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CFD simulation of swirling flow induced by twist vanes in a rod bundle

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ABSTRACT

Swirling flow induced by the twist vanes can enhance the heat transfer in the rod-bundle fuel assembly. In order to investigate accuracy of the k-ε models in predicting the swirling flow in a rod bundle subchannel, the CFD simulations with the standard and realizable k-ε model are benchmarked with In et al.'s experiment. The nonlinear closure models are utilized with the standard k-ε model to account for the curved and rotational flow, while the curvature correction model is employed in the realizable k-ε model. Comparison with the experiment indicates that the CFD simulations predict the relatively large core region of swirling flow. Utilization of the nonlinear closure models in the standard k-ε model leads to the larger initial angular momentum. The curvature correction in the realizable k-ε model reduces the initial angular momentum, but it does not affect the decay rate, which indicates that the curvature correction is effective near the twist vanes where the flow curvature is strong. The decay rate of swirling flow is generally overestimated by all the models. The cross-flow velocity profile in the gap is affected by prediction of swirling flow separation from rod surface. The cubic and quadratic closure model can improve turbulence modelling in the core of swirling flow, especially near the spacer, where the linear closure models significantly underestimate the production of turbulence. However, in the further downstream all the models underestimate the turbulence intensity in the swirling core, as a consequence of low-frequency large-scale flow structure in the core region. Underestimation of turbulence in the annular and wall region will result in the underestimation of wall heat transfer and inter-subchannel mixing.

1. Introduction

In water-cooled nuclear reactors fuel rods are assembled with spacer grids as rod-bundle fuel assembly. Coolant flows through the space between rods vertically and removes heat generated in the fuel rods. Natural mixing, including flow pulsation, between neighboring subchannels (Rehme, 1992; Rowe et al., 1974) and secondary flow in the subchannel are intrinsic mechanisms enhancing mixing in a subchannel or between neighboring subchannels. The mixing vanes, usually located on the spacer grid, are introduced to further enhance mixing and heat transfer in the fuel assembly.

Numerous experiments have been carried out to measure the flow mixing downstream of the spacer grid and the mixing vanes, e.g. (Caraghiaur et al., 2009; Chang et al., 2012; Conner et al., 2013; Dominguez-Ontiveros and Hassan, 2009; Hille et al., 2013; In et al., 2015; Li et al., 2018; McClusky et al., 2002; Shen et al., 1991; Wells et al., 2015; Xiong et al., 2018; Xiong et al., 2014a; Xiong et al., 2014b; Yang and Chung, 1995). In order to validate the computational fluid dynamics (CFD) and establish the best practice guideline for the CFD practitioners, several benchmark activities have been organized. The MATiS-H benchmark coordinated by OECD/NEA was based on the flow measurement experiments in a 5x5 rod bundle with split-type and swirl-type mixing vanes in which the axial flow velocity and lateral cross flow velocities are measured in the selected subchannels (Chang et al., 2012). The CFD simulation results and the experiment measurement were compared at two cross sections, i.e. $1D_h$ and $4D_h$ downstream of the spacer grid. Another CFD benchmark for rod bundle flow was coordinated by the Electric Power Research Institute (EPRI) based on the dataset from the NESTOR experimental program. In the EPRI benchmark the CFD results is validated for the axial mean and root mean square (RMS) velocities (Kang and Hassan, 2016). More recently, (Nguyen and Hassan, 2017) utilized time-resolved stereo PIV to measure the flow field downstream of mixing vanes and studied the vortex shedding downstream of mixing vanes.

(In et al., 2015) measured the cross flow induced by a spacer grid installed with twist vanes in the central subchannel of a 4x4 rod bundle. Based on the experimental data contributed by (In et al., 2015), the International Atomic Energy Agency (IAEA) coordinated research project (CRP) entitled "Application of CFD Codes for Nuclear Power Plant Design" have initiated a benchmark. As the effort contributed by Shanghai Jiao Tong University (SJTU) in the framework of this CRP, the accuracy of standard and realizable k-ε model in predicting the swirling flow induced by the twist vanes is investigated based on Star-CCM+. The nonlinear closure models are utilized with the standard k-ε model to account for the curved and rotational flow, while the curvature correction model is utilized in the realizable k-ε model. The decay of

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Nomenclature

D	Rod diameter, mm
D_ε	Dissipation rate of ε, m^2/s^4
k	Turbulent kinetic energy, m^2/s^2
P_k	Production term of k transport equation, $kg/m/s^3$
P_ε	Production term of ε transport equation, m^2/s^4
Re_t	Eddy-size based Reynolds number, $k^2/\varepsilon\nu$
Re_y	Wall-distance based Reynolds number, $\sqrt{k}y/\nu$
S	Modulus of the mean strain rate tensor, $\sqrt{2S_{ij}S_{ij}}$, s^{-1}
S_{ij}	Mean strain rate tensor, $\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)$, s^{-1}
T	Turbulent time scale, s
U	X velocity, m/s
U_i	Mean velocity, m/s
u_i	Fluctuating velocity, m/s
U_{rms}	RMS velocity in x direction, m/s
U^*	$\sqrt{S_{ij}S_{ij}-\Omega_{ij}\Omega_{ij}}$, s^{-1}
$\overline{u_iu_j}$	Reynolds stress, m^2/s^2
V	Y velocity, m/s
v	Fluctuating velocity in y direction, m/s
v_θ	Fluctuating velocity in tangential direction, m/s
v_r	Fluctuating velocity in radial direction, m/s
V_{rms}	RMS velocity in y direction, m/s
W	Z velocity, m/s
w	Fluctuating velocity in z direction, m/s
W_{rms}	RMS velocity in z direction, m/s
δ_{ij}	Kronecker delta
ε	Dissipation rate of k, m^2/s
ϕ	$\frac{1}{3}\arccos(\sqrt{6}\omega)$
μ_t	Eddy viscosity, kg/m/s
ρ	Density, kg/m^3
ω	$S_{ij}S_{jk}S_{ki}/(\sqrt{S_{ij}S_{ij}})^3$
Ω	Modulus of the mean rotation rate tensor, $\sqrt{2\Omega_{ij}\Omega_{ij}}$
Ω_{ij}	Mean rotation rate tensor, $\frac{1}{2}\left(\frac{\partial U_i}{\partial x_j}-\frac{\partial U_j}{\partial x_i}\right)$, s^{-1}

swirling flow and evolution of turbulence in the swirling flow are also investigated.

