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Analysis of temperature fluctuations caused by mixing of non-isothermal water streams at elevated pressure

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ABSTRACT

Temperatures were measured at the inner surface of an annulus between two coaxial tubes, where three water streams mixed. These temperatures were sampled at either 100 Hz or 1000 Hz. The acquisition time was set to 120 s. Two water streams at 549 K, with a Reynolds number between 3.56×10^5 and 7.11×10^5, descended in the annular gap and mixed with a water stream at 333 K or 423 K, with a Reynolds number ranging from 1.27×10^4 to 3.23×10^4. Water pressure was kept at 7.2 MPa. Inner-surface temperatures were collected at eight azimuthal and five axial positions, for each combination of boundary conditions. To better analyze these temperatures and mixing in the vicinity of the wall, scalars estimating the mixing intensity at each measurement position were computed from detrended temperature time series. Fourier and Hilbert–Huang marginal spectra were calculated for the time series giving rise to the highest values of a mixing estimator of choice. The relationship between temperature and velocity was explored by examining the results of an LES simulation using the same boundary conditions as in one of the experimental cases.

1. Introduction

In nuclear power plants, the mixing of non-isothermal flows can lead to cyclic thermal stresses in the wall, which could then cause thermal fatigue damage. This kind of damage is regarded as a relevant factor in the ageing and management of nuclear power plants (Walker et al. [39]), as well as in the life extension of operating plants and in the design of a new generation of reactors (Metzner and Wilke [25]). Until now, thermal mixing potentially leading to thermal fatigue has been explored by both experiments (see, e.g., Westin et al. [40], Kuschewski et al. [23], and Chen et al. [7]) and simulations (see, e.g., Hu and Kazimi [11], Naik-Nimbalkar et al. [26], and Ayhan and Sökmen [3]), in order to develop common evaluation methods and design codes (Kawamura et al. [19]).

However, when examining large datasets on thermal mixing, irrespective of whether they consist of experimental or computational data, it can be inferred from literature that aggregating data together into meaningful descriptors and finding tools to properly interpret these data happen to be convoluted issues. Some of these tools were implemented in Angele et al. [2]. Here, the mixing of non-isothermal water streams and its relevance for thermal fatigue were analyzed, building on the comparison of experimental data with the results of unsteady Reynolds-averaged Navier–Stokes (U-RANS) and scale-adaptive simulations (SAS). Experimental temperatures were measured at a rate of 50 Hz by means of 0.13-mm ∅ thermocouples, recording water temperatures at 1 mm from the wall surface, at several azimuthal and axial positions. These temperatures were then made dimensionless and examined, in terms of mean and RMS values, at several axial and azimuthal coordinates. After that, a power spectral density (PSD) of both SAS results and experimental data was computed, to prove that low-frequency fluctuations ($f < 0.5$ Hz), characteristic of thermal fatigue, were detected correctly.

Sakowitz et al. [34] investigated the mixing quality in a T-junction with three parameters, all computed from a large-eddy simulation (LES) mixing scalar. First, a uniformity index was calculated, assessing how much the time-averaged mixing scalar differed from its mean over some cross sections of the computational domain. Second, the RMS of the mixing scalar was evaluated, to better estimate the evolution of its fluctuations over time. Lastly, the integral time scale of the fluctuating part of the mixing scalar was appraised, to gage the speed of such oscillations.

Other studies examined mixing parameters related to either large or small scales. For example, in Koop and Browand [22], a quantity termed “mixedness” (Konrad [20]) measured the extent

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List of Symbols

Acronyms

DFT	discrete Fourier transform
EMD	empirical mode decomposition
HHT	Hilbert–Huang transform
IMF	intrinsic mode function
OI	orthogonality index

Greek symbols

ζ	dimensionless axial coordinate
$\bar{\pi}$	Fourier-based mixing estimator
σ	standard deviation
$\bar{\sigma}$	variance-based mixing estimator
ω	instantaneous frequency

