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SOME OBSERVATIONS ON THE TURBULENT CROSS FLOW THROUGH TUBE BANKS

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ABSTRACT

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 simplification in the study of shell-and-tube heat exchangers. Geometric characterization of a tube bank is made by the tube arrangement and the P/D-ratio, being D the tube diameter and P, the distance between the centerlines of adjacent tubes. In general, fluid flow loads in a tube bank (and any other structure submitted to a flow) can be classified in static and dynamic. The former due to the mean pressure variation along the flow through the bank and the latter due to pressure and velocity fluctuations of the turbulent flow, which characteristics are strongly influenced by the geometry of the bank. Dynamic loads are produced by phenomena like vortex shedding, turbulence buffeting as well as acoustic resonances in gas flow, which can induce vibration on the banks leading to fatigue crack and fretting-wear damage of the components.

In this paper, 20 years research, presented in SMiRT Conferences, of measurements with hot wires and pressure transducers of the cross flow through tube banks with square and triangular arrangements are summarized. Analysis is made by statistical, spectral and wavelet tools as well as flow visualizations in a water channel. Wavelet decomposition allows the analysis in time-frequency domain.

Evidences from the results show the presence of instabilities in tube banks which can be associated to the phenomenon of bistability in the flow on two cylinders side-by-side.

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 simplification for the study of fluid flow and heat transfer of shell-and-tube heat exchangers, where the flow is forced transversely to the tubes by the action of baffles. Attempts to increase heat exchange ratios in heat transfer equipment do not consider, as a priority of project criteria, structural effects caused by the turbulent fluid flow across the tube bank, unless failures occur (Païdoussis, 1982). To reduce the size of the equipment and, at the same time to increase the heat transfer process, the aspect ratio of the tube bank (pitch-to-diameter ratio) is reduced. This leads to the appearance of dynamic loads, which are not associated to vortex shedding, as in large aspect ratios tube banks. The influence of other hydrodynamic processes, like fluidelastic instabilities, turbulent buffeting and acoustic resonance, may also be present in tube banks of all aspect ratios. Recently, the presence of switching flow and bistable processes in tube banks were also identified. Therefore, the continuing study of tube bank flow is still necessary to contribute for the improvement of design and development methods of new equipment, due to the close relationship between fluid flow and the exciting forces on the tubes.

Studies on fluid flow and heat transfer have been carried out in the last 70 years, being the first systematic studies known to the Author, the doctoral thesis of Wiemer (1937) and the work of Griminson (1937).

Studies on tube banks until the ‘70s were mostly focused on global information on heat transfer coefficient and pressure drop. In 1972, Žukauskas made a comprehensive study on heat transfer and fluid flow in tube banks. He 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, approximately, 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 (Möller, 1982).

In the ‘70s and ‘80s, porous media approach was the trend. In nuclear industry, motivated by the so called “open channel cooling concept” for LMFBR (Weiss et al., 1971; Möller and Qassim, 1985). Due to the simplification in the mathematical formulation adopted, macroscopic approach ignored the fine velocity structure and local pressure distribution, being insufficient for the structural analysis.

Even in the ’70s and ‘80s starting detailed local heat transfer coefficient measurements, and from then on, studies on local heat transfer coefficient and pressure fluctuations, together with flow-structure interaction, including aeroacoustics problems, had the focus of the researchers. In a more recent study, Ziada (2006) shows that vorticity shedding excitation is generated by either jet, wake, or shear layer instabilities. The tube arrangement (in-line or staggered), the spacing ratio, and Reynolds number determine which instability mechanism will prevail, and thereby the relevant Strouhal number for design against vorticity shedding and acoustic resonance excitations.

As flow induced vibration and structure-fluid interaction are very dependent of the tube arrangement, continuing studies are necessary to improve its understanding, exploring all additional excitation mechanism on the tubes with new methods of analysis. This paper summarizes the main results from experimental studies on tube bank flow presented by the Author since 1995 in SMiRT Conferences.

TEST SECTION AND MEASUREMENT TECHNIQUE

The test section is a 1370 mm long rectangular channel, with 146 mm height and a maximal (adjustable) width of 193 mm. Air, at room temperature, is the working fluid, driven by a centrifugal blower, passed by a settling chamber and a set of honeycombs and screens. The upstream turbulence intensity was about 2 %. In 2000, improvements of the aerodynamic channel reduced the turbulence intensity to about 1%. Details of the test apparatus can be found in Endres and Möller (2001) and in Indrusiak et al. (2005). Inside the test section, a tube bank was placed. The tubes were smooth with 25.4 or 32.1 mm outside diameter and several P/D-ratios, being P the distance between the center of the tubes and D, the diameter. They were rigidly mounted in the channel and not heated. Most of the results in this paper refer to a P/D = 1.26.

