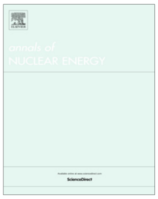
Annals of Nuclear Energy 101 (2017) 293–300

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Numerical investigation on the thermal stratification in a pressurizer surge line

Benan Cai [a], Hongfang Gu [a], Yu Weng [a], Xingchen Qin [a], Yanyan Wang [a], Shouxu Qiao [a,b], Haijun Wang [a,*]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, United States

ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 14 November 2016
Accepted 17 November 2016

Keywords:
Computational Fluid Dynamics (CFD)
Thermal stratification
Pressurizer surge line

ABSTRACT

Thermal stratification is a common phenomenon in the surge line of Pressurized Water Reactors (PWRs). A study using Computational Fluid Dynamics (CFD) has been performed to analyze the thermal stratification in the pressurized surge line with different surge line and main pipe velocity conditions. This study is typical of considering both the flow subjected to the buoyancy and the conjugate heat transfer between the fluid and the pipe wall. What makes the research complex is exactly the impact of buoyancy on thermal stratification. To validate the accuracy of CFD calculations, necessary comparison is performed with experiment results. Models with different computational conditions resulting from various similarity criterion parameters are used. More meaningful information than that from the experimental results can be obtained. At the same time, many actual operating conditions which are difficult for experiment can be also accomplished by applying CFD mode. Temperature distributions inside and on the outer surface of the surge line are provided by the CFD mode with different turbulent models. Compared to the standard k-ε turbulence model and Reynolds stress model (RSM), the SST k-ω turbulent model is more adapted for this study. Based on the conclusion, the numerical results with the SST k-ω turbulence model for the prototype on the actual nuclear power plant unit were mainly described.

1. Introduction

Such serious damages due to excessive thermal stratification as pressurizer surge line movements and pipe leakage incidents happened in many nuclear power plants every year. For example, unexpected movements of a pressurizer surge line that led to gap closures and overall line displacement were observed by Trojan (USNRC, 1988) several years ago.

The temperature gap was sometimes up to 300 K. Therefore the consideration of thermal stratification plays a crucial role in the aging management and extending the lifetime of the nuclear power plants. On this basis the United States Nuclear Regulatory Commission (USNRC) put forward Bulletin 88-08 (USNRC, 1988) and Bulletin 88-11 (USNRC, 1988) requesting all licensees to take steps to resolve the issue.

When thermal stratification occurs in locations where low velocity water with high temperature differences exist, such as mixing T-junctions, injection nozzles, leaking check valves and pressurizer surge lines, hot fluid flows over cold fluid with high density. Due to high heat capacity and small thermal conductivity of water, as well as the low velocity in these locations, the difference in the buoyancy between hot and cold water could prevent their mixing, resulting in a stratified flow (Yu et al., 1997). The hot water at the top of the pipe causes greater thermal expansion compared with the cold water at the bottom of the pipe, tending to bend the pipe and accelerate pipe failure (Chattopadhyay, 2010).

During the past decades, since the publication of Bulletins 88-08 and 88-11, numbers of experimental and numerical studies have been performed to investigate thermal stratification. The experimental studies were summarized in our previous work (Qiao et al., 2014). Hereafter, the simulation work is presented.

Abou-rjeily and Barois (1994) performed two-dimensional numerical simulation of thermal stratification using the TRIO-EF code. The experimental data from I'EXPRESS experimental facility representing the pressurizer surge line of a Framatome PWR was used to verify the simulation methodology both in steady and transient conditions. It was concluded that the numerical simulation had allowed obtaining a good prediction of the quantities representative of the thermal loading. This study was one of the few which took into consideration the flow of main pipe and such that the surge line configuration is very close to that in a real nuclear power plant.

---

* Corresponding author.
E-mail address: whj@mail.xjtu.edu.cn (H. Wang).

http://dx.doi.org/10.1016/j.anucene.2016.11.024

Jo et al. (2001) applied a numerical code based on the finite volume approach to predict the behavior of fluid flow and temperature distributions in a pressurizer surge line. Different from other researchers, they used the transient simulation method and took into account the existence of the pipe wall. The results showed that to determine the temperature distributions in thick-walled pipes as realistically as possible, the unsteady conjugate heat transfer analysis for considering effects of wall thickness was required to be incorporated into the numerical analysis of thermally stratified flow in the pipes.

Boros and Aszódi (2007) simulated thermal stratification in the pressurizer surge line and the injection pipe for VVER-440 type reactors using CFX code. The simulation results were compared with the measurement data of a real power plant unit and provided the time development and the breaking up of the stratification and the temperature distribution of the stratified flow. Therefore, the CFD code could provide an effective method for the thermal stratification as well as lead an important role in the aging management. However, the main difficulties of the simulation were the uncertainties of the boundary conditions, because the necessary parameters were usually not measured at the boundaries of flow region.

