Heat transfer phenomenon and characteristics study of C-shaped tube with nucleate boiling in water tank

Xiangyu Meng, Yanbin Liu, Xuesheng Wang, Jiaming Cao

School of Mechanical and Power Engineering, East China University of Science and Technology, Room 637, Building 17,130 Meilong Road, Shanghai 200237, China

Author addresses:872026442@qq.com, lyb2006666@163.com, wangxs@ecust.edu.cn, 17621778372@163.com

Corresponding author’s e-mail address: wangxs@ecust.edu.cn

Abstract. The Passive Residual Heat Removal Heat Exchanger (PRHR HX) is an important equipment of the passive safety system in advanced nuclear power plants such as AP1000. Heat transfer phenomenon and characteristics study of the PRHR HX has received more and more attention. However, the research of transient heat transfer under C-shaped tube outside pool boiling condition is insufficient and needs further investigation. An experimental facility was built and a series of experiments were conducted. Distributing and changing tendencies of some important parameters including tank water temperature, tube wall temperature and heat transfer coefficient were obtained and analyzed. This study can provide a reference for the thermal hydraulic design for the PRHR HX in nuclear power plant.

1. Introduction
The C-shape Passive Residual Heat Removal Heat Exchanger (PRHR HX) installed in the In-containment Refueling Water Storage Tank (IRWST) is an important component of the Passive Residual Heat Removal System (PRHRS) in AP600 and AP1000 nuclear power plants. The PRHR HX protects the plants against several accidents such as loss of feedwater, feedwater line breaks, and steam line breaks[1].

For decades, especially after the Fukushima Daiichi nuclear-plant accident, passive safety system has received more and more attention. Several component Tests and integral system tests were conducted to determine the heat transfer characteristics and demonstrate the passive core cooling system (PXS) for AP600 and AP1000, including the ROSA[2] in Japan, the APEX[3] at the Oregon State University and the SPES-2[4] in Italy. The ROSA facility provided the most detail and experimental data of the PRHR HX in the three test facilities. Yonomoto et al.[5] conducted experimental study on the ROSA test facility and analyzed the heat transfer characteristics on the outer surface of the PRHR HX C-shaped tubes, and numerically simulated the natural circulation flow in the IRWST by using Fluent. Also, the heat removal capacity of the PRHR is evaluated. The ROSA test data were often chosen for comparison and validation by researchers. Wright et al.[6] used the PRHRCFD computational fluid dynamic computer code to simulate the AP1000 PRHR HX and to verify its operational performance. Before this, the code was validated against the ROSA AP600 test data. Results showed the PRHR HX performance is adequate to remove the reactor decay heat effectively. Zhang et al.[7] developed a PRHR-MHT Code (PRHR HX-Modified Heat Transfer Code) to evaluate the C-shaped PRHR HX in...
CAP1400. In order to verify the applicability of the PRHR-MHT Code, the ROSA/AP600 experimental data were also used for comparison.

During the heat removal process, the main heat transfer mechanisms through the tubes submerged in the IRWST are single phase convection, subcooled pool boiling and saturation pool boiling[8, 9]. Zhang et al.[10] numerically and experimentally investigated the transient single phase natural convection heat transfer characteristic of the PRHR HX model. The calculated results were validated by comparing with the empirical correlations and the experimental data. Men et al.[11] investigated the applicability of different heat transfer correlations in literature for the PRHR HX heat transfer calculation under tube outside single phase natural convection condition. Gui et al.[12] experimental studied the heat transfer performance of C-shape tube immersed in a water pool, four pool boiling correlations were assessed to predicted the tube outside heat transfer results and a new correlation is developed. Tao et al.[13] experimentally and numerically investigated the transient single phase thermal hydraulic characteristics of the reduced scale PRHR HX model. Both the heat transfer coefficients inside and outside the tube were calculated by empirical correlations in literature. Porous media method was using for numerical simulation. The numerical methods were validated by the experimental results.

The fundamental heat transfer mechanism of the PRHR HX submerged in the IRWST is heat transfer through the C-shaped tubes in a large volume of water pool. This study focuses on the transient heat transfer research under C-shaped tube outside pool boiling condition. Some important heat transfer parameters such as tank water temperature, tube wall temperature and heat transfer coefficient will be observed/calculated during the experiments. Furthermore, some obvious changing regularities of these parameters will be analyzed in detail.