Wall pressure measurements were performed with help of pressure taps drilled in one tube of each row and connected to Hartmann & Braun electronic manometers. Pressure and velocity fluctuations were measured by means of as ENDEVCO pressure transducer and DANTEC constant temperature hot wire anemometry system. For the interpretation of the results, flow visualization with dye injection in a water channel was also applied.

Analysis was made through basic statistics (mean values), spectral and wavelet tools (time-frequency domain).

RESULTS AND DISCUSSION

Time-averaged quantities

The research started with the measurement of the mean pressure distribution around the tubes. The resulting pressure field in the square and triangular arrays are presented in Figs. 1-a and b in dimensionless form as contours interpolated in the flow region. Results show that the highest pressure drop occurs in the narrow gaps between the tubes, which is not compensated by the pressure recover in the widest regions after the gaps. For the square array, the maximal pressure occurs at a position of 45^o, while for the triangular array this maximum appears at 0^o. These angles are measured clockwise from the position of direct flow incidence and indicate the position of the pressure tap. Zero degree corresponds to the location where the pressure tap faces the main flow.

Spectral analysis of velocity and wall pressure fluctuations is presented in Figs. 2 and 3 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.

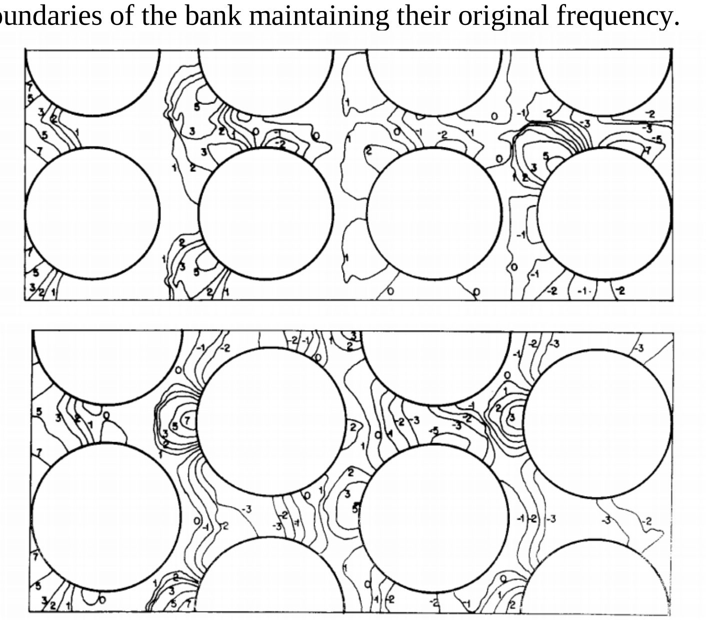
Power spectral distribution for the wall pressure fluctuation, Fig. 2, show that, in general all curves for square arrays have the same decay pattern after a Strouhal number Str = 0.1, with dimensionless values of the autospectral densities of the same order. For Strouhal numbers below this value, the 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.

Results for, P/D = 1.16 and 1.06, not shown here, presented almost coinciding spectra of pressure fluctuations, showing that the distribution of the pressure fluctuations around the tube tends to be uniform as the P/D is reduced as observed in the local heat transfer coefficient distribution by Möller, 1982.

Peaks at about Str = 2.0 and 9.0 correspond to the calculated resonance frequencies (Strasberg, 1965) inherent of the use of tubings to connect pressure transducer to pressure tap. These peaks can be completely disregarded in this analysis.

Figure 3 shows 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 of the small eddies increases.

An interesting feature of tube bank flow was observed later on by Endres and Möller (2007), by producing a far field disturbance with a fixed frequency upstream of the flow through a square array tube bank. The results show that the frequency of the disturbance remains unchanged as it passes through the bank, and subsists until the 4th row in spite of the high turbulence intensities and of the fact that flow velocity inside the bank varies with the position. This fact indicates that external excitations can be transferred to the solid boundaries of the bank maintaining their original frequency.



(a)

(b)

Figure 1: Dimensionless pressure field in square (a) and triangular (b) arrays presented as contours interpolated in the flow region – flow from left to right (P/D-1.26, Re=1.5•10^4). Endres et al., 1995.

