SOME CHARACTERISTICS OF THE FLUCTUATING WALL PRESSURE FIELD
IN TUBE BANKS

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ABSTRACT

This paper presents the experimental analysis of pressure and velocity fluctuations of the cross flow in tube banks, with triangular and square arrangements, and four different aspect ratios. Measurements were performed with hot wires and pressure transducers. Behavior of fluctuating quantities is described by means of dimensionless autospectral density functions and their interdependence is discussed based on cross-correlation functions.

INTRODUCTION

Banks of tubes or rods are found in the nuclear and process industries, being the most common geometry used in heat exchangers. Attempts to increase heat exchange ratios in heat transfer equipments do not consider, as a priority of project criteria, structural effects caused by the turbulent fluid flow across the tube bank, unless failures occur [1]. By reducing the aspect ratio (pitch-to-diameter ratio) of a tube bank, to improve the heat transfer process, dynamic loads will appear, which are not associated to vortex shedding, as in large aspect ratios tube banks. The influence of the other hydrodynamic processes, like fluidelastic instabilities, turbulent buffeting and acoustic resonance, may also be present in tube banks of all aspect ratios. Therefore, new informations about the hydrodynamic phenomena in tube banks are necessary for the design and development of new equipments. The generalization of the large amount of experimental data, through similarity studies, and the constant improvement of the existing experimental techniques in the last decades, allowed a better comprehension of thermal and hydrodynamic phenomena in tube banks, leading also to the need of knowing the features of the resulting flow and its effects on the walls of the tubes in the bank. In spite of the recent developments in numerical results in this area, e.g. ref. [2], where large eddy simulation is applied, showing to be a promising technique, experimental results are necessary for the development and validation of new numerical models or methods.

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 the flow distribution downstream
of this point, in the narrow gap between two tubes in the next row, and so on. Zukauskas [3] 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, being the velocity distribution strongly influenced by the velocity in the narrow gaps. Heat exchange coefficients follow the same distribution as the velocity, increasing where velocity increases, and becoming almost uniform, at least in triangular arrays, as the aspect ratio is reduced [4].

The heat exchange is also influenced by the presence of the viscous sublayer adjacent to the walls, where the heat is transferred mainly by conduction. Velocity fluctuations in the viscous layer will occur under the influence of large eddies in the main flow. Therefore, to increase heat exchange ratios, the viscous sublayer must be reduced, while turbulence intensity in the main flow must be increased. In 1958, Knudsen and Katz [5] emphasized that the presence of large eddies in the main flow would increase the energy consumption, leading to the search of equilibrium between low pumping costs and high heat transfer efficiency or increase turbulence intensities and reduce pumping energy. It is clear that increasing pumping power, without influencing the viscous sublayer (to increase heat transfer) will lead to energy waste and prejudice equipment integrity.

The concern about heat transfer equipment integrity is due to the close relationship between fluid flow around a solid surface or a structural element and the vibrations induced by the flow in the structure. Differently from large aspect ratio tube banks, where dynamic loads are mainly associated with the vortex shedding process, the turbulent flow in tube banks with small aspect ratios is characterized as broad band turbulence, without a defined shedding frequency [6].

Pressure fluctuations result from velocity fluctuations at several points of the flow field. The resulting pressure field is described by the Poisson's equation, obtained from the divergence of the Navier-Stokes equation [7].

\[
\nabla^2 p = -\rho \frac{\partial^2 (u_i u_j)}{\partial x_i \partial x_j}
\]

(1)

where \( \rho \) is the density of the fluid, \( u_i \) and \( u_j \) are velocity components and \( x_i \) and \( x_j \) are spatial coordinates.

By introducing in equation (1) the Reynolds statement, representing velocity components and pressure by their time average value and the fluctuating part, and rewriting the resulting equation in terms of pressure fluctuation, equation (1) becomes

\[
\nabla^2 p' = -2 \rho \frac{\partial u_i}{\partial x_j} \frac{\partial u_j'}{\partial x_i} - \rho \frac{\partial^2 (u_i u_j')}{\partial x_i \partial x_j} + \rho \frac{\partial^2 u_i' u_j'}{\partial x_i \partial x_j}
\]

(2)

Pressure fluctuations are, thus, produced by the interaction of velocity gradients with velocity fluctuations and Reynolds stresses [8]. According to Townsend [9], the amplitude of the pressure fluctuations may be influenced by velocity fluctuations at a distance comparable to the wave length of these fluctuations. The search of form and magnitude of pressure and velocity fluctuations and the interdependence between these quantities is necessary for the comprehension of the complex phenomena described here.
The purpose of this paper is, therefore, to investigate the behavior of pressure and velocity fluctuations, and their interdependence, in tube banks, with triangular and square arrangements and several aspect ratios.

