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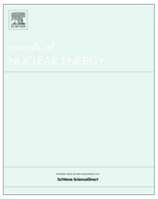

Numerical simulation of thermal stratification in an elbow branch pipe of a tee junction with and without leakage ☆

T. Lu [a,*], H.T. Li [a,b], X.G. Zhu [a]

[a] School of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, China
[b] China Nuclear Power Engineering Co., Ltd., Beijing 100840, China

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ABSTRACT

Thermal stratification can cause thermal fatigue of the piping system of a nuclear power plant. One of the regions most at risk of suffering from thermal fatigue is a small elbow pipe branching off from the main pipe of the coolant loop for the drain or letdown system in the chemical and volume control system (CVCS). This work focuses on a fundamental description of the thermal stratification caused by turbulent penetration and buoyancy effects in the elbow branch pipe using large-eddy simulations (LESs). The LES results for the normalized temperature, mean temperature, and root-mean square (RMS) temperature were found to be in good agreement with the available experimental data which confirms that LES can predict the thermal stratification in a closed elbow branch pipe where cold fluids are stagnant. Subsequently, the flow and heat transfer were numerically predicted using LES when leakage occurred in the elbow branch pipe. The numerical results show that the thermal stratification region is pushed towards the horizontal part and may remain there for a long time for a leakage ratio of 1%. However, thermal stratification is quickly eliminated for a leakage ratio of 5%, although there is a higher power spectrum density (PSD) of the temperature in the early stages of the leakage. It may be concluded that a small leakage ratio can result in the elbow branch pipe being at high risk of thermal fatigue caused by thermal stratification.

1. Introduction

Thermal stratification or striping is of significant importance in nuclear power plants because it can lead to transient temperature fluctuations at the adjacent pipe walls which may result in thermal fatigue and failure of the pipe. In a previous review Iida (1992) noted that serious fatigue failures have occasionally been experienced in piping systems, pumps, and valves. The causes of fatigue failures can be divided into two categories: mechanical-vibration-induced fatigue and thermal-fluctuation-induced fatigue. By comparison of the stresses due to thermal shock and thermal stratification, Miksch et al. (1985) concluded that the cracks observed were in essence caused by thermal stratification. Tenchine (2010) suggested that piping thermal stratification or mixing is one of several thermal hydraulic challenges which progressively increase with the power and the size of a sodium cooled nuclear reactor. Thermal fatigue incidents occurring in a tee piping system are susceptible to turbulent temperature mixing effects. A European study of the thermal fatigue evaluation of piping systems has been initiated, including assessment of the fatigue significance of turbulent thermal mixing effects in piping systems and identification of the significant fatigue parameters (Metzner and Wilke, 2005).

Thermal stratification or striping can be predicted using computational fluid dynamics (CFD) simulations as well as measured experimentally. Turbulent isothermal and thermal mixing phenomena have been numerically and experimentally investigated by Frank et al. (2010). The isothermal case involved turbulent mixing of two water streams at the same temperature in a tee junction in the horizontal plane to exclude any buoyancy effects, while the thermal case had a temperature difference of 15 °C between the hot and cold water in a tee junction in the vertical plane in order to induce thermal striping phenomena. Experimental temperature and velocity measurements and numerical simulations were carried out by Kamide et al. (2009) in order to study the thermal hydraulic aspects of thermal striping in a mixing tee. Depending on the momentum ratio of the main pipe to the branch pipe (M_R), flow patterns in the tee were classified into three groups: wall jet ($M_R > 1.35$), deflecting jet ($0.35 < M_R < 1.35$), and impinging jet ($M_R < 0.35$). Tests to investigate the interaction between the main coolant piping and the stagnant attached lines by turbulence

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* Corresponding author. Tel.: +86 10 64417994.
E-mail address: likesurge@sina.com (T. Lu).

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penetration have been carried by Kim et al. (1993), and a loading definition for thermal striping was proposed.

Large-eddy simulations (LESs) are a very popular way of predicting flow details such as velocity, temperature, and vortex. Both collision and co-current thermal striping in a mixing tee have been numerically simulated by Hu and Kazimi (2006) using LES solved by the commercial CFD code FLUENT. Numerical results of normalized mean and fluctuation temperatures were compared with experimental measurements. The mixing in tee junctions made of different materials with different pipe wall thicknesses were investigated by Kuhn et al. (2010) using different LES subgrid scale (SGS) models in order to identify the influence of the SGS on the simulation results, and the results were also compared with available experimental data. Their study showed the ability of LES to accurately predict thermal fluctuations in turbulent mixing. Temperature fluctuations in a mixing tee were simulated by Lu et al. (2010) in FLUENT using the LES with the Smagorinsky–Lilly (SL) SGS model with consideration of buoyancy effects. Their numerical results were in good agreement with the available experimental data, showing the validity of the LES model for predicting the mixing of hot and cold fluids in a mixing tee junction. The temperature fluctuations and structural response of coolant piping at a mixing tee were investigated using LES by Lee et al. (2009). Their study showed that the temperature difference between the hot and cold fluids in a tee junction and the enhanced heat transfer coefficient due to turbulent mixing are the dominant factors affecting the thermal fatigue failure of a tee junction.

