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Convective Heat Transfer Enhancement by Spacer Grids in Single-Phase Steam Flow

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1. Introduction

In a nuclear reactor, spacer grids support the fuel rods and maintain proper geometrical configuration of fuel rods within a rod bundle assembly. The spacer grids alternate the thermal-hydraulic behaviors near the spacer grids. They reduce the flow area by contracting the flow area and then expanding it downstream of the spacer grid. Thus, the flow and thermal boundary layers are disrupted and re-established by the spacer grid. This enhances the local heat transfer within and downstream of the spacer grid.

When single-phase steam flow occurs in the early phase of the reflood, the cladding temperature may increase abruptly and reaches usually a maximum value due to the low heat transfer from the fuel to the steam. Hence, it is of importance to investigate the effect of the spacer grid on the heat transfer enhancement in single-phase steam flow. Yao et al. [1] reported that the heat transfer between wall and steam shows the maximum value at the top end of the spacer grid and that the Nusselt number decays exponentially downstream of the spacer grid. They developed an empirical correlation that only takes into account the flow blockage ratio and is applicable for simple egg-crate types of grids.

2. Experimental Facility

Figure 1 shows the a schematic diagram of the 6x6 rod bundle reflood test facility, ATHER (Advanced Thermal Hydraulic Evaluation of Reflood phenomena) where the experiment of the heat transfer enhancement by spacer grids were performed in single-phase steam flow. The ATHER test facility consists of a 6x6 rod bundle test section, a separating system for measuring the amount of entrained liquid droplet, a pressure oscillation damping system to control the system pressure, a coolant supply system, and a steam supply system. A single-phase steam generated in the steam generator was injected into the bottom of the test section. Figure 2 shows the cross-sectional view of the 6x6 rod bundle. The rod bundle consists of 36 heater rods which have prototypic geometry of APR1400. In the figure, G1, G2, and G3 stand for the rod group numbers which have different axial locations of thermocouples (T/Cs) for the measurement of heater surface temperatures. The heated length and diameter of the heater rods are 3.81 m and 9.5 mm, respectively. The heater rods with a pitch of 12.85 mm are located in a 6x6 square array and heated indirectly by AC (alternating current) power. The sheath and heating element of the heater rods are made of Inconel 600 and Nichrome, respectively. A total of eleven Plus-7 spacer grids having the same geometry with those used in APR1400 were installed along the axial location in the rod bundle. For instrumented heater rods, six K-type thermocouples with a sheath diameter of 0.5 mm are embedded on the outer surface of the heater rod to measure the heater rod surface temperature. The total number of thermocouples for measuring the wall temperature of heater rods is 96. A total of 17 thermocouples are installed along the heated section to measure the fluid temperature. The temperatures of flow housing are also measured using thermocouples. The heated section is divided into 15 steps to simulate a symmetric cosine axial heat flux profile. The radial power distribution is uniform so that the heater rods have the same power.

The experiments were carried out by injecting single-phase superheated steam from the bottom of the test section. Provided a steady-state was obtained over sufficiently long period, the experimental data were measured and recorded.

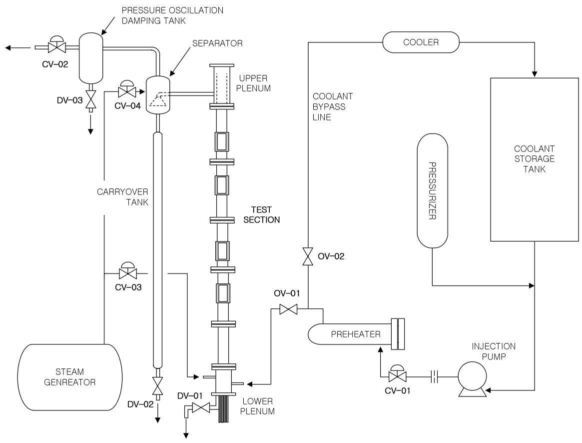

Figure 1 Schematic diagram of ATHER facility

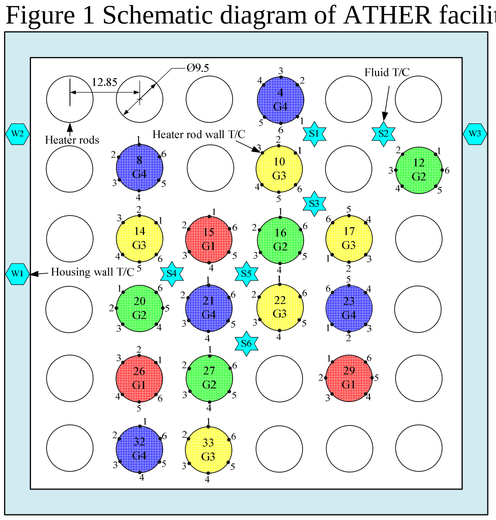

Figure 2 Cross-sectional diagram of test section

3. Heat Transfer Enhancement in Single-Phase Steam Flow

Figure 3 and 4 shows the typical wall temperatures and heat transfer coefficients along the heated length for the steam flow rate of 0.0501 kg/s and the total power of 29.94 kW. The heat transfer coefficient was determined based on the rod bundle average surface temperature, steam temperature, and heat flux. The local Nusselt number, *Nu*, is greatly increased at the spacer grids, and after that it is decreased with the axial distance from the spacer grids. This means that the heat transfer enhancements are significantly large near the spacer grids, and then decreased with downstream distance from the spacer grid.

