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Stress assessment in piping under synthetic thermal loads emulating turbulent fluid mixing

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HIGHLIGHTS

- Generation of complex space-continuous and time-dependent temperature fields.
- 1D and 3D thermo-mechanical analyses of pipes under complex surface thermal loads.
- Surface temperatures and stress fluctuations are highly linearly correlated.
- 1D and 3D results agree for a wide range of Fourier and Biot numbers.
- Global thermo-mechanical loading promotes non-equibiaxial stress state.

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ABSTRACT

Thermal fatigue assessment of pipes due to turbulent fluid mixing in T-junctions is a rather difficult task because of the existing uncertainties and variability of induced thermal stresses. In these cases, thermal stresses arise on three-dimensional pipe structures due to complex thermal loads, known as thermal striping, acting at the fluid-wall interface. A recently developed approach for the generation of space-continuous and time-dependent temperature fields has been employed in this paper to reproduce fluid temperature fields of a case study from the literature. The paper aims to deliver a detailed study of the three-dimensional structural response of piping under the complex thermal loads arising in fluid mixing in T-junctions.

Results of three-dimensional thermo-mechanical analyses show that fluctuations of surface temperatures and stresses are highly linearly correlated. Also, surface stress fluctuations, in axial and hoop directions, are almost equi-biaxial. These findings, representative on cross sections away from system boundaries, are moreover supported by the sensitivity analysis of Fourier and Biot numbers and by the comparison with standard one-dimensional analyses. Agreement between one- and three-dimensional results is found for a wide range of studied parameters. The study also comprises the effects of global thermo-mechanical loading on the surface stress state. Implemented mechanical boundary conditions develop more realistic overall system deformation and promote non-equibiaxial stresses.

1. Introduction

Thermal loads generated by turbulently mixing fluids at different temperatures in T-junction piping are known to be the cause of thermal fatigue in the surrounding material. Steel components in existing nuclear power plants (NPPs) have experienced cracking due to thermal fatigue induced by this type of fluid phenomenon and, in several cases, the cracks propagated through wall, provoking primary water leakage within the containment (NEA/CSNI, 2005, 2012). These incidents proved that thermal fatigue has important implications on structural integrity of plant components and, subsequently, on nuclear safety.

Various research projects have been dedicated to the understanding of thermal fatigue in general, which include the particular case of turbulent fluid mixing. Clear examples are the European THERFAT project (Metzner and Wilke, 2005), the international project coordinated by IAEA under the framework of fast reactor technologies (IAEA, 2002), the American research project (EPRI, 2003) and the Japanese research project (Fukuda et al., 2003). The multidisciplinary nature of thermal fatigue assessment forced the involved areas of research to progress in parallel.

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Nomenclature

t	time
τ	simulated time
z, θ	non-dimensional axial $z \in [0, l/r_i]$ and circumferential $\theta \in [0, 2\pi)$ coordinates
$A_n(z, \theta)$	field of amplitudes of harmonic n
k_n^z, k_n^θ	non-dimensional wave numbers in axial and circumferential directions
v	main flow velocity normalized with pipe inner radius
a	integer defining the range for k_n^θ distribution: $k_n^\theta \in \mathcal{U}[-a, a]$
n	harmonic number
φ_n	phase of harmonic n
ω_n	discrete angular frequency
f_n, f_c	discrete frequency and Nyquist frequency
N	number of temperature readings
$\Delta t, \Delta f$	time and frequency intervals
l, r_i, r_o	length, inner and outer radius of the pipe
r	radial coordinate of the pipe wall, $r \in [r_i, r_o]$
h	heat transfer coefficient
Fo, Bi	Fourier and Biot numbers
D	thermal diffusivity
ρ, c_p	density and specific heat of pipe wall material
k, α	thermal conductivity and expansion of pipe wall material
E, υ	Young modulus and Poisson's ratio of pipe wall material
$T_f(z, \theta, t)$	two-dimensional and time-dependent fluid temperature
$F_f(z, \theta, t)$	two-dimensional and time-dependent fluid temperature fluctuation
$T_f^{var}(z, \theta)$	variance field of fluid temperature fluctuations
$T_f^{\mathrm{mean}}(z, \theta)$	field of fluid mean temperatures
$T_f^{\mathrm{rng}}(z, \theta)$	field of fluid temperature ranges maxima
T_f^{rms}	root mean square of fluid temperature fluctuations at certain position
$T_s(r, z, \theta, t)$	time-dependent temperature fields of the pipe wall
$F_s(r, z, \theta, t)$	time-dependent temperature fluctuation fields of the pipe wall
$T_s^{\mathrm{rms}}(r)$	radial profile of root mean square temperature fluctuations of the pipe wall
q''_{conv}	convective surface heat flux
$\sigma_r, \sigma_\theta, \sigma_z$	radial, hoop and axial stresses
$\sigma^{\mathrm{rms}}(r)$	radial profile of root mean square stress fluctuations of the pipe wall
σ^{max}	maximum stress at the surface under fully clamped surface expansion
Sf	scale factor to input data
$r(F-z)$	linear correlation factor between temperature and axial stress fluctuations
$r(F-\theta)$	linear correlation factor between temperature and hoop stress fluctuations
$r(\theta-z)$	linear correlation factor between axial and hoop stress fluctuations

