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Large-eddy simulations of structure effects of an upstream elbow main pipe on hot and cold fluids mixing in a vertical tee junction

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ABSTRACT

Thermal striping is a possible cause of thermal fatigue in the piping systems used in e.g. nuclear power plants. In the present work, the mixing of a hot and a cold fluid stream in a vertical tee junction with an upstream elbow main pipe is numerically predicted with large-eddy simulation. Two parameters were varied in this study: the ratio of the curvature of the elbow pipe over the diameter of the main pipe, and the dimensionless horizontal distance between the elbow pipe and the branch. The normalized mean and RMS temperature and velocity were numerically examined to investigate how the two above parameters influence the mixing. The numerical results show that the larger elbow curvature ratio and dimensionless distance would weaken the temperature and velocity fluctuations because of a reduction of the secondary flow in the elbow.

1. Introduction

Thermal striping characterizes the phenomenon where hot and cold flows join and result in random temperature fluctuations of the coolant near the piping wall. The wall temperature fluctuations can cause cyclical thermal stresses and subsequent thermal fatigue cracking of the piping (Lee et al., 2009). Thermal striping several accidents took place both in nuclear plants involving light water and sodium cooled reactors due to thermal fatigue. In 1998, a crack was discovered in an area where hot and cold fluids were mixed on the residual heat removal (RHR) system in Civaux, France. Metallurgical studies concluded that the crack was caused by high cycle thermal fatigue (Blondet and Faidy, 2002). In April 1990, sodium leakage happened in the French reactor Superphenix; the leakage was reportedly resulting from thermal fatigue (Ricard and Sperandio, 1996). It is established that mixing hot and cold sodium can induce temperature fluctuations and related thermal fatigue (IAEA, 2002). The fluctuations of fluid temperature are transported to the solid walls by heat convection and diffusion, which can induce thermal fatigue and structural failure. Therefore, thermal striping phenomenon is significant for the structural integrity and safety of nuclear power plant.

Thermal fatigue is an important degradation mechanism for the life time assessment of nuclear reactor components. A reliable life-assessment of these components is difficult because usually only the nominal temperature differences between the hot and cold fluids are known but the instantaneous temperatures and heat fluxes at the surface are unknown (Paffumi et al., 2012). So temperature fluctuation is one of the important parameters for thermal fatigue analysis. Kamaya and Nakamura (2011) used the transient temperature obtained by a fluid dynamics simulation to assess the thermal fatigue damage at a mixing tee in which cold water flowed into the main pipe from a branch pipe. The precise distributions of the thermal stress and fatigue damage could be identified. Lee et al. (2009) validated the coolant temperature fluctuations obtained from large-eddy simulation (LES) with experimental data, and used the numerically predicted fluctuations to analyze the thermal fatigue of a mixing tee. Their study shows that the temperature difference between the hot and cold fluids and the enhanced heat transfer coefficient due to turbulent mixing are the dominant factors of thermal fatigue failure of a tee junction as well as the temperature fluctuation frequency is a key factor for the temperature oscillation propagation into the wall region. Therefore, instantaneous temperature should be quantitatively determined by experiment or simulation to provide the thermal load for thermal fatigue analysis.

In order to evaluate thermal striping phenomena in a mixing tee junction or in similar structure, many numerical simulations and

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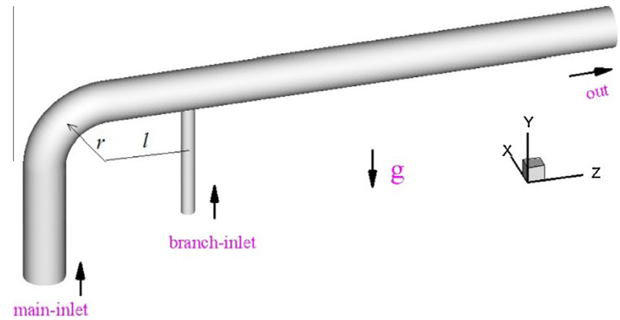

Fig. 1. Physical model of a mixing tee.

experiments have been carried out (Hu and Kazimi, 2006; Hosseini et al., 2008; Durve et al., 2010; Frank et al., 2010; Jayaraju et al., 2010; Galpin and Simoneau, 2011; Aulery et al., 2012; Cao et al., 2012). As most of the industrially-relevant mixing flows in tee junctions are turbulent, Reynolds stress models (RSMs) is typically used to describe the momentum conservation of the mixing (Durve et al., 2010; Frank et al., 2010). Turbulent mixing phenomena in a tee junction have been numerically investigated using the k–ω based baseline Reynolds stress model (BSL RSM) by Frank et al. (2010) for two different cases: (1) two isothermal water streams mixing in a horizontal plane with the Reynolds number of 4.3×104, to exclude any buoyancy or thermal effects; and (2) two non-isothermal water streams mixing in a vertical plane with the Reynolds number of 1.9×105, which resulted in thermal striping. Durve et al. (2010) used the Reynolds stress model to predict the velocity field of three non-isothermal parallel jets flow at the core outlet region of the fast breeder reactor (FBR) with a Reynolds number of 1.5×104.

