the validation results, the proposed MARS/PAFS provided the significantly improved prediction of HX performance (condensation, natural convective and nucleate boiling, and HX heat removal rate) compared to the default model in the original MARS. This study confirmed that it is possible to predict the U-shaped HX performance effectively using the BE code. It is expected that the proposed new HX model is helpful to the reliable design of the HX and the safety analysis of the NPP with the passive safety system.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (the Nuclear Research & Development program of the Ministry of Trade, Industry & Energy (grant number 20131510101620)).

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