

EXPERIMENTAL ANALYSIS OF THE TURBULENT FLOW INSIDE A TUBE BANK WITH BAFFLE PLATES

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Abstract. *This paper presents the experimental study of velocity distribution and pressure fluctuations of the cross flow in a simulated tube bank, with square arrangement and a pitch to diameter ratio of 1.26. Measurements were performed with hot wires and a pressure transducer. Behavior of fluctuating quantities is described by means of dimensionless autospectral density functions and their interdependence is discussed. Results show the flow redistribution after the baffles and a dimensionless characteristic frequency in form of a Strouhal number Str = 0.33.*

Keywords*: tube banks; pressure fluctuations; velocity fluctuations; baffle plates.*

1. 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 behavior, without any characteristic frequency (Endres et al., 1995). Pressure fluctuations result from velocity fluctuations at several points of the flow field (Willmarth, 1975).

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. Baffles have also the purpose of increasing turbulence levels and, thus, heat exchange ratios. On the other side, boundary layer separation after the baffles may occur, as demonstrated in the old, but still very interesting results of flow visualization in models of heat exchangers and steam generators by Wiemer, 1937, in his Thesis. This can be an additional and important source of disturbances in the flow, which can travel through the bank, influencing the tube bank and the baffles. Together with the work of Grimison (1937), these are the oldest works in tube bank flow known to the Authors.

Experimental results of velocity and wall pressure fluctuations in the turbulent flow through a simulated tube bank with square arrangement, between two baffle plates 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 & Möller, 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 fluctuation, could not be associated neither to effects of pure cross flow through the bank nor to effects produced solely by the baffles.

By means of hot wire experiments and numerical simulation, Demartini (2001) presents the analysis of the pressure and velocity field in the same channel as Möller et al. (1999). The tube bank was removed to allow the study of the influence of the baffles solely since there, the extension of the recirculation regions could not be properly considered. The most important features observed are the high pressure regions formed upstream of both baffle plates, and the extent of the low pressure regions on the downstream regions. The latter are strongly associated with the boundary layer separation on the tip of the baffle plates, which is also influenced by the thickness of the baffle plates, in accordance with former results by Hwang et al. (1999). Low and high pressure regions were associated to recirculation regions.

Baffle plates and obstacles submitted to laminar and turbulent flows has being analyzed in the recent years by several authors, using numerical and/or experimental techniques. A careful review was made by Demartini (2001). In tube banks, the flow distribution resulting from the action of baffles will not be perpendicular to tube axes.

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.

Barcellos et al. (2003) used hot wires and pressure transducers to investigated the flow through tube banks with P/D = 1.26, square arrangement and several yaw angles. Results of spectra showed the presence of two frequency peaks: the lowest frequency corresponding to the vortex shedding process;. the highest was associated to a second flow process, which could be due to the flow recirculation on the back side of the tube. 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.

In spite of the long time since Wiemer's and Grimison's studies, turbulent flow through tube banks still remains a challenge with many open questions (Borsoi, 2001).

The purpose of this paper is to investigate pressure and velocity distribution in a simulated tube bank, where the turbulent flow is deflected by baffle plates.

2. Test section and measurement technique

The test section is a modification of the test section used in Möller et al. (1999), being a 1720 mm long rectangular channel, with 146 mm height and a width of 193 mm. Air is the working fluid, driven by a centrifugal blower, passed by a diffuser and a set of honeycombs and screens, before reaching the tube bank with about 1 % turbulence intensity. The tube bank is a two-row P/D=1.26 set of tubes in square arrangement, rigidly mounted in a plexiglass plate perpendicular to the main flow direction. Tube axes are, therefore, parallel to the channel. A second baffle is placed on the opposite channel wall, 146 mm after the first baffle plate, in the other extremity of the tubes. On the top of the second baffle plate, a plexiglass plate was placed so to form a channel with 82 mm height containing the bundle of tubes. Before the tube bank a Pitot tube, at a fixed position was applied to measure the reference velocity for the experiments. The Reynolds number, calculated with the tube diameter (32.1 mm) and the entrance (reference) velocity is $Re = 1.55 \cdot 10^4$.

