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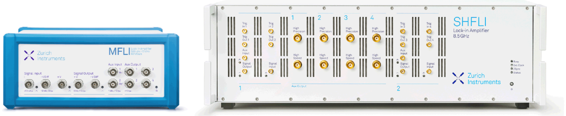

Study of Heat Transfer in a Water Cooling Tank with C-shaped Heat Exchanger and Straight Heat Pipe under Natural Circulation

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Abstract. In order to cope with the absence of the external electricity source condition, such as the accident occurred in Fukushima Dai-ichi nuclear power plant, several designs of nuclear reactor incorporate a natural circulation based emergency cooling system (ECS). To understand the phenomena and assess the reliability of the natural circulation in the ECS, one experimental facility named FASSIP-02 is being constructed. The facility consists of a water heater tank (WHT), a water cooling tank (WCT), which contains a C-shaped heat exchanger (CHX) and a straight wickless heat pipe (SHP), and a piping system. The current work focuses on numerical simulation of the thermal-hydraulic characteristics in the WCT. The study uses RELAP5 code as a numerical simulating tool. The objective is to assess the applicability of the numerical model, to study the characteristics of the heat transferred to the cooling water from the CHX submerged in the water cooling tank, and the SHP performance to remove heat from WCT by numerical simulation methodology. Two conditions in the WTC are simulated, i.e. with and without SHP. With the given hot source condition in CHX, the simulation results show that without any SHP, the water temperature in the WCT increases continuously reaching saturation temperature in about 130,000 s due to the heat transferred from the CHX. However, using five SHPs with a defined geometry of 1 inch diameter, 2 m total length and water filling ratio of 80% and inside temperature of 25°C, the WCT's water coolant temperature could be maintained about 40°C. It is concluded that the RELAP's model provides a good results showing the general thermal-hydraulic characteristics of the WCT and that the given SHP could transfer the heat from the WCT to the a heat sink preventing continuous increase of WCT's water temperature.

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INTRODUCTION

After the accident of Fukushima Dai-ichi Nuclear Power Station (NPS), passive safety system receives a great intention again. A passive safety system is a safety system which is independent with any external input [1]. Their operation depends only on the natural forces. In a NPS, the passive safety system could be found in the emergency core cooling system (ECCS), which is based on natural circulation [2-3]. Several designs of NPS implements the natural circulation based cooling system, both for normal cooling and emergency cooling [4-5]. Accordingly, many efforts have been done to study the natural circulation and modelling The overview of the phenomena and its modelling in different designs of advanced NPS are highlighted in [6].

SMART (system integrated modular advanced reactor) is an example of integral type reactor that implements passive residual heat removal system (PRHRS) to accomplish the basic safety function[7]. PRHRS is to remove the decay heat through the steam side of the steam generator (SG). PRHRS consists of PRHRS heat exchanger which is immersed in the emergency cooling tank (ECT) [8]. The steam from the SG is extracted to the PRHRS heat exchanger, condensed while releasing the heat to the ECT. Then the condensate is reinjected into the SG. As the temperature increasing, the cooling water in the ECT will evaporate. The entire process occurs under natural circulation condition.

Considering the above PRHRS design and in order to investigate the natural circulation characteristic in such closed loop, an experimental loop named FASSIP-02 is designed at Center for Nuclear Reactor Technology and Safety of BATAN [9]. The facility consists of water heater tank (WHT), water cooling tank (WCT), C-shaped heat exchanger (CHX) immersed in the WCT, straight wickless heat pipe (SHP) and piping system. The SHP is put in the WCT to reduce the evaporation of the cooling water in the WCT, which is in turn expected to reduce the water cooling volume.

The performance of SHP for passive cooling in nuclear spent fuel pool had been studied by Kusuma et al. [10-11]. Those studies showed a very small thermal resistance of the SHP indicating good possibility to be used as passive cooling apparatus even in low temperature. A preliminary study to use the SHP in the WCT of FASSIP-02 facility was conducted [12]. In that study, the RELAP5 code [13] was used to simulate the performance of the SHP as function of the water temperature of WCT and the flow rate of the condenser coolant. The water temperature in the WCT is determined constant. The CHX, which is the heat source in the WCT was not modelled. In this present work, the RELAP5 code is also used to simulate the thermal-hydraulic phenomena in the WCT. The WCT and CHX are modelled based on the current design of FASSIP-02. While, the SHP is represented with a heat structure, which has a function to sink the heat from the WCT. The specific aim is to study the characteristics of the heat transfer from CHX to the WCT and from WCT to the SHP and to assess the effect of the number and the temperature of the SHP.

DESCRIPTION OF INSTALLATION AND MODEL

The WCT is 1 m width (y-direction), 3m length (x-direction) and 2.5 m height (z-direction) of tank filled with water as shown in Figure 1. A CHX made from cooper tube is located at the bottom of the WCT. The inlet of the CHX is at about 0.8 m from the bottom, while the outlet is at 0.2 m forming an angle of 60 degree with the inlet. The length of the CHX is approx. 1.7 m with tube diameter of 1 inch. The hot water or steam enters to the CHX from the WHT, which is located about 11 m below the WCT, and the cooled water returns to the WHT. The SHP is made from pure cooper with 6m of total height, 106.1 mm of inner diameter and 1.5 mm of thickness. The SHP is vacuumed. The SHP consists of evaporator, adiabatic and condenser region of 2 m length each and is located in the ECT at the other side of the CHX's location. The evaporator region, which is the lowest part of the SHP, is submerged in the WCT. That evaporator is fully or partly filled with the water with certain filling ratio. Thermal isolator is used to insulate the adiabatic part of the SHP. The condenser, at the top of the SHP, is cooled by water, which flows inside the water jacket covering the condenser region. The cooling water itself is supplied from a thermostatic bath.

Fig. 2 shows the model and nodalization of the system studied. In this study, the focus is only at the WCT, the WHT and the piping connecting from and to WHT are not considered. So, the hot water or steam is assumed to flow into the CHX at the inlet side at a given temperature, pressure and flow rate. On the other hand, the detail of the process in the SHP is also not considered in the current study. The SHP is assumed to be able to remove all the heat absorbed in the evaporator at a given in inside pressure. In such condition, the temperature of the water in the evaporator is assumed at constant saturation value associated with the pressure applied in the SHP.

The WCT is modelled in two hydrodynamic volume (P-400 and P-460) connected each other with cross flows. The time dependent volume are used to model heat source (TMDV-100) and heat sink (TMDV-101) of the CHX (P-800). While, to model a constant flow rate of the hot water in the CHX, the time dependent junction is applied. The SHP is modelled with a heat structure (HS-501). The time dependent volume TMDV-600 and branch B-601 model the atmosphere above the pool.

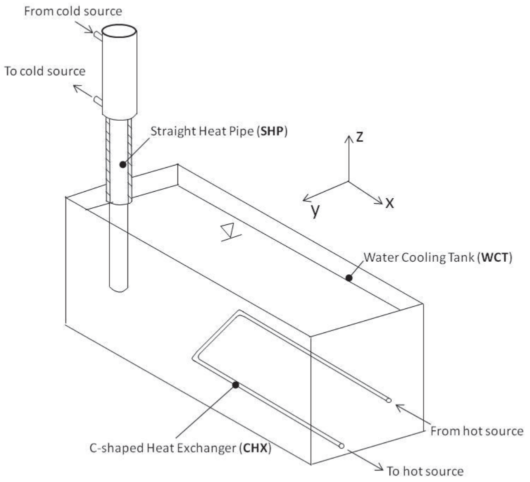


FIGURE 1. The sketch of the WCT equipped with CHX and SHP.

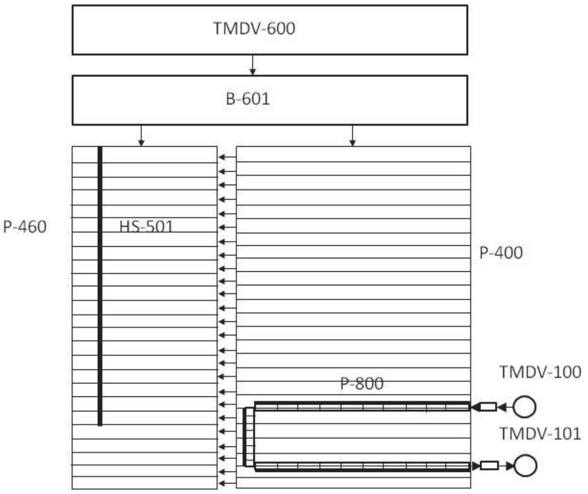
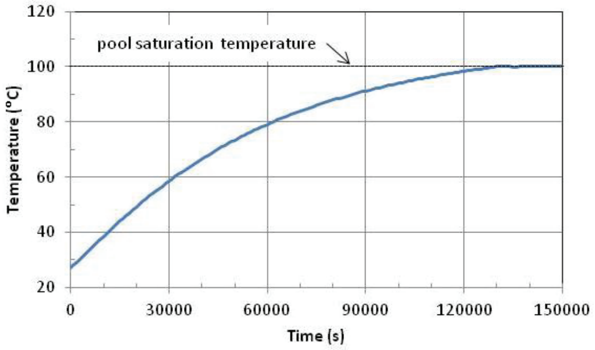


