COMPARISON OF SPECTRAL METHODS WITH CFD SIMULATION OF TURBULENT FLUID MIXING

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ABSTRACT

The turbulent mixing of fluids at different temperatures in T-junctions may be the cause of thermal fatigue damage in the surrounding pipes. In the nuclear industry, primary water leakages have occurred in the safety related piping due to this fluid phenomenon and, currently, there are no generally accepted design rules to avoid the thermal fatigue.

The accuracy of thermal fatigue assessment of nuclear components strongly depends on the accuracy of the estimated fluid temperatures near the pipes. Nowadays, these are typically obtained from complex and time-consuming computational fluid dynamics (CFD) simulations with a clear restriction on the length of the simulated time compared to the predicted fatigue life. In order to overcome these limitations and with the aim to analyse the uncertainties in the fatigue predictions an improved spectral method has been recently developed to generate synthetic fluid temperatures at affordable costs.

The aim of this paper is to compare the synthetically generated fluid temperatures with those obtained in a validated CFD, large-eddy simulation of the mixing fluids. In the comparison, temperature as well as variable amplitude rainflow counting distributions are employed to estimate the applicability of synthetic temperatures in fatigue assessments. The life predictions scatter with synthetic temperatures may also indicate that longer CFD temperature histories are needed to reliably predict the safe fatigue lifetime.

INTRODUCTION

Several events in the nuclear industry have shown that thermal fatigue damage may develop in the pipes containing turbulently mixing fluids at different temperatures. Under these circumstances, the fluid temperature fluctuations near the pipe surface induce stress fluctuations in the pipe wall which may lead, in some circumstances, to fatigue and leakage (Dahlberg et al., 2007; NEA/CSNI, 2005).

The prediction of this thermal fatigue follows an interdisciplinary approach to evaluate the fluid and pipe wall temperatures and stresses (Chapuliot et al., 2005). In the recent years, these are obtained from the dedicated computational fluid dynamics (CFD) simulations of the mixing fluids and heat transfer and mechanical analyses of the pipe wall (Kamaya and Nakamura, 2011). Regardless of the stage of development and validation of the CFD models, it is believed that the large-eddy simulation (LES) of the fluid phenomenon, with coupled conjugate heat transfer (CHT) to the pipe and the subsequent transient mechanical analysis yield rather accurate predictions of the fatigue driving loads (Jhung, 2013; Timperi, 2014). Unfortunately, the high computational requirements of this approach typically limit the simulated flow mixing time rather short, from which the fatigue lifetime needs to be extrapolated. Uncertainty in the fatigue damage and lifetime prediction may thus be expected given the variability of the short loading histories obtained with the fluid mixing simulations.

The uncertainties involved in the thermal fatigue predictions have been recently studied taking into consideration the variable statistics and time lengths of the fluid temperature histories used in the fatigue assessment (Costa Garrido et al., 2016). In these analyses, synthetic fluid temperatures generated with an improved spectral method and the simplified one-dimensional (1D) pipe model were employed. The results seem to indicate that fatigue predictions may be uncertain for typical levels of temperature fluctuations and simulated time lengths of the mixing fluids. However, the synthetic fluid temperatures were not validated against real ones. On the other hand, the use of the 1D pipe model, which assumes the uniformity of pipe wall temperatures in the circumferential and axial directions, was revised in a previous research (Costa Garrido et al., 2015). For typical heat transfer properties between water and steel pipes, the 1D model was found to deliver conservative stress fluctuations (10% higher) when compared to the three-dimensional (3D) pipe model under equivalent fluid temperatures. Moreover, the 1D pipe model omits the global and 3D stress state of the pipe and typically assumes the surface equi-biaxial stress state. At positions away from any material, geometrical or structural discontinuities, these assumptions are consistent with the fatigue assessment following the ASME – design by analysis – varying principle stress criterion which also omits steady state loads such as pressure (Costa Garrido et al., 2016).

