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Conduction Shape Factor and Turbulent Mixing Rate Between Subchannels in Rod Arrays

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1. Introduction

The prediction of a detailed flow and temperature distribution in a reactor core using a subchannel analysis code is one of the most important parts in the design of a nuclear reactor. To obtain the flow and temperature distributions with a subchannel analysis code, the conservations of the mass, momentum, and energy in a subchannel are modelled and solved. Therefore, it is required to model the inter-subchannel heat transfer between the adjacent subchannels as accurately as possible to enhance the predictability of a subchannel analysis code.

One of the critical parameters which determine the thermal-hydraulic behavior of the coolant in sub-channels is the heat conduction between two neighboring sub-channels. This portion of a heat transfer becomes more important when the flow rate is very low, such as in the case of a blockage accident in an LMR. The other important part of heat transfer is by the turbulent mixing caused by the eddy motion of the fluid across the gap between the subchannels.

In most traditional sub-channel codes, [1] thermal mixing due to a conduction is usually selected arbitrarily by the code users based on their own experience and judgments. This is also true for the prediction of a turbulent mixing of a fluid across the gap between the subchannels. Some enhanced subchannel analysis codes are equipped with the basic turbulent models, which are not enough to describe the anisotropic turbulence generated in rod arrays. Therefore, it is reasonable to determine these factors by considering the influence of the physical parameters. In the present study, major results of recent efforts on these modeling have been implemented in a subchannel analysis code MATRA-LMR-FB [2] and the accuracy of each model is evaluated.

2. Modeling of Heat Transfer

In a subchannel analysis, the minimum control volume is a ‘subchannel’ and it is assumed that the thermal-hydraulic state of a subchannel is constant. Fig. 1 shows a schematic diagram of the rod bundle and flow subchannels in a typical layout of an LMR.

The simplest way to calculate a conduction heat transfer between subchannels is to obtain a heat flux based on channel-averaged temperatures and a center-to-center distance as a characteristic length as follows:

$$Q_{ij} = \sum_j \eta \frac{k}{\delta} S_{ij} \left(\overline{T}_j - \overline{T}_i \right). \tag{1}$$

In the above equation, the factor η is a conduction shape factor which is equivalent to the ratio of an actual heat rate to the reference heat rate. The conduction shape factors have to be determined by taking into account the subchannel geometry, flow conditions, etc. For this, several researchers have evaluated the lumped parameter approach and derived the data for the correction factor mainly through theoretical investigations.

Recently, Jeong et al. [3] evaluated the conduction shape factor with a CFD code for a liquid metal in heated trianglular rod bundles to makeup for the scarcity of experimental data. They fitted their results into the following correlation of the conduction shape factor:

$$\eta = 0.777 \left(\frac{P}{D} \right) \left(\frac{S}{D} \right)^{-0.263}. \tag{2}$$

The turbulent mixing flow rate through a gap between two neighboring subchannel i to j per unit length is described as follows:

$$w'_{ij} = \frac{\rho S_{ij} \overline{\varepsilon}_M}{\delta_{ij}} Y. \tag{3}$$

The rate of turbulent mixing in rod bundles has not been predicted well with a conventional turbulent diffusion theory. This is mainly due to a high mixing rate in compact rod bundles caused by an anisotropic turbulent motion. Therefore, several researchers have concentrated their efforts on developing a useful correlation by taking into account the anisotropic component of turbulence in rod bundles.

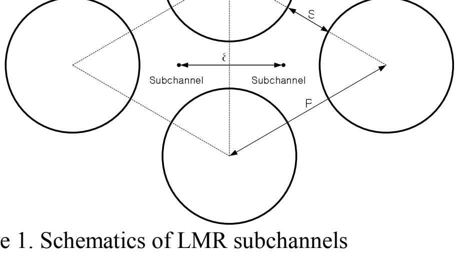

Figure 1. Schematics of LMR subchannels

Among many correlations on turbulent mixing, the following one suggested by Rehme [4] is simple and effectively used for any gap geometry:

$$Y = \frac{0.7}{\left(S_{ij} / D \right)} . \tag{4}$$

It is evaluated that the structure of turbulence due to periodic flow pulsations is incorporated well in the correlation.

More recently, Jeong et al. [5] studied the parameters affecting the turbulent mixing rate in rod bundles. They obtained a useful correlation for a turbulent mixing in rod arrays as a function of only δ_{ij} / D_h as

$$Y_H = 1.5615 \cdot \left(\frac{\delta_{ij}}{D_h} \right)^{2.013} . \tag{5}$$

3. Model Assessment

To assess the appropriateness of the recent advances in the modeling of a conduction shape factor and a turbulent mixing rate, the new models are implemented into the MATRA-LMR-FB code, which has been developed for the thermal-hydraulic analysis of an LMR.

For the assessment, ORNL THORS FFA-2A and FFM-5B [6] tests are selected. In these tests, the spacers are wire-wrapped around the fuel rods whose diameter is 5.842 mm. The diameter of the wire wrap around the internal rods is 1.4224 mm and its diameter around the peripheral rods near the hexagonal duct is 0.7112 mm.

In the FFM-5B test, the rod power was varied in the radial direction. The sodium flow enters from the bottom and passes the entrance region, then the heated section, and finally the exit region where the thermocouples are located. A plate type of blockage is positioned at 101.6 mm from the start of the heated section. About one third of the flow area is blocked at the edge around corner subchannels.

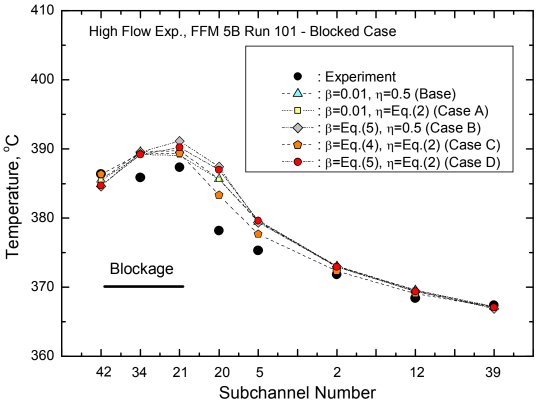

Figure 2. Analysis results for FFM5B high flow case.

In Fig. 2, the FFM-5B Run 101 test is simulated for the various heat transfer parameters. The conduction shape factor affects the temperatures at the boundary of the blockage a little. The outlet temperatures at the subchannels of the blockage boundary are slightly over-estimated with Eq. (5) because the turbulent mixing is slightly underestimated. Rehme's correlation gives better results than the Jeong's correlation but it still underestimates the mixing. These results imply that the turbulent mixing correlations by Rehme or by Jeong need to be reinforced to reflect the effect of the Reynolds number more accurately.

4. Conclusion

Some significant recent studies on the conduction shape factor and the turbulent mixing factor were implemented into a subchannel analysis code MATRA-LMR-FB. The analysis shows that the temperature distribution in a flow path simulating an LMR subassembly was predicted quite accurately without any user dependency in the input preparation for these factors.

The importance of turbulent mixing increases at a higher flow rate. On the contrary, the role of the conduction shape factor becomes more significant at a lower flow rate. Both of the Rehme's and Jeong et al.'s correlations underestimated the turbulent mixing at a high flow rate. More studies are expected to improve the model of a conduction shape factor based on realistic data. The accuracy of a subchannel analysis code is expected to be improved further if we enhance the models for the conduction shape factor and the turbulent mixing factors.

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