Measurement of the Axial Heat Flux Profile of an Electric Heater for Moderator Circulation Test Facility at KAERI

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The Moderator Circulation Test (MCT) facility built at Korea Atomic Energy Research Institute (KAERI) has been used to produce the validation data for CFD tools, by the Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF) techniques[1]. So far non-heating isothermal flow pattern tests and numerous heating flow pattern tests up to maximum power of 167 kW under various flow and inlet temperature conditions have been carried out[2]. As a part of this test several spare electric heaters the same as those used for MCT were modified and refabricated to install the thermocouples(TCs) to measure the axial heat flux distribution of them. This was to confirm how close the actual axial heat flux distribution of the electric heaters used in MCT facility is to the axial heat flux of the electric heater as designed for the MCT test, and hopefully to provide the accurate thermal boundary condition to the CFD simulations of MCT. The procedure how the heat flux was measured using TCs, and the results obtained are described, discussed and two other alternative methods to compensate the drawback of this method, i.e., tiny bubble distribution observation and electric resistance measurement, are described, and the results presented. It is concluded that the heat flux measurement using TCs across the stainless cladding pipe could be easily faulty due to the nature of the electric heater using heating wire, and the electric resistance measurement method is more reliable and the bubble distribution observation on the heater cladding could be another way to qualitatively confirm the axial heat flux distribution of the heaters.

2. Motivation and Current Status

One of the important test boundary conditions that has not been confirmed was the axial heat flux profile of the electric heaters used for MCT. So it was decided to set up an experimental facility where the axial heat flux of the heaters used at MCT can be measured. In this paper three different methods measuring the axial heat flux distribution of the heater actually tested are presented.

2.1 Measurement of the heat flux using TC readings

The most plausible and simplest method to measure the heat flux across a thin metal plate is to measure the temperature difference across the plate using TCs, and this is what has been tried in this test. The stainless steel or carbon steel pipes where two vertical holes of different depth very close to each other are drilled and two TCs are installed at those axial positions which correspond to the axially middle position of each 12 different heater segments which correspond to the 12 CANDU fuel bundle in a fuel channel. The way how TC holes are made and depth measured, and how TC readings are recorded via DAS data logging system was described in the previous paper of the same authors[3]. Figure 1 shows the electric heater wiring density according to the channel no, and Figure 2 shows the axial heat flux distribution of the heater in figure and tables. The actually measured TC temperature difference (or equivalently the heat flux) at 12 positions denoted by fuel channel no. are shown in Figure 3.

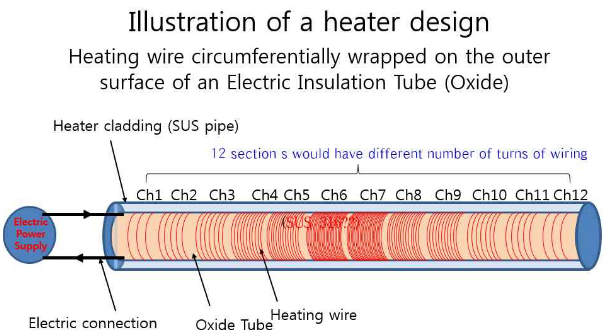
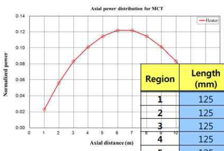


Fig. 1. Schematics of the electric heater design

- Total power: 3 kW
  - 12 section-wise power fraction is almost symmetric as shown.



Region	Length (mm)	Heated region(mm)	Un-heated region(mm)	Heating ratio	Outside Diameter(mm)	Heat capacity (W)	Power density (W/cm2)
1	125	100	25	0.023	33	69	0.67
2	125	125	0	0.056	33	168	1.30
3	125	125	0	0.083	33	249	1.92
4	125	125	0	0.101	33	303	2.34
5	125	125	0	0.115	33	345	2.66
6	125	125	0	0.122	33	366	2.82
7	125	125	0	0.122	33	366	2.82
8	125	125	0	0.115	33	345	2.66
9	125	125	0	0.101	33	303	2.34
10	125	125	0	0.083	33	249	1.92
11	125	125	0	0.056	33	168	1.30
12	125	100	25	0.023	33	69	0.67
합계	1500	1450	50	1.000	33	3000	

Fig. 2. Segment-wise thermal power fraction of the electric heater (Normalized axial power distribution)

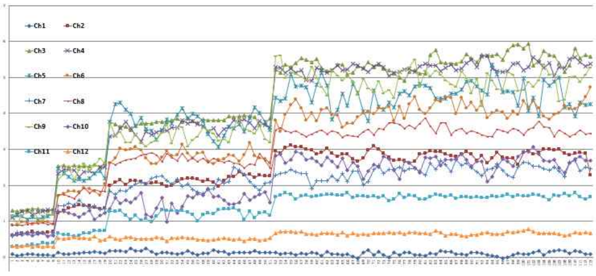


Fig. 3. Measured channel-wise heat flux distribution

Surprisingly the order of the channel from the highest heat flux was channel 3, channel 4, channel 9, channel 5, channel 6, channel 8, channel 2, channel 10, channel 7, channel 11, channel 12, channel 1 at the highest total power level of the heater. The reason for this unexpected order of the heat flux of the various segment was conjectured that the depending on whether the axial location of the TC holes falls to the position right above the electric heater wire or not, the heat flux could be quite arbitrarily different, and not necessarily proportional to the designed heat flux,
Therefore, other ways of confirming the axial heat flux distribution were devised, and described in the following sections.