TEST SECTION AND MEASUREMENT TECHNIQUE

The test section is the same described in Ref. [10], being a 1370 mm long rectangular channel, with 146 mm height and a maximal (adjustable) width of 193 mm. Air is the working fluid, driven by a centrifugal blower, passed by a settling chamber and a set of honeycombs and screens, before reaching the tube bank at an incidence angle of 90º and about 2% turbulence intensity. The angle of incidence of the air on the tubes was 90º. The flow rate, and thus the Reynolds number, was controlled with help of a gate valve. Before the tube bank a Pitot tube was placed, at a fixed position to measure the reference velocity for the experiments. The tube banks were, both triangular and square arrangement, 5 rows deep for the measurements of fluctuating quantities. A scheme of the test section is shown in Figure 1. The geometries investigated and presented in this paper had aspect ratios (P/D) of 1.60; 1.26; 1.16 and 1.05, with tubes of 32.1 mm diameter and corresponding Reynolds numbers (ReR), based on the tube diameter and the incidence velocity, of 1.7 \times 10^4; 1.2 \times 10^4; 1.0 \times 10^4 and 5.8 \times 10^3. By taking the velocity measured in the center of the narrow gap between the rods, the values of the Reynolds numbers (ReG) are, respectively, 5.1 \times 10^4; 7.1 \times 10^4; 8.5 \times 10^4 and 8.2 \times 10^4. Subscripts R and G denote reference velocity or the velocity in the narrow gaps between the tubes, respectively.

For the measurement of velocity and velocity fluctuations between the tubes a DANTEC constant temperature hot wire anemometer was applied. Wall pressure fluctuations were measured by ENDEVCO piezo-resistive pressure transducers, mounted inside the tubes and connected to a pressure tap by plastic tubes. Prior measurements in pipe flow showed that this mounting technique was adequate to the measurements to be performed [11]. Figure 2 shows an scheme of the pressure transducer mounted inside the tube. The tube instrumented with the pressure transducer was the central one in the third row, as shown in Figure 3. Measurements were performed at each 10º by turning the tube about its axis. These angles are measured clockwise between the direction of the main flow and the position of the pressure tap. Zero degrees (0º) corresponds to the position where the pressure tap faces the main flow. Velocity and velocity fluctuations were measured in three positions: in the center of the narrow gap between the tubes, directly in front of the pressure tap at position 90º, and at a half row distance upstream and downstream of that point. These positions are marked “gap”, “upstream” and “downstream”, respectively, in the figures of results.

Data acquisition of pressure and velocity fluctuations was performed simultaneously by a Keithley DAS-58 A/D-converter board controlled by a personal computer, which was also used for the evaluation of the results. Experimental results in this paper were characterized by autospectral density functions of velocity and pressure fluctuations, and their interdependence was investigated with help of cross-correlation functions, described through the Fourier Analysis, since they have a random behavior.

The Fourier Analysis is a valuable tool for the study of random phenomena being widely applied to turbulence studies. Usually, random data are presented in form of time series, representing a continuous (analog) function of time, sampled for digital analysis with a frequency f as a sequence of numbers at regular time intervals.
The autospectral density function (or power spectrum) represents the rate of change of the mean square value of a certain time function \( x(t) \) with the frequency \( f \) [12]

\[
\phi_{xx}(f) = \frac{1}{B\theta} \int_{0}^{\theta} x^2(f, B, t) dt \tag{3}
\]

where \( \theta \) is an adequate integration (observation) time and \( B \) the bandwidth.

In the Fourier space, the autospectral density function will be defined as the Fourier transform of the autocorrelation function \( R_{xx}(t) \), defined as the mean value of the product of this function at a time \( t \), with its value at a time \( t+\tau \).

Let \( x(t) \) and \( y(t) \) be two generic functions of time, so that a correlation function of \( x(t) \) and \( y(t) \) can be written as

\[
R_{xy}(\tau) = \frac{1}{\theta} \int_{0}^{\theta} x(t)y(t+\tau) dt \tag{4}
\]

The function defined via equation (4) is called cross-correlation function, normalized by the RMS values of \( x(t) \) and \( y(t) \), will be noted as \( C_{xy} \). The particular case of \( x(t)=y(t) \) is the autocorrelation function, therefore, the autospectral density will be given by

\[
\phi_{xx}(f) = \int_{-\infty}^{+\infty} R_{xx}(t)e^{-i2\pi ft} dt \tag{5}
\]

In this research work, time functions \( x(t) \) and \( y(t) \) are velocity and pressure fluctuations at different points of the flow.
For the determination of autospectral density functions the sampling frequency was of 16.1 kHz, while the signals of the instruments were high pass filtered at 1 Hz and low pass filtered at 8.05 Hz. Cross-correlation functions were determined from data sampled at 3 kHz and low pass filtered at 1 kHz. In this case, the high pass filter was set at the same frequency of 1 Hz.

