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SIMULATION OF TUBE BANK FLOW-INDUCED VIBRATION

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Results from a numerical simulation are reported for amplitudes of cross-flow induced vibrations at the fluid elastic instability regime in a tube bank. The tube bank has identical geometry and characteristics as for an experimental wind-tunnel facility described in the literature, for which there are experimental measurements of the amplitudes of vibrations at the fluid elastic instability regime. The rotated triangular array has a pitch ratio of 1.375 and consists of 1 movable tube surrounded by 134 rigid tubes. The numerical simulation is accomplished with a commercial CFD (Computational Fluid Dynamics) software. For the region around each tube, a mesh with elements dimensions growing geometrically normal to the tube was considered, with growing factor 1.13 and the dimension for the element adjacent to the tube wall equal to 0.1% of the tube external diameter. The flow was considered incompressible, monophasic, turbulent, bidimensional for the numerical simulation. The flow data considered were the same as for the experiments at the wind-tunnel facility. The results presented in this paper for the amplitudes obtained by numerical simulation are compared with the experimental results obtained in the above mentioned experimental facility.

Keywords: *tube bank, fluid elastic instability, cross-flow induced vibration, CFD, numerical simulation*

1. INTRODUCTION

The tubes of shell and tubes heat exchangers can be subjected to vibration with significant amplitudes, depending of operating conditions and geometry. The amplitudes of vibration are related to fluid characteristics, geometry, tube pattern and fluid velocity.The vibration can cause problems such as mechanical wear, fatigue failure, impact between tubes. Failures in large heat exchangers can have significant economic consequences caused by repair cost and production loss, among others.

Until the years 60 of the XXth century, it was believed that the tube vibration on a tube bank subjected to cross-flow was associated with von Karman vortices (or a similar mechanism). At this time the significant increase in the number of equipment failures due to tube vibration has resulted in an increased research effort that showed a much more complex landscape.

It is nowadays generally accepted that there are three main mechanisms of cross-flow vibration of tubes in tube banks: turbulent buffeting (TB), vortex induced vibration (VIV) and fluidelastic instability (FEI).

The amplitude of vibration as a function of flow velocity typically follows the pattern shown on Fig. 1

For small flow velocities the amplitude of vibration is relatively small and grows gradually with the increase in flow velocity. Increasing the velocity, a point is reached where, for small increases in flow velocity, the amplitude grows fast, achieves a peak and then returns to a relatively small value again. Continuing to increase the velocity, the amplitude again grows gradually until a velocity is reached (known as threshold velocity) where it begins to grow very fast with small increases in velocity and does not return again to low values.

The mechanism responsible for the regions where the amplitude grows gradually when increasing the flow velocity is known as turbulent buffeting (TB). The fluctuations of pressure on a turbulent flow causes fluctuation of loads applied on the tubes. The tubes response is that of a randomly forced vibration.

The mechanism responsible for the region where the amplitude grows fast with small increases in flow velocities, achieves a peak and then returns to relatively small values is known as vortex induced vibration (VIV). The most probable explanation postulates that the mechanism is excited when the frequency of vortex shedding in the tube bank coincides with the natural frequency of the tubes. This vortex shedding occurs at a constant value of Strouhal number, which is a function of tube pattern and pitch.

The mechanism responsible for the region where the amplitude grows very fast with small increases in flow velocity without returning to relatively small values is known as fluidelastic instability (FEI). The fluidelastic instability is associated with the motion of the tubes. When the velocity achieves a critical value (threshold velocity) , the motion of the tubes at their natural frequency couples with the flow in such a way that energy is transferred from the flow to the tubes increasing their vibration amplitudes.