The conventional correlations for the heat transfer enhancement by spacer grids in single-phase have an exponential decay function and do not take into account hydrodynamic (i.e, Reynolds number) effects. Recently, Miller et al. [2] showed that the decay function is affected by not only the blockage ratio but also the flow Reynolds number. They reported that the heat transfer enhancement decreases with the Reynolds number.

Figure 5 and 6 shows the prediction of heat transfer enhancement factor by the conventional correlations. The heat transfer enhancement factor, *k*, is defined as Nu/Nu_0-1. The Nu_0 means the Nusselt number at locations far downstream from a spacer grid without spacer grid effects. Subscripts *m* and *p* mean the measured and predicted values. While the Yao et al's correlation does not consider the Reynolds number effect on the heat transfer enhancement, it shows reasonable predictions even at low Reynolds numbers.

Even though the Miller et al.'s correlation takes into account the effect of Reynolds numbers on the heat transfer enhancement, it shows an over-prediction of the enhancement factor at low Reynolds number less than 5000. The conventional correlations should be improved for the heat transfer enhancement by spacer grids at low Reynolds numbers.

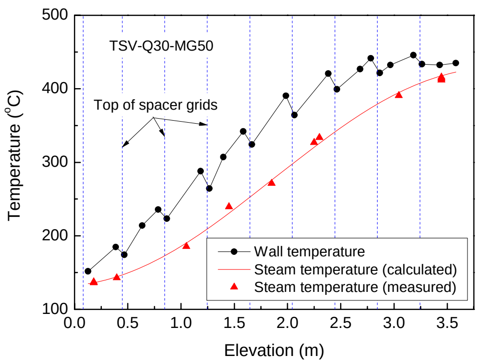

Figure 3 Wall and steam temperatures

4. Conclusions

Experiments have been done to investigate the effects of spacer grids on the heat transfer enhancement in single-phase steam flow during reflood in a nuclear reactor. The heat transfer enhancements were significantly increased near the spacer grids and then decreased with downstream distance from the spacer grids. The conventional correlations of Yao et al. and Miller et al. predicted reasonably the heat transfer enhancement by spacer grids at sufficiently high Reynolds numbers. However, it is necessary to improve the conventional correlations considering Reynolds number effect on the heat transfer enhancement at low Reynolds numbers.

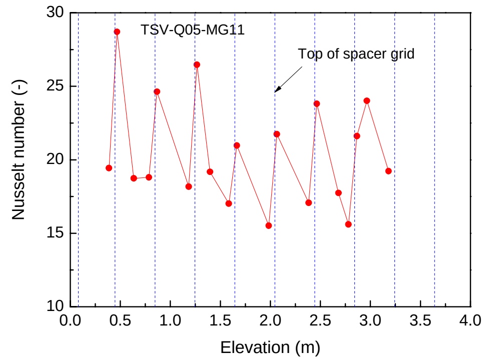

Figure 4 Local Nusselt numbers

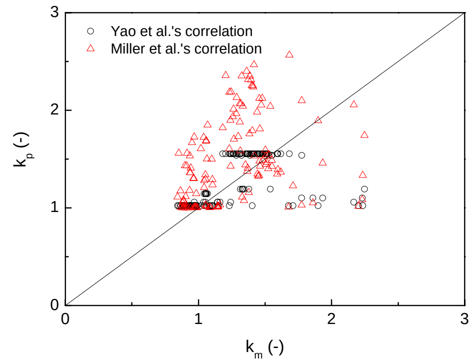

Figure 5 Heat transfer enhancement factor

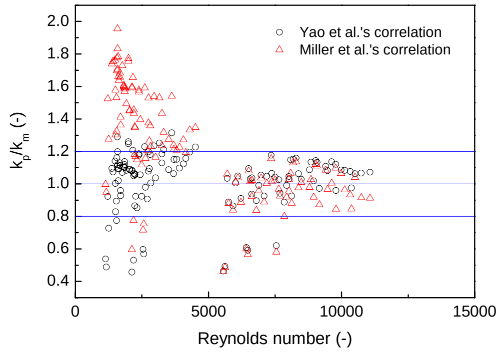

Figure 6 Prediction of heat transfer enhancement

REFERENCES

[1] S. C. Yao, L. E. Hochreiter, and W. J. Leech, Heat-Transfer Augmentation in Rod Bundles Near Grid Spacers, J. Heat Transfer, 104, 76-81, 1982.

[2] D. Miller, F. B. Cheung, and S. M. Bajorek, On the Development of a Grid-Enhanced Single-Phase Convective Heat Transfer Correlation, NURETH-14, Toronto, Canada, September 25-30, 2011.