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Development of a spectrum method for modelling fatigue due to thermal mixing

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ABSTRACT

Turbulent mixing of cold and hot fluids can lead to high-cycle thermal fatigue in T-junctions. In this work, a spectrum method for the thermal fatigue modelling was further developed. Estimation of the reference frequency, which determines the frequency range of the temperature spectrum, was considered in particular by utilizing flow mixing data from two T-junctions. Fatigue and crack growth obtained with the method were compared with the sinusoidal (SIN) method and with a computational fluid dynamics (CFD) load. The reference frequency was determined by fitting the model spectrum with temperature spectra obtained from measurements and CFD simulations. A formula for the reference frequency was proposed, which can be used in approximating the frequency also for other flow conditions. The SIN method resulted in over-conservatism in the fatigue and crack growth assessment. Results from the spectrum method agreed quite well with those obtained with the CFD load, showing that the method could result in significant improvement over the SIN method.

1. Introduction

Turbulent mixing of cold and hot fluids can lead to thermal fatigue and crack growth in piping and components of nuclear power plants (Shah and MacDonald, 1993; Dahlberg et al., 2007). The mixing causes fluctuating fluid temperature loads on structures, inducing stress fluctuations which may lead to material damage in case of sufficiently high amplitudes. An important feature of the turbulent mixing load is a wide range of different fluctuation frequencies, which results from the turbulence spectrum. Although computational fluid dynamics (CFD) can be used for calculating the structural thermal loads fairly accurately (see e.g. Hannink and Blom, 2011; Timperi, 2014; Howard and Serre, 2017), the high computational cost of the CFD simulations nonetheless necessitates also more simplified thermal fatigue assessment methods.

A simplified engineering approach for analysing the fatigue is the sinusoidal (SIN) method, where a 1D thermo-mechanical model is used for describing the pipe wall in the thickness-direction (see e.g. Dahlberg et al., 2007; Paffumi et al., 2013). The fluid temperature signal is assumed to be sinusoidal with amplitude that covers the whole available temperature range or 80% of this. Frequency which results in the shortest fatigue or crack growth time is usually selected, i.e. the so-called critical frequency. The heat transfer coefficient may be scaled up conservatively from correlations of fully developed pipe flow (Kimura et al., 2007, 2009; Lee et al., 2009). The SIN method leads often to overly conservative results, and the level of conservatism varies significantly case-by-case. This is largely due to the use of the critical frequency, and hence more realistic estimation of the temperature fluctuation spectrum has been deemed as one of the most important tasks for developing more accurate methods (see e.g. Paffumi and Radu, 2009).

A more realistic method can be achieved by replacing the sinusoidal fluid temperature with a more complex loading. Radu and Paffumi (2010) applied a simplified thermal load spectrum, defined as constant at a specified frequency range, for stochastic crack growth modelling. They obtained the pipe wall stresses and stress intensity factors (SIFs) from frequency response functions. A turbulent temperature signal either from experiments or CFD simulations can also be used, if such data is available. In order to avoid performing an experiment or simulation, Hannink and Timperi (2011) proposed a method where a synthetic temperature signal is generated based on a turbulence spectrum by superposition of harmonic components having different amplitudes and frequencies. They used a model spectrum derived from turbulence theory (Hinze, 1975) and assumed that the phase differences are randomly distributed. Hannink and Timperi (2011) compared the model spectrum with spectra measured from the Vattenfall mixing Tee experiments (Andersson et al., 2006; Westin et al., 2008) with fairly good results. They also found reasonably good agreement between the fatigue times obtained with the real and synthetic temperature signals. However, a major limitation of the work by Hannink and Timperi (2011) is that no account was made on how to calculate the reference frequency for the model spectrum, which determines the most important low-frequency range of the fluctuations. They applied a

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reference frequency for the studied case by approximately choosing a frequency which gives overall closest agreement for the actual and model spectra. However, having a realistic estimate for the reference frequency is essential for the fatigue assessment, since the reference frequency depends strongly on the flow parameters. The subsequent fatigue time is critically dependent on the frequency range.

The method by Hannink and Timperi (2011) gives the turbulent temperature load at a point on the pipe inner surface, i.e. a 1D thermo-mechanical model is generally used for the pipe wall as in the SIN method. The method was later extended to realistic 2D surface thermal loads by Costa Garrido et al. (2014, 2015), so that 3D thermo-mechanical pipe models can be utilized. In addition, Costa Garrido et al. (2014) used an iterative method for keeping the fluctuating temperature values inside the physical bounds (i.e. the cold and hot inlet temperatures) even for high root-mean-squared (RMS) values of the signal. Costa Garrido et al. (2016) performed fatigue calculations by using the 1D version of the method; they studied e.g. the effect of signal skewness on the fatigue and uncertainties resulting from different time-lengths of the signals. These calculations utilized the same value for the reference frequency as in Hannink and Timperi (2011), and estimation of the frequency for varying flow cases was not considered.

