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Bistable features of the turbulent flow in tube banks of triangular arrangement

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ABSTRACT

In the present work, some features of the turbulent flow in tube banks of triangular arrangement are discussed. The experimental study is performed by means of hot-wire measurements in an aerodynamic channel, and flow visualizations in a water channel. The tube banks had pitch-to-diameter ratio 1.26 and 1.6, and the Reynolds numbers are in the range from 7.5×10^3 to 4.4×10^4, computed with the diameter of the tubes and the percolation velocity. The experimental data are analyzed through statistical, spectral and wavelet tools. The results show stable wake patterns after the first row of tubes. Visualizations show that the flow which arises from the gap between the tubes form coalescent jets. In some cases, a changing flow direction occurs. This phenomenon is called in the literature as "metastable". After two rows of tubes, the flows present a transverse vertical component. For $P/D = 1.26$, the flow direction changes at irregular time intervals, called "bistable flow". For $P/D = 1.6$, the wake pattern is stable. The features of turbulent flow through three, four and five rows of tubes seems to be similar, where the gap flop presents a fast swapping, from one side to another (flip-flop).

1. Introduction

Banks of tubes or rods are found in the nuclear and process industries, being the most common geometry used in heat exchangers. Tube banks are the usual simplified configuration for fluid flow and heat transfer studies of shell-and-tube heat exchangers, where the coolant is forced to flow transversely to the tubes by the action of baffle plates. Geometric characterization of a tube bank is made by the P/D-ratio, being D the tube diameter and P, the pitch, which is the distance between the centerlines of adjacent tubes. Tube arrangement is also equally important in the characterization of fluid flow and heat transfer of a tube bank. By attempting to improve the heat transfer process, dynamic loads are increased and may produce vibration of the structures, leading, generally, to fatigue cracks and fretting-wear damage of the components, which are one of the failure sources affecting nuclear power plant performance (Pettigrew et al., 1998).

The need for more efficient heat exchangers leads the operating conditions of these equipments to become critical. As a consequence, static and dynamic loads will be increased (Endres et al., 1995). According to Blevins (1990), the dynamic loads of the turbulent flow over small aspect ratio tube banks are characterized by broad band turbulence, without a defined shedding frequency. Weaver (1993), comment that the possibility of vortex shedding in closely spaced tube arrays has been the subject of controversy through the decades, and for staggered arrays, Abd Rabbo and Weaver (1986) and Polak and Weaver (1995), show that periodic forces are often present in small P/D tube bundles, by alternate vortex shedding in the early tube rows. It can be concluded that the excitation mechanism in staggered arrays is alternate vortex shedding in the first few tube rows. For large aspect ratio tube banks, the dynamic loads are basically associated with vortex shedding process.

The concern about the integrity of heat transfer equipments is, therefore, due to the close relationship between fluid flow around a solid surface and the vibrations induced by the flow in the structure by wall pressure fluctuations. Ziada (2006), makes a comprehensive analysis using spectral tools and visualizations for several tube bank geometries where the classical results are summarized. For in-line tube arrays, he concludes that this geometry is dominated by symmetric instability of the jets issuing between the tube columns. This mode of vorticity shedding persists on the whole depth of intermediate tube arrays. As the tube spacing is reduced, the jet instability and the spatial correlations are weakened.

Zdravkovich and Stonebanks (1988) comment that the leading feature of flow-induced vibration in tube banks is the randomness of dynamic responses of tubes. Even if the tubes are all of equal size, have the same dynamic characteristics, are arranged in regular equidistant rows and are subjected to a uniform steady flow, the initial response of tubes is non-uniform and random, and the vibration of the tubes can be compared to a Brownian motion.

By means of hot-wire and pressure transducer measurements and Fourier analysis, Endres and Möller (2001a) made a comprehensive study of velocity and pressure fluctuations in triangular

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Nomenclature

a, b	wavelet parameters
$c(J,k)$	wavelet series of approximation coefficients
$d(j,k)$	wavelet series of detail coefficients
C_{xy}	cross correlation function
D	diameter (m)
f	frequency (Hz)
F_s	sampling frequency (Hz)
j, k	indexes
J	index of the last decomposition of a wavelet
P	pitch (m)
$P_{xx}(a,b)$	wavelet spectrum (m^2/s^2)
Re	Reynolds number ($U_{per} \cdot D/\nu$)
S	Strouhal number ($f \cdot D/U_{gap}$)
t	time (s)
TI	turbulence intensity (%)
U_{gap}	gap velocity (m/s)
U_{per}	percolation velocity (m/s)
U_{ref}	reference velocity (m/s)
V_1	velocity measured with hot wire probe #1 (m/s)
V_2	velocity measured with hot wire probe #2 (m/s)
$x(t)$	generic function in time domain
$\tilde{X}(a, b)$	generic function in wavelet domain (continuous)
$\phi(t)$	generic scale function
$\Psi(t)$	generic wavelet function
CWT	continuous wavelet transform
DWT	discrete wavelet transform

and square arrangements. The results of spectra of velocity fluctuations in both tube banks with $P/D = 1.60$ show the presence of small peaks at Strouhal number equal to 0.21, which coincide with the value expected for vortex shedding in the case of a single cylinder. The peak is pronounced only in the tube bank with triangular arrangement. By reducing the P/D-ratio, the turbulence structure is reduced. In the range of 1.60–1.16, the energy of velocity fluctuations with small scales (large Strouhal numbers) is increased as P/D is reduced, while the highest values of crosscorrelations between velocity and pressure fluctuations were found at $P/D = 1.26$.