The aim of this paper is to compare the synthetic fluid temperature histories against those obtained in a CFD simulation of the mixing fluids. The synthetic temperatures are generated with the first two statistical moments and the power spectral density (PSD) of selected fluid temperatures from Timperi (2014). The predicted fatigue lives are then compared assuming, for the synthetic and CFD temperatures, identical 1D pipe model and heat transfer, mechanical and fatigue analyses. The observed variability in lifetime predictions further contributes to the understanding of the uncertainties involved in the thermal fatigue assessment of pipes.

FLUID TEMPERATURES FROM CFD SIMULATIONS

Timperi (2014) performed CFD simulations using LES for the Vattenfall T-junction experiment where the cold (T_{cold}) and hot (T_{hot}) fluids turbulently mixed with a temperature difference of $\Delta T = T_{hot} - T_{cold}$ = 15°C (Westin et al., 2008). The results reported in Timperi (2014) for the flow case named as Case 100% with fine mesh, CHT with the surrounding steel pipe and steady inlet boundary conditions are used in the present study. Specifically, the near-wall fluid temperatures at the two locations with the highest root-mean-square temperatures (T_{rms}), i.e. the highest levels of temperature fluctuations, are used in the following analyses. These include the point located 4 diameters downstream and 266° circumferentially and the point 0.4 diameters upstream and 0° circumferentially. The latter corresponds to the sharp upstream corner of the T-junction. Figure 1 shows the non-dimensional temperature histories of the fluid at 1 mm from the pipe surface for these points, hereafter named as D4R and COR, respectively. The non-dimensional temperature, mean temperature and root-mean-square temperature are defined as:

$$T^* = \frac{T - T_{cold}}{\Delta T}, \quad T^*_{mean} = \frac{T_{mean} - T_{cold}}{\Delta T}, \quad T^*_{rms} = \frac{T_{rms}}{\Delta T}. \tag{1}$$

The simulated temperature histories of total length τ = 55.70 s were recorded with a time step of Δt = 0.005 s. The frequency content of these temperatures, represented by their PSDs, are shown in Fig. 2. The distribution of temperatures, represented by histograms, are given in Fig. 3. The T^*_{mean} and T^*_{rms} of the fluid temperatures are, respectively, 0.32 and 0.20 at D4R and 0.39 and 0.33 at COR. Note that the higher level of temperature fluctuations at COR can be clearly observed in Figs. 1b and 3b, where the temperatures often fluctuate over the entire range. The temperature distribution at D4R, Fig. 3a, is bimodal and clearly skewed. In this case, the entire range fluctuations are of low probability.

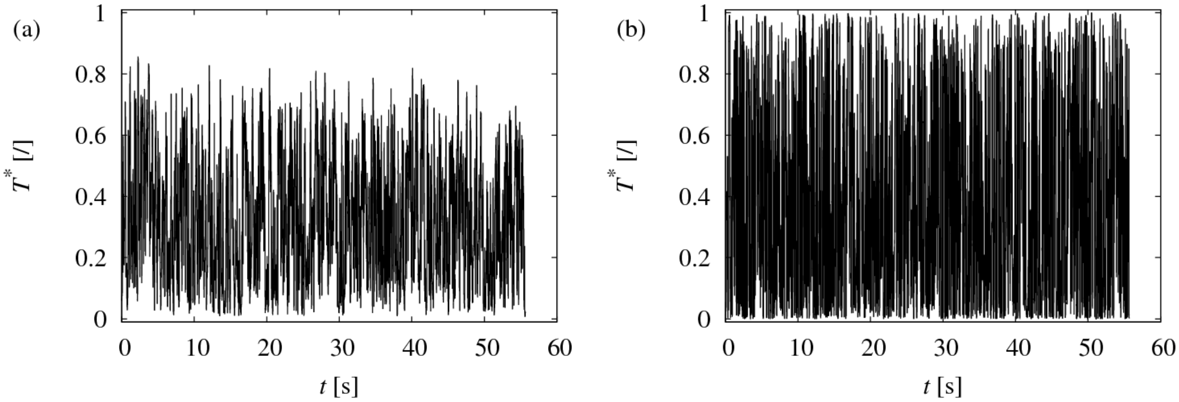

Figure 1. Fluid temperature histories at 1 mm from the pipe surface at the D4R (a) and COR (b) points from the CFD-LES (Timperi, 2014).