The study of the wall pressure and wall pressure fluctuations in the flow through a two row tube bank with square arrangement and two baffle plates showed higher values than in pure cross flow, and peak frequencies which could not be associated neither to the effects of pure cross flow, nor to effects produced solely by the baffles, leading to the need of the measurement of this quantities in the flow through inclined tube banks (Möller et al., 1999).

Figure 4 shows the mean pressure distribution on one channel side wall, with the presence of the tube bank, as contours. 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, r, and a reference velocity.

Although some misdistributions of the contour lines are observed, isobaric lines are not parallel to tube axes, indicating that the pressure gradient is neither perpendicular to the tubes, nor parallel to main flow direction (Barcellos et al. 2001), confirming macroscopic results by Möller and Qassim (1985).

Instantaneous quantities

Unsteady flows occur frequently in nuclear and process installations, due to reciprocating pumps, water hammer phenomenon and process control. Analysis of such flows is often based on a quasi-steady approximation, which is not always feasible. Therefore, dynamic loads like those produced by vortex shedding and other hydrodynamic processes, like fluidelastic instabilities, turbulent buffeting and acoustic resonance should be investigated under transient conditions.

For this purpose, a square array tube bank was submitted to an accelerating flow, from zero velocity to the steady state condition. Two hot wires were inserted in the bank after the third row, each one in a flow lane formed by the tubes. Velocity and frequency behavior along time are presented in Fig. 5. Result from each hot wire are indicated by different colors, showing that the velocity is not the same in each lane, having alternate higher values. This phenomenon is accompanied by alternating increase and decrease of the amplitude as the velocity increased or decreased (Indrusiak et al., 2003).

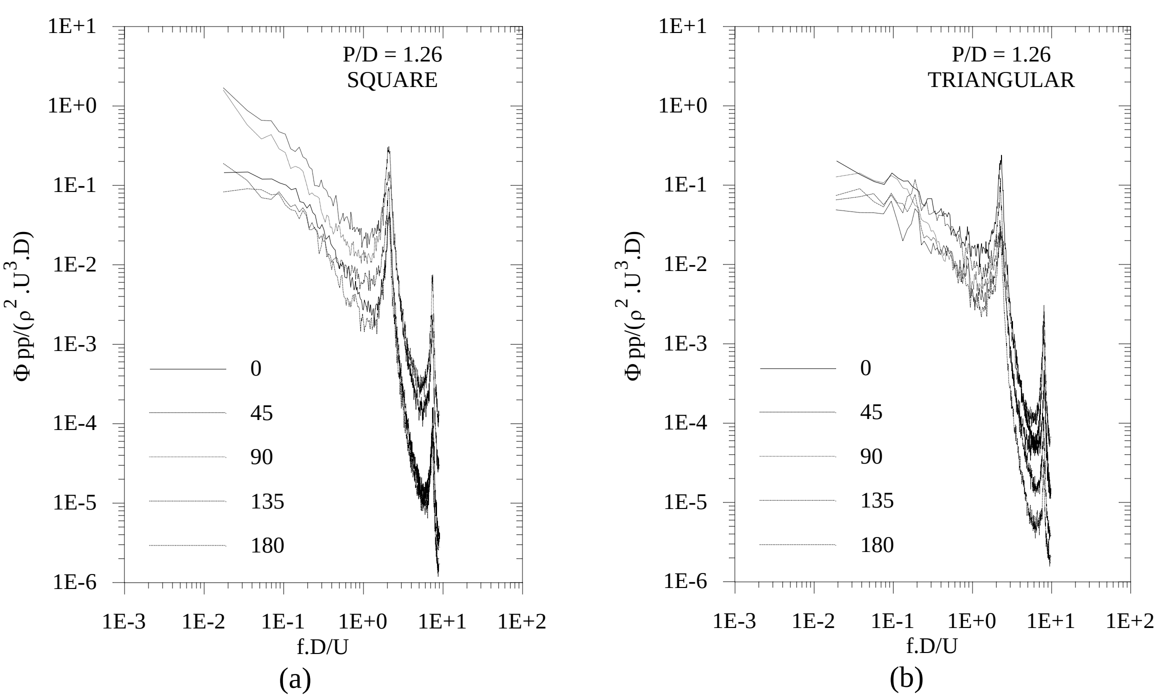


Figure 2: Autospectral densities of pressure fluctuations in several angular positions of a tube in a bank with P/D = 1.26 and square (a) and triangular (b) arrays. Endres and Möller, 1997.