2. Experimental facility

Fig. 1 is the general process diagram of experimental system and the general layout of thermocouples in experimental system. The experimental facility consists of single tube, water tank, thermal oil drum, electric heater, centrifugal pump, flowmeter, oil filling port, thermocouples, pressure gages, etc. Table 1 is a list of main equipments and instruments in experimental system.

![Fig. 1 The general process diagram of experimental system and the general layout of thermocouples in experimental system](image)

| Item                  | Specification | Quantity | Note              |
|-----------------------|---------------|----------|-------------------|
| C-tube                | Φ19.05×1.65mm | 1        | 304 stainless steel |
| Water tank            | Φ600×1500×2.5mm | 1        | 304 stainless steel |
| Thermal oil tank      | Φ300×700×3mm  | 1        | 304 stainless steel |
| Electric heater       | 15kW          | 1        | /                 |
| Centrifugal pump      | Maximum head 28m | 1    | 380V, 1.5kW        |
| Flowmeter             | 0.6~6 m³/h    | 1        | /                 |
Direct reading data was collected by data acquisition system, such as temperature and volume flow rate. Centrifugal pump and electric heater were controlled through the control cabinet. Electric heater was automatically powered on or off by setting temperature. All thermocouples and other instruments were calibrated before experiment. In order to decrease heat loss during experiment process, insulation layer was installed outside the water tank, oil tank and pipe. A tank cover filled with water was used to cool most of the steam generated during the experiment. As the cover was not tightly sealed with the tank wall, the operation pressure of the water is atmospheric pressure.

T-1 and T-2 were separately installed at the inlet and outlet of the C tube to measure oil temperature. Tw-1 to Tw-8 were tube wall temperature measuring points, three thermocouples were equidistantly installed at each point and take an average. Tb-1 to Tb-6 were water temperature measuring points (vertical direction). Tb-7 to Tb-10 were water temperature measuring points (horizontal direction). Tb-7 and Tb-8 were located at L-2 level, and Tb-9 and Tb-10 were located at L-3 level.

Before experiment, overall circulation loop was cleaned by water and dried completely. Thermal oil was filled through the oil filling port, the filling process was finished when atmospheric valve V3 was full of oil and oil level in the filling port was not lower than 5cm. All sealing points were both checked in cold and hot state carefully to ensure the experiment continuity. Desalted water was used as cooling medium to provide better photo taking condition and reduce corrosion. Water level was set at 10cm to the tank top. Non-condensable gas was discharged after the water adding process. The degassing process finished until all the water in tank was boiling. The setting of experimental condition needed comprehensive consideration of power supply, oil flash point and experimental purpose. Table 2 is summary of the experimental working condition.

### Table 2 Summary of the experimental working condition

| Oil flow rate (m³/h) | Oil inlet temperature (°C) | Water initial temperature (°C) |
|---------------------|-----------------------------|-------------------------------|
| 2.0                 | 178.5                       | 35.0                          |

Before experiment, closed V-1 and V-2, open V-6, V-7, electric heater and centrifugal pump, heat thermal oil to setting temperature. Then open V-1 and V-2, and regulated flow rate to working condition. During the process, continuously collected experimental data and photographed bubble features outside the c-tube. When all water in tank boiling for a period of time, experiment was finished. Closed electric heater, maintained centrifugal pump running for some time to cool tank water. When reaching safety temperature, closed centrifugal pump and all valves, finally switched off the power.

### 3. Data processing method and error analysis

During experimental process, directly obtained data included thermal oil inlet and outlet temperature, tube wall temperature, tank water temperature and thermal oil flow rate. Experimental data was calculated through heat balance equation and Newton cooling law:

$$ Q = Mc_{pf} \Delta T = qA = hA \left( T_w - T_f \right) $$

In the formula, $Q$ is heat transfer rate through tube wall, W; $M$ is mass flow rate, kg/s; $c_{pf}$ is specific heat, J/(kg·°C); $\Delta T$ is temperature difference between oil inlet and outlet, °C; $q$ is heat flux through tube wall, W/m²; $A$ is effective heat transfer area of C tube, m²; $h$ is tube outside heat transfer coefficient at corresponding measuring point, W/(m²·°C); $T_w - T_f$ is the difference of tube outside wall temperature and tank water temperature at corresponding height, °C.

