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Velocity and pressure fluctuations on inclined tube banks submitted to turbulent flow

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ABSTRACT

This paper presents the experimental study of pressure and velocity fluctuations and their interdependence, in the turbulent flow impinging on arrangements of yawed circular cylinders simulating inclined tube banks with square arrangement and a pitch to diameter ratio of 1.26. Measurements were performed with hot-wires and a pressure transducer. Behaviour of fluctuating quantities is described by means of dimensionless autospectral density functions and cross correlations. Experimental results indicates the presence of two different phenomena of vortex generation in inclined tube banks.

Keywords: Tube banks, turbulent flow, hot wires, pressure transducers

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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, unless failures occur (Païdoussis, 1982). 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., 1997). While static loads seem to appear mainly due to the strong pressure drop which occurs in the narrow gaps between the tubes, in small aspect ratio tube banks, dynamic loads, arising from the fluctuating pressure field, have a random behaviour, without any characteristic frequency (Endres et al., 1995).

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 (Willmarth, 1975).

$$\nabla^2 p = -\rho \frac{\partial^2 (u_i u_j)}{\partial x_i \partial x_j} \qquad (1)$$

where ρ 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

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

Pressure fluctuations are, thus, produced by the interaction of velocity gradients with velocity fluctuations and Reynolds stresses (Rotta, 1972). According to Townsend (1976), 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 in tube banks, since the resulting forces applied to the tubes by the turbulent flow, will be given by the integral of the pressure field around each tube in the bank. From the fluctuating pressure field, a fluctuating excitation force will result, which may induce vibration of the tube if its natural frequency is present in the excitation force. The natural frequency of the tubes is estimated from the fundamental natural frequency of a beam pinned at both ends, being a function of the distance between support grids (Blevins, 1990).

The concern about heat transfer equipment integrity 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.

Tube banks have being widely studied in the last decades. The first systematic studies of fluid flow distribution and pressure drop in tube banks of shell and tube heat exchangers and steam generators, known to the Authors, are the work of E. Grimison and the doctoral thesis of P. Wiemer, both in 1937. Both works dealed mainly with friction factors, but Wiemer made a very interesting flow visualization study using sand boxes models of heat exchangers and steam generators. His results show the strong influence of baffle plates in the whole flow pattern due to boundary-layer separation and recirculation processes.

In shell-and-tube heat exchangers, the cross flow through the banks is obtained by means of baffles, responsible for changing the direction of the flow and for increasing the heat exchange time between fluid and the heated surfaces, the turbulence levels and the heat exchange ratios. Baffles can also be responsible for additional dynamic loads due to boundary layer separation after them, which can travel through the bank, influencing the tube bank and the baffles (Wiemer, 1937).

Experimental results of velocity and wall pressure fluctuations in the turbulent flow through a simulated tube bank with square arrangement, after passing a baffle plate were performed by Möller et al. (1999). In general, results of wall pressure and wall pressure fluctuations showed higher values than in pure cross flow (Endres and Möller, 1997, 2001-a). The characteristic value of the Strouhal number found was about 0.2. Important additional peak frequencies, appearing in spectra of tube wall pressure fluctuations, could not be associated neither to effects of pure cross flow through the bank nor to effects produced solely by the baffles. The results presented in that paper were, therefore, not conclusive, leading to the need of the experimental study of the flow through inclined tube banks for their correct interpretation.

Former studies of the flow through inclined tube banks, focused more on flow distribution and pressure drop problem using macroscopic theories in the search of constitutive models for multidimensional flow through rod or tube bundles (Böttgenbach, 1977; Möller and Qassim, 1985). Both references showed the coincidence of the flow incidence angle and the pressure gradient occurred only at 0^o and 90^o (pure axial and cross flow normal to tube axis).

In the study of flow induced vibrations in inclined tube banks, Žukauskas et al. (1980) found that hydrodynamic forces exciting the tubes depended on the incidence angle of the flow. The higher the incidence angle, the higher the critical velocity for fluidelastic instabilities. These Authors concluded also that the excitation mechanisms were the same for normal or inclined tube banks, depending on the velocity normal to the tube axes.

