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He-Water boiling tests with PCHE and its MARS Analysis

In Hun Kim [a], Hee Cheon NO [a*]
[a] *Department of Nuclear & Quantum Engineering, KAIST, Dae-jeon, Republic of Korea*
[*] *Corresponding author: hcno@kaist.ac.kr*

1. Introduction

The main advantage in High Temperature Gas Cooled Reactors (HTGRs) is to produce both of electricity and hydrogen. We consider several methods such as SI cycle, steam electrolysis, and so on for the hydrogen production in HTGRs. When selecting the steam electrolysis for hydrogen production, a lot of steam with high temperature should be generated. We think that the PCHE can be one of good candidates for the production of the superheated steam, because the PCHE has large surface area per unit volume, high heat transfer coefficient, and wide operation range. Thermal-hydraulic performances were investigated in the several conditions by previous researches [1,2].

In this study, we produced superheated steam using the He-Water boiling test loop with PCHE. Numerical solutions without heat loss and with heat loss were obtained by using MARS code.

2. He-Water boiling tests

We constructed the He-Water boiling test loop with the PCHE. It is composed of a closed helium loop and an open water loop (Fig. 1). The closed loop was charged with helium gas after creating a vacuum state. The helium was moved by a gas-bearing type circulator, which showed no oil leakage. Purified water kept in a water tank was driven by a water pump. The water temperature increased in the PCHE as heat was transferred from the hot side to the cold side. The superheated steam was then vented out.

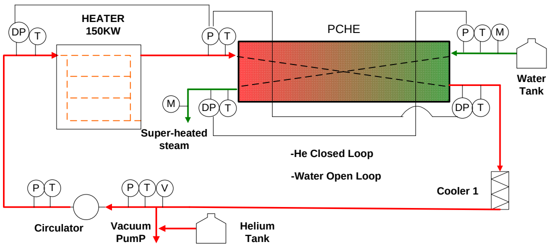

Fig. 1. Helium-Water boiling test loop.

The tested PCHE, made of Alloy 800HT by Heatric, has 1280 micro-wavy channels with semi-circle shape on the hot and the cold sides, respectively. The geometry on both sides is identical. The diameter, wavy channel length, heat transfer area, and cross-sectional area are 1.51 mm, 765 mm, 3.8 m^2, and 0.001155 m^2. The angle and the pitch length are 15° and 24.6 mm. The core dimension is 150 mm x 144 mm x 896 mm. Insulations were installed to prevent heat loss.

The helium side inlet conditions were in the ranges of 310~320℃ and 1.82 MPa, while the water side inlet conditions were in the ranges of 18~20℃ and 0.1 MPa. The mass flow rates on the helium and the water sides were in the ranges of 65~120 kg/h and 0.3~3 kg/min, respectively. Superheated steam was produced. Pressure and temperature were measured at the inlet and the outlet of the PCHE. A data sample was obtained as shown in Table 1.

Table 1. Experimental data from the He-Water boiling tests

	Hot (Helium)	Cold (Water/Steam)
Inlet temperature	316.73℃	18.94℃
Outlet temperature	94.89℃	279.42℃

The heat loss was approximately 14%, which was much larger than the heat loss in the He-He tests [1]. In spite of high operating temperature up to 550℃ in the He-He tests, the heat loss of only 1.53% was obtained.

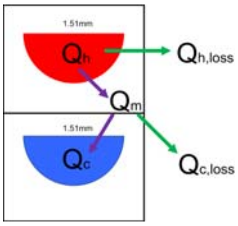

Fig. 2. Heat transport passages in the PCHE

We simplified the heat transfer phenomena in the PCHE, as shown in Fig.2. Heat balance can be described as Eqs.(1) and (2).

$$Q_h = Q_m + Q_{h\_loss} \tag{1}$$

$$Q_m = Q_c + Q_{c\_loss} \tag{2}$$

The critical parameters to determine the heat loss are the heat transfer coefficients in the cold side and in the ambient region. If the heat transfer coefficient in the cold side is much higher than the ambient heat transfer coefficient, heat transfer along the purple line is dominant and heat loss is negligible. Otherwise, heat transfer along green line is dominant. The heat loss is considerable. Considerable heat loss in the He-Water boiling tests can be caused by the low heat transfer coefficient of superheated steam in the region with mist flow regime leading to the high temperature in that region.

3. Calculations by MARS code

MARS is a code primarily used for the safety analysis of light water reactors which is useful for two-phase analysis. Nodalization was completed as shown in Fig.3 to obtain numerical solutions using MARS.

