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Uncertainties in the thermal fatigue assessment of pipes under turbulent fluid mixing using an improved spectral loading approach

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ABSTRACT

This paper proposes improved thermal fatigue assessment of pipes subjected to turbulent fluid mixing using an improved spectral loading approach. The fluid temperature histories are generated synthetically from the spatially incomplete experimental or very expensive computational data, preserving consistency with the first two statistical moments and power spectral densities of the measured/computed temperatures. This enables a variety of affordable and physically adequate fluid temperature distributions. These have been used in a novel and rather straightforward analysis of the uncertainties involved in the calculated fatigue life times.

The proposed thermal fatigue assessment procedure has been fully developed for the equi-biaxial stress fields on the pipe surface. This rather realistic assumption allows for a simple one-dimensional model of the pipe with numerically resolved time-dependent temperatures and analytical expressions for the linear elastic wall thermal stresses varying only in the radial direction. The fatigue lives are predicted for diverse variations in fluid temperatures following the ASME Nuclear Boiler and Pressure Vessels codified rules for varying principal stress direction, Rainflow counting algorithm, linear damage accumulation and the NUREG/CR-6909 design fatigue curve.

The results of the proposed method are less conservative than results of similar methods in the literature. This is expected, since the proposed method accounts for a much wider variability and more physical description of the fluid temperatures. Further, the reduction in the conservatism is effectively compensated through the ability to assess the uncertainties inherent in the calculations of fatigue life time. The proposed assessment could be straightforwardly extended to other fatigue design rules and, with the use of finite elements, to possibly nonlinear behavior and discontinuous shapes of the pipes. In this way the proposed improved thermal fatigue assessment of pipes could facilitate further development of currently very scarce and simple design rules for thermal fatigue.

1. Introduction

Thermal fatigue is a structural damage mechanism which has been among the causes of reactor coolant leakages in pressurized reactor nuclear power plants [1,2]. A well-recognized source of thermal fatigue in piping is the turbulent mixing of fluids with different temperatures in T-junction components. In such case the possibly random fluid temperature fluctuations, caused by the turbulent mixing, induce temperature fluctuations in the surrounding pipe walls. Rather fast temperature fluctuations at the pipe surface induce fluctuations in the localized thermal strains, which could be constrained by the adjacent material at different temperature. In this way, the fluid temperature fluctuations induce stress fluctuations in the pipe, which may lead, in some circumstances, to fatigue and subsequent leakage [3] or potentially even loss of structural integrity. This phenomenon is also known as thermal stripping.

The full understanding and meaningful predictive modeling of thermal fatigue requires a multi-physics approach, including fluid dynamics, heat transfer, structural mechanics and materials science [4]. Early research recognized that fluid temperature fluctuations near the pipe surface could generate multiaxial stress state at or close to it [5–8]. Furthermore, assuming that no other loads act on the component without discontinuities, almost perfect equi-biaxial stress state is induced at the pipe surface with the vanishing stress component in the thickness direction. In addition, the possibly random nature of the fluid temperature variations

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Nomenclature

1D, 3D	one-dimensional and three-dimensional pipe models [/]
t, f	time [s] and frequency [Hz]
Δt, Δf	time [s] and frequency [Hz] intervals
τ	time-length of the fluid temperature history [s]
f_0	transition frequency [Hz]
K	number of temperature readings [/]
A_k	amplitude of the kth harmonic [°C]
θ_k	phase [rad]
ω_k	angular frequency [rad/s]
T	fluid temperature history [°C]
T_{fluc}	fluid temperature fluctuation [°C]
T_{mean}	fluid mean temperature [°C]
T_{rms}	root-mean-square of fluid temperature fluctuations [°C]
T_{var}	variance of fluid temperature fluctuations [°C^2]
T_{cold}	temperature of the cold fluid [°C]
T_{hot}	temperature of the hot fluid [°C]
T_w	pipe wall temperature history [°C]
ΔT	temperature difference of the mixing fluids [°C]
β	exponent in error function of minimization process for optimal θ_k [/]
ε_T	ending condition tolerance of minimization process for optimal θ_k [/]
PSD	power spectral density [°C^{2}s]
r_i, r_o	inner and outer radius of the pipe [m]
λ	thermal conductivity [W/mK]
c_p	specific heat [J/kgK]
ρ	density [kg/m^3]
α	thermal expansion coefficient [K^{-1}]
E	Young's modulus [MPa]
υ	Poisson's ratio [/]
σ	stress history at the pipe's inner surface [MPa]
σ_i	principal stress [MPa]
S_{ij}	stress difference [MPa]
S_{rij}	fluctuating range of each S_{ij} [MPa]
S_{alt}	alternating stress intensity [MPa]
N	allowable number of cycles from the S–N design fatigue curve [cycles]
m	number of stress reversals obtained by Rainflow counting [reversals]
n_i	number of cycles for the reversal i counted by Rainflow [cycles]
N_i	allowable number of cycles for stress intensity in reversal i [cycles]
S_e	endurance limit [MPa]
$D, \dot{D}$	damage and damage rate [/, s^{-1}]
x^*	non-dimensional variable [/]
$\langle x \rangle$	ensemble average [units of x]