In a large P/D-ratio staggered yawed array of tubes, Ziada et al. (1984) found that the Strouhal number of vorticity shedding defined with the velocity component normal to the tubes is independent of the yaw angle. The shedding frequencies can be estimated through Strouhal number charts. The velocity and pressure fluctuations in yawed tube arrays are substantially lower than those inside similar unyawed tube arrays. Excitation mechanisms are progressively weakened as the incidence angle of the flow is increased.

In spite of the long time since Grimison's and Wiemer's studies, and all the efforts devoted since then by many authors concerning the several aspects of the flow through tube banks, the need of deeper understanding the physics of fluid structure interaction, including the turbulent flow through tube bundles in cross flow, still remains (Borsoi, 2001). In general, the flow field surrounding a slender structure is three-dimensional. Similarly to the velocity field, the net force applied on the structure by the fluid flow can be resolved into components parallel to and perpendicular to the structural axis. These normal and tangential forces are function of the incidence angle (cross-flow principle) (Blevins, 1990). Nevertheless, the approach found in the literature is usually two dimensional, being measurements performed in a cross sectional plane parallel to main flow direction.

The purpose of this paper is, as presented by Barcellos (2001), to investigate the wall pressure distribution and the behaviour of pressure and velocity fluctuations, and their interdependence, in the turbulent flow impinging on arrangements of yawed circular cylinders simulating an inclined tube bank.

Nomenclature

$C_{xy}(\tau)$ = Correlation coefficient -
D = Diameter m
e = Base of natural logarithm -
f = Frequency Hz
$\Phi_{xx}(f)$ = Autospectral density function $[x(t)]^2.s$
L = Length m
ν = Kinematic viscosity $m^2.s^{-1}$
P = Pitch m
p = Pressure Pa
P/D = Aspect ratio -
ρ = Density $kg.m^{-3}$
Re = Reynolds number : $Re = U\ D/\nu$ -
RMS(x) = Root mean square value [x]
$R_{xy}(\tau)$ = Correlation function [x(t).y(t)]
Str = Strouhal number : $Str = f D / U$ -
τ = Time delay s
t , θ = Time s
U , v = Velocity $m.s^{-1}$
$u_{i,j}$ = Velocity components $m.s^{-1}$
U_{mea} = Measured gap velocity $m.s^{-1}$
U_{ref} = Reference velocity $m.s^{-1}$
$x_{i,j}$ = Spatial coordinates m
x(t) , y(t) = Generic time functions [x(t) , y(t)]
[...] denotes **units of ....**

Test Section and Measurement Technique

The test section, shown schematically in Fig.1, was the same described in (Endres and Möller, 2001-a, b), being a rectangular channel, with 146 mm height and a width of 193 mm. The length of the test section was variable, depending on the bank inclination. All the banks were located at 1600 mm after the settling chamber and had the same outlet length after the bank of 220 mm. Air was 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 with about 2 % turbulence intensity.

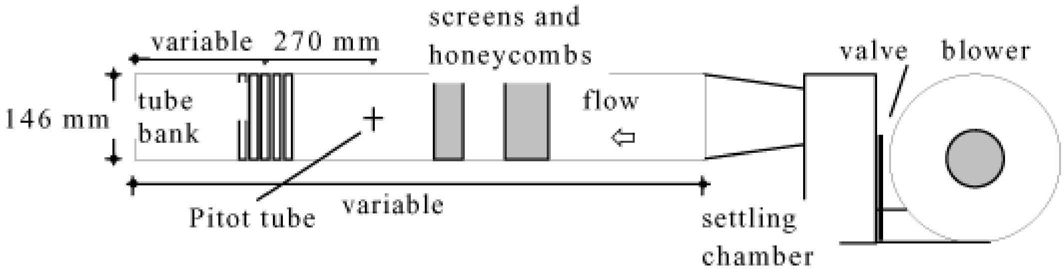


Figure 1. Test section (schematic).

The angles of incidence of the air on the tubes corresponded to the bank inclination, namely 90°, for pure cross flow, 60°, 45° and 30°. The tube banks had square arrangement and were 5 rows deep with 25 tubes in each bank. Figure 2 shows schemes of the tube banks investigated. 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 mean Reynolds number for all experiments, are shown in Table 1 together with the corresponding velocities. Reynolds numbers were calculated with the tube diameter (32.1 mm) and the reference velocity (U_{ref}) or with the velocity measured (U_{mea}) in the narrowest gap between two tubes. The choice of the dimensionless parameters definition is according to Endres and Möller (2001-b).