In this work, the reference frequency for the model spectrum is calculated for different flow cases and the calculations are validated against measured and simulated spectra. The outcome can be directly utilized in the 1D (Hannink and Timperi, 2011; Costa Garrido et al., 2016) and 2D spectrum methods (Costa Garrido et al., 2014, 2015). A simple iterative method is used for limiting the synthetic temperatures according to the cold and hot inlet values. The RMS temperature to be used in the spectrum method is also discussed based on CFD data from various T-junctions. Thermal mixing in the Vattenfall (Andersson et al., 2006; Westin et al., 2008) and FATHER (Courtin et al., 2011; Stephan, 2011) T-junction experiments is considered. 1D fatigue and crack growth calculations by using the sinusoidal, spectrum and CFD loads are finally performed for the FATHER T-junction.

The T-junction cases and the related CFD modelling are described briefly in Section 2. The spectrum method for generating realistic temperature signals and determination of the reference frequency are presented in Section 3. In Section 4, fatigue and crack growth calculations using the sinusoidal, spectrum and CFD temperature loads are considered. Finally, in Section 5 summary and conclusions are presented.

2. Description of flow cases

2.1. Vattenfall T-junction

In the experiments by Vattenfall Research and Development, thermal mixing in a plexiglass T-junction was studied (Andersson et al., 2006; Westin et al., 2008). The test facility shown in Fig. 1 consists of a horizontal cold water pipe with inner diameter of 140 mm and a vertical hot water pipe with inner diameter of 100 mm. Flow rate ratio was $Q_{\mathrm{cold}}/Q_{\mathrm{hot}} = 2$ which resulted in approximately equal flow velocities in the cold and hot pipes. The cold and hot temperatures were 15 °C and 30 °C, respectively. Flow velocities were measured with laser Doppler velocimetry (LDV) and fluid temperatures with thermocouples located about 1 mm from the pipe wall. The sensor locations are depicted in Fig. 2. The experiments are described in detail by Andersson et al. (2006). The flow parameters of the experiment are listed in Table 1. The Reynolds number is defined as $\mathrm{Re} = \rho UD/\mu$, where ρ, μ and U are the fluid density, molecular viscosity and average flow velocity, respectively, and D is the pipe diameter.

2.2. FATHER T-junction

The FATHER experiment by CEA, France, studied thermal fatigue in a stainless steel T-junction having nominal pipe diameter of 150 mm (Courtin et al., 2011; Stephan, 2011). Wall thickness of the pipe sections was 7.1 mm, whereas wall thickness near the T-junction was about 20 mm. Temperatures of the cold and hot water were 44 °C and 204 °C, respectively, resulting in $\Delta T = 160$ °C. The flow rate ratio was $Q_{\mathrm{hot}}/Q_{\mathrm{cold}} = 4$ and flow velocity of the mixed stream was 3.85 m/s. The mixing region consisted of welded sections with different surface finishes, resulting in different crack initiation times. The test lasted 300 h, after which many cracks with depths 0.1–1 mm were found at the T-junction. The experiment is described in more detail in the cited references.

The temperature signals for this flow case are taken from large-eddy simulation (LES) performed with the Star-CCM + code (Timperi, 2015). The flow parameters used in the CFD modelling are shown in Table 2. The LES was performed with a mesh having about 740 000 hexahedral cells. The pipe wall was assumed to be adiabatic contrary to the experiment with a steel pipe. The adiabatic wall condition is sufficient for the present study where the main interest is calculation of the reference frequency for the spectrum method. The Smagorinsky sub-grid scale (SGS) model with wall functions was applied. Temperature dependent water properties were used due to the large temperature difference between the inlet flows, and the effect of buoyancy was accounted for due to the variable water density. Instantaneous, mean and variance values of temperature in the T-junction are shown in Fig. 3. Instantaneous and mean heat transfer coefficient are shown in Fig. 4. The CFD modelling and the results are described in more detail in Timperi (2015).

Coordinates for the output locations of the temperature signals are defined in the same way as for the Vattenfall experiment, i.e. the

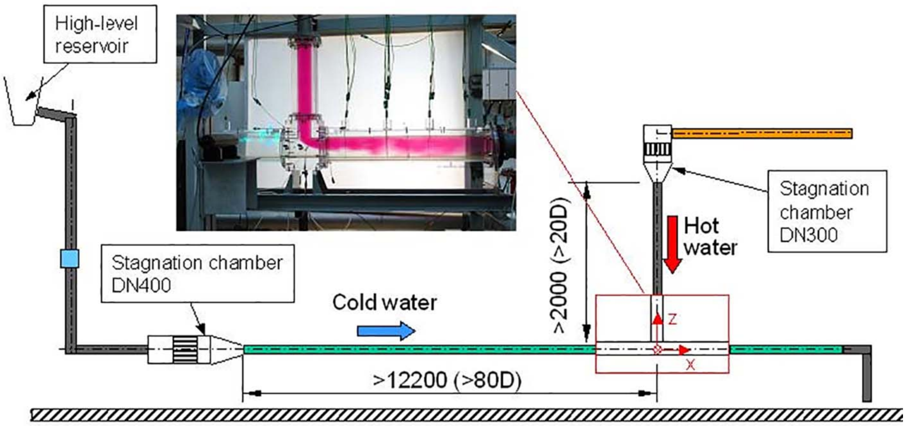

Fig. 1. Vattenfall thermal mixing test facility. (Andersson et al., 2006).