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Numerical simulation of long-period fluid temperature fluctuation at a mixing tee for the thermal fatigue problem

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HIGHLIGHTS

- A large eddy simulation of a mixing tee was carried out.
- Fluid temperature fluctuation could be predicted qualitatively.
- Grid convergence was almost attained and the simulation continued until 100 s.
- A longer-period temperature fluctuation than the well-known St = 0.2 appeared.
- Prediction of long-period temperature fluctuations improves the thermal fatigue assessment.

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ABSTRACT

Thermal fatigue cracks may be initiated at mixing tees where high and low temperature fluids flow in and mix. According to a previous study, damage by thermal fatigue depends on the frequency of the fluid temperature fluctuation near the wall surface. Structures have the time constant of structural response that depends on physical properties of the structure and the gain of the frequency response tends to become maximum at the frequency lower than the typical frequency of fluid temperature fluctuation. Hence the effect of the lower frequency, that is, long-period temperature fluctuation is important for the thermal fatigue assessment. The typical frequency of fluid temperature fluctuation is about St = 0.2 (nearly 6 Hz), where St is Strouhal number and means non-dimensional frequency. In the experimental study by Miyoshi et al. (2014), a longer-period fluctuation than St = 0.2 was also observed. Results of a fluid–structure coupled analysis by Kamaya et al. (2011) showed this long-period temperature fluctuation causes severer damage to piping. In the present study, a large eddy simulation was carried out to investigate the predictive performance of the long-period fluid temperature fluctuation more quantitatively. Numerical simulation was conducted for the WATLON experiment which was the water experiment of a mixing tee performed at the Japan Atomic Energy Agency. Four computational grids were used to confirm grid convergence. In the short time (9 s) simulations, tendencies of time-averaged and fluctuated velocities could be followed. Time-averaged temperature distributions were also reproduced, although overestimation appeared near the wall. The fluid temperature fluctuation intensity near the wall surface could be predicted qualitatively, while the peak value was overestimated. From the engineering viewpoint, it was concluded that the numerical simulation provided results that were conservative and on the side of safety. From the grid convergence study, the coarsest grid for which grid convergence was almost attained was selected and the simulation was continued until 100 s. Frequency analysis of the fluid temperature fluctuation showed that the long-period fluctuation appeared as well as the well-known typical frequency (St = 0.2). This indicated that numerical simulation could reproduce the long-period temperature fluctuation at the mixing tee.

1. Introduction

Mixing tees are inevitable piping structures in fossil fuel and nuclear power plants. When high- and low-temperature flows are mixing in the mixing tee, high-cycle thermal fatigue may occur.

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Nomenclature

D	inner diameter of pipe, [m]
e_a^{21}, e_a^{32}	approximate relative error, [−]
e_{ext}^{21}	extrapolated relative error, [−]
f	vortex shedding frequency, [1/s]
GCI_{fine}^{21}	fine-grid convergence index, [−]
GCI_{coarse}^{32}	coarse-grid convergence index, [−]
h	grid size, [m]
N	number of samples for statistics, [−]
N_1, N_2, N_3	number of cells of three sets of grids (fine, medium and coarse) selected for grid convergence estimation in Section 3.4, [−]
p	apparent order of grid convergence, [−]
r'	distance from the pipe wall to the pipe center, [mm]
r_{21}, r_{32}	grid refinement factor, [−]
St	Strouhal number ($=fD_b/U_m$), [−]
T	flow temperature, [°C]
T_{std}^*	non-dimensional standard deviation of temperature, [−]
ΔT_{cr}	critical value of temperature difference, [°C]
ΔT_f	fluid temperature fluctuation amplitude after mixing, [°C]
ΔT_{in}	temperature difference between inlet and outlet boundaries, [°C]
u	flow velocity, [m/s]
u_τ	friction velocity, [m/s]
U	mean cross-sectional flow velocity, [m/s]
Uf	cumulative usage factor, [−]
x	Cartesian coordinates, span-wise direction, [m]
y	Cartesian coordinates, vertical direction, [m]
z	Cartesian coordinates, stream-wise direction, [m]
y^+	dimensionless sublayer-scaled distance, [−]

Greek letters

θ	circumferential angle subtended at the center of the pipe, [°]
σ_{alt}	thermal stress amplitude, [N/mm^2]
σ_{cr}	fatigue limit considering the effect of mean stress, [N/mm^2]
ν	kinematic viscosity, [m^2/s]
φ	key variable of the GCI estimation ($=T_{std}^*$ in this study), [K]
φ_{ext}^{21}	extrapolated value when h = 0, [K]