Table 1: Mean flow parameters for the tube banks investigated.

	90° Bank	60° Bank	45° Bank	30° Bank
U_{ref} [m/s]	6.49	6.22	6.72	7.69
Re_{Uref}	1.85×10^4	1.87×10^4	1.85×10^4	1.87×10^4
U_{mea} [m/s]	28.39	28.30	27.79	24.26
Re_{Umea}	8.09×10^4	8.51×10^4	7.65×10^4	5.90×10^4

Mean pressure distribution along the bank was determined by means of a 30x30 mm mesh of pressure taps drilled on one side wall and measured with help of H&B pressure transmitters.

Velocity and velocity fluctuations were measured by means of a DANTEC *StreamLine* constant temperature hot-wire anemometer. Pressure fluctuations were measured by an ENDEVCO piezo-resistive pressure transducer, mounted inside one of the tubes in the bank, and connected to pressure taps by plastic tubes (Endres and Möller, 1994, 2001-b). Figure 3 shows a scheme of the instrumented tube and of the mounting technique of the transducer. The tube instrumented with the pressure transducer in the bank could be rotated, so that measurements of pressure fluctuations at the tube wall were performed at several angular positions. The use of tubings was necessary due to the dimensions of the test section used, although pressure transducers are preferably mounted flush to the walls. Prior measurements in pipe flow showed that this mounting technique was adequate to the measurements to be performed (Endres & Möller 1994, 2001-b).

Previous analysis of the behaviour of the test section, by means of METRA accelerometers, and of the measurement technique, allowed to identify peaks in spectra due to resonances not related to the investigated phenomena. 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 RMS values of the wall pressure fluctuations, autospectral density functions of velocity and pressure fluctuations, while their interdependence was investigated with help of cross-correlation functions, described through the Fourier Analysis, since they have a random behaviour.

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* (Bendat and Piersol, 1986) and it is given by

$$\phi_{xx}(f) = \frac{1}{B\theta}\int_0^\theta x^2(f, B, t)dt\ , \qquad (3)$$

where θ 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 and position, so that a correlation function of *x(t)* and *y(t)* can be written as

$$R_{xy}(\tau) = \frac{1}{\theta}\int_0^\theta x(t)y(t+\tau)dt\ . \qquad (4)$$

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

$$\phi_{xx}(f) = \int_{-\infty}^{+\infty} R_{xx}(t)e^{-i2\pi f\tau}d\tau\ . \qquad (5)$$

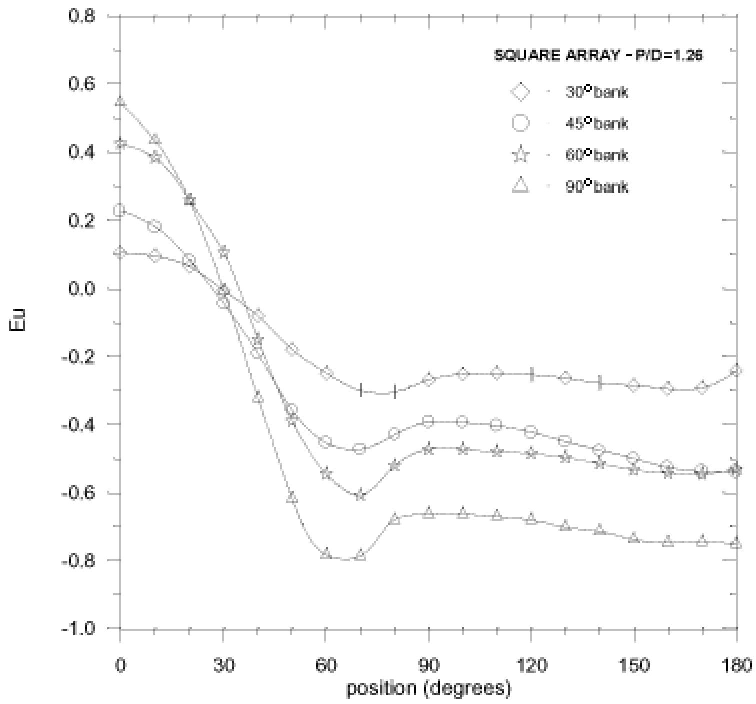
In this research work, time functions *x(t)* and *y(t)* are velocity and pressure fluctuations at different points of the flow. By means of Eqs. (4) and (5), analysis of the fluctuating quantities can be made in space and time as well as frequency domains.