assumes varying amplitudes and multi-frequency content, which is difficult to characterize, especially in the cases where the resulting thermal strains reside mostly in the high cycle regime.

The full scale experimental data available is necessarily spatially incomplete and limited to minutes [9] or, in exceptional cases, to about an hour [10] of measured temperature histories. Similarly, computational fluid dynamic analyses are a very difficult and rather expensive way to obtain full fields. Unfortunately, the computational intensity restricts the results to typically minutes [11] or less [12] of temperature histories. Further, the complex and exceedingly time-consuming experiments and simulations provide only indirect means to estimate the fatigue life time of the pipes and marginal support to much needed statistical analyses of the uncertainties inherent to the estimated fatigue life.

The one-dimensional sinusoidal (SIN) and spectral methods on the other hand are much easier to apply and computationally very affordable [13,14]. The major drawbacks of these methods include consideration of single, although critical, frequency in the SIN-method [4], or random phases in spectral approaches [15], which effectively narrow down the simulated fluid temperature fluctuations to Gaussian ones.

In this paper an improved spectral loading approach, based on the synthetically generated temperature histories [16], is proposed to enable fatigue assessment of piping together with the assessment of uncertainties in the predicted fatigue life. The synthetic temperature histories employ sets of optimal phases to fully satisfy the necessary physical constraints of the mixing fluids through the limiting temperatures, the first two statistical moments and appropriate power spectral density (PSD) of the measured/calculated fluid temperature histories. The variability inherent in the temperature histories of mixing fluids, due to rather short temperature histories obtained from either experiments or computational simulations, is assumed to be the overriding contributor to the uncertainty of the fatigue life. The description and validation of the proposed assessment, through the application example of the Civaux case [3], is therefore attempted within a rather simple and linear one-dimensional (1D) model of the pipe with numerically resolved time-dependent temperatures and analytical expressions for the linear elastic wall thermal stresses varying only in the radial direction. This is consistent with the equi-biaxial stress field, which develops in the pipe subjected to variable temperatures away from any geometrical, structural or material discontinuities. The fatigue lives are predicted for diverse variations in fluid temperatures following the ASME Nuclear Boiler and Pressure Vessels [17] codified rules for varying principal stress direction, Rainflow counting algorithm, linear damage accumulation and the NUREG/CR-6909 design fatigue curve [18].

The structure of the paper is as follows. In Section 2, the procedure in the proposed thermal fatigue assessment is described including the generation of synthetic fluid temperatures, the heat transfer and mechanical analyses of the pipe wall as well as the estimation of uncertainties in the prediction of fatigue lives within the fatigue analyses. The results of the fatigue assessment and discussions are given in Section 3 and in Section 4 the conclusions are drawn.

2. Improved thermal fatigue assessment procedure

The goal of the proposed assessment procedure, which is outlined below, is to predict the uncertain fatigue life of a pipe exposed to the turbulent mixing of fluids from the uncertain temperature histories of the fluid close the pipe wall. To this end, the temperature histories of the fluid and in the pipe wall are used to estimate the pipe surface stress histories. This is then followed by a fatigue analysis using fatigue design curve.

In the following we assume that the overriding contributor to the uncertainty of the fatigue life is the variability inherent in the temperature histories of the mixing fluids. Evaluation and interpretation of the influence that the uncertainties in the input data have on the uncertainties in the result (fatigue life) could be enhanced by the use of as simple as reasonable model. The experience from 3D simulations [12,16,19] clearly shows that the stress fields in the thermally fatigued pipes, away from any material, geometrical or structural discontinuities, are nearly perfectly equi-biaxial. This facilitates the use of 1D models of the pipe with numerically resolved time-dependent temperatures and analytical