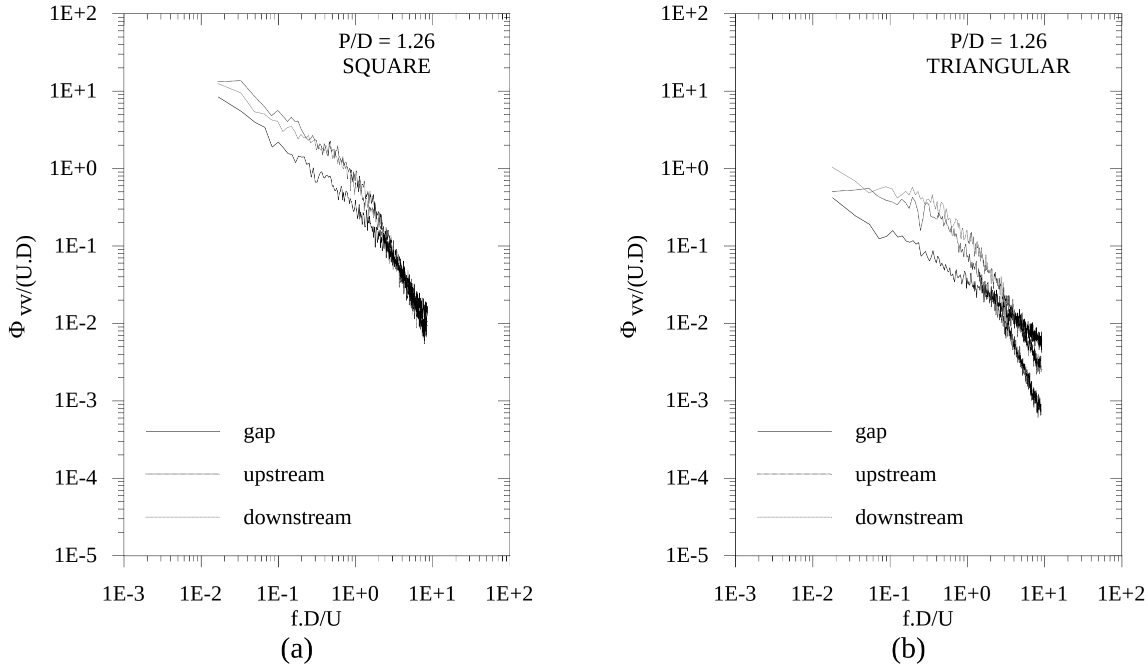


Figure 3: Autospectral densities of velocity fluctuations in tube banks with P/D = 1.26 and square (a) and triangular (b) arrays. Endres and Möller, 1997.

The continuation of this study lead to the need of flow visualizations, showing that the flow was deviated to the right or the left side after passing the first row of the bank due to the interaction of the boundary layer separation process of two neighboring cylinders. The flow deviation was also accompanied by a velocity component parallel to tube axes. This three dimensional flow behavior produces a strong mass redistribution, leading to so far unexpected velocity values and Strouhal numbers (Olinto et al., 2005).

In 2007, Olinto et al. presented a detailed study using hot wires and flow visualizations where this phenomenon presented in 2003 and 2005 could be explained. Figures 6 and 7 show two different flow configurations. In each figure, a) shows the visualization of the flow near the upper wall and b) the flow near the lower wall. In Fig. 6, the flow near the upper wall is deviated to the right, while near the lower wall the flow is deviated to the right. The flow near the central tube is downwards. In Fig. 7 an opposite condition is observed: the flow near the upper wall is deviated to the left, neat the lower wall, to the right and an upward velocity component appears.

This phenomenon is non-stationary, produces a velocity variation along time and is similar to the bistable flow found in the flow through two side-by-side tubes (Alam et al. 2003). The flow behind the second or the third row has a strong transversal velocity component which causes a mass redistribution. Through the visualizations, this phenomenon was understood as a flow rotation generated behind the first rows. The direction of rotation changes randomly in each new experiment in water, while in air this random change occurs along time.

In the tube banks with triangular arrangement (Fig. 8), the bistability phenomenon also occurs but no so clearly. This is due to the fact that in a subsequent row there is a tube in front of the gap between tubes of preceding row and so son. This hinders the formation of bistable conditions. When the P/D-ratio is large (e.g. P/D = 1.6), there is enough space after the tubes for flow recirculation. However, when this relation is small (e.g. P/D = 1.26), the proximity of the next tube row seems to increase the mass distribution inside the tube bank, where the flopped flow is directed up or downward, in a parallel direction to the tubes axes. This behavior gives a strong three-dimensional characteristic to the flow.