For the determination of autospectral density functions, the sampling frequency was of 5 kHz, while the signals of the instruments were high pass filtered at 1 Hz and low pass filtered at 2 kHz. Previous studies of pure cross flow through tube banks showed, for this test sections, to be the frequency range of importance (Endres and Möller, 2001-a). 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 %.

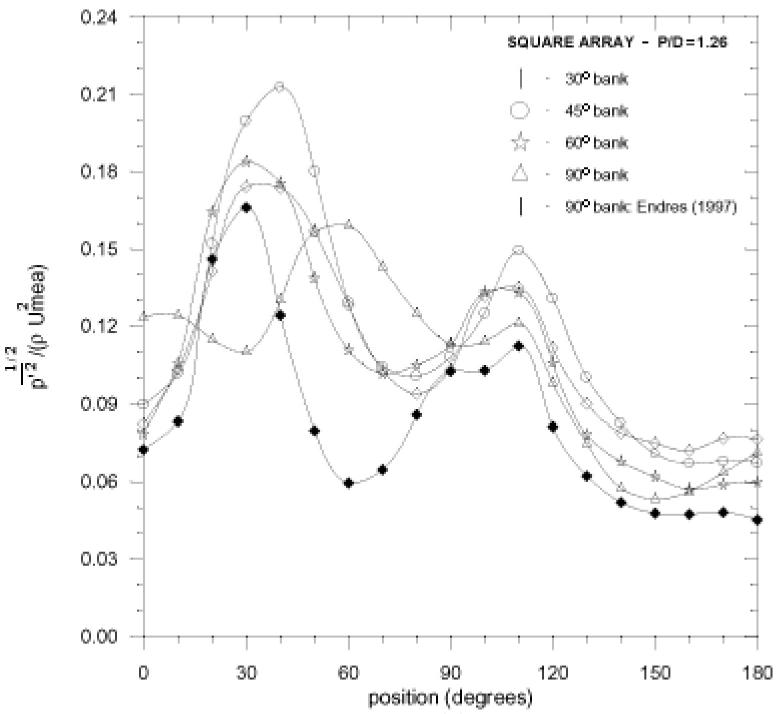
Results

Figure 4 a-d shows the isocontours of mean pressure distribution on one channel side wall, with the presence of the tube bank. The locations of the tubes in the bank are also indicated in the figures. Results are presented in form of Euler numbers, obtained by means of fluid density, ρ, and a reference velocity. Some misdistributions of the contour lines due to the resolution of the mesh are observed, but isobaric lines are clearly not parallel to tube axes. They are also not perpendicular to the channel axis. This indicates that the pressure gradient is neither perpendicular to the tubes, nor parallel to main flow direction confirming prior results by Böttgenbach, 1977 and Möller and Qassim, 1985. This is explained through the cross flow principle (Blevins, 1990). According to it the net forces, in this case due to the pressure gradient, applied to a slender structure can be resolved into components parallel to and perpendicular to the structural axis. Although this principle is to be considered an approximation, it clearly explains the isobaric lines distribution measured on the channel wall, representing the pressure field across the bank.

Figures 5 a-b show dimensionless values of the mean wall pressure and RMS-values of pressure fluctuations, also, in form of Euler numbers. Measurements were performed in the central tube of the third row where, according to Žukauskas, 1972, entrance effects are dissipated. Results are presented as functions of the angular position of the instrumented tube: 0^{o} corresponds to the position facing the main flow. Mean pressure distribution for all investigated incidence angles have similar distribution as in the flow perpendicular to a single cylinder, with increasing dimensionless absolute values as the incidence angle decreases. The values become negative at about 30^{o}. RMS values show local maxima at about 30^{o} and 110^{o} indicating the incidence of shedded vortexes from upwind tube row and the shedding process occurring in that tube. The first local maxima coincides approximately with the change of signal of mean values. Differences observed in the results in the 90^{o} tube bank were later attributed to misalignments of the instrumented tube in the bank employed by Barcellos (2000). Later repetition of the measurements confirmed prior results showed by Endres, (1997).