Subscripts

1, 2, 3	three sets of grids (fine, medium and coarse) selected for grid convergence estimation in Section 3.4
ave	time-averaged value
b	branch pipe
cr	critical
i	value of i-th sample
in	inlet
m	main pipe
rms	root mean square
std	standard deviation
z	stream-wise component

The mechanism of thermal fatigue is as follows: mixing of high- and low-temperature fluids causes temperature fluctuation in a pipe material, but the deformation of the pipe material is constrained and then stress fluctuates in the pipe material. Pipe cracking may be caused by this stress fluctuation if it is bigger than the fatigue limit. Thermal fatigue is one of the major degradation mechanisms that must be considered in nuclear power plant management. To prevent thermal fatigue, sophisticated evaluation methods of temperature and stress distributions in the pipe wall are needed. Hence, it is necessary to have a better understanding of the mixing behavior and the temperature fluctuation mechanism.

The Japan Society of Mechanical Engineers has issued a guideline for piping systems (hereafter, JSME guideline) (Japan Society of Mechanical Engineers, 2003) to prevent thermal fatigue. The targeted piping geometries are the mixing tee and branch pipe with a closed end, where thermal fatigue events were often reported. The JSME guideline provides evaluation flowcharts of thermal fatigue for both piping geometries. The JSME guideline for the mixing tee was based on extensive tests which cover various flow conditions (the inlet velocities and diameter ratios). The evaluation flowchart for the mixing tee consists of a four-step assessment procedure as shown in Fig. 1. If one of the four steps is satisfied, the evaluation is finished. When the evaluation does not satisfy any steps, the "detailed evaluation" option remains in the evaluation flowchart. The JSME guideline allows substitution of another appropriate procedure as the "detailed evaluation" for the four-step assessment procedure.

Hence, the authors have tried to develop a method for "detailed evaluation" using numerical simulations (Nakamura et al., 2009, 2010, 2012, 2015; Kamaya et al., 2011). The numerical simulation method is intended to cover computational fluid dynamics (CFD) for local fluid temperature fluctuation, heat transfer from fluids to the pipe and heat conduction into the pipe structure, and then structural analysis for thermal stress distribution. The aim of the numerical simulation method is to predict the local distribution of the fatigue damage at the pipe inner surface. In addition,

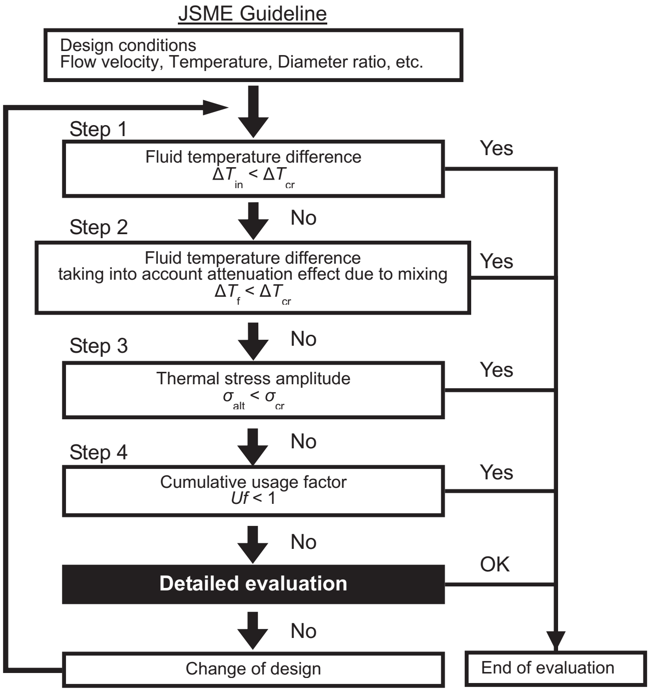

Fig. 1. The evaluation flowchart of thermal fatigue for a mixing tee prescribed by the JSME Guideline (JSME, 2003). Here ΔT_{in} is fluid temperature difference before mixing, ΔT_{cr} is critical temperature difference, ΔT_f is fluid temperature fluctuation amplitude after mixing, σ_{alt} is thermal stress amplitude, σ_{cr} is fatigue limit considering the effect of mean stress, and Uf is cumulative usage factor.