Experiments and two different turbulence models comparisons on thermal mixing phenomenon in a tee piping

CHAO-JEN LI, YAO-LONG TSAI, TAI-PING TSAI, LI-HUA WANG
Material and Chemical Research Laboratories
Industrial Technology Research Institute
Rm. 637, Bldg. 52, 195, Sec.4, Chung Hsing Rd., Chutung, Hsinchu,
TAIWAN
lichaojen@itri.org.tw

Abstract: - Thermal fatigue failures in reactor cooling systems of nuclear power plants are caused by the fluctuating stresses on a piping system due to the hot and cold flows are mixed together in a mixing piping. The present paper describes BSL Reynolds Stress (BSL-RSM) and k-epsilon (k-ε) simulation data of thermal mixing in a mixing piping compared with results from experimental data. The fluid in the experiment is concentration of de-ionized water and the liquid electrical conductivities are measured by the use of the 16×16 electrode. To verify the mixing phenomenon between electrical conductivity of de-ionized water and temperature of water, the inlet temperatures of the hot and cold water in the simulation process are set to 80°C and 15°C separately. The analytic results calculated by the commercial CFD code ANSYS CFX 11.0 show that the different turbulence model (BSL-RSM, k-ε) and different turbulent Prandtl number (0.9, 0.2, 0.1) will affect the simulation results of temperature fluctuations. The computational results are in qualitative good agreement with experimental data and the correlation between electrical conductivity of de-ionized water and temperature of water is good. For smaller turbulent Prandtl number, the predictions are in good agreement with measurements.

Key-Words: - BSL-RSM, k-ε, Thermal Fatigue, Turbulent Prandtl Number

1 Introduction
In 1998, a leak occurred in the Civaux 1 reactor residual heat removal system (RHRS) at the extrados of an elbow near the RHR heat exchangers. Temperature fluctuations in pipe systems can lead to thermal fatigue in the pipe walls, since it can lead to highly transient temperature fluctuations at the adjacent pipe walls, cyclic thermal stresses in the pipe walls and consequently to thermal fatigue and failure of the pipeline. The flow in the mixing-tee is a challenging test case, and the CFD-methods based on RANS (Reynolds Averaged Navier-Stokes equations) which are typically used in industrial applications have difficulties to provide accurate results for this flow situation. Recent studies using advanced scale-resolving methods such as LES and DES have compared the simulated results [1,2,3] with the experimental results [4] measured by Vattenfall at the Älvkarleby laboratory, Vattenfall Research and Development AB.

In this study, a isothermal de-ionized water experiment [5] was performed at the Laboratory for Nuclear Energy Systems, Institute for Energy Technology, ETHZ, Zürich, Switzerland. The electrical conductivity of the fluid is used as a parameter that can investigate the influence of the mixing phenomena in a mixing tee. In order to verify that the mixing phenomenon of two different temperature water that can be explained by that of two different electrical conductivity de-ionized water, the present paper describes the CFD solutions for traditional RANS approaches using BSL-RSM and k-ε turbulence models, which the mixing of two fluid streams of different temperatures.

2 Experimental Setup of ETHZ
The detailed measurements of turbulent isothermal and thermal mixing was carried out at a perpendicular connection of two pipes of 50mm inner diameter (Fig.1), which were made from acrylic glass. The used test section consists of a horizontal mixing-tee geometry of Plexiglas pipes of 50 mm inner diameter for both the main and the branch pipes. The length of the main branch is 1.5 m whereas the length of the side branch is 0.5 m. Tap water is flowing from left to right and the demineralized water is pumped from a storage tank through the side branch, as indicated in Fig.1. The electrical conductivity difference between tap water and desalinated water was used as the parameter characterizing the changing concentration of salts dissolved in the tap water during the mixing process.
The instantaneous two dimensional electrical conductivity distributions from measuring planes in the common exit branch of the mixing-tee were obtained by the main instrumentation, two 16×16 electrode wire-mesh sensors (WMS), installed right behind each other downstream of the mixing-tee in the mixing region. The sensors can be also positioned further downstream of the mixing-tee by inserting distance rings and pipe segments. The measurement cross-sections in the experiments for the WMS measurements were located at L=51mm, 71mm, 91mm, 111mm, 151mm, 191mm, 231mm, 271mm and L=311mm downstream of the mixing-tee. Details of the WMS measurement technique can be found in [5,6,7].

Fig.1 Mixing-Tee test facility of ETHZ [5]

3 Numerical Approach Precondition

3.1 Geometry Setup and Boundary Conditions

The three-dimensional mixing-tee models that represent the ETHZ experiments, as shown in Fig.2, were constructed with ANSYS DesignModeler, a pre-processor of the ANSYS CFX 11.0 code. Several experiments have been carried out at ETHZ by varying the flow rates in the main and branch pipe, by exchanging the injection of tap water and de-ionized water and by changing the location of the WMSs. To verify that the mixing phenomenon of two different temperature water that can be explained by that of two different electrical conductivity de-ionized water, the ANSYS CFX 11.0 code has been selected and the main parameters of the simulation are given in Table 1.