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 in a nylon plug, drilled to form a cavity for the transducer and a connection to the pressure tap, as shown in Fig. 2. This is an improvement of the technique investigated in Endres, Möller (1994, 2001-b), being the amplifying effect according to the method proposed by Holmes and Lewis (1987) outside of the measurement frequency due to the smaller volume of the cavity. One of the difficulties in the study of pressure fluctuations in tube banks is to place the sensors in the tubes (Weaver et al., 2001). The mounting technique developed intends to solve that problem.

Previous analysis of the behavior 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 phenomena investigated. 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. Pressure and pressure fluctuations were measured also at the channel walls. A slant (45^o) hot wire probe was moved along the tubes in each row, was used for the measurement of the velocity vector and the angle formed with the channel axis. Resolution of this probe is to flows impinging at angles beteen +30^o to –30^o. Data acquisition of pressure an velocity fluctuations was performed simultaneously by a Keithley DAS-58 A/D-converter board controlled by a personal computer.

For the determination of autospectral density functions, the sampling frequency was of 4 kHz, while the signals of the instruments were high pass filtered at 1 Hz and low pass filtered at 1.6 kHz. Previous studies of pure cross flow through tube banks showed, for this test sections, to be the frequency range of importance (Endres, 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, transducer housing and cavities 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 %.

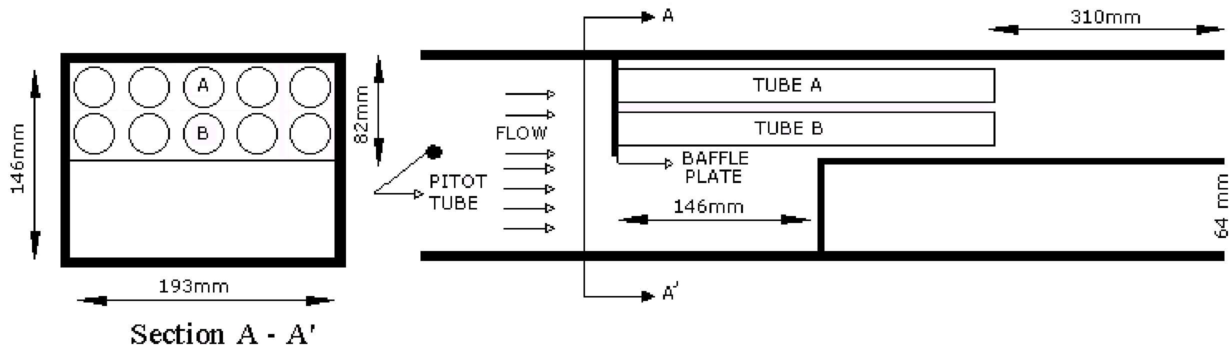


Figure 1. Test section (schematic).

3. Results

Experimental results are presented in form of dimensionless mean and RMS-values, as well as auto spectral density functions. Pressure and pressure fluctuations form of Euler numbers, obtained by means of fluid density, ρ, and the reference velocity, U. Results are presented as functions of the angular position of the tube: 0^o corresponds to the position facing the main flow and the longitudinal positions starting 10 mm from the first baffle plate.

Figure 3 shows experimental results of velocity distribution along the lines in the narrow gaps between upper and lower tubes and intermediate large gap. Results of vertical component, perpendicular to tube axes, Fig. 3-a, show lower values than the horizontal component, parallel to tube axes. Position 14 corresponds to location of the second baffle, and beginning of the narrower channel, where remarkable changes in the velocity behavior of both components is noticeable. Right after that location a strong flow redistribution occurs, observed by the rapid change in the magnitude of the velocity components. Near the outlet (pos. 28-30), about 270 mm downstream of the first baffle plate, the differences in vertical components are very small, indicating that the entrance effects, observed through the differences in the horizontal velocities, will need large distances to be dissipated. This will occur when velocities in the narrow gap between the upper tubes equals the velocity in the narrow gap between the lower tubes. In the intermediate gap velocity will be higher than in the narrow gaps.