Analysis of uncertainties in the results have a contribution of 1.4 % from the measurement equipments (including hot wire, pressure transducer and A/D converter). In the measurements of pressure fluctuations, tubings are responsible for 5 % of the uncertainties, leading to a total value for the spectra of pressure fluctuations, up to 1000 Hz, of 6.4 %.

RESULTS AND DISCUSSION

Before starting the experiments the flow distribution and the turbulence intensity in the test section were measured, showing an uniform velocity profile with 2% of turbulence intensity. Measurements of vibrations of the test section (including the tubes of the tube bank) were also performed with help of a METRA accelerometer, to identify possible influence produced by the blower or by its electrical motor. Two important resonance frequencies of the test section were detected, these being about 2 and 8 kHz.

Figures 4 to 7 show dimensionless autospectral densities of wall pressure fluctuations measured in several angular positions of a tube in the third row, as described in Figure 3. Experimental results of spectra are presented as functions of the dimensionless frequency in form of the Strouhal number, defined with the tube diameter and the velocity in the narrow gaps between the rods. This velocity was measured with the hot wire probe except in the tube bank with P/D = 1.05, where the gap was too narrow to place there the hot wire probe. In this case the Pitot tube was used.

In general, all curves for square arrays have the same decay pattern after a Strouhal number Str = 0.1, with dimensionless values of the autospectral densities of the same order. For Strouhal numbers below this value the curves have lower decays, mainly in the region of flow incidence - for square arrays between 45º and 90º. This fact may indicate differentiated characteristics of the flow in the regions before and after the narrow gap, producing unbalanced forces over the tubes due to the different energy distribution with the frequency. This is evident in the spectra taken at 45º and 90º in the tube banks with P/D = 1.60 and 1.26, Figures 4-a and 5-a. The higher values of energy in the curves show this unbalanced force distribution, produced by the impinging flow coming from the narrow gap in the previous row. By reducing P/D ratio, Figures 6-a and 7-a, P/D = 1.16 and 1.06, pressure fluctuations have almost coinciding spectra, showing that the distribution of the pressure fluctuations around the tube tends to be uniform as the P/D is reduced.

The results for triangular arrays do not have a defined pattern as in square arrays. In this case, the spectrum of pressure fluctuations have different features for each P/D-ratio analyzed. Figure 4-b shows an energy peak at Str = 0.68 at positions of 45º, 135º and 180º, characterizing vortex shedding with a frequency of 398 Hz. This is in accordance with the results of Pollak and Weaver [13] obtained from anemometry and flow visualization, in a range of 14 %. By reducing P/D-ratio, peaks of vortex shedding disappear and spectra show a more uniform decay as the Strouhal number increases. This produces also an increase in the energy in the positions of 0º, due to the impinging flow coming from the narrow gap of the preceding row. In the bank with lower P/D-ratio, Figure 7-b, an energy peak is found at Str = 0.74, at positions of 45º, 135º and 180º, with a frequency of 589 Hz. This is in accordance with the results of Fitzhugh, presented in Ref. [6], with a deviation of 4.4 %. It is
not clear if these peaks are produced by vortex shedding since no similar result appear in the spectra of the intermediate P/D-ratios, Figures 5-b and 6-b.

All the curves show pronounced peaks at about Str = 2.0 and 9.0. These values correspond to the calculated resonance frequencies [14], inherent of the use of tubings to connect pressure transducer to pressure tap [11], Figure 2. These peaks can be completely disregarded in this analysis.