2. Turbulence modelling

2.1. Closure model

Direct numerical simulation (DNS) and large eddy simulation (LES) have been mainly applied to study the fully developed flow in bare rod bundle, e.g. (Mayer et al., 2007), (Baglietto et al., 2006) and (Ikeno and Kajishima, 2010). LES has also been tested in the benchmarks with mixing vanes, e.g. the MATiS-H benchmark. In the swirl-type mixing vane case of the MATiS-H benchmark LES shows superiority over the Reynolds-averaged Navier-Stokes (RANS) and unsteady RANS models. While the opposite conclusion was obtained for the split-type mixing vanes (Lee et al., 2012). Recently, (Busco and Hassan, 2018) employed the partially-averaged Navier-Stokes (PANS) model to simulate the turbulence in a 5x5 rod bundle and showed the capability of PANS model to resolve the space and energy scales downstream of the spacer. However, from the viewpoint of computation efficiency, it is still the practical solution to rely on more sophisticated Reynolds-Averaged Navier-Stokes (RANS) models, especially the two-equation model, in the CFD analysis of turbulent mixing and heat transfer in nuclear fuel assemblies, especially for the high-Reynolds number cases. The standard, low Reynolds number (LRN), realizable k-ε model are assessed here. In the k-ε models, the Boussinesq hypothesis

$$-\rho\overline{u_iu_j} = -\frac{2}{3}\rho k\delta_{ij} + 2\mu_t S_{ij} \tag{1}$$

is usually used for the Reynolds stress closure problem with the eddy viscosity determined by

$$\mu_t = C_\mu kT \tag{2}$$

The turbulent time scale T defined in the models are listed in Table 1. In contrast to constant $C_\mu = 0.09$ in the other models, the realizable k-ε model defines

$$C_\mu = \frac{1}{4.0 + \sqrt{6}\cos\phi U^* k/\varepsilon} \tag{3}$$

It has been recognized that the isotropic assumption in the linear eddy viscosity model, i.e. Eq. (2), cannot predict the anisotropic turbulence in the rod bundles (Házi, 2005). Starting from (Lien et al., 1996)'s nonlinear viscosity model (NLVM) for the Reynolds stress, (Baglietto et al., 2006) optimized the coefficients for prediction of secondary flow in bare rod bundle and demonstrated that the anisotropic closure model can be adopted to further improve the prediction by the k-ε models. The streamline curvature can be strong in the vicinity of mixing-vane spacer grid. (Lien et al., 1996)'s quadratic and cubic closure models are applied to model the turbulence in the flow with streamline curvature.

$$\begin{aligned}-\rho\overline{u_iu_j} = &-\frac{2}{3}\rho k\delta_{ij} + \mu_t S_{ij} - 4C_1\mu_t\frac{k}{\varepsilon}\left(S_{ik}S_{kj}-\frac{1}{3}\delta_{ij}S_{kl}S_{kl}\right)\\ &-4C_2\mu_t\frac{k}{\varepsilon}(\Omega_{ik}S_{kj}+\Omega_{jk}S_{ki})-4C_3\mu_t\frac{k}{\varepsilon}\left(\Omega_{ik}\Omega_{jk}-\frac{1}{3}\delta_{ij}\Omega_{kl}\Omega_{kl}\right)\\ &-8C_4\mu_t\frac{k^2}{\varepsilon^2}(S_{ik}S_{kl}\Omega_{lj}+\Omega_{jk}S_{kl}S_{li})-8C_5\mu_t\frac{k^2}{\varepsilon^2}(S_{kl}S_{kl}-\Omega_{kl}\Omega_{lk})S_{ij}\end{aligned} \tag{4}$$

with

$$C_1 = \frac{0.75}{(1000+Q^3)C_\mu}$$

$$C_2 = \frac{3.75}{(1000+Q^3)C_\mu}$$

$$C_3 = \frac{4.75}{(1000+Q^3)C_\mu}$$

$$C_4 = -10C_\mu{}^2$$

$$C_5 = -2C_\mu{}^2$$

$$C_\mu = \frac{0.667}{1.25+(S+0.9\Omega)k/\varepsilon} \tag{5}$$

2.2. k-ε models

The generic transport equation of k and ε are as follows.

Table 1
Parameters and model coefficients in the k-ε models.

	Standard k-ε	Realizable k-ε
$C_{\varepsilon1}$	1.44	$\max\left(0.43, \frac{\eta}{5+\eta}\right)$, $\eta = \frac{Sk}{\varepsilon}$
$C_{\varepsilon2}$	1.92	1.9
C_μ	0.09 or Eq. (5) for NLVM	Eq. (3)
σ_k	1.0	1.0
σ_ε	1.3	1.2
P_ε	Eq. (9)	Eq. (11)
D_ε	Eq. (10)	Eq. (12)
T	$\max\left(\frac{k}{\varepsilon}, 0.6\sqrt{\frac{\nu}{\varepsilon}}\right)$	$\frac{k}{\varepsilon}$