(b)



(a)

Figure 5. a) Mean wall pressure distribution on a tube of the bank (dimensionless); b) RMS values of the wall pressure fluctuations on one tube of the bank (dimensionless).

Figure 6 shows autospectral density functions of the wall pressure fluctuation in the tube banks investigated for angular positions from 0^o to 180^o. While the tube bank with 90^o incidence angle show spectra with uniform decay, in the spectra measured in the banks with 60^o incidence angle or less, peaks appear, with the highest values at the 45° bank. The highest peak in the plots of 60°, 45° and 30° occur at angular positions of 30° and 120° coinciding with the local maxima observed in the RMS plots, Fig. 5-b. Dimensionless frequencies, in form of Strouhal numbers, defined with gap velocity (Endres and Möller, 2001-b) increase, as the incidence angles decrease. After a Strouhal number about 2.10^{-1} they show the same decay until values about 2.10^{o}, where pronounced peaks are found. These values correspond to the calculated resonance frequencies (Strasberg, 1963), inherent of the use of tubings to connect pressure transducer to pressure tap (Endres and Möller, 1994, 2001-b), Figure 2. These peaks can be completely disregarded in this analysis.

In the same figure, below a value of the Strouhal number of 2.10^{-1}, the slopes are lesser steep and peaks appear in the spectra of the inclined banks with values of about $2x10^{-2}$ for the 60° bank, $6x10^{-2}$ for the 45° bank and for the 30° bank the value is $1x10^{-4}$. The peak with highest energy is that of the 45° bank.

Similar behaviour is observed also in the spectra of velocity fluctuations measured in the narrow gap between two tubes of the third row, Fig. 7: peaks appear at about the same values of the Strouhal number, with the highest peaks at the bank with 45° incidence angle. The highest energy values occur for this bank until a Strouhal number of about 2.10^{-1}. After this value all spectra have the same behaviour.

As observed in Figs. 5 and 6, peaks are present in all spectra, except the 90° tube bank, with increasing frequency as the incidence angle is reduced. Velocity spectrum for the 45° bank shows two peaks. The first one at a Strouhal number of $5.5x10^{-2}$ and the second one at $1x10^{-1}$. Indeed, the latter appears in all spectra of pressure fluctuations, with increasing magnitudes at positions of 0°, 150° and 180°. This indicates that, besides the vortex shedding, a second phenomenon may be present in inclined tube banks, which may be associated with a recirculation process on the back side of the inclined tubes. As the incidence angle is reduced, the vortex shedding frequency, and thus the Strouhal number, increases as a consequence of the streamlined shape of the elliptical cross section of the inclined tube.

Figure 8 presents results of cross correlations between velocity fluctuations, measured at the narrow gap between two tubes of the third row and wall pressure fluctuations at that location. Cross correlation measured in the bank with 90° incidence angle, presents a peak with negative value. The magnitude of this peak increases in the 60° bank, while some oscillations start to appear. These oscillations are very clear at 45° and at 30°. The frequency of these oscillations are about 40 Hz for the 60° bank, 60 Hz for the 45° bank and 130 Hz for the last one, and correspond to the Strouhal numbers of the peaks in spectra, Figs. 6 and 7. Noticeable is that the highest oscillation occurs for the 45° bank, where the spectra have the highest energy. Since, in this study, these oscillations appear only in the inclined tube banks, it can be attributed to phenomena occurring in association with a change in the flow pattern, when compared to the 90° bank. Variations in the flow direction, lead by the pressure difference between fore and back side of the tube, Fig. 5-a, are expected.

The three-dimensional flow effects generated in the inclined tube banks before and after the tubes seem to be more important in the 45° bank. Their dominant frequencies are, probably, associated with vortex shedding on the back side of the inclined tubes and flow recirculations in those regions.

Concluding Remarks

This paper presents the experimental study of the velocity and wall pressure fluctuations in the turbulent flow through arrangements of yawed circular cylinders simulating inclined tube banks with square arrangement. Air was the working fluid impinging on the tube banks at several incidence angles. Experimental results of velocity fluctuations and wall pressure fluctuations were obtained by means of hot-wires and a pressure transducer.