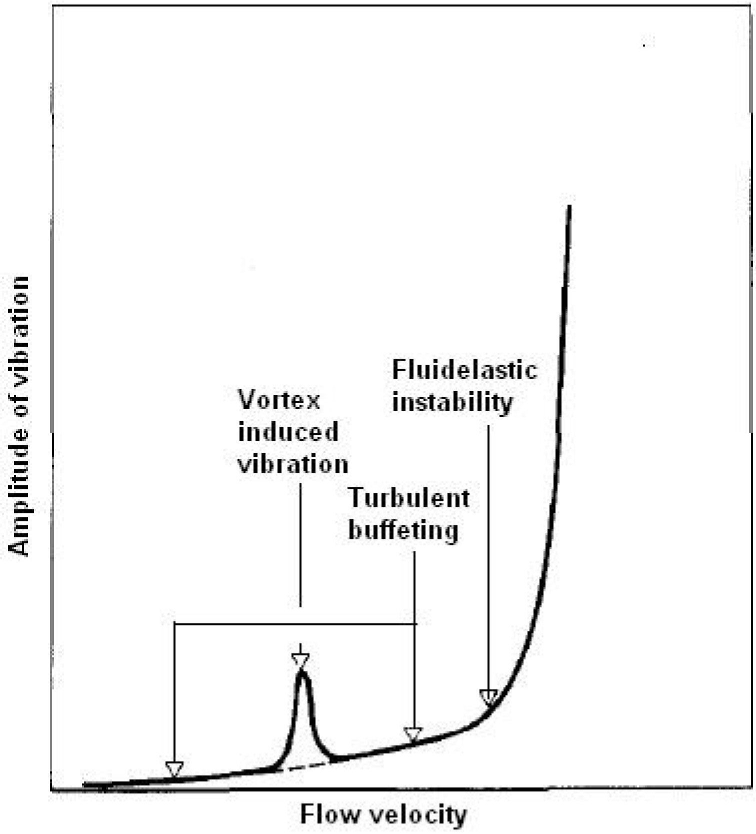

Figure 1. Typical curve amplitude of vibration x velocity
Reference: Paidoussis (1981)

The relative probability of significant damage caused by each mechanism can be seen on Tab. 1 (Khushnood, 2012).

Table 1. Relative possibility of damage due to vibration
Reference: Khushnood (2012)

Flow situation (cross-flow)	Fluidelastic instability	Vortex induced vibration	Turbulent buffeting
Single cylinder			
Liquid	Unlikely	Most probable	Most probable
Gas	Unlikely	Possible	Possible
Two-phase	Unlikely	Unlikely	Most probable
Tube bank			
Liquid	Most probable	Possible	Possible
Gas	Most probable	Unlikely	Possible
Two-phase	Most probable	Unlikely	Most probable

It can be seen that for tube banks and monophasic fluids, the most probable damaging mechanism is the fluidelastic instability mechanism.

This paper refers to the computation of the amplitudes of vibration at the fluid elastic instability regime for a tube bank. The results are compared to experimental results in the literature for the same geometry and conditions.

2. EXPERIMENTAL DATA

Grover and Weaver (1978), developed an experimental wind-tunnel facility to study cross-flow vibration in a tube bank. The facility consisted of a wind tunnel with adequate instrumentation to measure among others, velocities and amplitudes of vibration.

The overall geometry of the test array can be seen in Fig. 2.

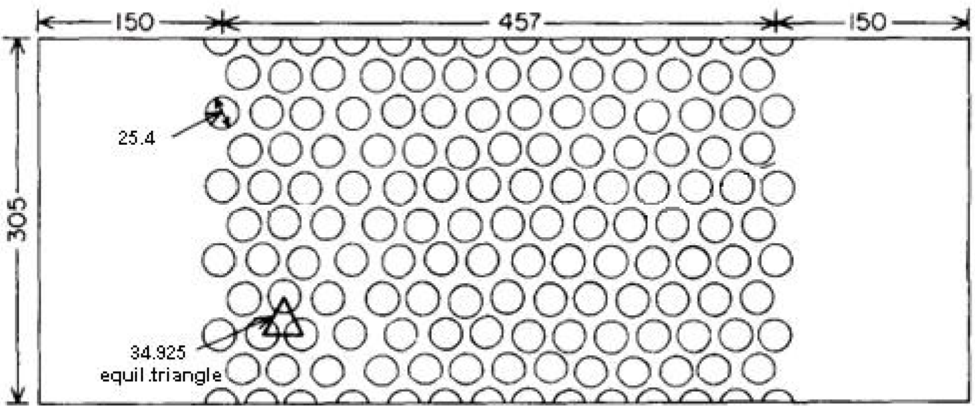

Figure 2. Experimental facility geometry
Reference: Grover and Weaver (1978)

Several experiments were made with results presented for vortex induced vibration (Grover and Weaver, 1978), turbulent buffeting (Weaver and Grover, 1978), fluidelastic instability (Weaver and Grover, 1978).

Among others , it was measured the amplitudes of vibration for the fluidelastic instability region considering two situations: the first with a center tube free to move and the other tubes fixed, the second where all the tubes were allowed to move. The results showed that the instability due to fluidelastic instability mechanism begins at essencially the same velocity for the two situations. This implies that for estimating the threshold velocity it is enough to consider the situation of one tube free and the others fixed.

The experimental results for the amplitude of vibration for the situation with the central tube free to move and the others fixed can be seen on Tab. 2.

Table 2. Measured amplitude of vibration
Reference: Weaver and Grover (1978)

Free upstream velocity (m/s)	Pitch velocity (m/s)	Amplitude of vibration-peak to peak (mm)
1.61	5.9	0.38
1.77	6.5	0.40
2.21	8.1	1.00

3. NUMERICAL SIMULATION

A bidimensional simulation model was applied for the computation of flow induced vibrations of a tube bank subjected to monophasic cross flow. The flow induced vibrations were simulated with the CFD (Computational Fluid Dynamics) commercial software "*ANSYS*®FLUENT version 14.5". The geometry of the tube bank was considered equal to the geometry of the Grover and Weaver (1978) experiment, as well as the operating conditions. The object of the simulation was to obtain amplitudes of vibration in the fluidelastic instability regime and to compare them with the experimental values obtained by Weaver and Grover (1978).

