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Modeling of spacer grid mixing effects through mixing vane crossflow model in subchannel analysis

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HIGHLIGHTS

- The improvement of the mixing vane crossflow model in subchannel analysis was presented.
- The improved model satisfactorily predicts the qualitative trends for flow in rod bundle, and also predicts the values of crossflow better than those of the conventional code.

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ABSTRACT

Spacer grids, especially those with mixing vanes or other mixing devices in the rod bundle, have great influence on local flow fields in the reactor core. This mixing effect has been demonstrated by both experimental and numerical simulations, however, the spacer grids' effect on flow field is not well reflected in most subchannel codes that are currently used as main instruments in calculating local conditions and safety analysis for the nuclear industry. This paper focuses on improvement of the mixing vane crossflow model in subchannel analysis for simulating the mixing effects of spacer grids. The distributed resistance method (DRM) is applied, and the source terms associated with the spacer grids are added to momentum equations to account for the mixing vane grids' influence on local flow fields in rod bundles (U.S. patent, application number: 61841961, confirmation number: 8224; U.S. patent, application number: 62375023, confirmation number: 2306; Chinese patent, application number: 201611179395.1). The improved DRM model is used to analyze the thermal hydraulic performance in the 5×5 rod bundle. The calculation results are compared with experimental data and CFD simulation results respectively. The subchannel calculation results are also compared with those from the conventional code without the DRM model. The flow characteristics, such as the crossflow direction, the crossflow values at grid zone, and the decay trend of the crossflow downstream of the mixing vane grid are analyzed. The improved mixing vane crossflow model is assessed by comparison analysis, and some conclusions are obtained.

1. Introduction

In most PWR designs, spacer grids are proposed to keep the fuel rods in fixed positions. Besides structural support, spacer grids also promote inter-subchannel mixing in rod bundles. Spacer grids with mixing vanes contribute to crossflow mixing in rod bundles, which has been demonstrated by both experimental and numerical studies (Shen et al., 1991; In et al., 2002; Karoutas et al., 1995; Navarro and Santos, 2011; Yang et al., 2016; Zhang et al., 2015). Shen et al. (1991) performed experiments in a 4×4 rod bundle to investigate crossflow mixing effect caused by spacer grids. The experimental data shows that mixing vanes on spacer grids play a distinct role in the sweeping flow of the coolant, and the mixing rate depends on the angle of the mixing vanes. In et al. (2002) explored flow field characteristics in a 5×5 rod bundle with split vane grid by CFD simulation. The calculation results show that the lateral velocity produced by the mixing vane is highest near the spacer grid, but decreases significantly further downstream of the spacer grid. This finding directly correlates to the measurements of lateral mean velocities conducted by Karoutas et al. (1995). Navarro and Santos (2011) simulated the flow performance in a PWR 5×5 rod bundle with a split vane grid by the commercial code CFX, and compared the calculation results with both Karoutas et al.'s experimental data (Karoutas et al., 1995) and previous CFD simulations conducted by In et al. (2002). The comparison shows that the qualitative and quantitative behaviors of the lateral velocities obtained in the CFX simulation show reasonable agreement with

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Nomenclature

Δp	pressure drop of spacer grid
K	effective loss coefficient
m_i	axial mass flow rate of subchannel i
ρ_i	flow density of subchannel i
A_i	flow area of subchannel i
W_{ij}	crossflow per unit length
ΔX	axial calculation increment
F_u	axial component of the force exerted by the rod surface
F_v	lateral component of the force exerted by the rod surface
F_{u1}	tangential component of the force exerted by the mixing vane
F_{v1}	normal component of the force exerted by the mixing vane
A'_W	total wetted solid surface area of the subchannel including the mixing vane
A_R	wetted solid surface area of the subchannel excluding the mixing vane
V_{total}	local velocity in the subchannel
θ	angle between the rod axial and the local velocity direction
α	angle between the rod axial and the mixing vane's tangential direction
u	rod axial component of the local velocity
v	rod lateral component of the local velocity
u_1	mixing vane tangential component of the local velocity
v_1	mixing vane normal component of the local velocity
F_A	total axial force
F_L	total lateral force
A	the flow area of the subchannel
D'_V	equivalent hydraulic diameter including the mixing vane
D_V	equivalent hydraulic diameter without the mixing vane
P	rod-to-rod pitch
S	gap width
z	axial height
D_h	hydraulic diameter of the 5×5 rod bundle
$W(i,j)$	crossflow between subchannel i and subchannel j

the experimental profiles, and better agreement than previous CFD simulations near the mixing vane grid (MVG).