The cross-flow passing a tube in a bank is strongly influenced by the presence of the neighboring tubes. In the narrow gap between two tubes in a row, the strong pressure gradient will influence not only the flow in that region, but also the flow distribution downstream of this point, in the narrow gap between two tubes in the next row, and so on. Žukauskas (1972) compares the flow through tube banks with staggered arrays to the flow in a curved channel with periodically converging and diverging cross-sections. For in-line arrays, the comparison is made with a straight channel, and the velocity distribution is strongly influenced by the velocity in the narrow gaps.

However, in the study using wavelets and flow visualizations in tube banks with square arrangements, Olinto et al. (2006, 2009) show the presence of instabilities, generated after the second row of the tube bank, which propagates to the interior of the bank. Authors observed that a dye thread aligned with the channel axes, after reaching the bank, is deviated to one side (left or right), traveling and spreading in diagonal direction. In the resulting flow, the three orthogonal components are equally significant. The three-dimensional behavior of the flow is responsible for a mass redistribution inside the bank that leads to velocity values not expected for the studied geometry, according to the known literature.

This process is associated with the phenomenon of bistability known in the flow on two cylinders side-by-side (Fitzhugh, 1973). It may also be responsible for the large scatter in Fitzhugh's Strouhal number diagrams for tube banks (Blevins, 1990).

Measurements of non-stationary phenomena, like the bistable flow, produce time varying series, where the Fourier analysis cannot be used. Instead, modern literature presents the wavelet technique as a valuable tool to analyze non-stationary time series and their possible singularities (Farge et al., 1999).

The objective of this paper is to study the behavior of the cross flow through tube banks with triangular arrangement and discuss its relation with the bistable flow that occurs in some circular cylinder arrays, like side-by-side arrangements and tube banks with square arrangement. With this purpose, wavelet analysis of velocity time series obtained through hot-wire measurements are associated with visualizations to investigate flow behavior inside and after tube banks with triangular arrangement.

2. Background: Fourier and wavelet transforms

The statistical (or time domain) analysis consists on determining the first four moments of the probability density function: mean (average), standard deviation, skewness and kurtosis. The spectral (or frequency domain) analysis can be done through the power spectral density function (PSD). The joint time-frequency domain analysis was made trough wavelet transform. The wavelet analysis can be applied to time varying signals, where the stationary hypothesis cannot be maintained, to allow the detection of non permanent flow structures.

The Fourier transform of a discrete time series gives the energy distribution of the signal in the frequency domain evaluated over the entire time interval.

While the Fourier transform uses trigonometric functions as basis, the bases of wavelet transforms are functions named wavelets, with finite energy and zero average that generates a set of wavelet basis.

The continuous wavelet transform of a function $x(t)$ is given by:

$$\tilde{X}(a, b) = \int_{-\infty}^{\infty} x(t)\psi_{a,b}(t)\,dt \quad (1)$$

where ψ is the wavelet function and the parameters a and b are, respectively, scale and position coefficients ($a, b \in \Re$) and $a > 0$.

The respective wavelet spectrum is defined as:

$$P_{xx}(a, b) = |\tilde{X}(a, b)|^2 \quad (2)$$

In the wavelet spectrum, Eq. (2), the energy is related to each time and scale (or frequency) (Daubechies, 1992). This characteristic allows the representation of the distribution of the energy of the signal over time and frequency domains, called spectrogram.

The discrete wavelet transform (DWT) is a judicious sub sampling of the continuous wavelet transform (CWT), dealing with dyadic scales, and given by (Percival and Walden, 2000):

$$d(j, k) = \sum_{t} x(t)\psi_{j,k}(t) \quad (3)$$

where the scale and position coefficients ($j,k \in I$) are dyadic sub samples of (a, b).

Any discrete time series with sampling frequency F_s can be represented by:

$$x(t) = \sum_{k} c(J, k)\phi_{J,k}(t) + \sum_{j \le J}\sum_{k} d(j, k)\psi_{j,k}(t) \quad (4)$$

where the first term is the approximation of the signal at the scale J, which corresponds to the frequency interval $[0, F_s/2^{J+1}]$ and the inner summation of the second term are details of the signal at the scales j ($1 \le j \le J$), which corresponds to frequency intervals $[F_s/2^{j+1}, F_s/2^{j}]$.