The geometry of the tube bank corresponds to that shown in fig. 1. The center tube is free to move and the other are fixed.

The tubes have distributed mass of 0.1583 kg/m , the tubes natural frequency in air is 24 Hz , the logarithmic decrement of damping is 0.01 (1%) , the fluid is atmospheric air at 20°C.

The flow is considered bidimensional , monophasic , incompressible , turbulent.

Regarding turbulence, the papers from Schroder and Gerber (1999) and Williams, et al. (2004) consider the k-ε model to be inappropriate for this type of flow. Schroder and Gerber (1999) recommend the k-ω model and Williams, et al., recommend the SST-k-ω model. In this simulation the SST-k-ω model was considered.

Regarding the mesh discretization , the region of the tubes was considered partitioned in hexagons. Each tube is surrounded by an imaginary hexagon whose sides dimension is half pitch between adjacent tubes. The mesh elements size grow geometrically in the normal direction of the tubes with ratio 1.13. The elements in contact with the tube have a dimension normal to the tube of 0.1% of the tube diameter.

The height of the first cell and the grid stretching ratio were chosen based on the assumption that the Reynolds number calculated with the upstream velocity and cylinder diameter is below 4000. The boundary layer can be assumed laminar and we can say that $\delta \sim Re^{-1/2}$ where δ is the boundary layer thickness and Re is the Reynolds number. With a small stretching ratio of 1.13 and a first cell height of 0.1% of the tube diameter the boundary layer flow should be well resolved. Moreover, Dombard and Iaccarino (2012) found that for CFD calculations of channel flows, the near wall mean velocities and the skin friction coefficients are unaffected when the grid stretching ratio is below 1.2.

For the time step it was considered 0.1% of the natural period (the inverse of natural frequency).

The overall geometry at the start of the simulation can be seen in Fig. 3.

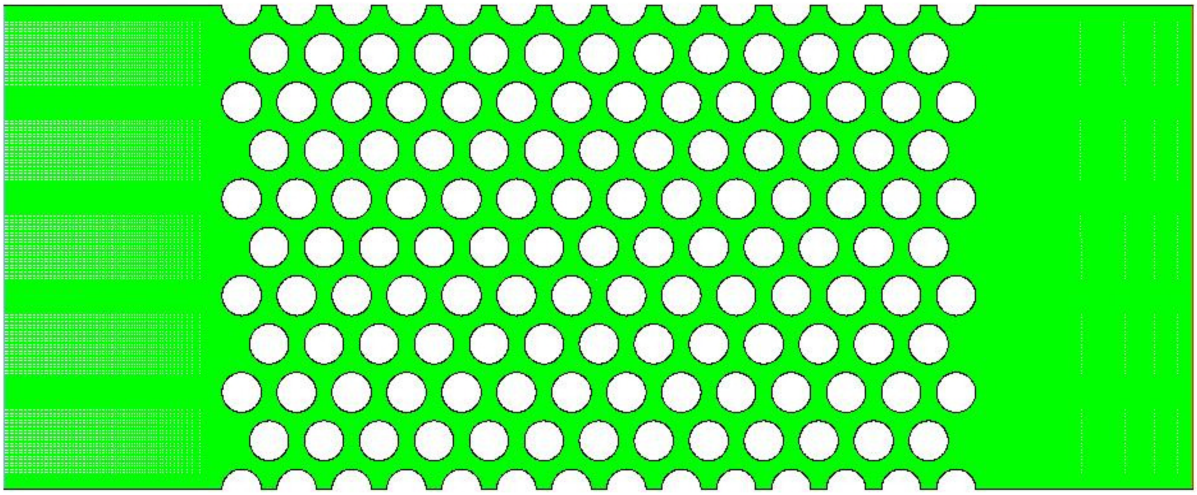

Figure 3. Overall geometry for simulation

The mesh discretization around the tubes at the start of the simulation can be seen in Fig. 4