Firstly, characterization of thermal loads acting on structural components and the flow patterns that develop downstream of the T-junction have been possible by means of experimental facilities (Kamide et al., 2009; Smith et al., 2013). In particular, the Vattenfall benchmark facility (NEA/CSNI, 2011) was initially conceived for the development and validation of computational fluid dynamic (CFD) codes, mathematical approaches and turbulence models for the reliable simulation of fluid mixing phenomena. At the present moment, CFD with large-eddy simulations (LES) scheme give accurate thermal loads acting on the surrounding structure when simulations are performed considering adiabatic surrounding walls (Kuczaj et al., 2010). In these cases, heat transfer between fluid and structure is modeled employing a heat transfer coefficient approach (Chapuliot et al., 2005). In parallel to the validation of these advanced computational tools, mechanical response of the material to thermal loads has been predicted analytically using one dimensional (1D) methods (Kasahara et al., 2002), leading to the European Procedure for Assessment of High Cycle Thermal Fatigue (Dahlberg et al., 2007). The procedure provides screening criteria of temperature difference between the mixing fluids for the requirement of fatigue analyses, usual values of heat transfer coefficients between fluid and structure as well as suitable correction factors to be applied on the derived stresses using the proposed sinusoidal (SIN) method. In the SIN method the fluid temperature is anticipated at a single point and assumed to vary sinusoidally with time at a given frequency and amplitude. Then, thermal, mechanical and fatigue analyses are performed for different temperature parameters assuming that the pipe wall temperature varies only in radial direction. However, it is known that 1D methods intrinsically omit the global response of the structure.

The second field of research tries to quantify heat transfer between fluid and structure, i.e., to predict pipe wall temperature fluctuations. By means of novel sensors in experimental facilities, the fluid and structure temperatures are captured simultaneously (Fontes et al., 2009; Kimura et al., 2009) and transfer functions are derived in the frequency domain. Computer simulation tools are also available which allow obtaining structural temperature fields by computing the fluid thermo-hydraulics, the fluid-wall heat convection and wall heat conduction simultaneously (Kloeren and Laurien, 2011; Kuhn et al., 2010). These tools employ LES with conjugate heat transfer (CHT) and give very promising results. However, they are under development and the required computer resources and time are excessively elevated. Nevertheless, the validation of this kind of computer codes will be possible through ongoing international projects which aim to determine proper thermal loads induced on piping; see (Kuschewski et al., 2013; Miyoshi et al., 2012) and references therein.

In structural mechanics, the derivation of wall stresses from the induced temperature fields is performed with computer codes that employ finite-element (FE) solvers. These are necessary to obtain appropriate structural responses emerging from the complex three-dimensional (3D) thermo-mechanical loading as a consequence of large-scale flow instabilities of different frequencies and global deformation of the system. In the literature one can find few examples of mechanical analyses performed with thermal loads derived from CFD-LES-CHT simulations. However, these state-of-the-art and computationally demanding tools simulate one specific experimental case with stress levels that are usually scaled up to crack initiation levels (Kamaya and Nakamura, 2011) or, when more realistic cases are simulated, the study of the structural response is limited, most probably, due to the complexity of the overall computer simulation and uncertainties in the involved phenomena (Hannink and Blom, 2011; Niffenegger et al., 2013). Nevertheless, a comparison of thermal stresses obtained with different approaches has been performed by Blom et al. (2007).

Certainly, necessary and most important input to 3D thermo-mechanical analyses of T-junction piping are space-continuous surface thermal loads which cannot be obtained in experimental facilities. Hence, in support to experiments and in parallel to the development of CFD codes, a novel approach has been recently developed for the generation of two-dimensional (2D), continuous