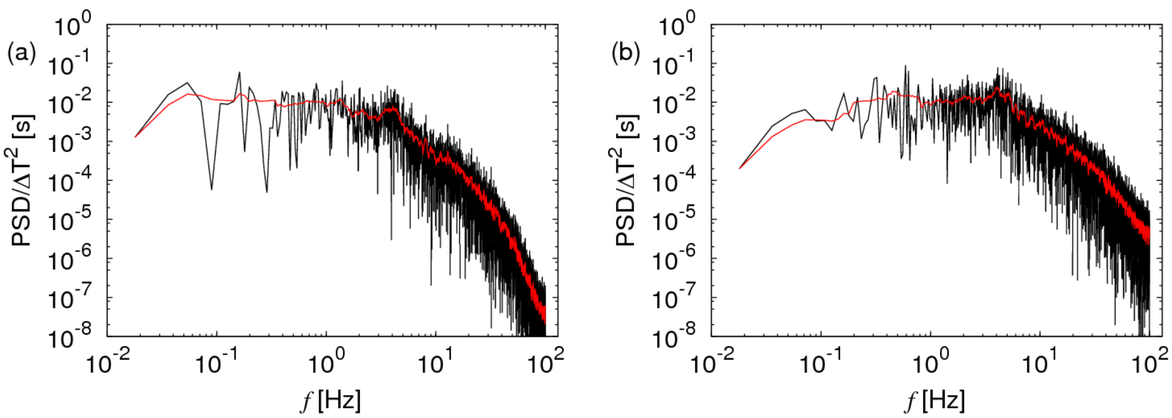

Figure 2. As computed (black) and filtered (red) PSDs of the fluid temperatures at the D4R (a) and COR (b) points from the CFD-LES (Timperi, 2014).

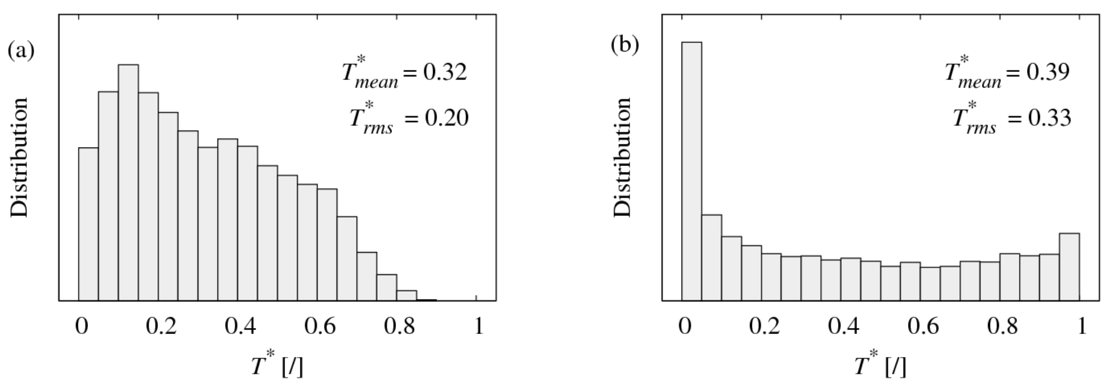

Figure 3. Histograms of the fluid temperatures at the D4R (a) and COR (b) points from the CFD-LES (Timperi, 2014).

FLUID TEMPERATURES FROM SPECTRAL METHOD

The synthetic fluid temperatures are generated with the improved spectral method presented in Costa Garrido et al. (2016) and Costa Garrido and Cizelj (2016). The method is similar to that proposed by Hannink and Timperi (2011), with the addition of limiting the synthetic temperatures according to the inlet values. Following an optimization process of the harmonics' phases, the temperature histories generated with the improved spectral method satisfy the limiting temperatures of the cold and hot mixing fluids. In this way, non-Gaussian temperature distributions may be obtained. Like any spectral method, it allows generating sets of temperature histories with given T^*_{mean}, T^*_{rms} and PSD profile.

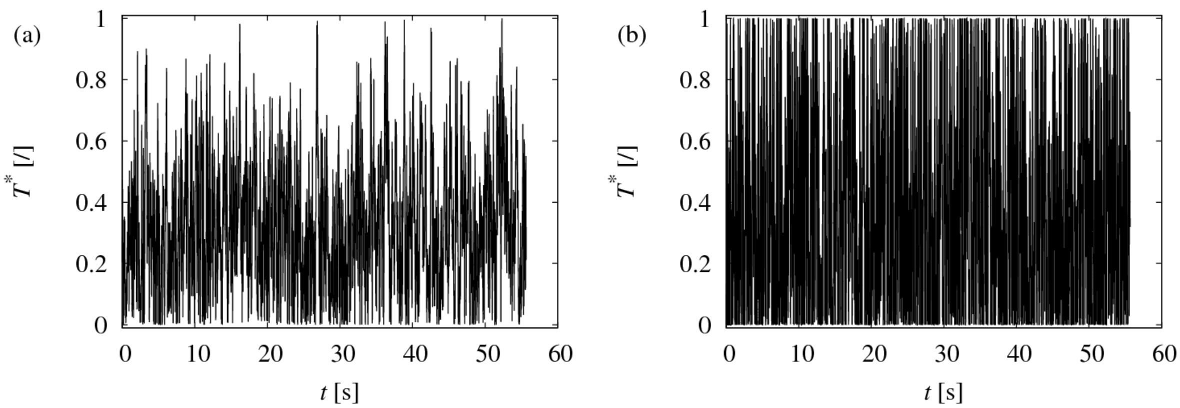

Figure 4. Representative samples of synthetic fluid temperature histories generated with the D4R (a) and COR (b) statistics.

In this study, sets of 100 temperature history samples are generated with T^*_{mean}, T^*_{rms} and PSD of the D4R and COR points presented above. The synthetic temperatures also share the same time length τ = 55.70 s and time step Δt = 0.005s of the CFD-LES temperatures. Figure 4 shows representative samples of the synthetic temperature histories and Fig. 5 the resulting temperature distributions. Note that the frequency content of the synthetic temperatures are identical to those from CFD-LES temperatures in Fig. 2.

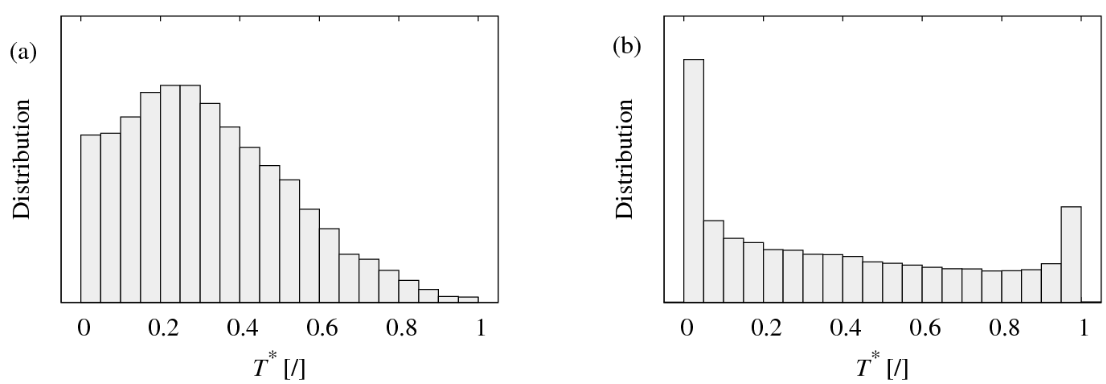

Figure 5. Histograms of representative samples of synthetic fluid temperatures with the D4R (a) and COR (b) statistics.

