Single Phase Turbulent Mixing in Square Rod Arrays at Highly Turbulent Condition

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1. Introduction

When a single-phase flow exists in the subchannels, the mixing of the mass, energy and momentum between the subchannels consists of two parts, the forced mixing and the natural one. The natural mixing again consists of the diversion flow and the turbulent mixing. The diversion flow mixing is mainly caused by the pressure gradient due to flow obstacles such as spacers or due to the density difference. The turbulent mixing, caused by the eddy motion of fluid across the gap between subchannels, enhances the exchange of momentum and energy through gap with no net transport of mass.

When there is no diversion flow or forced mixing flow, the energy transport across a gap between subchannels per unit length in rod bundles is equivalent to

$$q_{ij} = k\left(1+\Pr\frac{\varepsilon_H}{\nu}\right)S_{ij}\left(\frac{\partial T}{\partial n}\right)_S \quad . \tag{1}$$

The above equation means that the energy transfer occurs due to the heat conduction through coolant itself and to the turbulent eddy motion of fluid. At the typical operating condition of a pressurized water reactor (PWR), the second term in the bracket of Eq. (5) is of the order of 10^3. On the contrary, the order of the same quantity for a liquid metal-cooled reactor (LMR) is about 10^{-1}~ 10^0, which implies both the heat conduction and the turbulent mixing play important role in the thermal-hydraulics of LMR.

Many experimental results in rod bundles obtained much higher turbulent mixing rates than those predicted by a conventional turbulent diffusion theory for simple geometry. These experimental results imply that the eddy diffusivity of energy, ε_H for rod bundles is much higher than that obtained in a circular tube. The main cause of the high mixing rate in compact rod bundles is presumed to be the cyclic and periodic flow pulsation.

The most general form of existing correlations on turbulent mixing in rod bundles have been developed with the definition of the mixing factor, Y, which was first suggested by Ingesson and Hedberg [1]. The turbulent mixing factor, Y, is defined in the following equation for heat transfer through the gap per unit length by

$$q_{ij} = \rho c_p \overline{\varepsilon}_M S_{ij}\, Y\, \frac{T_i - T_j}{\delta_{ij}}\,, \tag{2}$$

where $\overline{\varepsilon}_M$ is the reference eddy viscosity obtained in a circular tube.

In the present study, however, some existing mixing data are correlated with the definition of

$$Y_H = \frac{\nu_{eff}\,\delta_{ij}}{\overline{\varepsilon}_H}\,, \tag{3}$$

which satisfies the following exact relation of heat transfer across the gap:

$$q_{ij} = \rho c_p \varepsilon_H S_{ij}\left(\frac{\partial T}{\partial n}\right)_S = \rho c_p \varepsilon_H S_{ij}\frac{T_i - T_j}{z_{ij,H}}\,. \tag{4}$$

2. Analysis

Through some mathematical manipulations, a useful relation of turbulent mixing factor is yielded as follows:

$$Y_H = \left(\frac{\delta_{ij}}{D_h}\right)\cdot\left(\frac{\overline{\varepsilon}_M}{\nu}\right)^{-1}\cdot \mathrm{Re}\cdot\beta\cdot\Pr_t\,. \tag{5}$$

Now, a simple relation on the turbulent mixing factor, Y_H can be obtained if we have general expressions on the eddy diffusivity and the turbulent mixing coefficient, β .

2.1 Eddy diffusivity and mixing Stanton Number

As suggested by several previous researchers, we can evaluate the reference eddy viscosity expressed by

$$\frac{\overline{\varepsilon}_M}{\nu} = \frac{\mathrm{Re}}{20}\sqrt{\frac{f}{8}}\,, \tag{6}$$

where f is the Darcy friction factor. Further, Kays [2] proposed an empirical equation of friction factor in a circular tube applicable over the range $3\mathrm{x}10^4 < \mathrm{Re} < 10^6$ as follows:

$$f = 0.184\cdot \mathrm{Re}^{-0.2} \quad . \tag{7}$$

Therefore, a reference eddy viscosity for $3\mathrm{x}10^4 < \mathrm{Re} < 10^6$ is given by

$$\frac{\overline{\varepsilon}_M}{\nu} = 0.00758\cdot \mathrm{Re}^{0.9}\,, \tag{8}$$

