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Numerical Study of Two Equation Turbulence Models for Subchannel Thermal Hydraulics

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1. Introduction

The need for more accurate computational methods for the analysis of nuclear reactor systems has generated rising interests for computational fluid dynamics (CFD) and growing range of applications of commercial CFD software.

This study presents results of the sensitivity analysis using the two equation turbulence models for several grid configurations. The Turbulence Enhanced Mixing Analysis (TEMA) result contributes further to turbulent convective heat transfer mechanisms in a subchannel of a square array rod bundle.

2. Methods and Results

2.1 Numerical Simulation

This work has numerically studied one span of a subchannel formed by four rods with a standard split vane. The rod diameter, rod-to-rod pitch and hydraulic diameter are 9.5, 12.6 and 11.78 mm, respectively. The computational domain is 600 mm long and the flow is fully developed 100 mm upstream of the grid spacer. The subchannel geometry and the grid were generated using the GAMBIT preprocessor of FLUENT. Steady-state Reynolds-averaged Navier-Stokes, mass, energy, and turbulence equations were discretized and solved using FLUENT 12.1.

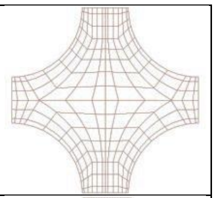
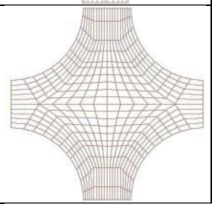
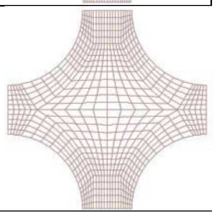
Comprehensive mesh sensitivity study was done to check on the influence of the mesh resolution on the results and to minimize numerical influences introduced by the size of meshes and their distributions. The cells were varied from 1.16×10^6 to 3.6×10^6 for sensitivity analysis. Note from the cross-sectional view of meshes in Table I that mesh was refined in each process particularly nearing to the fuel rod surfaces. The mesh refinement ratio (MRR) is defined as the ratio between consecutive meshes of refinement.

In the current CFD simulation different forms of two equation turbulence models are employed: standard k–ε, renormalized group (RNG) k–ε, standard k–ω, and shear stress transport (SST) k–ω models.

These turbulence models are widely exercised in CFD simulations for subchannel geometry due to their simplicity and good convergence [1-3]. The higher-order turbulence models require additional memory and central processing unit (CPU) time as a result of the increased number of the transport equations for the Reynolds stresses.

A series of differing boundary condition are applied. The working fluid enters with a uniform temperature T_o and constant velocity V_o profile at the inlet. In order to validate the CFD model the Reynolds number *Re* and thermal boundary condition were chosen to match *Re* of the available experimental data [4, 5].

Table I: Mesh Specifications and Mesh Refinement Ratio

	Cell size	MRR	
1	1,160,000	---	
2	2,136,000	MRR_{21} = 1.84	
3	3,600,000	MRR_{32} =1.68	

A segregated, implicit solver option was utilized to solve the governing equations. The first-order upwind discrimination scheme was employed for the terms in the energy, momentum and turbulence parameters. A second-order pressure interpolation scheme was used. In addition, the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) pressure-velocity coupling was implemented. A residual root-mean-square (RMS) target value of 10^{-6} (10^{-12} for the energy equation) was defined for the CFD simulations so as to guarantee full convergence. The number of iterations for convergence was 3000 to 3600. The dimensionless wall distance y^+ for the near-wall cells is between 28 and 44 with the standard wall function which is in reasonable range based on previous studies [1-3].

2.2 Results

Figure 1 demonstrates the normalized axial velocity and turbulent kinetic energy profile downstream of the grid spacer. Note that there is a significant clockwise rotation at the center of subchannels.