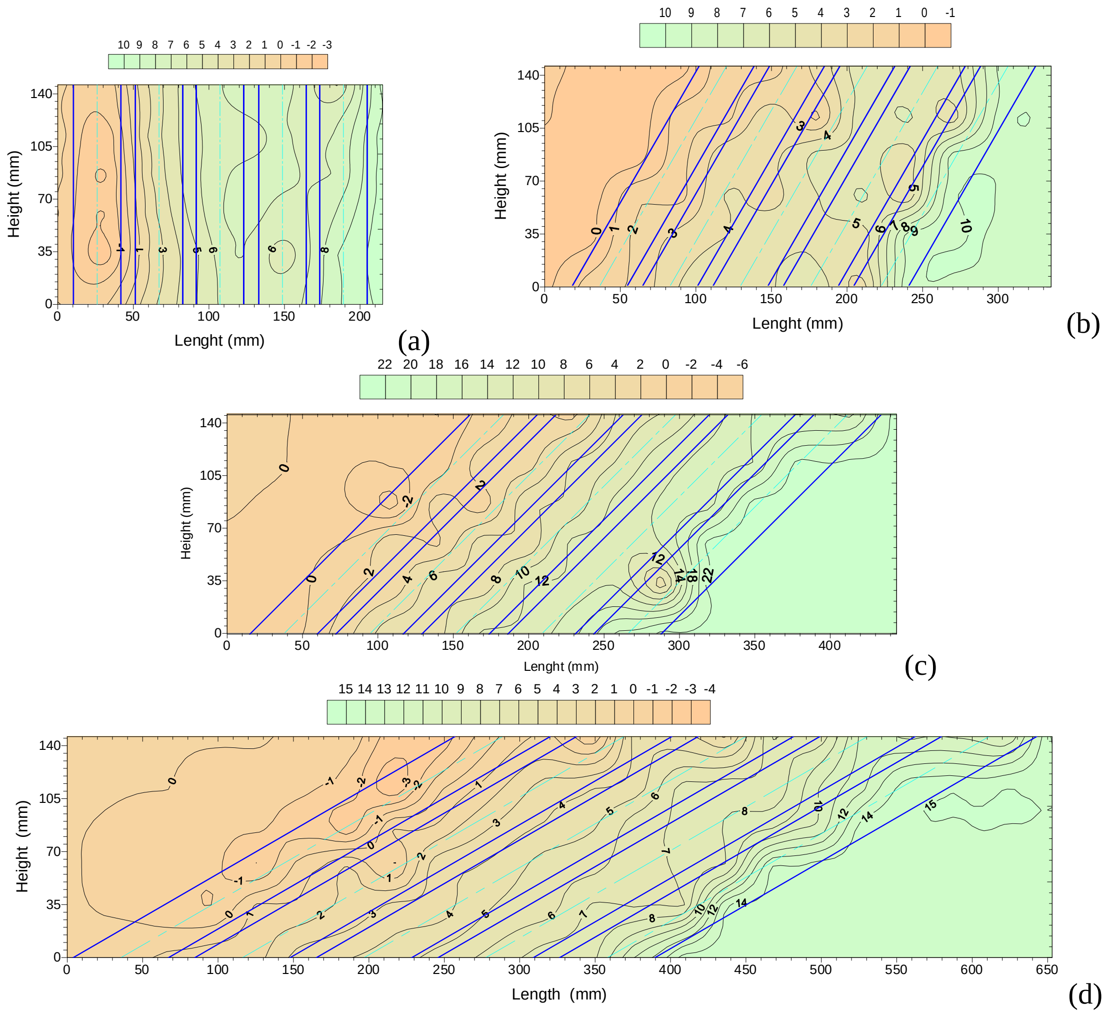


Figure 4 - Channel side wall pressure distribution as contours for several angles of the bank: a) 90°, b) 60°, c) 45°, d) 30°. Flow is from right to left. Barcellos et al. (2001).

For both aspect ratios studied, after the third row of cylinders, no changes in the flow characteristics were observed. For these cases, a fast swapping of the gap flow direction, from one side to another, is observed. This is the so called “flip-flop” effect. The vertical component of the flow observed after the second row of cylinders in the flow visualizations is increased until the fifth row. Inside the complete tube bank (five rows) the flow is highly disordered, without a characteristic shedding frequency. The energy of the velocity signals decreases by increasing the rows in the bank. The last row of the bank behaves as a single row of cylinders, where the gap flow form coalescent jets (de Paula et al., 2009).