Experimental error consists of direct measurement error and indirect measurement error. Direct measurement error includes temperature, flow rate and geometrical sizes measuring error. Indirect measurement error includes heat transfer area, heat transfer rate, heat flux and heat transfer coefficient error. In the experiments, direct measurement error was calculated based on instrument specification,
and indirect measurement error was analyzed by using the method mentioned in literature[37], table 3 is summary of the experimental error.

| parameter                     | error   |
|-------------------------------|---------|
| Thermal oil temperature       | ±0.51°C |
| Tank water temperature        | ±0.40°C |
| Tube outside wall temperature | ±0.46°C |
| Thermal flow rate             | ±0.02 m³/h |
| Heat transfer rate            | 1.6%    |
| Heat flux                     | 2.7%    |
| Heat transfer coefficient     | 3.5%    |

4. Result and discussion

4.1. Trends analysis of tank water temperature

Fig. 2 is temperature distribution of the four measuring points in horizontal direction and the six measuring points in vertical direction. From 2000s to 18000s, 9 moments are selected and corresponding experimental data was used to analysis temperature changing regularity. The maximum difference between Tb-7 and Tb-8, Tb-9 and Tb-10 is within 2°C. Considering installation error between two thermocouples located at the same level, 2°C temperature difference is acceptable and it indicates that water at the same height mixes well. Before saturation boiling, obvious temperature difference occurs between L2 and L3. The maximum difference is 11.1°C at 12000s and the minimum difference is 5.1°C at 2000s.

Temperature gradient is obvious along vertical direction. For example, at 6000s, from Tb-1~Tb-6, the temperatures respectively are 85.2°C, 66.0°C, 62.5°C, 61.1°C, 60.2°C, 58.9°C. From another perspective, at Tb-5 tank water measuring point, temperatures respectively are 43.7°C, 51.0°C, 60.2°C, 67.7°C, 75.1°C, 82.7°C, 93.6°C, 100.0°C, 100.3°C at nine different moments.

4.2. Trends analysis of heat transfer coefficient, tube wall temperature and tank water temperature

Fig. 3 shows the trends of tube outside heat transfer coefficient with time at the three measuring points. Heat transfer coefficient at Tw-1 measuring point is the largest and heat transfer coefficient at Tw-6 measuring point is the smallest. For a certain measuring point, heat transfer coefficient increases with time going on. Firstly, the increasing speed is small. When reaching a certain moment, heat transfer coefficient begins rising rapidly. The changing moment of higher measuring point is earlier than that of lower measuring point. Finally, heat transfer coefficient tends to be stable. The fluctuation of heat
transfer coefficient becomes obvious after the rapid rising period, the possible reason is temperature fluctuation caused by bubble disturbance under boiling condition.

Fig. 3 The trends of tube outside heat transfer coefficient with time at the three measuring points

Fig. 4 The trends of tube outside wall temperature, corresponding tank water temperature and heat transfer coefficient with time at the Tw-1 measuring point and the Tw-4 measuring point

Fig. 4(a) is the trends of tube outside wall temperature, corresponding tank water temperature and heat transfer coefficient with time at the Tw-1 measuring point. Double Y axes are adopted. The left Y axis is heat transfer coefficient and the right Y axis is temperature. The X axis is time. Tube outside wall temperature, corresponding tank water temperature and heat transfer coefficient continuously increase with time going on and finally tend to be stable. Tube outside wall temperature is initially relatively high and the changing tendency is gentle. Tank water temperature maintains high increasing speed, and finally reaches saturation temperature. For tube outside heat transfer coefficient, the changing tendency is influenced by tube outside wall temperature, water temperature and bubble disturbance. Firstly, tube outside heat transfer coefficient increases slowly then speeds up, eventually becomes stable. During the process, it comes with of transformation of heat transfer mechanism and macro phenomenon of bubble generation and movement.

Fig. 4(b) is the trends of tube outside wall temperature, corresponding tank water temperature and heat transfer coefficient with time at the Tw-4 measuring point. Compared with Fig. 4(a), the trends of tank water temperature and heat transfer coefficient have obvious differences in Fig. 4(b). There are short fast changing stages on tank water temperature and heat transfer coefficient curves. Before the stages, both tube wall temperature and heat transfer coefficient increase slowly. The most possible reason is the Tw-1 measuring point is higher than the Tw-4 measuring point, the heat transfers more easily to water than that of the Tw-4 measuring point. Furthermore, the changing stage of tank water temperature is slightly lagging than that of heat transfer coefficient in Fig. 4(b), the reason probably is
there is a distance between water temperature measuring point and tube wall temperature measuring point, heat transfer process needs some time to complete.