Through the analysis of the pressure field on the channel side wall it was possible to observe that the isobaric lines are not parallel to the tube axes. This fact confirms results of Böttgenbach (1977) and Möller and Qassim (1985), that for inclined tube banks the pressure gradient is neither perpendicular to tube axes nor parallel to main stream direction.

RMS values of pressure fluctuations show a more uniform distribution for the banks with 90^o and 30^o. Pressure fluctuation distributions, scaled with the mean flow velocity in the narrow gap between the tubes of the banks with 30º, 45º and 60º present a similar behaviour, while the 90^o bank shows a RMS distribution similar to the others only after an angular position of 90^o. Local maxima were found between angular positions about 30^o and 110^o, corresponding respectively to the location were the flow coming from the upstream tube row impinges on the tube and to boundary layer separation.

Discrepancies in the results of RMS distributions at the 90^o tube bank produced by misalignement of the istrumented tube in the test section of the experiments by Barcellos (2000) demonstrate the strong influence of tube alignment in experimental studies in tube banks.

Autospectral densities of pressure fluctuations on the instrumented tube of each bank analyzed have the same slope between values of the Strouhal number from $2x10^{-1}$ to $1x10^{0}$. Below these values, the slopes are lesser steep and peaks appear in the spectra of the inclined banks with increasing values as the incidence angle is reduced. The peak with highest energy is that of the 45^o bank.

Spectra of velocity fluctuations shows a less steep decay as the incidence angle is increased. Peaks appear at the same values of Strouhal numbers found in spectra of pressure fluctuations.

This seems to confirm the results by Ziada et al. (1984) in staggered-yawed tube arrays that the velocity parameter for Strouhal numbers is the velocity component normal to tube axis. Nevertheless, the result of spectra of pressure and velocity fluctuations do not confirm their results that excitation mechanisms are reduced as the flow incidence angle is decreased.

The interpretation of the phenomena studied here is directly connected to the cross correlation plots: as the tube bank angle decreases, strong three-dimensional effects appear which can be associated with vortex shedding on the back side of the inclined tubes. These effects, characterized by the oscillations in cross correlations at 45^o seem to vanish as the inclination angle is continued to be reduced. This indicates that the observed phenomenon has different behaviour of the pure cross flow, and occur at angles about 45^o with frequencies associated to the vortex shedding process and to recirculations on the back side of the tube. Two peaks were identified, the lowest frequency corresponding to the vortex shedding process. The highest associated to a second flow process, which can be due to the flow recirculation on the back side of the tube. As the incidence angle is reduced, the vortex shedding frequency approaches the frequency of this expected recirculation. An additional interesting hydrodynamic problem arises, therefore, this being the angle where cross flow characteristics ceases to be dominant and axial flow starts. Constitutive models using macroscopic theories (Böttgenbach, 1977, Möller and Qassim, 1985) indicate that flow resistance is a combination of the resistance of pure axial and pure cross flow. This is in agreement with the cross-flow principle (Blevins, 1990). Expected flow distribution based on the experimental results make evident that a two-dimensional analysis of the flow through tube banks is not complete, since it can not entirely describe such flow features.

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References

Barcellos, C. R., 2001, "Dynamic characteristics of the turbulent flow trough inclined tube banks" (in portuguese), M. Eng. Dissertation, PROMEC, Federal University Rio Grande do Sul. [Links]

Bendat, J. S. and Piersol, A. G., 1986, "Random data: analysis and measurement procedures". 2nd ed. John Wiley and Sons, New York. [Links]

Blevins, R. D., 1990, "Flow induced vibration", 2nd ed, Van Nostrand Reinhold, New York. [Links]

Borsoi, L., 2001, "Flow-induced vibration of nuclear components: future r&d perspective derived from the french experience", Transactions of SMiRT 16 - International Conference on Structural Mechanics in Reactor Technology, CD-Rom, Paper #1460, Divison J, Washington-DC. [Links]

Böttgenbach, H., 1977, "Messungen von Strömungsfeldern in engen Stabbündeln zur Überprüfung einer anisotropen Strömungsfelderntheorie", Dr.-Ing. Dissertation, Ruhr-Universität Bochum, Bochum. [Links]

