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Model development of single-phase convective heat transfer to vapor in the partially-blocked rod bundles

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1. Introduction

During the early stage of reflooding phase in a large-break loss-of-coolant accident (LB LOCA) in the pressurized-water reactors (PWRs), the wall-to-vapor convective heat transfer plays an important role on the heat removal process. Several single-phase heat transfer enhancement models have been proposed in the COBRA-TF code [1] which is widely used for reactor safety analysis.

The fuel temperature continue to rise up because the stored energy and the decay heat of the fuel cannot be removed adequately by the poor heat transfer coefficient of the surrounding vapor. The clad of fuel rods may become overheated and experience large strain causing severe flow blockages. The blockages restrict the subchannel flow area thereby significantly altering the hydrodynamic features of the upstream vapor flow. The upstream vapor flow passing through the blocked subchannel is accelerated within and then expanded downstream of the blockage region. The expansion at the top end of the blockage create adverse pressure gradient acting on the flow direction and the thermal-hydraulic boundary layers resulting in the occurrence of flow separation. The flow separation phenomenon in the partially-blocked rod bundle shares resemblance to the flow separation in pipes [2,3,4,5]. The schematics of flow separation and its effect on local heat transfer is presented in Fig.1

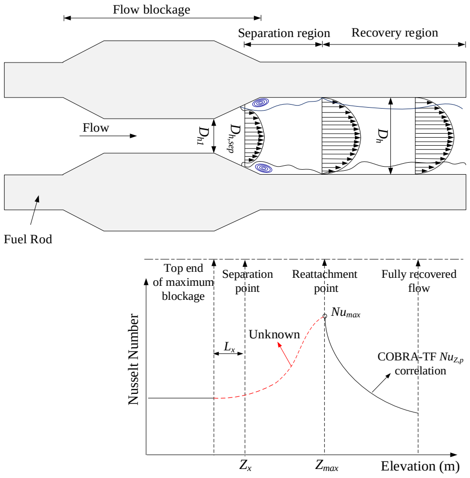

Fig. 1 Flow separation and a promising local Nusselt number profile in the downstream blockage region

A series of experiments on single-phase convective heat transfer to vapor under typical conditions of the early stage of reflooding phase in an LB LOCA considered fuel relocation phenomenon [6] were carried out in the present study. The experimental results were used to develop a new flow blockage correlation.

2. Brief description of experimental setup

Experiments on single-phase convective heat transfer to vapor were performed in the Advanced Thermal-Hydraulic Evaluation of Reflood (ATHER) facility of the Korea Atomic Energy Research Institute. Slightly superheated vapor was injected into the test section through the lower plenum. The vapor flow moved upwards and exited the test section through the upper plenum then released to the ambient environments.

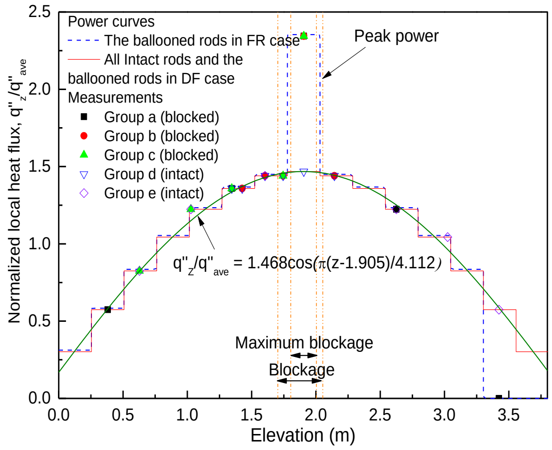

Fig.2 Axial power distributions of the heater rods

A total of 25 heater rods are arranged in a square lattice array with rod-to-rod pitch of 12.85 mm in the test section. The ballooned heater rods with a blockage ratio of 90% are located near the wall to form symmetric geometries along the diagonal of the square lattice array. Experiments for two types of LB LOCA conditions including deformed fuel (DF) and fuel relocation (FR) cases were conducted by using two different sets of heater rod bundles. The net total power of all heater rods were kept almost the same but the power distribution curves were dependent on the test types as shown in Fig. 2

3. Derivation of the new flow blockage correlation

Fig.3 showed derivation of the new flow blockage correlation. The square symbols represent the product of spacer grid and flow blockage effects. The spacer grid model was plotted by the round scatters. Thus, the flow blockage effect was determined by dividing the combined effect by the spacer grid effect, represented as the triangular symbols.