Another turbulence model is large-eddy simulation (LES) with different subgrid scale model often applying to predict velocity and temperature fluctuations. Indeed many numerical studies showed the capability of LES to capture thermal fluctuations in turbulent mixing (Kuhn et al., 2010; Lu et al., 2010; Ndombo and Howard, 2011). Large-eddy simulations were performed by Jayaraju et al. (2010) to analyze the suitability of wall-functions in accurately predicting the thermal fluctuations acting on the pipe walls due to turbulent mixing in a tee junction. Thermal hydraulic investigations on the configuration of a tee junction of the Phenix reactor have been completed by Aulery et al. (2012) using both Reynolds-averaged Navier–Stokes (RANS) and LES calculations. The simulations quantified the amplitudes and frequencies of the thermal fluctuations, and the location of the thermal fatigue cracks of the tee junction. The LES study for parallel triple-jet flows conducted by Cao et al. (2012) numerically identified that the amplitudes of temperature fluctuation vary along the main flow

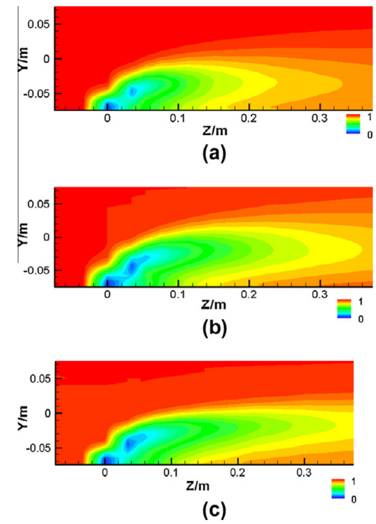

Fig. 3. Distributions of the normalized mean temperatures with different elbow curvature ratios in the plane $x/d_m = 0$ (a) $C_r = 1$; (b) $C_r = 1.5$; and (c) $C_r = 2$.

direction, but that the frequency of temperature fluctuation remains constant. The study also showed how an increase in Reynolds number (from 2×10^4 to 1×10^5) enlarged the convective mixing region. Numerical studies for both collision and co-current types of mixing tee configuration were carried out by Hu and Kazimi (2006) using the LES implementation of the commercial CFD code FLUENT. LES of a mixing tee was carried on by Galpin and Simoneau (2011) to evaluate the sensitivity of numerical results to the sub-grid scale model by comparing the experimental results and test the possibility to reduce the fluid computational domain at the inlet. Turbulent mixing in a tee junction was investigated by Kuczaj et al. (2010) using LES with Vremansubgrid scale model to capture the mixing phenomena. Simulations were performed by Kuhn et al. (2010) to identify the influence of different LES subgrid scale models on the mixing behavior in a tee junction with different material and wall thickness. Effect of turbulent inlet conditions in the mixing tee junction was investigated by Ndombo and Howard (2011) using LES with a dynamic Smagorinsky subgrid scale model. The above examples demonstrate that numerical simulation based on the RSM or LES are relevant to estimate the velocity and temperature fields induced by turbulent mixing in a tee junction.

Besides simulations, experiments are also useful to determine the velocity and temperature fluctuations at mixing junctions. As a quantitative evaluation on thermal striping is of importance for integrity of nuclear reactors, a sodium experiment of parallel triple-jet configuration was performed by Kimura et al. (2007) to

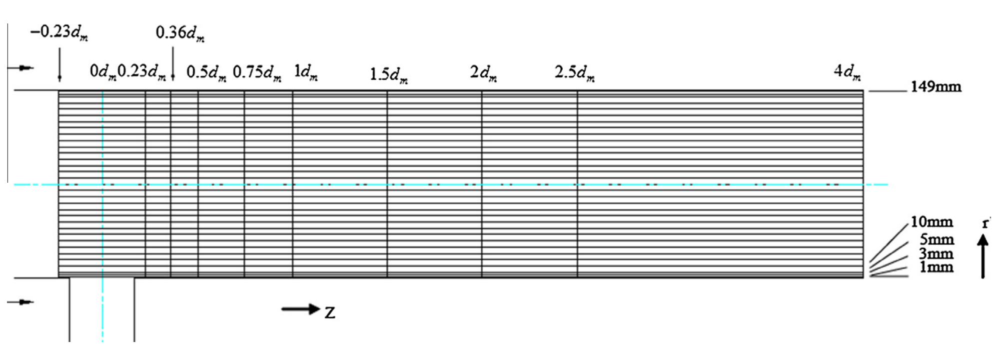

Fig. 2. Sample points.