A joint analysis of axial and transversal velocity components is presented in Fig. 9a, where the results of the ordered pair of data show the concentration in two distinct areas, referred to the two flow modes. A discrete wavelet reconstruction of level n = 5 (frequencies from 0 to 15.6 Hz) of the bivariate case is presented in the same figure, and shows five changes of the gap flow direction. This feature can be correlated to the space phase concept, where a particular state of a dynamical system can be represented as a point in this phase space. As the time varies, the point moves along a path. By analyzing this feature together with Fig. 9c, which presents the details of the axial velocity signal from 26 to 36 seconds of mode 1, is possible to observe two attempts of changing the gap flow direction of short time. The other change of the gap flow direction refers to transition to mode 2. The bivariate velocity PDF shows the presence of two prominences, where the higher velocity mode seems to be predominant in this case (Fig. 9b), (de Paula et al., 2011).

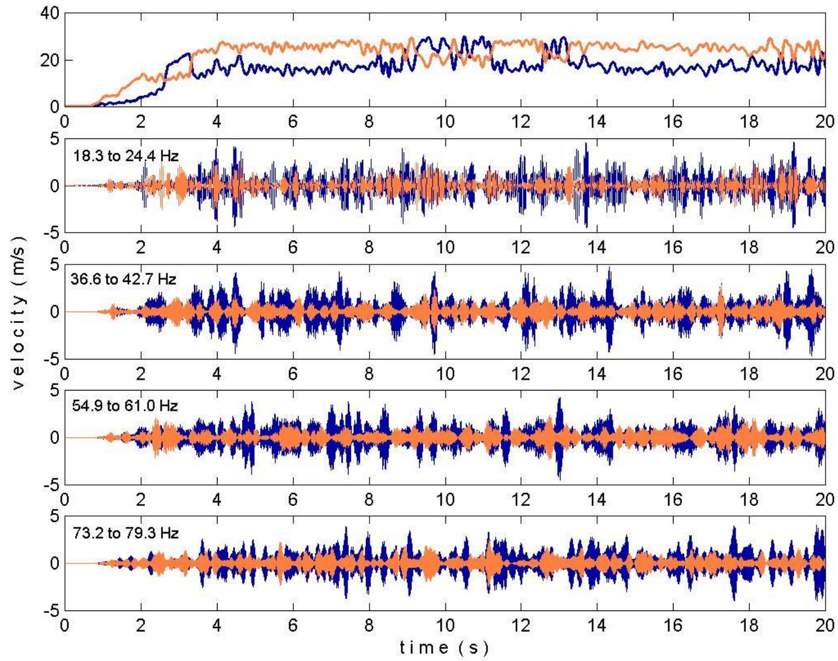
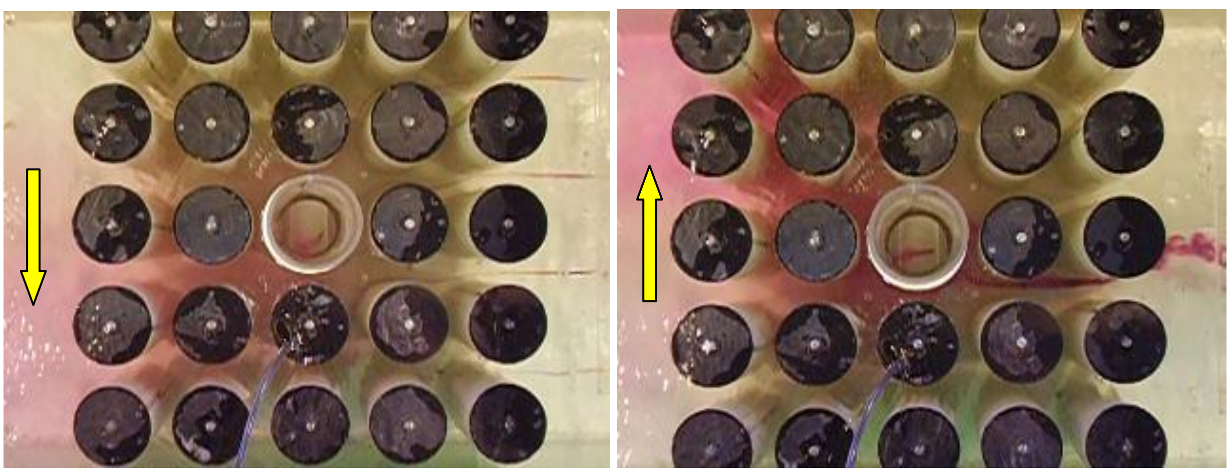


Fig. 5: Time-frequency analysis of velocity and velocity fluctuation behind the central tube of the third row of the bank. Red: flow lane 1; Blue flow lane 2 (Indrusiak et al. 2003)



(a) (b)

Figure 6. Flow visualization in the tube bank with P/D=1.26. Re = 3.07×10^4. (a) injection at 60 mm below upper wall, (b) injection at 60 mm above the bottom (arrows indicate direction of the deviation). Central tube: inclined mirror show flow deviation downwards. Main flow is from right to left.