In a nuclear power plant, several small pipes branch off from the main pipe of the coolant loop, with a temperature of 300 °C and a velocity of 10 m/s in the drain or letdown system in the chemical and volume control system (CVCS). These pipes are often bent and connected to a closed valve (Ourmaya et al., 2006). The turbulence of the main pipe flow usually initiates a perturbation flow in the elbow branch pipe and hot water penetrates into it. In addition, the fluid in the elbow is relatively stagnant and at a low temperature. Thermal stratification may arise if the perturbation momentum and buoyancy remain in dynamic balance in a region where the hot fluid is above the cold fluid.

This work focuses on a fundamental description of the thermal stratification caused by turbulent penetration and buoyancy effects using large-eddy simulations (LES), for the two cases where leakage of the elbow branch pipe does and does not occur. Firstly, based on the experimental model and flow parameters in the literature (Ourmaya et al., 2006), the LES for the case without leakage of the closed elbow branch pipe was completed. Then the numerical results of the transient temperature were compared with the experimental data to confirm that LES has the capability to predict the temperature fluctuations. After validation of the numerical simulations, LES for other cases with leakage of the elbow branch pipe were performed in order to predict extent of penetration of hot water into the horizontal part of the elbow branch pipe.

2. Mathematical model and numerical simulations

As shown for the model in Fig. 1 (Ourmaya et al., 2006), at the beginning hot water at temperature of 65 °C and velocity of 6 m/s flows in the top main rectangular channel, with cross-section of 60 mm × 10 mm, which is connected to an elbow branch pipe initially filled with stagnant cold water at temperature of 15 °C. The bore of the elbow pipe is 43 mm, which is similar to that of the 2 in branch pipe in a nuclear power plant. The details of geometry and flow parameters can be found in reference (Ourmaya et al., 2006). As a consequence of turbulence at the tee junction, mixing between hot and cold water occurs and may propagate downwards in the vertical – and even in the horizontal – part of the elbow branch pipe. Consequently, thermal stratification occurs with the fluctuating interface between hot and cold water, which results in the elbow branch pipe being at risk of thermal fatigue.

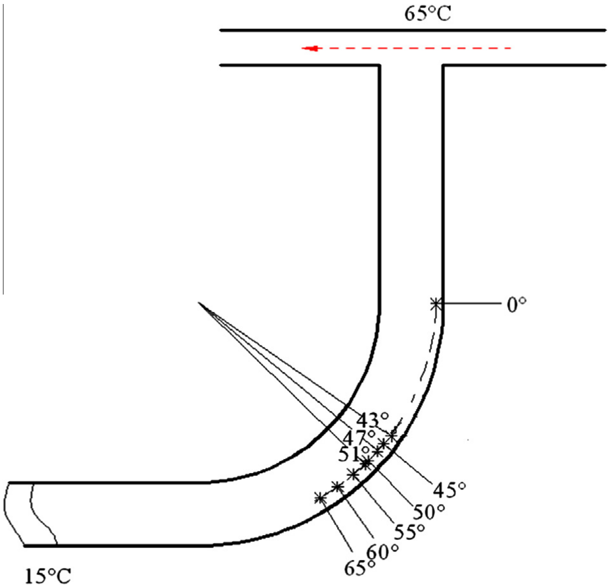

Fig. 1. Physical model and numerical sampling locations.

For incompressible flow, the filtered Navier–Stokes and energy equations can be written as (Ndombo and Howard, 2011)

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho \overline{u}_i}{\partial t} + \frac{\partial \rho \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} - \rho_0 \beta (T - T_0) g + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\right] \tag{2}$$

$$\frac{\partial \rho \overline{T}}{\partial t} + \frac{\partial \rho \overline{T}\overline{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\lambda}{c_p}\frac{\partial \overline{T}}{\partial x_j} - \rho \overline{T'' u_j''}\right) \tag{3}$$

Here $\overline{\psi}$ represents the implicit filtering operation on the flow variable, to the grid and ψ'' is the subgrid part of the flow variable, and ρ, β, μ, μ_t, λ, and c_p represent the density, thermal expansion coefficient, molecular viscosity, turbulent viscosity, thermal conductivity, and specific heat capacity, respectively.The effect of the unresolved scale on the resolved scale in the above equations is represented by the subgrid scale (SGS) stress, which is modeled using the eddy viscosity hypothesis. In this work, the Smagorinsky–Lilly model is used for the turbulent viscosity, and is given by

$$\mu_t = \rho L_s^2 |\overline{S}|^2 \tag{4}$$

where L_s is the mixing length for the subgrid scales. L_s and $|\overline{S}|$ are computed using

$$L_s = \min(kd, C_s V^{1/3}) \tag{5}$$

$$|\overline{S}| = \sqrt{2\overline{S}_{ij}\overline{S}_{ji}} \tag{6}$$

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{7}$$

where k is the von Karman constant of 0.42, d is the distance to the closest wall, C_s is the Smagorinsky constant, and V is the volume of the computational cell.