Figures 8 to 10 show spectra of velocity fluctuations in three positions of the tube banks investigated. In general, the curves have a very steep but uniform decay. As the P/D ratio is reduced the decay in the spectra taken in the narrow gaps become less steep than those taken at positions upstream and downstream of the narrow gap. There, the energy in the low Strouhal numbers, i.e. low frequency ranges, is reduced, while in the high Strouhal numbers it is increased. That means that, in the narrow gaps between the tubes, the energy in the large eddies is reduced while the energy in the range of small eddies becomes higher. This fact appears first in the results of measurements in the banks with triangular arrays Fig. 9-b, P/D = 1.26. For square array, this effect appears only in the bank with P/D = 1.16, Fig. 10-a. In the bank with triangular array and P/D = 1.16 spectra of velocity in upstream position is similar to the spectra in the gap with approximately the same magnitude. No measurements at position “downstream” in this geometry were performed, due to the difficulty of positioning the hot wire probe close to the tube wall in this P/D-ratio. Zukauskas description of the flow through tube banks [3] can explain this behavior: in square arrangements, the main flow behaves like a channel flow, and effects of reducing gap space will appear only with very small P/D-ratios; on the other side, in triangular arrangements, the main flow is constantly submitted to changes in its direction, leading to an increase in the energy of the smaller eddies. Thus, in triangular arrays, the small passages and the constant changes in flow direction contribute to reduce the size of turbulent structures as the P/D-ratio is reduced.

![Figure 4: Autospectral densities of pressure fluctuations in several positions of a tube in a bank with P/D = 1.60 and square (a) and triangular (b) arrays.](image)
Figure 5: Autospectral densities of pressure fluctuations in several positions of a tube in a bank with P/D = 1.26 and square (a) and triangular (b) arrays.

Figure 6: Autospectral densities of pressure fluctuations in several positions of a tube in a bank with P/D = 1.16 and square (a) and triangular (b) arrays.
Figure 7: Autospectral densities of pressure fluctuations in several positions of a tube in a bank with P/D = 1.05 and square (a) and triangular (b) arrays.

Spectra of velocity fluctuations in both P/D = 1.60 show, in the positions “upstream”, the presence of peaks at Str = 0.21, corresponding to a frequency of 152 Hz, which coincides with the value expected in the case of a single cylinder. This can be observed in the spectra of pressure fluctuations only in the bank with triangular array, Figure 4-b. This value is not in accordance with Fitzhugh’s compilation, presented in Ref. [6] (Str = 0.31), but is also present in the normalized cross-correlations $C_{vp}$, between velocity and pressure fluctuations, Fig. 11-a, where a periodicity of about 6.6 ms, indeed with low values, appears. While correlation values in the tube bank with P/D = 1.60 are very low, they show relatively high negative values for P/D = 1.26. As the gap width is reduced to P/D = 1.16, values of the maxima of cross-correlation coefficients decrease. This confirms the reduction of the scales of the turbulent flow and the raise in the energy content of the smaller eddies. Therefore, the small scales does not carry the major responsibility of producing wall pressure fluctuations in the tube banks with small aspect ratio investigated.

CONCLUDING REMARKS

This paper presents experimental results of pressure and velocity fluctuations in the turbulent cross flow through tube banks with triangular and square arrangements and four different aspect ratios. The experimental technique showed to be adequate for the experimental work performed.
Figure 8: Autospectral densities of velocity fluctuations in tube banks with P/D = 1.60 and square (a) and triangular (b) arrays.

Figure 9: Autospectral densities of velocity fluctuations in tube banks with P/D = 1.26 and square (a) and triangular (b) arrays.
Results of spectra of pressure fluctuations show, in general, that all curves for square arrays have the same decay pattern after a Strouhal number \( \text{Str} = 0.1 \), with dimensionless values of the autospectral densities of the same order, while in the results for triangular arrays the spectra have different features for each P/D-ratio analyzed. All results have almost uniform distributions, except the bank with triangular arrangement and the smallest P/D-ratio, where the highest values of pressure fluctuations were found at 0º, being this the point where the pressure tap faces the main flow.

Spectra of velocity fluctuations in both P/D = 1.60 show the presence of small peaks at \( \text{Str} = 0.21 \), which coincides with the value expected for vortex shedding in the case of a single cylinder, but only in the tube bank with triangular array and P/D = 1.60 a pronounced peak indicates the presence of this phenomenon. By reducing the P/D-ratio turbulence structure will be reduced. In the range of 1.60 to 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. This means that, although an increase in the energy is found by further reducing P/D-ratio, this does not affect the viscous sublayer, as observed in the measurements in the bank with P/D = 1.16 by the reduction of the correlation coefficient. This could not be confirmed in the present work, since correlation measurements in the tube bank with the smallest P/D-ratio were not possible with the present technique.
Therefore, the design of heat exchangers must consider that turbulence scale in tube banks have to be reduced, since small eddies can produce an efficient mixing, affecting the viscous sublayer on the tube walls, enhancing heat transfer, without producing high values of pressure fluctuations, which can induce vibrations of the structure. Even so, the natural frequency of the tubes must be out of this range, to avoid coupling due to turbulent buffeting as described by Paidoussis [1].

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