A general good agreement between the CFD-LES and synthetic temperatures can be observed by comparing Figs. 1,3 and 4,5. Full range temperature fluctuations, however, seem to be more probable in the synthetic temperatures. This is indeed the case for the D4R point where the tail of the synthetic temperature distribution in Fig. 5a is clearly located at higher temperatures than in the CFD-LES distribution in Fig. 3a. This feature arises from the only constraints in the synthetic temperatures being the limiting cold and hot temperatures. From the initial Gaussian distribution, which might exceed these limits, the improved spectral method delivers a bounded temperature distribution while preserving the input T^*_{mean}, T^*_{rms} and PSD statistics (Costa Garrido et al., 2016). The differences between the CFD-LES and synthetic temperatures therefore reside in higher moments, beyond T^*_{mean}, T^*_{rms} and PSD, of the temperature distributions. In the results section below, the consequences from these differences on the fatigue predictions are identified. Before that, a short description of the fatigue assessment is given next.

THERMO-MECHANICAL AND FATIGUE ANALYSES

The CFD-LES and synthetic fluid temperatures act as a thermal boundary condition near the inner surface of the stainless steel pipe with the geometrical, physical and material properties given in Table 1. A convection heat transfer coefficient h = 15,000 W/m^{2}K is assumed between the fluid and the pipe. The time-dependent radial temperatures of the pipe wall are then obtained by solving numerically the 1D heat equation with the insulated outer surface of the pipe. The initial temperature of the pipe wall is set to the mean temperature of the fluid.

Table 1. Austenitic stainless steel pipe characteristics

Inner radius	12.7 cm
Outer radius	13.6 cm
Thermal conductivity	14.7 W/mK
Specific heat	480 J/kg K
Density	7,800 kg/m^3
Thermal expansion coefficient	16.4x10^{-6} K^{-1}
Young's modulus	177x10^3 MPa
Poisson's ratio	0.3
Fatigue endurance (S_e)	93.7 MPa

The pipe wall temperatures are the input to calculate the time-dependent thermal stresses with the analytical expressions for the linear-elastic, 1D long pipe with free-end conditions (Costa Garrido et al., 2015). Under these conditions, the equi-biaxial stress state, i.e. the normal stress tensor components in the axial and circumferential directions are equal, is obtained at the inner pipe surface. It is also at the inner surface where the highest temperature and stress fluctuations are expected to occur. It should be noted at this point that, for the assumptions of temperature independent properties, constant heat transfer coefficient and the linear-elastic wall response, the thermo-mechanical analysis just described delivers stress amplitudes which behave linearly with the temperature difference of the mixing fluids, ΔT.

The circumferential (or axial) surface stress histories are the input to the fatigue analyses following the ASME – design by analysis – varying principle stress criterion (ASME, 1989). The fatigue life is estimated with the rainflow cycle counting method to obtain the list of stress amplitudes, S_a, from the complex stress history. Partial damages induced by the amplitudes above the endurance ($S_a > S_e$) are computed with the 2010 ASME fatigue design curve (Chopra and Shack, 2007) and linearly accumulated. The damage rate is then obtained by the accumulated damage over the time length τ of the stress history. Finally, the fatigue life is derived as the invers of the damage rate. The reader may refer to Costa Garrido et al. (2016) and Costa Garrido and Cizelj (2016) for the detailed description of the procedure.

RESULTS

The Vattenfall experimental facility (Westin et al., 2008) simulated by Timperi (2014) aimed at the validation of CFD codes and models. Hence, the temperature difference ΔT of the mixing fluids was kept well below the theoretical values (~80°C) required for the development of thermal fatigue damage (Costa Garrido et al., 2016; Dahlberg et al., 2007). In this work, the obtained stress amplitudes at the pipe surface are simply scaled linearly with ΔT. Note that this is consistent with the assumed linear behaviour of the heat transfer and mechanical analyses. The possible changes in the fluid mixing behaviour that may arise due to an increase of ΔT, such as buoyancy effects, are here omitted for the sake of clarity in the procedure.