By means of the Taken's (1981) theorem and the methodology proposed by Rosenstein et al., 1993, a positive Liapunov exponent was determined and the two attractors were found, as shown in the space state reconstruction of the filtered signals. This phenomenon presents the characteristics of being chaotic (de Paula and Möller, 2013), although inside the bank, turbulence intensity increases in the first three rows, with a maximum after the second row, and decreases significantly after the fourth row with a broad band characteristic without the presence of shedding frequencies. (de Paula and Möller, 2015).

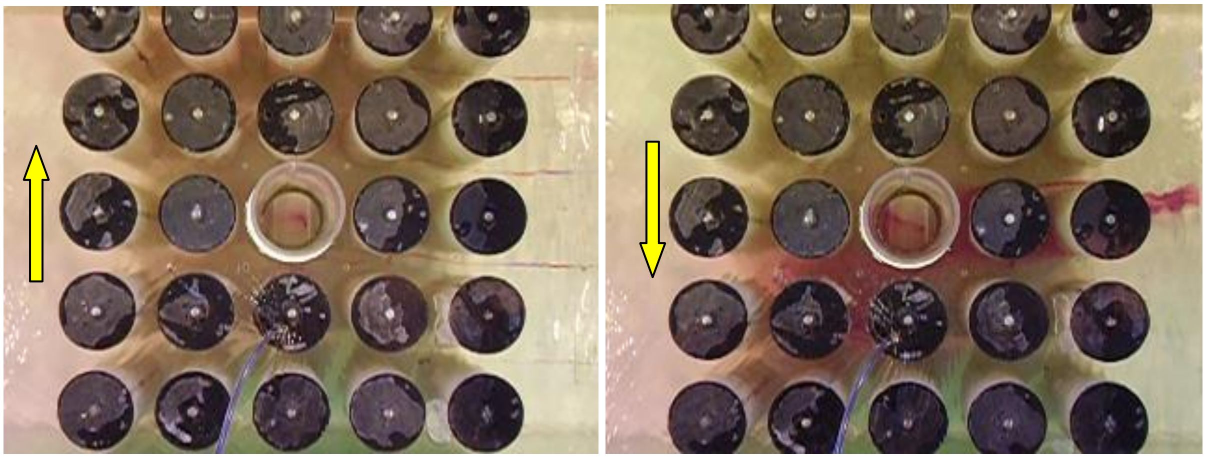


Figure 7. Flow visualization in the tube bank with P/D=1.26. Re = 3.18×10^4. (a) injection at 60 mm below upper wall, (b) injection at 60 mm above the bottom (arrows indicate direction of the deviation). Central tube: inclined mirror show flow deviation upwards. Main flow is from right to left. (Olinto et al. 2007).

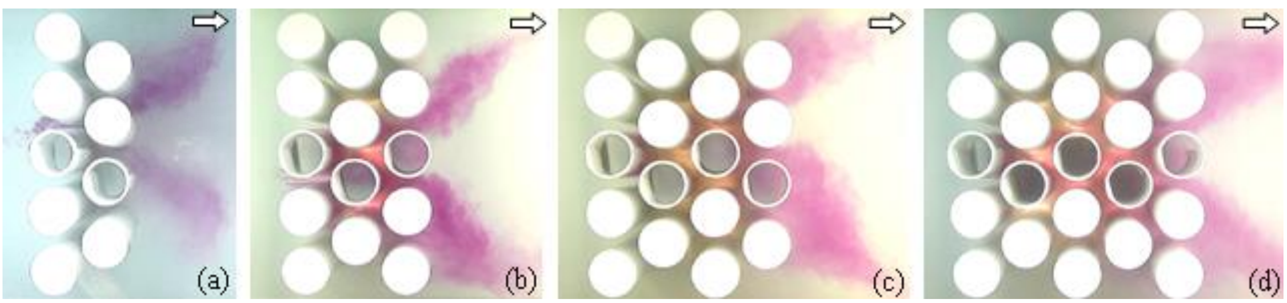


Figure 8. Flow visualizations with the injection of potassium permanganate directly in the free stream for two (a), three (b), four (c) and five (d) rows of cylinders, at $Re = 7.5\times10^3$ and P/D = 1.26, in the middle visualization plan. Arrow indicates flow direction (de Paula et al. 2009).