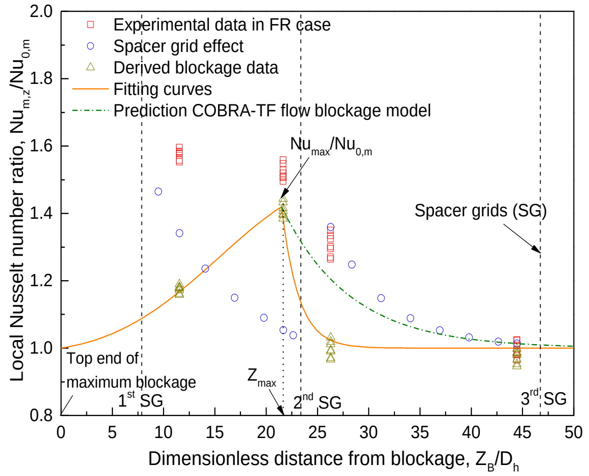

Fig. 3 Derivation of the new flow blockage correlation

The new correlation is supposed to have advantages compared with the conventional flow blockage models in [1]. First, the new correlation is able to predict the local heat transfer in the developing region. Second, the new correlation used the CFD calculation results in [7] to give better prediction of the reattachment point. Finally, the correlation is universal to apply for various flow blockage configurations. The new correlation has the form of a correction factor which is easily adopted into any system codes:

If $Z_B \le Z_{max}$, then

$$\frac{Nu_{p,z}}{Nu_{0,m}} = 1 + \left(\frac{Nu_{max}}{Nu_{0,m}} - 1\right) \times \left(\frac{Z_B}{Z_{\max}}\right) \exp\left(-3\times10^{-3} \times \left(\frac{Z_{max} - Z_B}{D_h}\right)^2\right)$$

If $Z_B > Z_{max}$, then

$$\frac{Nu_{p,z}}{Nu_{0,m}} = 1 + \left(\frac{Nu_{max}}{Nu_{0,m}} - 1\right) \times \exp\left(-\left(1.2 - 0.6\frac{D_h}{D_{h,sep}}\right)\left(\frac{Z_B - Z_{max}}{D_h}\right)\right)$$

where $Nu_{max} = 0.075 \times \left(Re_{max}\right)^{2/3}$ (correlated based on the present experimental data). To apply the correlation to other flow blockage configuration, the correlation for Nu_{max} should be corrected using the correction factor of flow blockage ratio and maximum blockage length assumed as the linear function:

$$K_L = \begin{pmatrix} -0.64\dfrac{L_{B,max}}{L_e} + 1.64 & \text{if } L_{B,max} < L_e \\ 1 & \text{if } L_{B,max} \ge L_e \end{pmatrix}$$

where $L_e = \left(14.3 \times log_{10}(Re_{in}) - 46\right) \times D_h$

$K_{\varepsilon_B} = -1.517\varepsilon_B + 2.365.$

Finally, the universal correlation for maximum Nusselt number can be rewritten as:

$$Nu_{max} = 0.075 \times \left(Re_{max}\right)^{2/3} \times K_{\varepsilon_B} \times K_L.$$

4. Validation of the new correlation

The new flow blockage correlation were validated universally by using various sets of experimental data including the present measurements. Several steam and air cooling data in the partially blocked rod bundle which are collected from [8,9,10], are used in the validation of the new correlation. Fig. 4 present the good prediction of the new correlation with mean error of 5.43% and root-mean-square (RMS) error of 13.01%.

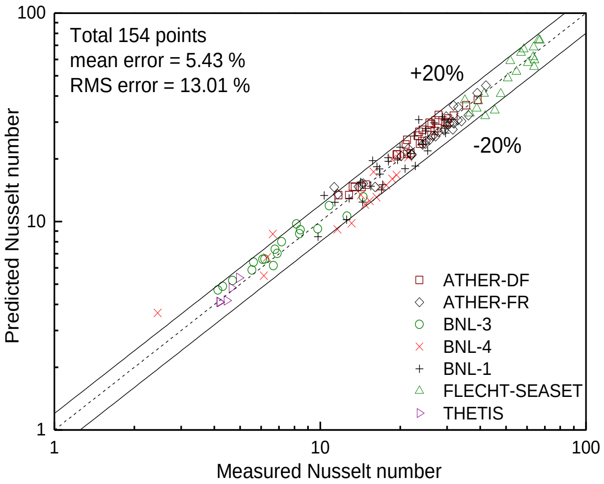

Fig. 4 Validation of the new flow blockage correlation

5. Conclusions

Experiments on single-phase convective heat transfer to vapor have been conducted in 5×5 rod bundles containing 3×3 ballooned heater rods of 90% flow blockage ratio under typical conditions of an LB LOCA in PWRs considered the fuel relocation phenomenon.

A new flow blockage correlation was derived to improve the COBRA-TF flow blockage model. The new correlation was composed of heat transfer enhancement in the separation region and the exponential decay of the heat transfer enhancement in the recovery region.

The new correlation removes the disadvantages of the conventional correlation. The new correlation is universal to apply for various flow blockage configurations. The validation results showed good prediction of the new correlation with mean error of 5.43% and root-mean-square (RMS) error of 13.01%.

NOMENCLATURE

D_h	Hydraulic diameter [m]
L_e	Entrance length of flow in the maximum blockage part [m]
$L_{B,max}$	Maximum blockage length [m]
Nu_{max}	Maximum Nusselt number at the reattachment point [-]
$Nu_{0,m}$	Measured Nusselt number just upstream of spacer grid or flow blockage [-]
$Nu_{p,z}$	Predicted Nusselt number at location of interest downstream of the blockage [-]
Re_{max}	Reynolds number at the reattachment point [-]
Re_{in}	Inlet Reynolds number [-]
Z_B	Location of interest downstream of the blockage [m]
Z_{max}	Reattachment point location [m]
Z_x	Separation point location [m]
ε_B	Flow blockage ratio [-]

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