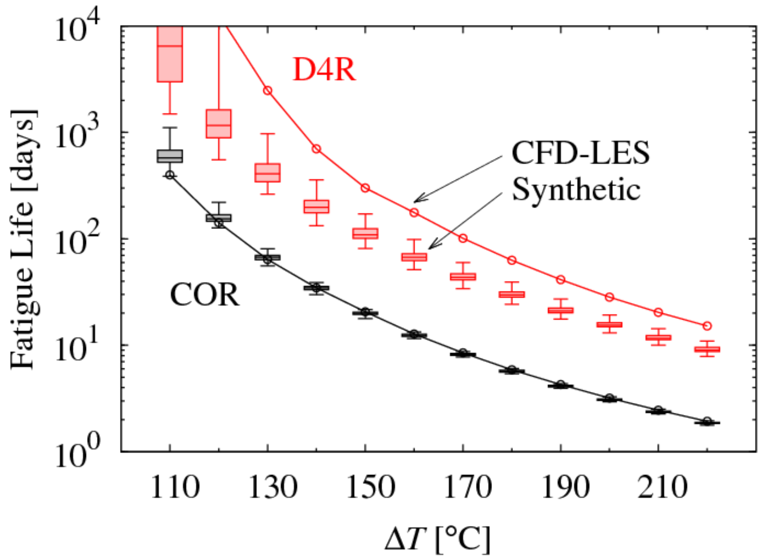

Figure 6. Results of the fatigue assessment with the CFD-LES (lines-circles) and synthetic (boxes and bars) temperatures for the fluid conditions at the D4R (red) and COR (black) points and varying ΔT.

Figure 6 shows the results of the thermal fatigue assessment performed with the CFD-LES and synthetic temperatures as a function of the assumed ΔT. For the CFD-LES temperatures, the predicted fatigue lives are represented with lines and circles. At each ΔT, the distribution of 100 fatigue lives obtained with the synthetic temperature history samples are illustrated with the help of boxes and bars (Costa Garrido et al., 2016). The lower, middle and upper limit of the boxes represent the 25th, 50th and 75th percentiles of the distribution and the bars extend from the 25th and 75th percentiles to the minimum and maximum lives, respectively. Figure 6 includes the results of the D4R and COR fluid conditions in red and black colours, respectively. A general observation of the results, already identified in previous studies (Costa Garrido and Cizelj, 2016; Costa Garrido et al., 2016), is that, for a given ΔT, shorter fatigue lives are expected for higher levels of normalized temperature fluctuations T^*_{rms}, i.e. shorter fatigue lives for the COR (black) than D4R (red) conditions. Additionally it can be observed that for the COR condition, the fatigue lives predicted with the CFD-LES temperature history fall within the distributions of fatigue lives obtained with synthetic temperatures. For the D4R condition, on the other hand, the results with the synthetic temperatures seem to be consistently lower, i.e. conservative, than with the CFD-LES temperatures. A tentative explanation for this could be the higher ranges of fluctuations observed in the synthetic temperatures when compared to the CFD-LES temperatures (see Figs. 1a,3a and 4a,5a). It should be recalled at this point, however, that these differences are beyond the T^*_{mean}, T^*_{rms} and PSD statistics of the temperature distributions. Following a similar reasoning, the matching results for the COR conditions could be attributed to the similarity of the distributions of the CFD-LES and synthetic temperatures (see Figs. 1b,3b and 4b,5b). Although additional research is needed to support these observations, the results in Fig. 6 preliminary show that the synthetic temperature histories may be employed for fatigue life predictions in this particular flow case.

As it can be seen also in Fig. 6, the scatter in the predictions with synthetic temperatures substantially grows with either lower ΔT or lower T^*_{rms}, if signals of constant time length are used in the analyses. As shown in previous studies (Costa Garrido et al., 2016) and from the rainflow counting results in Fig. 7, this may indicate that longer temperature histories are required for the reliable prediction of fatigue life.

