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A new turbulent mixing modeling approach for sub-channel analysis code

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ABSTRACT

Sub-channel code is one of the well-applied numerical tools in nuclear reactor thermal-hydraulics analysis. It takes consideration of the lateral transfer between adjacent sub-channels, which is its distinct characteristic. In most sub-channel codes, only one turbulent mixing coefficient for energy is used to account for lateral turbulent exchange. This imperfect description of the turbulent mixing parameter in different equations (e.g. mass, momentum and energy) significantly affects the accuracy of the calculation result. Besides, the empirical correlations to get the value of this coefficient have limited parameter ranges. In this paper, CFD simulations of two sub-channels in bare rod were performed with large geometry and flow condition ranges. The SSG turbulent model was used to simulate the non-isotropic turbulence and the calculation result was verified with experimental data. Based on the phenomenological analysis and theoretical consideration, a new turbulent mixing modeling approach was developed by studying β_m, β_E and β_M, the turbulent mixing coefficients for mass, energy and momentum, respectively. Three empirical correlations of these coefficients were suggested and compared with existing correlations.

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1. Introduction

In the nuclear reactor design and safety analysis, thermal-hydraulic behavior of the reactor core is of crucial importance. Sub-channel code is one of the well-applied numerical tools for nuclear reactor thermal-hydraulics analysis. In the sub-channel analysis, it divides the entire flow channels into different sub-channels according to certain rules. And it takes consideration of the lateral transfer of mass, momentum and energy between adjacent sub-channels, which is its distinct characteristic and affects the distribution of mass flux and temperature in fuel assemblies.

To get more accurate flow and temperature distributions of the reactor core in the sub-channel analysis, the models of the transversal flow should describe the lateral mass, energy and momentum exchange properly. One of the important processes of the lateral exchange is due to turbulent mixing, also called the turbulent diffusion, which is caused by the eddy motion of the turbulence (Todreas and Kazimi, 1990).

In this work, only the turbulent mixing in single phase flow is taken into account. In consideration of the complexity in two phase flows, it is much easier to separate the turbulent mixing from other transversal flow in single phase so that the phenomenon and mechanisms can be studied. In the sub-channel analysis code, the two-phase mixing coefficient is estimated by multiplying the single-phase mixing coefficient by a two-phase multiplier (Beus, 1972; Faya et al., 1979). Therefore, the single phase turbulent mixing model paves a way for the further study of the two-phase mixing model.

To describe the turbulent mixing, different definitions of the mixing parameters are developed. The most general one, the turbulent mixing coefficient β, as suggested by Row and Angle (Rowe and Angle, 1967), describes the ratio of the lateral flow fluctuation and the axial flow. It can be written as follows:

$$\beta = \frac{G'}{\bar{G}} \tag{1}$$

And G' is the average amplitude of turbulent fluctuating mass flux, $\bar{G}$ is the average axial mass flux of two adjacent sub-channels and is given by:

$$\bar{G} = \frac{A_i G_i + A_j G_j}{A_i + A_j} \tag{2}$$

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Nomenclature

A	Sub-channel flow area (m^2)
A_g	area of the interface between two sub-channels (m^2)
c_p	specific heat at constant pressure (J/kg·K)
D	rod diameter (m)
F_M	momentum flux (kg/m·s^2)
F_t	turbulent momentum factor (–)
G	axial mass flux (kg/m^2·s)
h	Enthalpy (J/kg)
k	turbulent kinetic energy (m^2/s^2)
l	the overall effect mixing length (m)
l'	The local effect mixing length (m)
P	rod pitch (m)
Pr_t	turbulent Prandtl number, $\varepsilon_M/\varepsilon_H$ (–)
q	heat flux (J/ m^2·s)
Re	Reynolds number (–)
S	gap size (m)
T	temperature (K)
w	axial velocity (m/s)
$\bar{w}$	average axial velocity (m/s)
u'	lateral fluctuating velocity (m/s)
$\overline{\lvert u'\rvert}$	average amplitude of the lateral fluctuating velocity (m/s)
$\overline{u'u'}$	RMS value of velocity fluctuation (m^2/s^2)
u^*	equivalent lateral velocity (m/s)
G'	lateral fluctuating mass flux (kg/m^2·s)
G^*	equivalent lateral mass flux (kg/m^2·s)