Endres, L. A. M. 1997. Experimental analysis of the fluctuating pressure field in tube banks subjected to turbulent cross flow, Dr. Eng. Thesis. PROMEC/UFRGS, Federal University Rio Grande do Sul, Porto Alegre-RS, Brazil (in Portuguese). [Links]

Endres, L. A. M. and Möller, S. V., 1994, "Experimental study of the influence of connections between pressure taps and transducers" (in Portuguese), Proc. SIBRAT 94, 2nd Latin-American Symposium on Pressure Vessels and Piping, pp. 416-424, Gramado-RS. [Links]

Endres, L. A. M. and Möller, S. V., 1997, "Some characteristics of the fluctuating wall pressure field in tube banks", Trans. SMiRT 14, 14th International Conference on Structural Mechanics in Reactor Technology, Vol. 6, pp. 161-172, Lyon. [Links]

Endres, L. A. M., Silva, C. and Möller, S. V., 1995, "Experimental study of static and dynamic fluid flow loads in tube banks", Trans. SMiRT 13, 13th International Conference on Structural Mechanics in Reactor Technology, Vol. 4, pp. 451-456, Porto Alegre. [Links]

Endres, L. A. M., Möller, S. V., 2001-a, "On the fluctuating wall pressure field in tube banks", Nuclear Engineering and Design, Vol. 203, pp. 13-26. [Links]

Endres, L. A. M., S. V. Möller, 2001-b, "Looking for correct dimensionless parameters for tube banks flow analysis", Journal of Fluids and Structures, Vol. 15, nr. 5, pp. 737-750. [Links]

Grimison, E. D., 1937, "Correlation and utilization of new data on flow resistance and heat transfer for cross flow of gases over tube banks", Transactions of the American Society of Mechanical Engineers, New York: Process Industries Division, pp. 583-594. [Links]

Möller, S. V., Endres, L. A. M. and Escobar, G, 1999, "Wall pressure field in a tube bank after a baffle plate", Trans. SMiRT 15, 15th International Conference on Structural Mechanics in Reactor Technology, Vol. 7, pp. 265-272, Seoul. [Links]

Möller, S. V., Qassim, R. Y., 1985, "A constitutive model for the flow through rod bundles and the verification of its applicability", Nuclear Engineering and Design, Vol. 88, pp. 1-9. [Links]

Païdoussis, M. P., 1982, "A review of flow-induced vibrations in reactors and reactor components", Nuclear Engineering and Design, Vol. 74, pp. 31-60. [Links]

Pettigrew, M. J., Taylor, C. E., Fisher, N. J., Yetisir, M. and Smith, B. A. W., 1997, "Flow-induced vibration: recent findings and open questions", Trans. SMiRT 14, 14th International Conference on Structural Mechanics in Reactor Technology, V. 0, pp. 19-48, Lyon. [Links]

Rotta, J. C., 1972, "Turbulente Strömungen". B. G. Teubner: Stuttgart. [Links]

Strasberg, M., 1963, "Measurement of fluctuating 'static'' and total-head pressure in a turbulent wake". NATO Report - AGARD-R-464, Paris. [Links]

Townsend, A. A., 1976, "The structure of turbulent shear flow". Cambridge U. P., Cambridge, UK. [Links]

Wiemer, P., 1937, "Untersuchung über den Zugwiederstand von Wasserrohrkesseln", Dissertation, RWTH, Aachen. [Links]

Willmarth, W. W., 1975, "Pressure fluctuations beneath turbulent boundary layers", Ann. Rev. of Fluid Mech., Vol. 7, pp. 13-88. [Links]

Ziada, S., Bolleter, U., Chen, Y. N., 1984, "Vortex shedding and acoustic resonance in a staggered-yawed array of tubes", in ASME Symposium on Flow-Induced Vibrations, Vol. 2, pp.227-241. [Links]

Žukauskas, A. A. 1972. "Heat transfer from tubes in crossflow". In: Advances in Heat Transfer. Papers: v. 8, pp. 93-160. [Links]

Žukauskas, A. A., Katinas, V. J., Perednis, E. E., Sobolev, V. A., 1980, "Viscous flow over inclined in-line tube bundles, and vibrations induced in the latter". Fluid Mechanics - Soviet Research, v. 9, nr. 4. [Links]

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