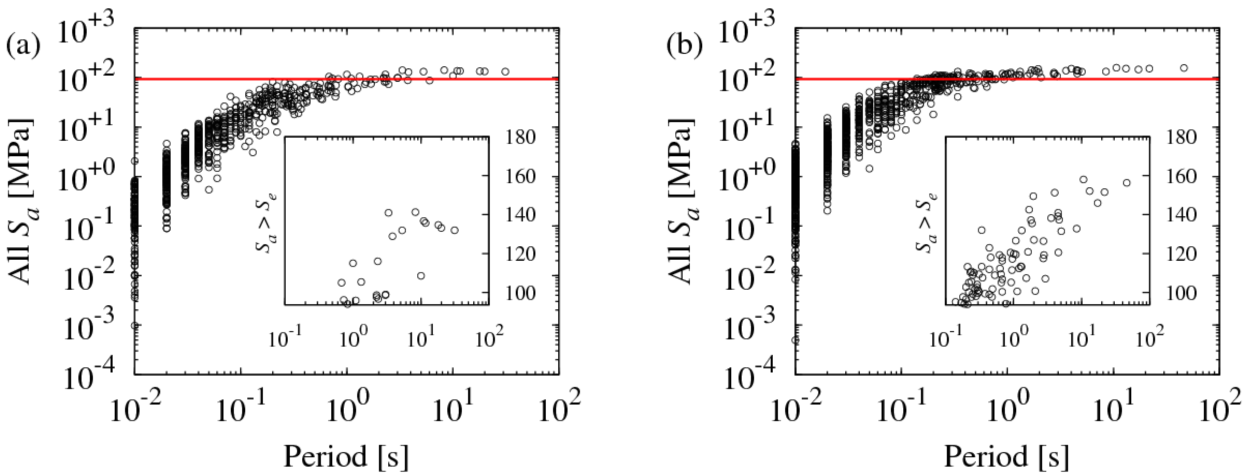

Figure 7. Results of the rainflow counting (amplitudes versus their period) for representative synthetic temperatures with fluid conditions at the D4R (a) and COR (b) points and assuming ΔT = 160°C.

Figure 7 shows the results of the rainflow counting, in terms of the amplitudes and their periods, obtained for representative synthetic temperatures with COR and D4R conditions and ΔT = 160°C. For both fluid conditions, the amplitudes have a similar distribution in the log scale. However, the number of damaging amplitudes is clearly reduced from COR to D4R conditions, as depicted in the insets of Fig. 7. The clear growth in the results' scatter from the COR to D4R conditions observed in Fig. 6 is then a consequence of predicting the fatigue life with decreasing number of damaging events. Similarly, the same occurs when lower ΔT is considered for a given fluid condition. Although the uncertainty in the predictions with the CFD-LES temperatures has not been explicitly studied in this work, the scatter in fatigue lives obtained with synthetic temperatures may thus indicate that a longer time length of CFD-LES simulation might be needed for reliable fatigue life prediction.

CONCLUSION

This paper presents the fatigue assessment of pipes under turbulent fluid mixing performed with synthetic and CFD-LES temperature histories that share the same time lengths and T^*_{mean}, T^*_{rms} and PSD statistics. The fatigue lives obtained with sets of 100 synthetic temperature history samples either matches the prediction with CFD-LES temperatures or are consistently conservative. These preliminary analyses indicate that the synthetic temperatures may thus be used in fatigue assessments for this particular flow case. Nevertheless, the differences in life predictions seem to be correlated with the differences in the synthetic and CFD-LES temperature distributions. This observation, however, requires further research. Moreover, the scatter in fatigue life predictions with synthetic temperatures arises from the insufficient number of fatigue damaging events detected in the relatively short stress histories. This may also indicate that longer CFD-LES temperature histories might be needed for reliable estimates of safe fatigue lifetime.

NOMENCLATURE

CFD	Computational fluid dynamics	S_a	Stress amplitude [MPa]
CHT	Conjugate heat transfer	T_{cold}, T_{hot}	Cold and hot temperatures of the mixing fluids
LES	Large-eddy simulation	T^*	Normalized temperature [/]
PSD	Power spectral density	T^*_{mean}	Normalized mean temperature [/]
ΔT	Temperature difference of the mixing fluids [°C]	T^*_{rms}	Normalized root-mean-square temperature [/]
Δt	Time increment [s]	τ	Time length of the temperature history [s]

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