MVGs in rod bundle will cause great effect on local flow field and local parameter conditions, and accurate prediction of MVGs' effect on flow field is essential to the prediction of rod bundle local parameter conditions and reactor core safety evaluation. Various types of models have been proposed to predict the effect of MVGs on flow field in subchannel analysis.

In the first generation of subchannel codes COBRA (Rowe, 1967), the contribution due to diversion crossflow is zero under the assumption of a totally ventilated bundle cross section, and only turbulent mixing is considered. This approach is acceptable for the capsuled BWR rod bundles, which differs tremendously from PWR rod bundles, especially when MVGs are installed in PWR rod bundles. In the later version of COBRA series, COBRA-II (Rowe, 1970), the pressure drop from spacer grids are lumped into an effective loss coefficient K which is defined as

$$\Delta P = \frac{K}{2\rho_i}\left(\frac{m_i}{A_i}\right)^2 \tag{1}$$

where m_i is the axial mass flow rate, ρ_i is the flow density and A_i is the flow area of subchannel i. The value of the effective loss coefficient, K, comes from experimental data with specific type of spacer grids, and it is difficult to expand to other types of spacer grids. Additionally, the effective loss coefficients only reflect spacer grids' mean axial effect and neglect spacer grids' effect in the transverse direction. This method considering the spacer grids' effect on flow field did not change too much in the COBRA series' subchannel codes until the release of COBRA-IIIC. In COBRA-IIIC (Rowe, 1973), the finite difference scheme allows forced diversion crossflow to be specified. This feature allows the forced crossflow mixing from MVGs or wire wraps to be considered in COBRA-IIIC. Hence, another parameter, flow diversion fraction, was proposed besides the effective loss coefficient to reflect the influence of MVGs on flow field. When subchannel grid spacer losses are specified for input to COBRA-IIIC, a flow diversion fraction is specified where the fraction is defined by the ratio

$$\begin{array}{ll} W_{ij}\Delta X/m_i, & \text{if} \quad W_{ij} > 0 \\ W_{ij}\Delta X/m_j, & \text{if} \quad W_{ij} < 0 \end{array} \tag{2}$$

where W_{ij} is the crossflow from subchannel i to subchannel j per unit length, ΔX is the axial calculation increment, and m_i and m_j are the axial mass flow rates for subchannel i and subchannel j respectively. The positive/negative signs of W_{ij} indicate whether it flows from subchannel i to subchannel j or vice versa. Just as D. S. Rowe claimed in the report (Rowe, 1973), this method of forced crossflow should be considered tentatively until experimental data are available to check the validity. In fact, this method tries to describe the phenomenon in general terms instead of reflecting the actual generation mechanism of crossflow. The values of flow diversion fractions are sensitive to flow conditions and are completely empirical, with a relatively large range of uncertainties. Besides, it is very difficult to expand the values of flow diversion fractions to different types of MVGs with not only mixing vanes of different shapes, sizes, directions, angles, and configurations, but also different designs.

In ASSERT-PV, two methods are available to deal with the effects of spacer grids on flow field in rod bundle: constant and variable (geometry-based) k-factors (Rao et al., 2014). Constant k-factors are form loss coefficients that the user specifies for each subchannel and axial plane. The variable, or geometry-based k-factors, are form loss coefficients to be calculated from the user-specified geometrical information. In addition, an obstruction factor is introduced to account for the influence of spacer grids on inter-subchannel turbulent mixing. Inter-subchannel turbulent mixing is modelled empirically using the method described by Carlucci et al. Carlucci et al. Carlucci et al. (2004), which assumes that the total inter-subchannel mixing rate is constituted of two independent components: the homogeneous component (for single-phase or homogeneous flow) and the incremental (two phase) component.

$$w'_l = w'_{l,\text{hom}} + w'_{l,inc} \tag{3}$$

$$w'_g = w'_{g,\text{hom}} + w'_{g,inc} \tag{4}$$

Since obstructions are expected to homogenize the flow downstream, the obstruction factor is assumed to increase the homogeneous component of mixing, and to decrease the incremental component. Hence, the homogeneous component is multiplied by the obstruction factor and the incremental component is divided by the obstruction factor to take into account the spacer grids' effect on turbulent mixing. The obstruction factor is defined by Leung and Novog (Leung and Novog, 2012) as

$$(F_{obs})_{k,j} = \left[1 + a_{obs}k\exp\left(-b_{obs}\frac{x_d}{D_e}\right)\right]_{k,j} \tag{5}$$