The experiments by Rowe and Angle [3], Castellana [4], and Seale [5] were performed at Reynolds numbers higher than $3.0\mathrm{x}10^4$ using the exit temperature or enthalpy measurement in square rod arrays. In these experiments, the error on turbulent mixing rate induced by measurement technique itself is much less than the experiment using tracer technique. Even though there exists some scattering in turbulent mixing coefficient, all the experimenters who measured the mixing coefficients at Reynolds number higher than 3.0x10^4 commonly summarized their experimental data into the form of

$$\beta = A \cdot \mathrm{Re}^{-0.1} . \quad (9)$$

Now, the Eq. (5) is converted to

$$Y_H = \frac{A}{K} \cdot \left(\frac{\delta_{ij}}{D_h} \right) \cdot \mathrm{Pr}_t . \quad (10)$$

By the way, the experimental results suggest that

$$A \cdot \mathrm{Pr}_t \propto \left(\frac{\delta_{ij}}{D_h} \right). \quad (11)$$

Considering this dependency, the data are correlated roughly to the following relation:

$$Y_H \approx 2.633 \cdot \left(\frac{\delta_{ij}}{D_h} \right)^2 . \quad (12)$$

2.2 Experimental correlation

A correlation in the form of Eq.(5) is also obtained through the direct evaluation of the experimental data on the turbulent mixing. The same data of β, provided by the previous authors, are used in the evaluation.

All the non-dimensional turbulent mixing coefficients are correlated into the following form as shown in Fig. 1:

$$Y_H = 2.037 \cdot \left(\frac{\delta_{ij}}{D_h} \right)^{2.071} . \quad (13)$$

The same data are correlated with the variable, s/d, into the following expression:

$$Y = 0.7709 \cdot \left(\frac{\mathrm{s}}{\mathrm{d}} \right)^{-0.9978} , \quad (14)$$

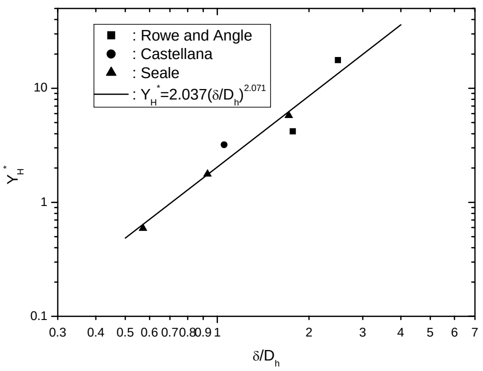

Figure 1. Dependency of turbulent mixing factor on δ / D_h

which is very similar to the Rehme's correlation [6] as shown in Fig. 2.

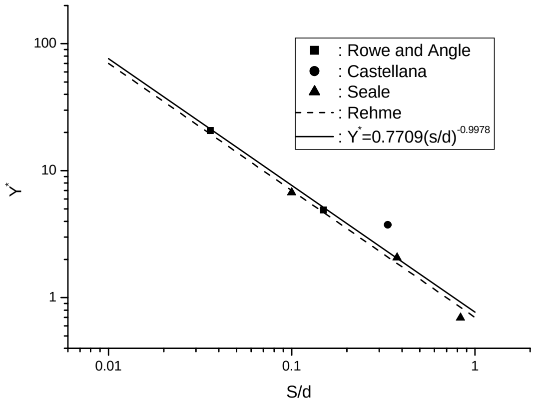

Figure 2. Dependency of turbulent mixing factor on s/d

3. Conclusion

A dominant parameter important to describe the turbulent mixing rate in square rod array has been induced and a simple correlation applicable over the range 3x10^4 < Re< 10^6 has been suggested. This correlation overcomes the inaccuracy of some existing correlations at lower s/d. To exclude the inaccuracy in the measurements, the data obtained with the tracer technique has not been used in the present study.

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