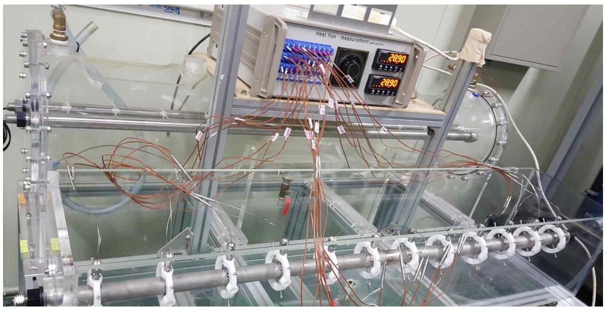


Fig.4. The Experimental Setup of the heat flux measurement using TC

2.2 Visual Observation of the bubble density distribution on the heater surface

As more densely the bubble will be generated on the heater surface with higher heat flux, the heater total power was raised to such a degree that the water temperature reaches high enough so that the bubble population density at the heater surface can be clearly visible and pictures were taken.

Fig. 5. Visually Observed Bubble Density Distribution at the Heater Surface

2.3 On-Power Electric Resistance Measurement of the 12 Heater Segments

As it was confirmed from the observation of bubble population on the heater surface that the axial heat flux distribution of the electric heater qualitatively matches to that of the designed heat flux distribution, the only possible way of confirming the heat flux left was concluded as the in situ measurement of the electric resistance of each heater segment at on-power. So the electric voltage drop of each segment, and the total voltage drop were measured and the electric resistance of each segment was calculated. The heating power profile, or equivalently the electric resistance profile estimated this way agrees reasonably well to the designed heat flux profile of the heater used as shown in Table 1.

Fig. 6. The electric heater used to measure the segment-wise electric resistance

Heater Voltage Drop Test

Date: 2018/03/02

Engaged power: Mesured at DPU
Total Voltage Drop: Measured by Multimeter
$\Delta V_1 \sim \Delta V_{12}$: Each Segment Voltage Drop
$\Sigma \Delta V_i$: Summation of the segment-wise Vtg Drop
Resistance: Voltage Drop/DPU Indicated Current

Engaged Power [kW]	Current[A]	Currentmeter)[A]	Total Voltage Drop [V]	ΔV_1	ΔV_2	ΔV_3	ΔV_4	ΔV_5	ΔV_6	ΔV_7	ΔV_8	ΔV_9	ΔV_{10}	ΔV_{11}	ΔV_{12}	$\Sigma \Delta V_i$
				Unit: V												
0.5	5.3	5.8	93.8	2	5.1	8	9.8	10.8	11.4	11.7	10.4	9.8	8.1	4.8	1.6	93.5
				Unit: Ω												
			전체 저항 [Ω]	ΔR_1	ΔR_2	ΔR_3	ΔR_4	ΔR_5	ΔR_6	ΔR_7	ΔR_8	ΔR_9	ΔR_{10}	ΔR_{11}	ΔR_{12}	$\Sigma \Delta R_i$
Used in Calc. Curent	DPU Indicated Current		17.6981132	0.37735849	0.96226415	1.50943396	1.8490566	2.03773585	2.1509434	2.20754717	1.96226415	1.8490566	1.52830189	0.90566038	0.30188679	17.6415094
	Hook meter Meas. Curren		16.1724138	0.34482759	0.87931034	1.37931034	1.68965517	1.86206897	1.96551724	2.01724138	1.79310345	1.68965517	1.39655172	0.82758621	0.27586207	16.1206897

Fig. 7. Sample Data Sheet of an electric resistance measurement at a specified power

Table 1. Comparison of the designed and measured heater power fraction

Axial Seg. Positio	Design Power Fraction	Measured Power Fraction
Ch 1	0.023	0.021
Ch 2	0.056	0.055
Ch 3	0.083	0.086
Ch 4	0.101	0.105
Ch 5	0.115	0.116
Ch 6	0.122	0.122
Ch 7	0.122	0.125
Ch 8	0.115	0.111
Ch 9	0.101	0.105
Ch 10	0.083	0.087
Ch 11	0.056	0.051
Ch 12	0.023	0.017

3. Conclusions

3 different methods of measuring the axial flux profile of the electric heater used for MCT were tested. Measuring the local heat flux using the temperature difference across the heater cladding pipe at the axially middle position of each of the 12 heater segments turned out to be not successful because of the unexpected heat flux level order, and the reason for this result is conjectured to be mismatch of the axial position of the TC holes from the heater wire position underneath. As an alternative method of confirming the heater axial heat flux profile, visual observation of the bubble population on the heater surface was tried, and the observed result qualitatively confirmed that the axial heat flux profile of the heater matches that of the designed profile. Finally to confirm the axial heat flux profile, the electric voltage drop of the heating wire of each heater segment was measured at various powers, and the resistance of each heater segment was estimated from the voltage drop, and the heating power of each heater segment could be estimated from the resistance.
The heating power profile, or equivalently the electric resistance profile estimated this way agrees reasonably well to the designed heat flux profile of the heater used.

ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (Ministry of Science, ICT, and Future Planning) (No. NRF-2017M2A8A4017283).

REFERENCES

[1] Hyoung Tae Kim, Bo Wook Rhee, and et. al., The isothermal-fluidic field of a secondary moderator jet in a 1/4 scale CANDU-6 reactor model, Nuclear Engineering and Design 323 (2017) 394-406.
[2]Sunghyuk Im, Hyoung Tae Kim, Bo Wook Rhee, Hyung Jin Sung, PIV measurements of the flow patterns in a CANDU-6 model, Annals of Nuclear Energy 98, p1-11 (2016)