Roman symbols

A	length of each $T_{f,DAS}$ after being low-pass filtered
c_0	number of the first mode in the trend
f	frequency
g	IMF
G	number of IMFs for $T_{f,lf}$
l	case identifier
M	length of each LES array
$\dot{m}$	mass flow rate
m_u	progressive number of the entries in the deduplicated movement pattern for case l
n^*	number of temperature arrays at a certain position for case l
NS_0	number of samples per first iteration per channel
(r, θ, z)	cylindrical coordinate system attached to the inner tube
$r_{u_i T}$	sample correlation coefficient between the Hilbert–Huang marginal spectrum of an LES temperature and that of an LES velocity component
R_1	azimuthal region defined as $R_1 = \{135^\circ \leqslant \theta \leqslant 225^\circ\}$
R_2	azimuthal region defined as $R_2 = \{315^\circ \leqslant \theta \leqslant 360^\circ\} \cup \{0^\circ \leqslant \theta \leqslant 45^\circ\}$
Re	Reynolds number
S	samples
t	time
T	temperature
T^*	normalized temperature
(u_r, u_θ, u_z)	velocities in the cylindrical coordinate system (r, θ, z)

Subscripts

C	cold inlets
d	detrended
DAS	acquisition of test-section temperatures
f	any of thermocouples $H1, H2, H3, H4, V1$, and $V4$ from Table 4 of Bergagio and Anglart [5]
H	hot inlets
if	inverse-filtered
L	LES
lf	low-pass filtered
w	windowed

of micromixing; that is, of mixing stemming from molecular diffusion.

In the present work, we examine surface temperature time series that have been recorded at the inner radius of a vertical annulus in which turbulent, non-isothermal water streams mixed together. Some inferences on the mixing phenomenon occurring there have been already drawn in Bergagio and Anglart [5], where, in addition, the experimental setup and data acquisition were illustrated in detail. In the current work, we try to assess mixing intensity and inhomogeneity by associating a descriptive scalar quantity with each measurement location.

As mentioned earlier, thermal fatigue is expected to be triggered by frequencies below 0.5 Hz (Angele et al. [2]) down to 0.01 Hz (Tinoco et al. [37]) for geometries close to ours, and by frequencies larger than 0.1 Hz (Chapuliot et al. [6]), up to 3–5 Hz (Ayhan and Sökmen [3]) in T-junctions where turbulent mixing of non-isothermal flows takes place. In this regard, Kasahara et al. [18] is considered to be prominent, as this work led to the determination of fatigue damage curves for fluid temperatures varying sinusoidally in time. Such curves reach their maximum values at intermediate frequencies between 0.1 and 10 Hz.

Thus, it becomes necessary to carry out a spectral analysis of the surface temperatures acquired. In this respect, performing (windowed) discrete Fourier transforms of CFD results and measurements seems to be by far the prevalent approach when comparing calculations with experimental data (see, e.g., Kamide et al. [17] and Pasutto et al. [29]). No further analysis of frequencies and amplitudes is usually attempted, since, generally speaking, authors focus on checking whether their results are consistent with the Kolmogorov $-5/3$ spectrum, and on identifying a frequency range for the prediction of thermal stresses in the walls. This is the case, e.g., in Radu et al. [32] and in Hannink and Blom [9], where, although non-isothermal mixing was under study, stresses in a pipe wall were computed by imposing a sinusoidally time-varying fluid temperature at the inner boundary, thus explicitly ignoring the nonperiodic, local nature of the load to try to identify a set of critical frequencies.

Despite that, with reference to turbulence in a wider sense, a broad variety of frequency analyses is starting to gain momentum; e.g., in the matter of time–frequency analyses, Meng et al. [24] studied turbulence and turbulent structures in a Kenics static mixer by analyzing the experimental pressure fluctuations inside it for a range of flow regimes (i.e., Reynolds numbers). These fluctuations were first decomposed by the empirical mode decomposition (EMD) method, in order to study their Hilbert–Huang transform (HHT) spectra and to derive Hilbert marginal spectra from them.

Concerning, once again, the application of EMD and Hilbert–Huang spectral analysis to turbulence, Huang et al. [14] analyzed the second-order Hilbert-based moments of the velocity time series from direct numerical simulations (DNS) of homogeneous isotropic turbulence at $Re_\lambda = 400$. Moreover, Konsoer and Rhoads [21] studied the normalized peak frequencies of the dominant modes of velocities, backscatter intensity, and temperature, for mixing interfaces at two river confluences – that is, in presence of thermal mixing –, as well as their relationship with the distance from the junction apex.

In the present work, depending on the value of the aforesaid descriptive scalar, we perform a Hilbert–Huang spectral analysis in two measurement zones and try to identify modes and frequency ranges peculiar to mixing.

2. Data acquisition

Experiments were performed in the High-pressure WAter Test (HWAT) loop in the thermal–hydraulic laboratory at the Royal Institute of Technology in Stockholm, Sweden. Test-section tem-