Lee et al. (2009) studied the thermal striping phenomenon in a T-junction using Fluent code. Thermal striping is thermal stratification with temperature fluctuation. To capture the high frequency temperature fluctuation, they selected the LES (Large Eddy Simulation) turbulent model. Their study focused on the numerical analyses of the temperature fluctuations and structural response of coolant piping at a mixing tee and showed that the temperature difference between the hot and cold fluids of a tee junction and the enhanced heat transfer coefficient due to turbulent mixing are the dominant factors of thermal fatigue failure of a tee junction.

Jo and Kang (2010) then simulated the unsteady conjugate heat transfer of an actual PWR pressurizer surge line pipe subjected to internal stratification caused by out- or in-surge flow. They switched to the CFX code with the SST $k-w$ turbulence model. Similarly, the simulation results showed that the wall thickness was important to realistically predict the thermal behavior in the transient study.

Cizelj and Simonovski (2011) performed fatigue analysis in a pressurizer surge line caused by thermal stratification. The investigated parameters included the film coefficients governing the heat transfer from fluid to the pipe wall and the velocity of the interface between the cold and hot water. And the choice of the film coefficients is essential to arrive at reliable fatigue estimate.

Meikle et al. (2011) performed simulation analysis of both temperature and stress distribution in a tilted surge line using ANSYS CFX code. They first verified their simulated temperature distribution result by comparing with the result predicted by the Westinghouse WESTEMS™ transient and fatigue monitoring software. They found the period and amplitude of temperature fluctuation in the CFD simulation corresponds to the general trend of the monitoring model data. With this result, stress analysis was performed by a fluid structural interface evaluation. Then, the thermal stress transfer function model using a five zone approximation was developed. The new model provided better indication of the impact of transient conditions and related plant operations on the fatigue life of the surge line hot leg nozzle.

Nakamura et al. (2014) carried out experimental studies and numerical simulations to investigate flow structures and the temperature fluctuation phenomenon near the thermal stratified layer in a straight branch pipe and a bent branch pipe. It was notable that they measured the penetration length of the main flow for various main pipe flow velocities. They also investigated the mechanism of temperature fluctuation near the thermal stratified layer by applying numerical simulations. The mechanism was interference by the spiral flow on the fixed thermal stratified layer at the bent section by the cold water provided from the horizontal section.

From the review above, there are a lot of simulation works to study thermal stratification phenomenon using CFD code. But few of them performed benchmark of the simulation results, especially the same model and boundary conditions for simulation with experiment. Different turbulent models were selected for the previous numerical research on the thermal stratification in a pressurizer surge line, however, no turbulent model has been unanimously approved so far. The standard $k-\varepsilon$ model, the shear-stress transport (SST) $k-w$ model and the Reynolds stress model (RSM) were applied by previous researchers to analyze thermal stratification phenomenon, respectively. Obviously, these three turbulence models were appropriate for CFD investigation on thermal stratification in the surge line. Now the focus of the study was on the selection of the optimal turbulence model. Therefore, the numerical simulations of thermal stratification using the standard $k-\varepsilon$ model, the shear-stress transport (SST) $k-w$ model and the Reynolds stress model were carried out in this paper. More importantly, the benchmark of the numerical simulation method was decided by means of comparing the numerical results with experimental results. In particular, the choice of turbulent model was mainly discussed. According to the comparison results, numerical simulation on the prototype of the pressurizer surge line applying the recommended turbulence model was also discussed.

2. CFD evaluation of surge line temperature field

A general purpose CFD code, CFX, was chosen for the simulation of thermal stratification. CFX is a high-performance CFD software tool that delivers reliable and accurate solutions quickly and robustly. It provides a wide range of turbulence models, ranging from the standard $k-\varepsilon$ model to the Reynolds stress model (RSM).

In Reynolds averaging, the solution variables in the instantaneous (exact) Navier-Stokes equations are decomposed into the mean (ensemble-averaged or time-averaged) and fluctuating components. Then the Reynolds-averaged Navier-Stokes (RANS) equations can be obtained. To solve the RANS equations, the addition terms, i.e. these Reynolds stresses, $-\rho\overline{u_i'u_j'}$, must be modeled. A common method employs the Boussinesq hypothesis (Hinze, 1975) to relate the Reynolds stresses to the mean velocity gradients:

$$-\rho\overline{u_i'u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}(\rho k + \mu_t\frac{\partial u_k}{\partial x_k})\delta_{ij} \tag{1}$$

where $\mu_t$is the turbulent viscosity and $k$is the turbulent kinetic energy. In the case of the standard $k-\varepsilon$ model and the SST $k-w$ model, two additional equations (for the turbulence kinetic energy k , and either the turbulence dissipation rate, ε , or the specific dissipation rate, w) are solved, and then μ_t can be obtained as a function of k and ε or k and w The standard $k-\varepsilon$ model (Launder and Spalding, 1972) is the most widely used complete turbulence model, and it is incorporated in most commercial CFD codes. The standard $k-\varepsilon$ model is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). $k$and ε are obtained from the following transport equations:

$$\rho\frac{Dk}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \mu_t S^2 - \rho\varepsilon \tag{2}$$

$$\rho\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}(C_{1\varepsilon}\mu_t S^2 - \rho C_{2\varepsilon}\varepsilon) \tag{3}$$