FIGURE 2. Model and nodalization of WCT.

RESULTS AND DISCUSSION

Firstly, the calculation is done without SHP. The heat transfer from CHX to the water pool is investigated. It is assumed that the pressure in the CHX is 2 bar and the inlet temperature is 383 K. The water flows inside the CHX with constant flow rate of 1 kg/s. Fig. 3 shows the WCT pool temperature as function of time. The WCT pool temperature increases until reach the saturation temperature at atmospheric pressure, i.e. 373 K, at about 130,000 s. The temperature continues to increase because the heat is continuously supplied from the CHX and contrarily, there is no cooling system to cool WCT. After the saturation temperature reached, the WCT pool temperature is constant, however the water level will decrease as the water is vaporized. Fig. 4 depicts the heat transferred from the CHX to the WCT pool during 150,000 s. The heat transferred decreases at the beginning because the temperature difference between the CHX and the WCT pool diminishes. At about 130,000 s when the pool's saturation temperature reached, the heat transferred is constant because the temperature difference between the CHX and the WCT pool is also constant.



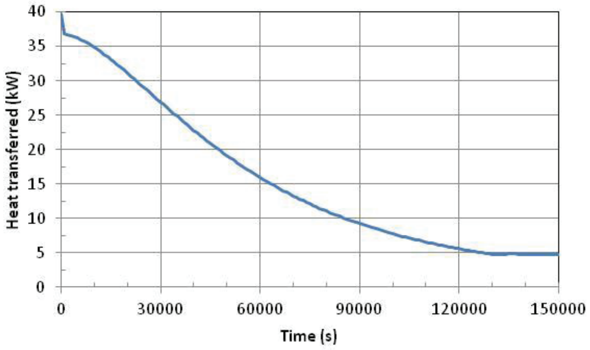


FIGURE 3. WCT pool temperature evolution.

FIGURE 4. Heat transferred from CHX to WCT.

The second step of the calculation is done by applying the SHP to the WCT pool. As mentioned in the above, in this study, the SHP is not modelled in detail, only by a heat structure, i.e. HS-501, with one surface temperature represents the temperature of the water and steam inside the SHP. The temperature is assumed constant because the SHP operates steadily in the given saturation pressure. While, the temperature of the other surface of the heat structure depends on the temperature of the WCT pool. The variable of the simulation is the inside temperature and the number of the SHP. The inside temperature of the SHP varies of 25 °C (0.0317 bar), 30 °C (0.0425 bar), 35 °C (0.0563 bar), 40 °C (0.0738 bar) and 45 °C (0.0959 bar). While, the number of SHP varies of 1 to 5 units with the specification described above. As the heat source, the inlet temperature, the pressure and the water flow rate of the CHX are constant, i.e. 110 C, 2 bar and 1 kg/s, respectively. The calculation time period is 20 hours.

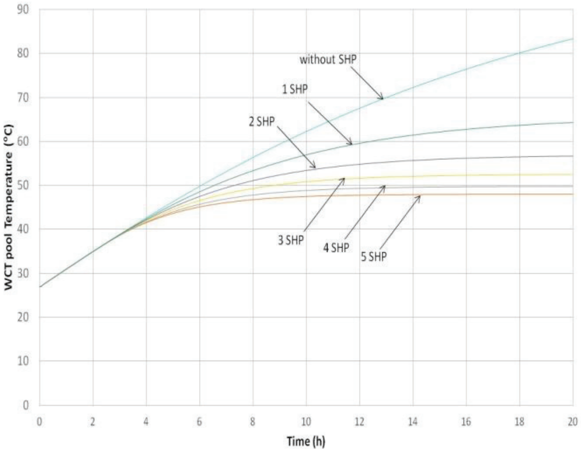


FIGURE 5. WCT pool temperature for different number of SHP at SHP temperature of 35°C.

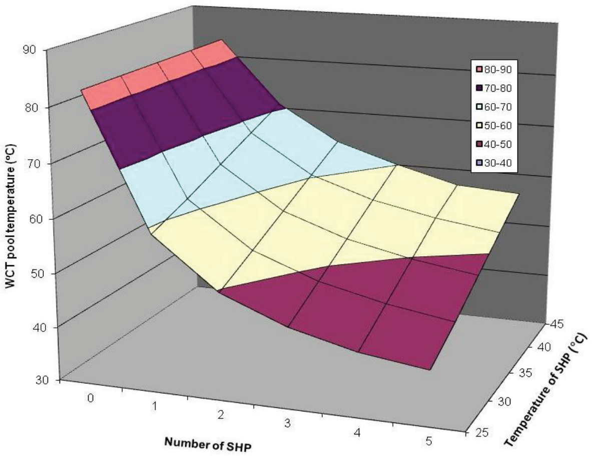


FIGURE 6. WCT pool temperature for different number of SHP and the temperature of SHP.

Figure 5 shows the WCT pool temperature for different number of SHP, while the temperature at the SHP is 35°C. It can be seen without the SHP, the WCT pool temperature increases continuously as predicted before. However, when the SHP is applied, the heat from the WCT pool can be removed. The result shows that the higher the number of SHP applied, the WCT pool temperature could be lower. With 5 SHPs, the WCT pool temperature can be kept constant at about 48°C. It can be understood because more the SHP, more heat could be removed from the WCT pool as the heat transfer surface area increases.

Figure 6 shows three dimensions representation of variation of the WCT pool temperature as function of the number and the operation temperature of SHP. As seen in the Figure 6, beside of the increase of the number of SHP, the lower operation temperature of SHP decreases also the WCT pool temperature. At 25°C operation temperature of the SHP, with 5 SHP, the WCT pool temperature is kept at approximately 40°C. Table 1 resumes the simulation results for several cases assessed in this study. A part of the WCT pool temperature, Table 1 also shows the parameters of the predicted heat transfer coefficient outside of the CHX and the SHP.

It should be noted that the heat transfer at the outside the CHX and the SHP (or in the WCT pool) is a natural convection. While, inside the CHX the heat transfer is a forced convection type, though in real installation it is also natural convection. As the thermal-hydraulic condition of the flow inside the CHX is constant, the heat transfer coefficient is also constant, about 13.3 kW/m^2°C. Then, the heat transfer coefficients outside of the CHX and the SHP govern the heat transfer from the CHX to WCT pool and from WCT pool to the SHP, respectively. From the Table 1, the outside heat transfer coefficient of CHX is in general higher than of the SHP. This trend is consistent with the results of the work in Hamzekhani et al [14] where the heat transfer coefficient of natural convection outside surface of a vertical cylinder is lower than a horizontal cylinder. In all cases, the heat transfer coefficient of natural convection, i.e. outside of the CHX and the SHP, is lower than of forced convection, i.e. inside of the CHX tube. On the other hand in general, the natural convection heat transfer coefficient, as in WCT pool, is higher when the WCT pool temperature is higher. This effect of the temperature agrees with the experimental results of Chung et al [15]. However, this effect is less significant for the horizontal cylinder, i.e. outside of the CHX, which only varies between 1203 to 1306 W/m^{2}°C such as can be seen in the Table 1.

TABLE 1. Resume of simulation results.

Temperature of the SHP (°C)	Number of the SHP					Parameters
	1	2	3	4	5	
45	70.86	63.86	60.09	56.85	56.09	WCT pool temperature (°C)
	1302	1305	1301	1295	1291	Outside CHX HTC (W/m^{2}°C)
	1098	941	850	789	744	Outside SHP HTC (W/m^{2}°C)
40	67.83	60.33	56.34	53.83	52.09	WCT pool temperature (°C)
	1306	1301	1291	1283	1277	Outside CHX HTC (W/m^{2}°C)
	1101	931	843	781	735	Outside SHP HTC (W/m^{2}°C)
35	64.77	56.76	52.5	49.82	47.95	WCT pool temperature (°C)
	1306	1292	1277	1265	1255	Outside CHX HTC (W/m^{2}°C)
	1098	922	822	770	723	Outside SHP HTC (W/m^{2}°C)
30	61.67	53.17	48.64	45.78	43.79	WCT pool temperature (°C)
	1303	1280	1259	1243	1230	Outside CHX HTC (W/m^{2}°C)
	1098	922	822	756	708	Outside SHP HTC (W/m^{2}°C)
25	58.94	49.69	44.84	41.8	40.13	WCT pool temperature (°C)
	1298	1264	1237	1215	1203	Outside CHX HTC (W/m^{2}°C)
	1099	911	807	739	685	Outside SHP HTC (W/m^{2}°C)

HTC: heat transfer coefficient

CONCLUSIONS

The RELAP5 model has successfully simulated the heat transfer characteristics in the water cooling tank equipped with a C-shape heat exchanger, as hot source, and a straight heat pipe as cold source. The use of the straight heat pipe could remove the heat from the water cooling tank and keep the water cooling temperature low. Higher number of the straight heat pipe, lower the water cooling temperature. While lower temperature of the straight heat pipe (or higher vacuum) decrease the water cooling tank pool temperature. The next step of the study will validated the simulation with the experiment and details the model of the straight heat pipe.

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REFERENCES

1. International Atomic Energy Agency. *Safety related terms for advanced nuclear plants, IAEA-TECDOC-626*, (IAEA, Vienna, Austria, 1991)
2. International Atomic Energy Agency. *Passive Safety System and Natural Circulation in Water Cooled Nuclear Power Plant. IAEA-TECDOC-1624*, (IAEA, Vienna, Austria, 2009)
3. International Atomic Energy Agency. *Natural circulation in water cooled nuclear power plants. IAEA-TECDOC-1474*, (IAEA,Vienna, Austria, 2005)
4. H. Hidayatullah, S. Susyadi, M.H. Subki. Prog. Nucl. Energy **79** (2015), pp. 127-135.
5. Z. Liu, J. Fan. Prog. Nucl. Energy **70** (2014), pp. 20-28.
6. International Atomic Energy Agency. *Natural Circulation Phenomena and Modelling for Advanced Water Cooled Reactors. IAEA-TECDOC-1677*, (IAEA, Vienna, Austria, 2012).
7. Y.S. Kim, S.W. Bae, S. Cho, K.H. Kang, H.S. Park. Ann. Nucl. Energy **89** (2016), pp. 56-62.
8. K.K. Kim, W. Lee, S. Choi, H.R. Kim, J. Ha. J. Energy Power Eng. **8** (2014), pp. 94-102.

9. A.R. Antariksawan, S. Widodo, M. Juarsa, D. Haryanto, M.H. Kusuma, N. Putra. *Numerical study on natural circulation characteristics in FASSIP-02 experimental facility using RELAP5 code*, in IOP Conf. Ser.: Earth Environ. Sci. 105 012090 (IOP Publishing, 2018).
10. M.H. Kusuma, N. Putra, A.R. Antariksawan, R.A. Koestoer, S. Widodo, S. Ismarwanti, et al. Int. J. Therm. Sci. **126** (2018).
11. M.H. Kusuma, N. Putra, A.R. Antariksawan, Susyadi, F.A. Imawan. Nucl. Eng. Technol. **49** (2017).
12. M.H. Kusuma, N. Putra, A.R. Antariksawan, M. Juarsa, S. Widodo, Tanti Ardiyati. *Preliminary Investigation of Wickless-Heat Pipe as Passive Cooling System in Emergency Cooling Tank*, in AIP Conference Proceedings **2001**, 020004 (2018), (AIP, 2017).
13. A.R. Antariksawan, E. Umar, S. Widodo, M. Juarsa, M.H. Kusuma. Int. J. Technol. **8** (2017), pp. 698-708.
14. S. Hamzekhani, A. Akbari, M.M. Falahieh, M. Rasoul, M. Fardinpour. *Natural Convection Heat Transfer from an Inclined Cylinder to Glycerol and Water*, in : (2014), pp. 79-83.
15. Y. Chung, H. Park, W. Lee, K. Kim. Ann. Nucl. Energy **77** (2015), pp. 402-407.