The angles formed between velocity vectors and tube axes are shown in Fig. 4 as a function of the position in the bank. The values decrease after the second baffle plate, position 14, showing the flow redistribution. Before the second baffle the angles measured in the upper gap are well ordered, showing the influence of the upper wall in directing the flow in that region. For the intermediate position and the lower gap, strong variation of the angle of the flow indicates the presence of the recirculation cells, therefore, measured values may be out of the hot wire resolution, with high uncertainty values. All the measured values are inside the sensitivity range of the probe, but in the recirculation region they can be higher than 30^o without being detected by the probe.

RMS values of velocity fluctuations in locations along tube axes are shown in Fig. 5. Both components have higher values in the wide intermediate gap between the two tube rows in the region between the baffle plates. Experimental values are a bit scattered, alternating local maxima and minima up to position 9, becoming stable after that position. The region where the scattering is observed coincides with the recirculation region observed by Demartini (2001).

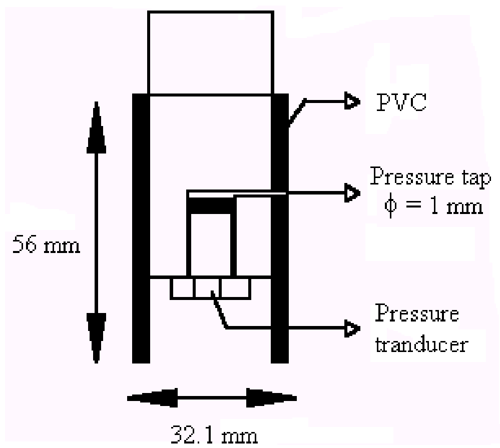
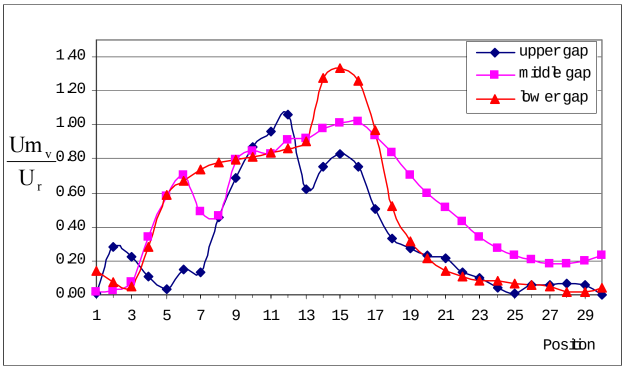
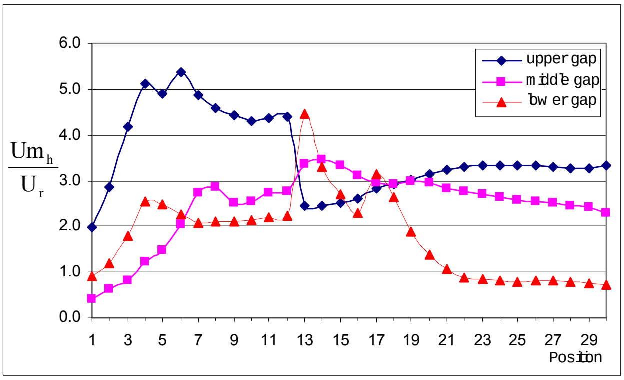


Fig. 2. Instrumented tube (schematic).



(a)



(b)

Figure 3. Velocity distribution along the bank. a) Vertical component, b) horizontal component.

After the second baffle plate, the values of the vertical components become very low and almost equal in the three measured gaps, due to the narrowing of the channel. Values of the horizontal (axial) component tend also to an uniform value, but remain with relatively high values without distinction between narrow or wide gap.

Since the tube bank has only two rows, the influence of the upper wall on tube “A”, at a distance of 100 mm from the first baffle plate, appears through the reduction of values of mean wall pressure (Fig. 6-a) and RMS-values (Fig. 7-a) after angular position of 50^o. The influence of the presence of the tube “B” appears as low pressure values at positions from 0^o to 20^o.

Mean wall pressure distribution in tube “B” (Fig. 6-b) is very similar to the distribution observed in tube banks without baffle plates (Endres, Möller, 2001-a) with higher values.

At 200 mm from the first baffle plate, downstream of the second baffle, values of mean wall pressure and pressure fluctuations are almost uniform, indicating that the flow is becoming axial, although velocity magnitudes, Fig. 3-b, demonstrate that the flow redistribution did not happen with these short tubes.

Figures 8 and 9 show dimensionless spectra of pressure fluctuations for several angular positions around the tubes “A” and “B” respectively. Dimensionless frequencies are in form of Strouhal numbers, defined with the tube diameter and the reference velocity.

At 100 mm from the first baffle plate, pressure fluctuation spectra from both tubes have higher energy in locations where the highest RMS values were observed (40^o), but they show no dominant frequency (peak). For the other locations, peaks appear at a Strouhal number of 0.33. This value is almost the double of the value observed by Möller at al. (1999), due to the definition in this paper of the Strouhal number with the reference velocity, which is half of the entrance velocity used there. It also no correspondence with the value observed in the baffle plates without tube banks nor with the values from Fitzhugh´s chart (Blevins, 1990) for tube banks. This discrepancies are solely due to the definition of the Strouhal number adopted.

Only one peak frequency can be observed in spectra. This means that, if the peak is produced by vortex shedding, the second frequency peak observed by Barcellos et al. (2003), corresponding to an expected flow recirculation on the back side of inclined tubes does not occur, probably due to the magnitudes of the velocity when the incidence angle is reduced.

Peaks appearing at values of Strouhal number greater then 2 correspond to amplification produced by the cavities where the pressure transducer was installed inside the instrumented tube (Strasberg, 1963), and can be fully disregarded in this analysis.

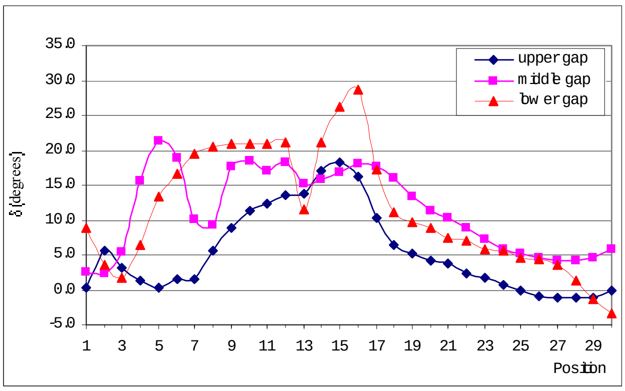
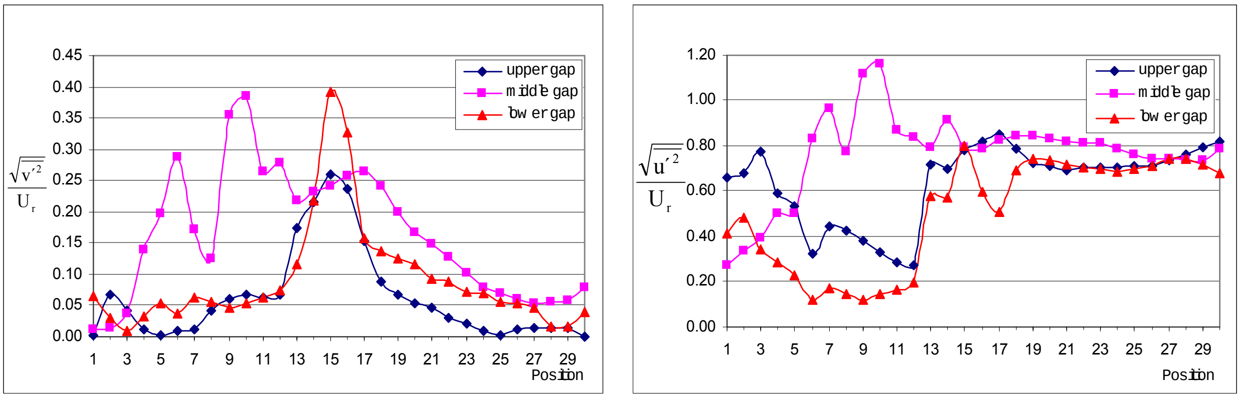


Figure 4. Angle between velocity vector and tube axes as functions of the position in the bank.



(a) (b)

Figure 5. RMS- values of the velocity fluctuation as a function of the position in the bank: a) vertical (transverse) component; b) Horizontal (axial) component.

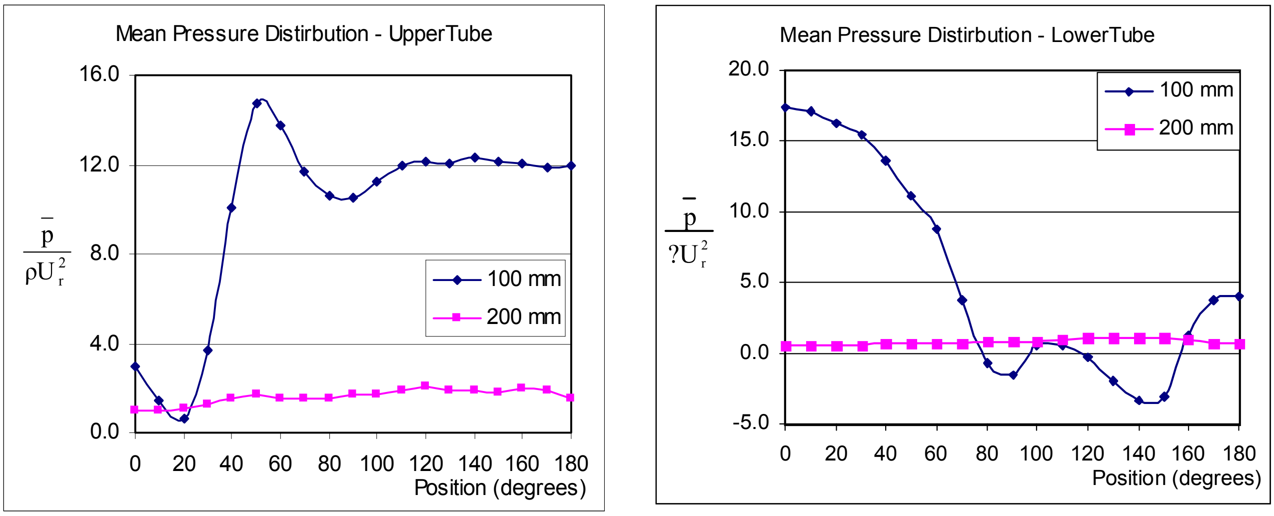


Figure 6. Mean wall pressure distribution on the two tubes of the bank (dimensionless) as a function of the angular position: a) Upper tube – “A”, b) Lower tube – “B”.

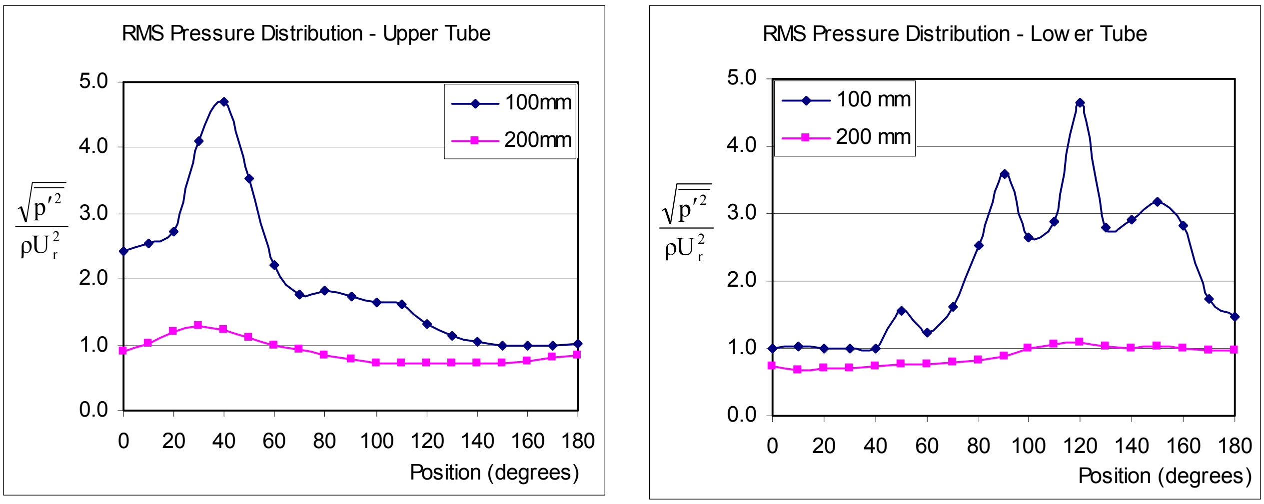
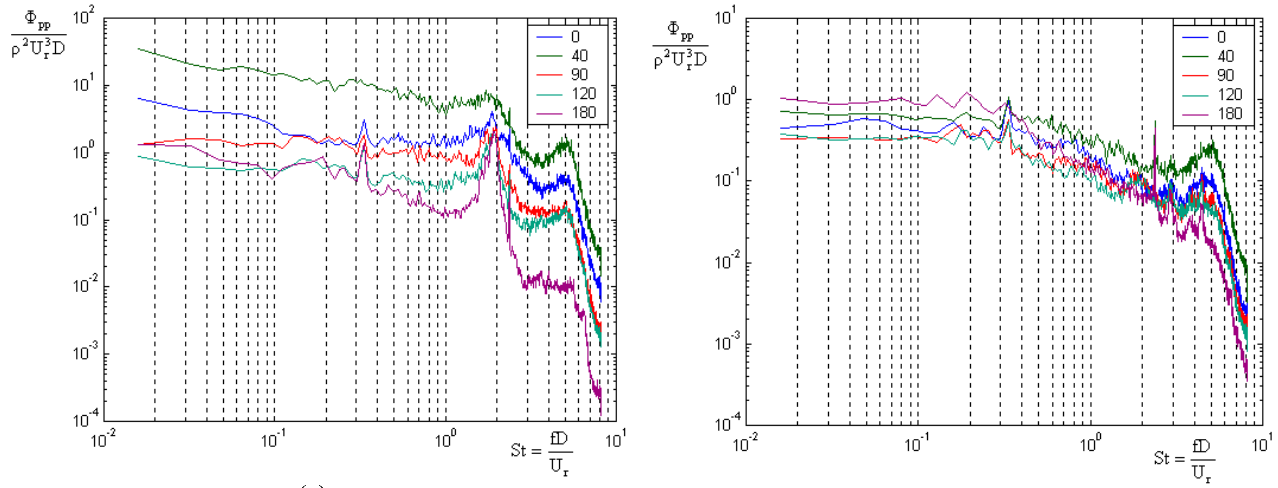
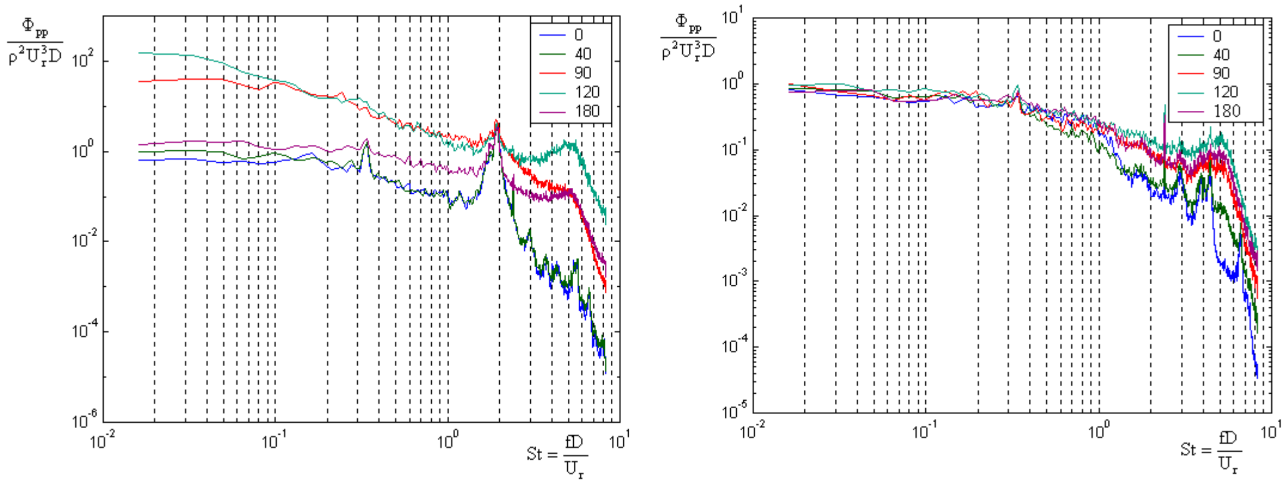


Figure 7. RMS values of the wall pressure distribution on the two tubes of the bank (dimensionless) as a function of the angular position: a) Upper tube – “A”, b) Lower tube – “B”..



(a) (b)

Figure 8. Autospectral densities of the wall pressure fluctuations in several positions of the tubes in the bank. (a) 100mm; (b) 200 mm - Tube (A).



(a) (b)

Figure 9. Autospectral densities of the wall pressure fluctuations in several positions of the tubes in the bank.
(a) 100mm; (b) 200 mm - Tube (B).

4. Concluding Remarks

This paper presents the experimental study of velocity distribution and pressure fluctuations of the cross flow in a simulated tube bank, with square arrangement and a pitch to diameter ratio of 1.26. Measurements were performed with hot wires and a pressure transducer.

Baffle plates produce flow redistribution inside the channel with high values of the transversal velocity component and turbulence intensities. The transversal component is responsible for a peak frequency in spectra at a Strouhal number Str=0.33. This value could not be associated with typical Strouhal numbers in tube banks and in a single cylinder (0.21) due to the definition for Strouhal adopted. Nevertheless, the value obtained correspond to former measurements in a tube bank with baffle plates (Möller et al., 1999). Only one frequency can be observed. This means that if the peak is produced by vortex shedding, the second frequency peak observed by Barcellos et al. (2003) does not occur.

Recirculation regions behind the first baffle plate produced a certain scattering in the values of flow velocity and of the incidence angle. After about the half distance between the plates this effect vanishes reducing the uncertainties in the results. The extent of the recirculation regions must be very well identified, since they can affect the structural and thermal behavior of the equipments.

Wall pressure distribution on the tube of the upper row “A” is influenced by the presence of the upper wall, resulting in that region an almost flat distribution. Is influenced in the same form by the lower tube (“B”) as well. The latter shows in the region between the baffles, a pressure distribution similar to a tube in bank without baffle plates, with higher values.

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