Greek symbols

β	turbulent mixing coefficient (–)
ε_H	eddy diffusivity for energy (m^2/s)
ε_M	eddy diffusivity for momentum (m^2/s)
τ	turbulent shear stress (kg/m·s^2)

Subscripts

E	energy
i	sub-channel i
ij	from sub-channel i to j, between the sub-channel i and j
j	sub-channel j
m	mass
M	momentum
TM	turbulent mixing

In sub-channel analysis, the lateral exchanges are treated as the source terms in the conservation equations of each sub-channel. The source terms for the lateral exchange of mass, heat and momentum is presented by the following three equations, respectively:

$$\dot{G} = u^* \cdot (\rho_i - \rho_j) \tag{3}$$

$$q_{TM} = G_E^* \cdot (h_i - h_j) \tag{4}$$

$$F_M = G_M^* \cdot (u_i - u_j) \tag{5}$$

The equivalent quantities u^* and G^* in Eqs. (3)–(5) represent the equivalent amplitude of turbulent fluctuation of transversal velocity and turbulent fluctuation of mass flux for heat and momentum exchange.

Similar to Eq. (1), the turbulent mixing coefficient for mass, energy and momentum can be defined to describe the equivalent mass flow rate:

$$u^* = \beta_m \cdot \bar{w} \tag{6}$$

$$G_E^* = \beta_E \cdot \bar{G} \tag{7}$$

$$G_M^* = \beta_M \cdot \bar{G} \tag{8}$$

Then, Eqs. (3)–(5) can be written as:

$$\dot{G} = \beta_m \cdot \bar{w} \cdot (\rho_i - \rho_j) \tag{9}$$

$$q_{TM} = \beta_E \cdot \bar{G} \cdot (h_i - h_j) \tag{10}$$

$$F_M = \beta_M \cdot \bar{G} \cdot (w_i - w_j) \tag{11}$$

These three coefficients β_m, β_E *and* β_M can't be determined directly in experiments. In conventional sub-channel code, these three coefficients are taken the same values.

For example, in the sub-channel code COBRA IV and its improved versions, usually it is assumed that there is no density difference between the sub-channels in single phase, the net mass flux across the gap is zero. β_E is applied into the energy and axial momentum conservation equation. The heat flux can be expressed by Eq. (10) and momentum flux caused by turbulent mixing can be expressed by (Stewart et al., 1977):

$$F_M = F_t \cdot \beta_E \cdot \bar{G} \cdot (u_i - u_j) \tag{12}$$

The turbulent momentum factor F_t is a factor to account for the difference between turbulent transport of thermal energy and momentum.

The coefficient β_E is defined in this paper as the turbulent mixing coefficient for energy, it should be differentiated from β. In the available literature, when β is mentioned, it means always β_E since the heat transfer between sub-channels is focused on. These two coefficients will be discussed in the new modeling approach, and all the β mentioned in the literature will be written as β_E in this paper.

Some experimenters measured the equivalent mass flow rate G_E^* using the tracer technique (Sadatomi et al., 2004; Singh, 1972), under the assumption that there is only turbulent mixing after eliminating the diversion crossflow. It can be considered that the change of the tracer concentration is caused only by the turbulent mixing, since the molecular diffusion can be neglected compared to the magnitude of the turbulent diffusion. Then G_E^* can be acquired by measuring the tracer concentration and β_E can be deduced from Eq. (7) as:

$$\beta_E = \frac{G_E^*}{\bar{G}} \tag{13}$$

Another way to get the value of β_E is by measuring the turbulent heat transfer between the subchannels. Eq. (10) can be written as:

$$\beta_E = \frac{q_{TM}}{\bar{G} \cdot (h_i - h_j)} \tag{14}$$

where h_i and h_j are averaged enthalpies of each sub-channel. The point is how to get the heat transfer caused by the turbulent mixing. For bare rod bundle, it has no effect of grid spacer or wire wraps, the energy transferred across a gap just consists of natural mixing and heat conduction as follows:

$$q_{ij} = q_{diversion} + q_{TM} + q_{conduction} \tag{15}$$

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