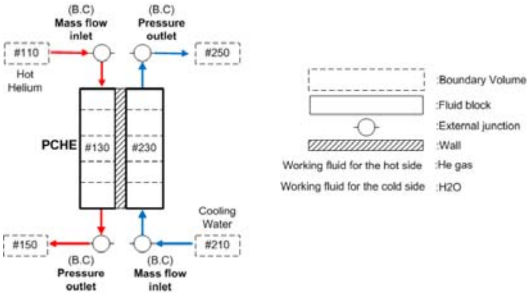

Fig. 3. MARS nodalization

The experimental inlet conditions in the hot and cold sides were used for MARS input file. Numerical solutions were obtained from the input file with 60 nodes. MARS calculations were performed for the cases with heat loss and without heat loss. The ambient heat transfer coefficient is from 2 to 25 W/m^2K (Incropera and DeWitt, 2002). Experimental data and numerical solution with heat loss and without heat loss were compared in Fig.4. Pink and brown points represented experimental data.

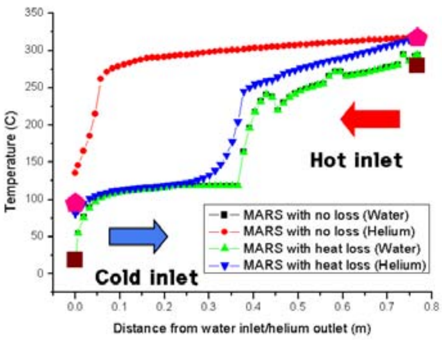

Fig. 4. Experimental data and numerical solutions with heat loss and without heat loss

The numerical solution with heat loss predicted experimental data more accurately than that without heat loss, as shown in Table 3. Local Reynolds number was provided from the numerical solutions as shown in Table 4.

Table 3. Variations of MARS solutions from experimental data

	Hot outlet temperature	Cold outlet temperature	Heat loss ratio
Experiment	94.89℃	279.42℃	14%
MARS without heat loss	146.18℃ (+51.29℃)	294.0℃ (+14.58℃)	-
MARS with heat loss	80.44℃ (-14.45℃)	294.0℃ (+14.58℃)	18.6%

Table 4. Local Reynolds number variations

	Hot	Cold
Pressure inlet	1.82 MPa	0.101 MPa
Temperature inlet	316.73℃	18.94℃
Mass flux	20.919 kg/s m^2	6.955~8 kg/s m^2
Re (no heat loss)	600~770	Water 3~22 Vapor 0~265
Re (heat loss)	605~853	Water 3~55 Vapor 0~265

The heat transfer coefficients according to flow regimes were provided from the MARS solutions. Details are in Table 5.

Table 5. Heat transfer coefficient according to flow regimes

Distance from water inlet/helium outlet	Flow regime in cold side	Heat transfer coefficient in cold side	Heat transfer coefficient in ambient region	Heat transfer coefficient in hot side
0~~0.2304 m	Bubbly	3007~3228 (W/m^2K)	1.09~2.92 (W/m^2K)	832~894 (W/m^2K)
0.2304~0.3712 m	Slug	3630~28175 (W/m^2K)	2.92~2.95 (W/m^2K)	895~983 (W/m^2K)
0.3712~0.3840 m	Annular	54200 (W/m^2K)	2.95 (W/m^2K)	1023 (W/m^2K)
0.3840~0.7680 m	Mist (Superheated steam)	151.8~170.5 (W/m^2K)	2.95~6.54 (W/m^2K)	1083~1185 (W/m^2K)

As soon as the flow regime in the cold side changed from annular flow to mist flow, the heat transfer coefficient drastically decreased from 54,200 W/m^2K to 160 W/m^2K, which was comparable to the ambient heat transfer coefficient. As a result, the heat transfer from the hot side to the cold side decreased and heat loss increases. The heat loss ratio from MARS solutions with ambient heat transfer coefficients was 18.6%. Comparing that to the heat loss ratio from experiments, we obtained the variation of 4.6%. Due to insulation of the test loop, we need to use the lower ambient heat transfer coefficient than those we assumed. With the use of low ambient heat transfer coefficient, we expect this variation to be smaller. In conclusion, the physical phenomena in the PCHE, which we mentioned using Fig. 2, are appropriate. We can say that low heat transfer coefficients of superheated steam cause considerable heat loss in experiments.

3. Conclusions

Superheated steam was produced in the He-Water boiling test loop with the PCHE. Large heat loss was observed during experiments. We performed MARS calculations with heat loss and without heat loss. It turned out that numerical solutions with heat loss were more accurate that those without heat loss. In our experimental range, we concluded that low heat transfer coefficient in superheated steam cause considerable heat loss.

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