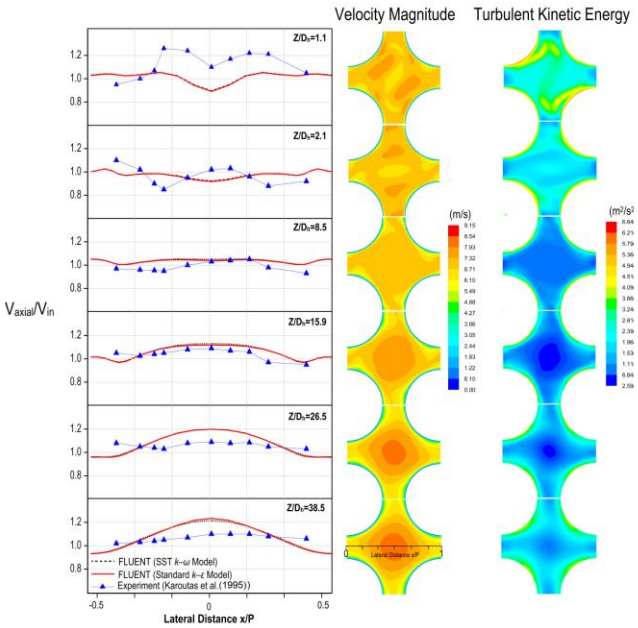


Fig. 1. Normalized axial velocity and TKE.

The swirl flow decays at z = 10D_h downstream of the mixing vanes to 10% of its value at the location of the grid spacer. The clockwise flow rotation at the center of subchannels modifies the boundary layer which can enhance the heat transfer and thermal transport. The comparison shows that the standard k–ω and SST k–ω turbulence models have a similar trend. However, the SST k–ω turbulence model predicts the pressure drop more accurately than the other turbulence models. Other models underestimate the pressure drop compared to the experimental correlation. The pressure drop for grid spacer obtained by the SST k–ω model was 5.462 kPa, which only yields a difference of 0.5%. Moreover, the SST k–ω predicts more accurately the pressure distribution compared against the experimental results.

Table II presents the span-averaged heat transfer enhancement for the turbulence models corresponding to Re = 35,000. Results clearly show the heat transfer enhancement for up to 10D_h downstream of the grid spacer. It is mainly due to presence of the mixing vane mounted on the grid spacer. The Nusselt Enhancement Ratio (NER) obtained by the SST k–ω model is 1.251 from 0 to 10D_h, and 1.064 from 0 to 35D_h downstream of the grid spacer.

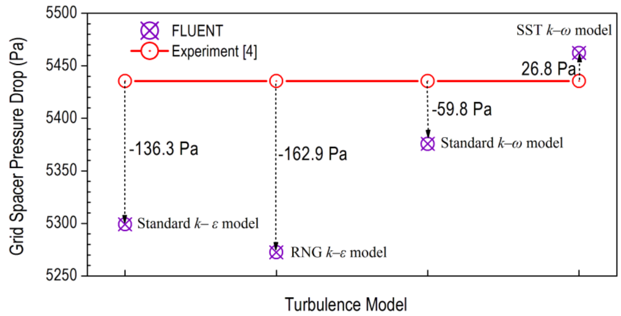


Fig. 2. Calculated pressure drop using available correlation with the four turbulence models (Re = 85,000).

Table II. Span-Averaged Heat Transfer Enhancement (Re=35,000) for Different Turbulence Model

	Turbulence model	NER	
		FLUENT	Experimental data
0 to 10×D_h	Standard k–ε	1.120	1.27
	RNG k–ε	1.189	
	Standard k–ω	1.245	
	SST k–ω	1.251	
0 to 35×D_h	Standard k–ε	1.017	1.08
	RNG k–ε	1.005	
	Standard k–ω	1.058	
	SST k–ω	1.064	

3. Conclusions

Results demonstrate the span averaged heat transfer enhancement of 1.25 from 0 to 10D_h, and 1.064 from 0 to 35D_h downstream of the grid spacer. The velocity, vorticity and helicity are determined to visualize the swirl flow along the channels. Among the considered turbulence model, the CFD results obtained by the SST k–ω model had best agreement with the experimental data, which shows that the SST k–ω model is an appropriate choice for predicting the heat transfer parameters along the subchannel. This TEMA study suggests that extra grids can be mounted at z > 30D_h downstream of the grid spacers along the fuel assembly. Good balance is thus required between the heat transfer enhancement and extra pressure drop.

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