5. Conclusion
Changing regularities of wall temperature, water temperature and heat transfer coefficient are obtained during experimental process. The main conclusions are as follows:

1) For a certain measuring point, wall temperature, water temperature and heat transfer coefficient continuously increase with time, and finally reach almost constant values.
2) Water temperature along vertical direction shows an obvious stratification, but temperature difference between measuring points located at the same level is quite small.
3) Heat transfer coefficient presents obvious fluctuation after boiling starts. It is mainly caused by bubble disturbance.
4) This study can provide a reference for the thermal hydraulic design for the PRHR HX.

References
[1] T.L. Schulz. Westinghouse AP1000 advanced passive plant[J]. Nuclear Engineering and Design. 2006, 236(14-16): 1547–1557.
[2] Y. Kukita, T. Yonomoto, H. Asaka, H. Nakamura, H. Kumamaru, Y. Anoda, T.J. Boucher, M.G. Ortiz, R.A. Shaw, R.R. Schultz. ROSA/APGOO testing: Facility modifications and initial test results[J]. Journal of Nuclear Science and Technology. 1996, 33(3): 259-265.
[3] J.N. Reyes, L. Hochreiter. Scaling analysis for the OSU AP600 test facility (APEX) [J]. Nuclear Engineering and Design. 1998, 186(1-2): 53–109.
[4] C. Medich, M. Rigamonti, M. Tarantini, R. Martinelli, L. Conway. SPES-2, the full-height, full-pressure, test facility simulating the AP600 plant: main results from the experimental campaign[C]. Proceedings of the 1995 International Joint Power Generation Conference. ASME Nuclear Engineering Division, Minneapolis. 1995, 10.08-10.12.
[5] T. Yonomoto, Y. Kukita, R.R. Schultz. Heat transfer analysis of the passive residual heat removal system in ROSA AP600 experiments[J]. Nuclear Technology. 1998, 124: 18-30.
[6] R.F. Wright, J.R. Schwall, C. Taylor, N.U. Karim, J.G. Thakkar, T. Schulz. AP1000 passive residual heat removal heat exchanger confirmatory analysis[C]. Proceedings of the Fourteenth International Conference on Nuclear Engineering (ICONE ’06). Nuclear Engineering Division, Miami, Fla, USA, July 2006.
[7] Y.H. Zhang, Y.L. Yuan, L. Feng, Z.H. Zhang, Z.M. Qiu, P.C. Tan, D.G. Lu. Application of the modified heat transfer formulas for the C-type Heat Exchanger in Passive Heat Removal System of CAP1400[J]. Applied Thermal Engineering. https://doi.org/10.1016/j.applthermaleng.2019.113876.
[8] M.G. Kang. Experimental investigation of tube length effect on nucleate pool boiling heat transfer[J]. Annals of Nuclear Energy. 1998, 25(4-5): 295-304.
[9] Y.B. Liu, X.S. Wang, Q.M. Men, X.Y. Meng, Q.Zhang. Heat transfer analysis of passive residual heat removal heat exchanger under tube outside boiling condition[J]. Science and Technology of Nuclear Installations. 2017.
[10] Y.H. Zhang, D.G. Lu, Z. Du, X.L. Fu, G.H. Wu. Numerical and experimental investigation on the transient heat transfer characteristics of C-shape rod bundles used in Passive Residual Heat Removal Heat Exchangers[J]. Annals of Nuclear Energy. 2015, (83): 147–160.
[11] Q.M. Men, X.S. Wang, X. Zhou, X.Y. Meng. Heat transfer analysis of passive residual heat removal heat exchanger under natural convection condition in tank [J]. Science and Technology of Nuclear Installations. 2014.
[12] M. Gui, Q.C. Bi, G. Zhu, J. Wang, T. Wang. Experimental investigation on heat transfer performance of C-shape tube immersed in a water pool[J]. Nuclear Engineering and Design. 2019, 346: 220-229.
[13] J.Q. Tao, H.Y. Gu, Z.Q. Xiong, X. Jiang, Y.C. Xie. Investigation on transient thermal hydraulics
of reduced scale passive residual heat removal heat exchanger in tank[J]. Annals of Nuclear Energy. 2019, (130): 402–410.

[14] Y. Zhang, D.Y. Li. Experiment of college physics, 4th edition. Beijing: Science Press. 2014.