FINAL REMARKS

This paper shows a glimpse on the evolution of methods and results along 20 year research on tube bank flow. Some simple conclusions can be drawn from this study. The first one is that the reduction of the aspect ratio increases the energy of the smaller scales, increasing mixing and leading to a tendency of a uniform distribution of pressure fluctuation. Far field disturbance are amplified in the first rows, than annihilated. The flow is three dimensional, the velocity distribution can be non-uniform inside the bank and its behaviour is chaotic.

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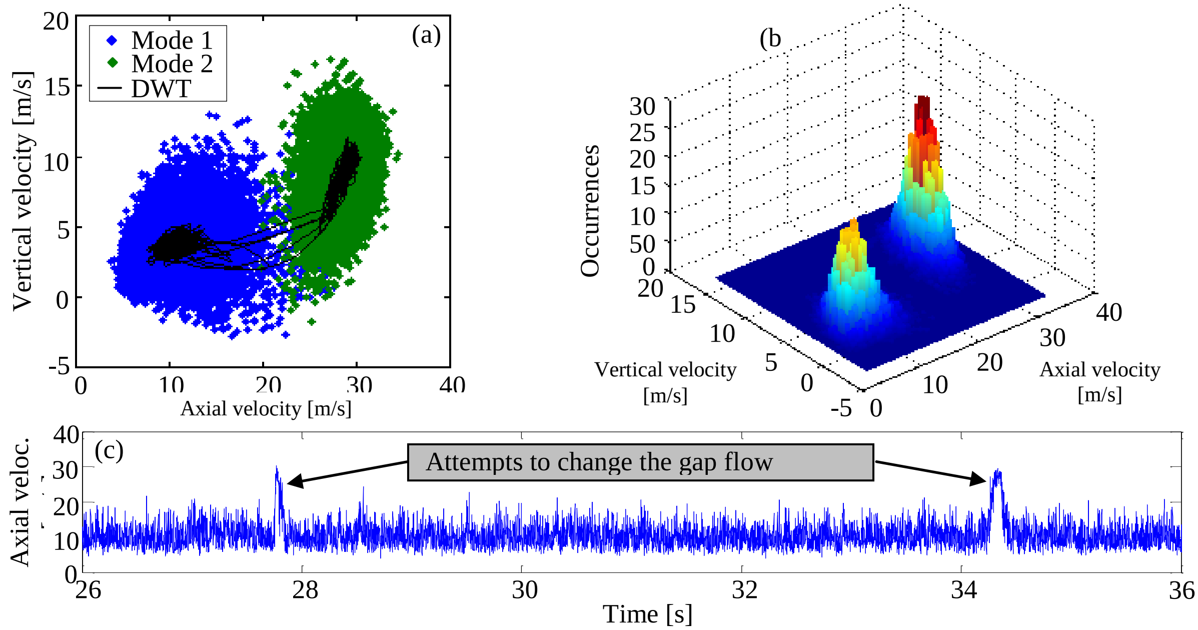

Fig. 9: (a) Ordered pair of data points of the flow velocity components. (b) Bivariate velocity PDF. (c) Details of the axial velocity signal from 26 to 36 seconds, showing two attempts to change the gap flow direction.

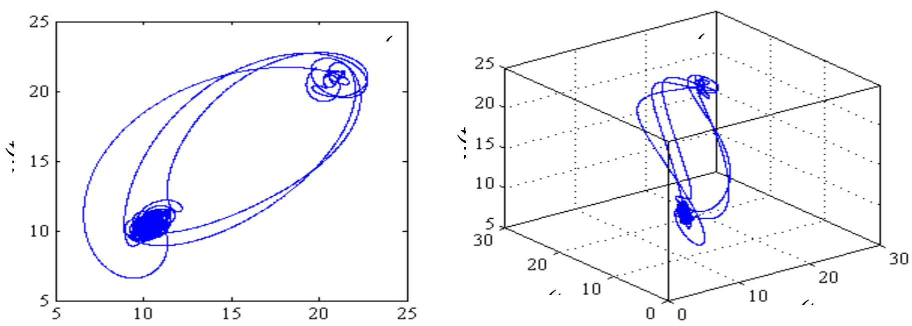

Figure 10: Reconstruction of the attractor from the filtered signal (with a frequency content between 0 to 1.9531 Hz). (a) 2D reconstruction. (b) 3D reconstruction.

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