Table 1 Simulation Conditions

<table>
<thead>
<tr>
<th></th>
<th>Main Pipe (Hot Water)</th>
<th>Branch Pipe (Cold Water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Temperature(℃)</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>Average Velocity</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Inner Diameter(m)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Length(m)</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

For the sake of achieving convergence and minimizing the computational time, three different mesh levels are used in the simulation (see Fig.3). Mesh Coarse consists of approximately 320000 hexahedral cells, mesh Intermediate consists of approximately 1600000 hexahedral cells, and mesh Fine consists of approximately 2350000 hexahedral cells.

Fig.3 Levels of Mesh Coarse, Intermediate, Fine
The steady-state RANS simulation with the BSL Reynolds Stress (BSL-RSM) and k-epsilon (k-ε) turbulence models are used in the simulation. Pr is the turbulent Prandtl number arises from the application of the eddy viscosity hypotheses in the Reynolds averaging process of this transport equation. Usually it is assumed in Ansys CFX 11.0, that the turbulent Prandtl number Pr=0.9. The two turbulence models with three different turbulent Prandtl number (Pr=0.9, Pr=0.2, Pr=0.1) are calculated in the study. No slip conditions are set at the walls and zero average static pressure outlet boundary condition has been applied.

To compare the computational and experimental results, the computed data are normalized as follows:

$$\text{Mixing Scalar} = \frac{T - T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}}$$  \hspace{1cm} (1)

where $T$ is the instantaneous mixing temperature at a given location. $T_{\text{hot}}$ is the temperature of the hot water(353 K), and $T_{\text{cold}}$ is the temperature of the cold water(298 K).

The convergence studies with the BSL-RSM turbulence model using Pr=0.9 have been carried on all three different mesh levels. The convergence criterion was set to $10^{-5} \sim 10^{-6}$ for the residuals. Fig.4 shows the comparison of profiles of the mixing scalar at L=51mm, L=91mm, L=191mm, and L=311mm behind the mixing-tee for an BSL-RSM turbulence model simulation with Pr=0.9 for three different mesh levels. Coarse mesh results differ from intermediate mesh and fine mesh results. Since the intermediate mesh results is almost the same as fine mesh results, the intermediate mesh can be used for further numerical analysis.

Fig.4 The Mixing Scalar at four locations for BSL-RSM turbulence model simulations on three different mesh levels

3  Numerical Simulation Results

3.1 Turbulent Prandtl Number Effect

Fig.5 shows corresponding comparison of parameter variation study using Pr=0.9, 0.2 and 0.1 for BSL-RSM turbulence model simulations in comparison to the experimental data at L=51mm, L=91mm, L=191mm and L=311mm downstream of the mixing-tee. Predicted results obtained by using Pr=0.1 are generally in slightly better agreement with the experimental data. The coefficient of determination, $R^2$, obtained by using Pr=0.1 is between 0.996 and 0.788, which is higher than that by using Pr=0.2 and Pr=0.9. The accuracy of calculational results improves as $R^2$ approaches 1.

The accuracy predicted we concerned most is the temperature near the pipe wall ($x=0.025m$ and $x=0.025m$). The absolute error, $\beta$, obtained by using Pr=0.1 at $x=0.025m$ is between 0.1232 and 0.0075, which is smaller than that by using Pr=0.2 and Pr=0.9. And the absolute error, $\beta$, obtained by using Pr=0.1 at $x=0.025m$ is between 0.066 and -0.0290, which is smaller than that by using Pr=0.2 and Pr=0.9. The correlation improves as $\beta$ approaches 0.
BSL-RSM are generally in slightly better agreement with the experimental data.

But the absolute error, $\beta$, obtained by using $k$-$\varepsilon$ turbulence model at $x=0.025m$ is between 0.0069 and -0.0118, which is smaller than that by using BSL-RSM turbulence model. On the other hand, the absolute error, $\beta$, obtained by using BSL-RSM turbulence model at $x=0.025m$ is smaller than that by using $k$-$\varepsilon$ turbulence model.

Fig.5 Effects of three different $Pr$ values for BSL-RSM turbulence model (** means the predicted results correlates not very closely with the experimental values)

4.2 Turbulence Model Effect

Fig.6 shows corresponding comparison of turbulence model variation study using BSL-RSM and $k$-$\varepsilon$ turbulence model simulations with $Pr=0.1$ in comparison to the experimental data at $L=51$mm, $L=91$mm, $L=191$mm and $L=311$mm downstream of the mixing-tee. Predicted results obtained by using

(d) 311mm

Fig.6 Effects of two different turbulence model for $Pr=0.1$
4.4 Cross-Sectional Distribution Comparison

Fig. 7 shows representative cross-sectional plots of the temperature distribution for the simulation by using BSL-RSM and k-ε turbulence models and the electrical conductivity distribution for the measurement by using WMS at L=51mm and L=191mm downstream of the mixing-tee. Predicted results obtained by using the mixing of two different temperature water are generally in good agreement with the experimental data by using the mixing of different electrical conductivity de-ionized water. For quite a short distance behind the mixing-tee (L=51mm), the stratification phenomenon of fluid is obvious.

4. This study can verify that the mixing phenomenon of two different temperature of water can be analogized by two different electrical conductivity of de-ionized water.

References: