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Experimental study of static and dynamic fluid flow loads in tube banks

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ABSTRACT

In this paper, results of measurements of the wall pressure field as well as velocity and wall pressure fluctuations in tube banks with triangular and square arrays are presented. Based on the measurements of the total pressure on tube walls, the pressure distribution inside the tube bank was estimated. The results, presented as contours in dimensionless form, show that large pressure variations occur mainly in the narrow gaps between the tubes. Pressure and velocity fluctuations are presented in form of their autospectral density functions and their relationship as crosscorrelation functions.

INTRODUCTION

Banks of tubes or rods are found in the nuclear and process industries, being the most common geometry used in heat exchangers. The operating conditions of these equipments become critical as the coolant velocity is increased and the aspect ratio (pitch-to-diameter ratio) of the tube bank is reduced. Due to velocity variations produced by the reduction of the flow area in the narrow gaps between the tubes and of the constant change in the direction of the flow inside the bank, static and dynamic loads will be increased. Static loads are associated to the mean pressure field, while dynamic loads are produced by pressure and velocity fluctuations.

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 [1].

Static loads, on the other side, are affected by the constant changes in the flow direction as well as by the successive variations of the flow area as shown in more detail in Ref. [2].

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 [3]. The amplitude of the pressure fluctuations may be influenced by velocity fluctuations at a distance comparable to the wave length of these fluctuations [4].

The purpose of this paper is to present results of measurements of the mean and the fluctuating pressure field in tube banks with triangular and square arrays with a small aspect ratio, and to investigate the relationship between pressure and velocity fluctuations as a function of the position inside the bank.

TEST SECTION

The measurements were performed in a rectangular channel with 146 mm height and 765 mm width, where the tube banks were placed. The working fluid, air, driven by a centrifugal blower, passed by a settling chamber and a set of honeycombs and screens, before reaching the tube bank. The angle of incidence of the air on the tubes was 90^o. 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 one fixed position to measure the reference velocity for the experiments. The tube banks were, both triangular and square arrangement, 4 rows deep for the mean pressure measurements and 5 rows deep for the measurements of fluctuating quantities. Results to be presented in this paper refer to a pitch-to-diameter ratio P/D = 1.259, being the tube diameter 32.1 mm and a Reynolds number $Re = 1.5 \bullet 10^4$. The Reynolds number was calculated with the reference velocity and the rod diameter.

Wall pressure measurements were performed with help of pressure taps, drilled in one tube of each row, and connected to electronic manometers (Hartmann & Braun). The tube was turned about its axis allowing measurements at each 5^o.

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 the pressure taps by plastic tubes. Prior measurements in pipe flow showed that this mounting technique was adequate to the measurements to be performed [5].

Data acquisition of pressure and velocity fluctuations was performed simultaneously by an A/D-converter board controlled by an IBM/PC-compatible computer, which was also used for the evaluation of the results [6, 7].

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. Auto and 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.

RESULTS

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.

The first step of the experiment was the measurement of the mean pressure around the tubes. The resulting pressure fields in the square and the triangular arrays are presented in Figures 1 and 2 in dimensionless form as contours interpolated in the flow region. Both figures 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 square arrays the maximal pressure occurs at a position of 45^{o} while for triangular array this maximum appears at 0^{o}. These angles are measured clockwise from the position of direct flow incidence before the tube bank and indicated the position of the pressure tap. Zero degrees corresponds to the location where the pressure tap faces the main flow.

Figure 3 shows the RMS values of the pressure fluctuations in dimensionless form as a function of the position for one tube in the third row of the square and triangular array. The former shows strong variations, with peaks at locations around 30, 110 and 150 degrees. The first peak appears on the location where the maximal values of the mean pressure in this geometry occur. The results from the triangular array show lower values and no pronounced variations as in the square array, with smaller peaks at 0, 100 and 140 degrees.

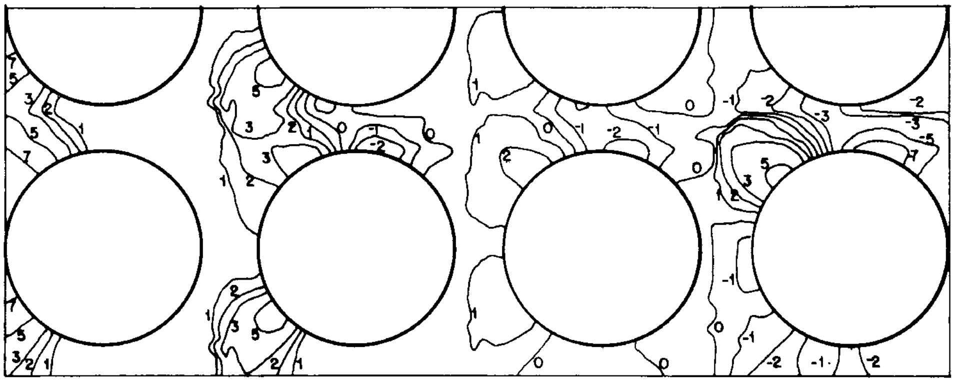

Fig. 1: Pressure field in the square array presented in dimensionless form as contours interpolated in the flow region - flow from left to right (P/D=1.259, Re = $1.5 \bullet 10^{4}$).

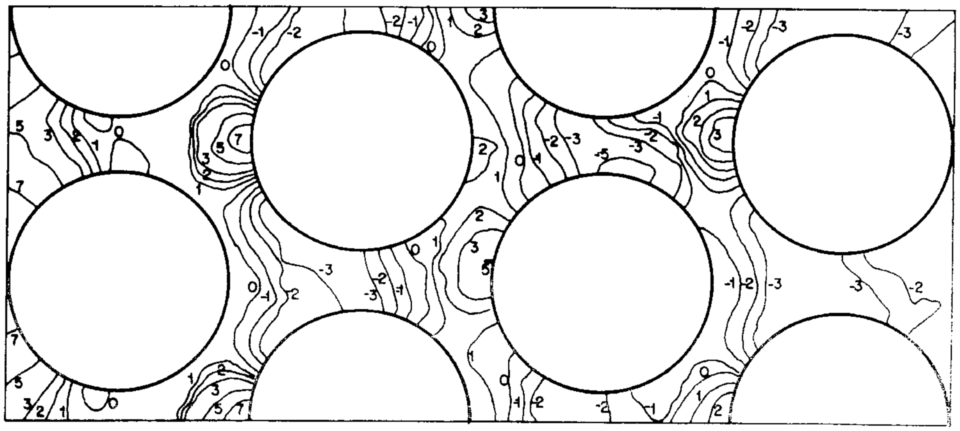

Fig. 2: Pressure field in the triangular array presented in dimensionless form as contours interpolated in the flow region - flow from left to right (P/D=1.259, Re = $1.5 \bullet 10^{4}$).

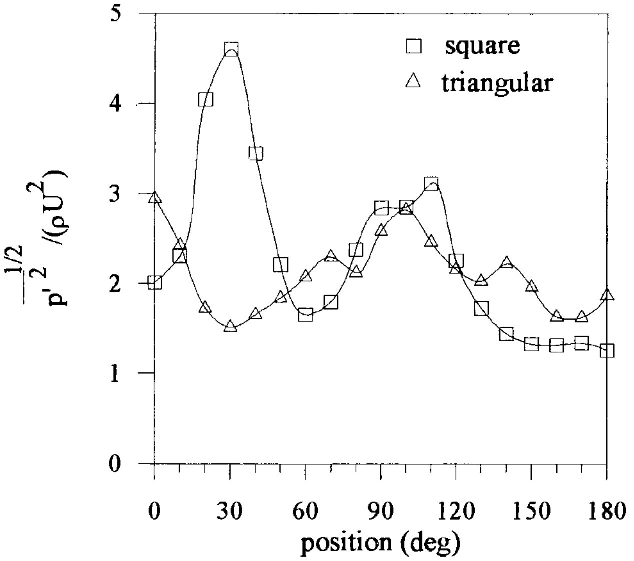

Fig. 3: RMS values of the pressure fluctuations in dimensionless form for tubes in the third row (P/D=1.259, Re = 1.5•10^4).

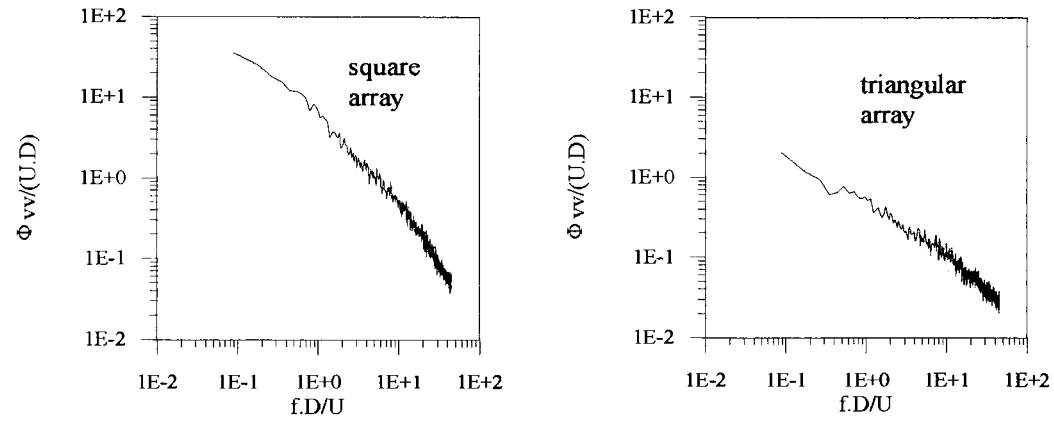

Fig. 4: Autospectral density of the velocity fluctuations in the narrow gaps between the tubes of the third row (P/D=1.259, Re = 1.5•10^4)

Figure 4 presents autospectral density of the fluctuating velocity in the center of the narrow gap between the tubes at the third row of the arrays. Both curves show no peaks or any other sign of a characteristic frequency, with a very uniform decay as the frequency, in Strouhal number form, increases. For the same mean velocity, the intensity of the velocity fluctuations in the square arrangement is higher than in the triangular arrangement.

Measurements of pressure and velocity fluctuations were performed simultaneously in locations 4.2 mm close to each other. Figure 5 shows the autospectral density of the wall pressure fluctuations in the narrow gaps between the tubes. Both have an uniform decay, in fact with higher intensities at the square arrangement, with the presence of peaks at a Strouhal number corresponding to the above mentioned frequencies, these being the measured resonance frequencies of the test section.

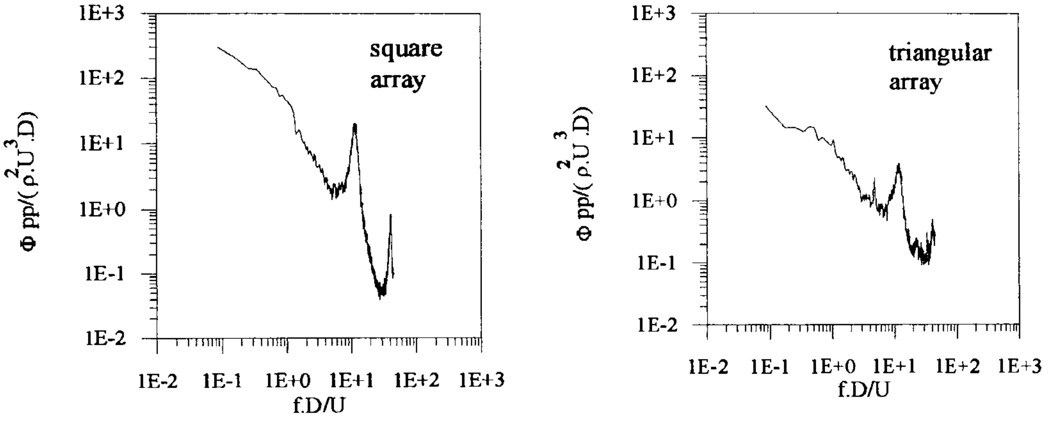

Fig. 5: Autospectral density of the pressure fluctuations in the narrow gaps between the tubes of the third row (P/D=1.259, Re = $1.5 \bullet 10^4$).

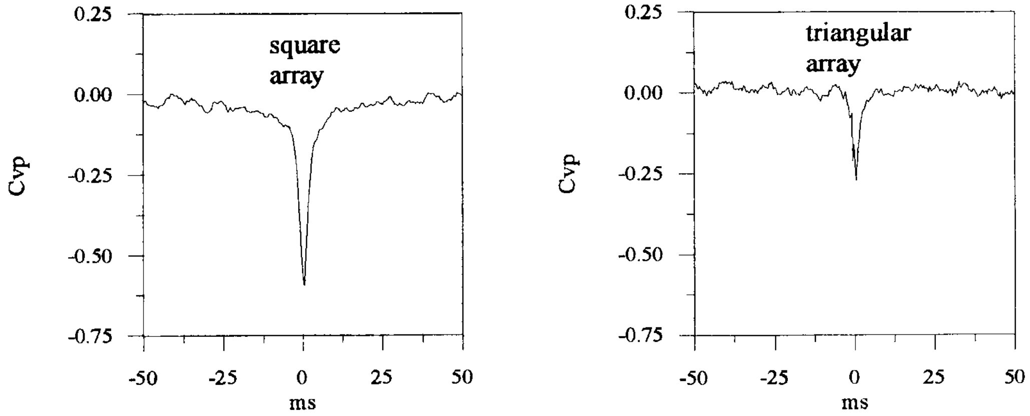

Fig. 6: Crosscorrelation between velocity and pressure fluctuations in the narrow gaps between the tubes of the third row (P/D=1.259, Re = $1.5 \bullet 10^4$).

Crosscorrelations of velocity and pressure fluctuations shown above, are presented in Figure 6. It is remarkable that the square arrangement has higher values (negative) of the cross correlation than the triangular arrangement. Positive velocity fluctuations, give rise to negative pressure fluctuations in the gaps. In general, the values of the correlations are very low, except for small time intervals, showing the highly random behavior of the flow between the tubes.

CONCLUSIONS

This paper presents results of measurements of the mean and the fluctuating pressure field in tube banks with triangular and square arrays with a small aspect ratio, with the purpose to investigate the relationship between pressure and velocity fluctuations as a function of the position inside the bank.

Static loads, observed through the plots of mean pressure, seem to appear mainly due to the strong pressure drop which occurs in the narrow gaps between the tubes. High values of the mean pressure occur for triangular arrays at a position of 0^{o}, where the tubes receive the impact of the flow directly, while in square arrays, this maximum appears at a position about 45^{o}.

Measurements of the root mean square value of the pressure fluctuations show that in square arrays they have maximal values at positions coinciding with the positions where the mean pressure have higher values, but, in triangular arrays this behavior is not observed: the RMS value of the pressure fluctuation has an almost flat behavior with small variations compared to the square array, with lower values.

Autospectral density functions and cross correlations of velocity and pressure fluctuations have higher values for the square array than for the triangular one. No characteristic frequency was observed in both cases. The short correlation time show the random characteristic of the turbulent motion in both cases.

This research work will investigate in the future different geometries and Reynolds numbers. The direction of the main flow and Reynolds stress distributions are also goals to be achieved.

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