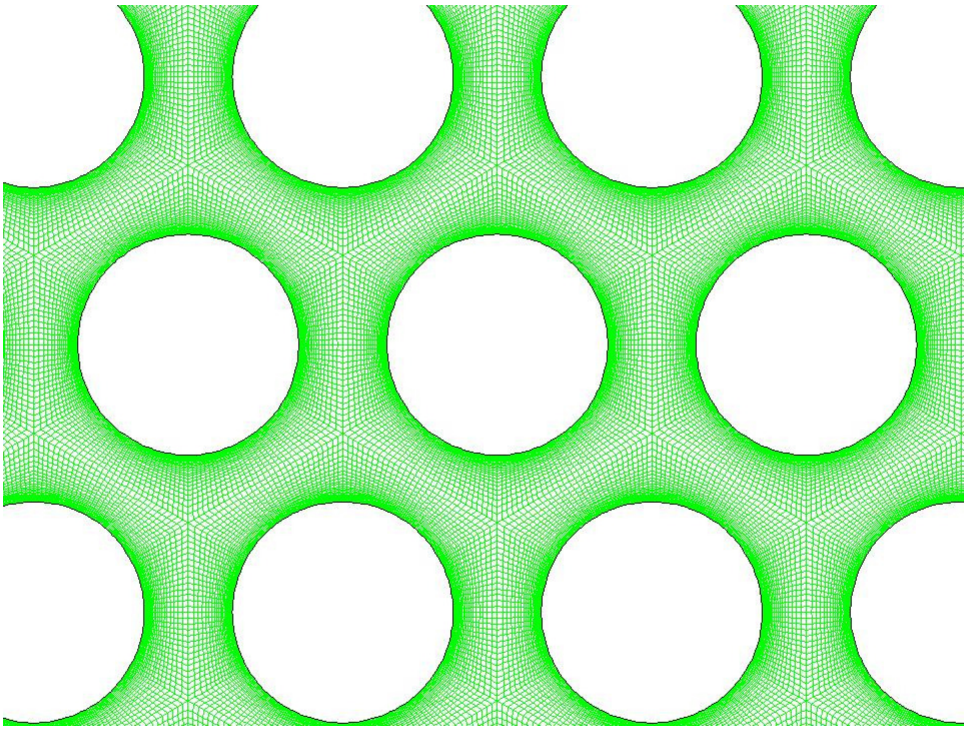

Figure 4. Discretization around tubes at start of simulation

4. RESULTS AND DISCUSSION

The motion of the free tube through time can be seen in Fig. 5 (for 1.61 m/s upstream velocity), in Fig. 6 (for 1.77 m/s upstream velocity), in Fig.7 (for 2.21 m/s upstream velocity).

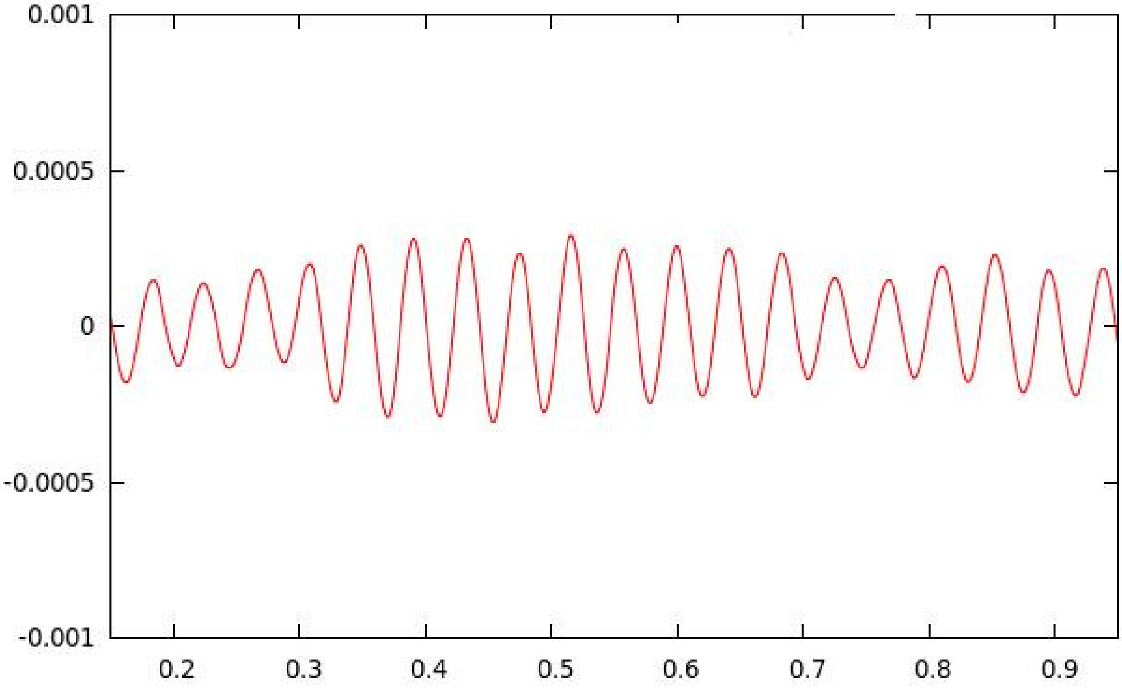

Figure 5. Motion of free tube
Upstream velocity 1.61 m/s

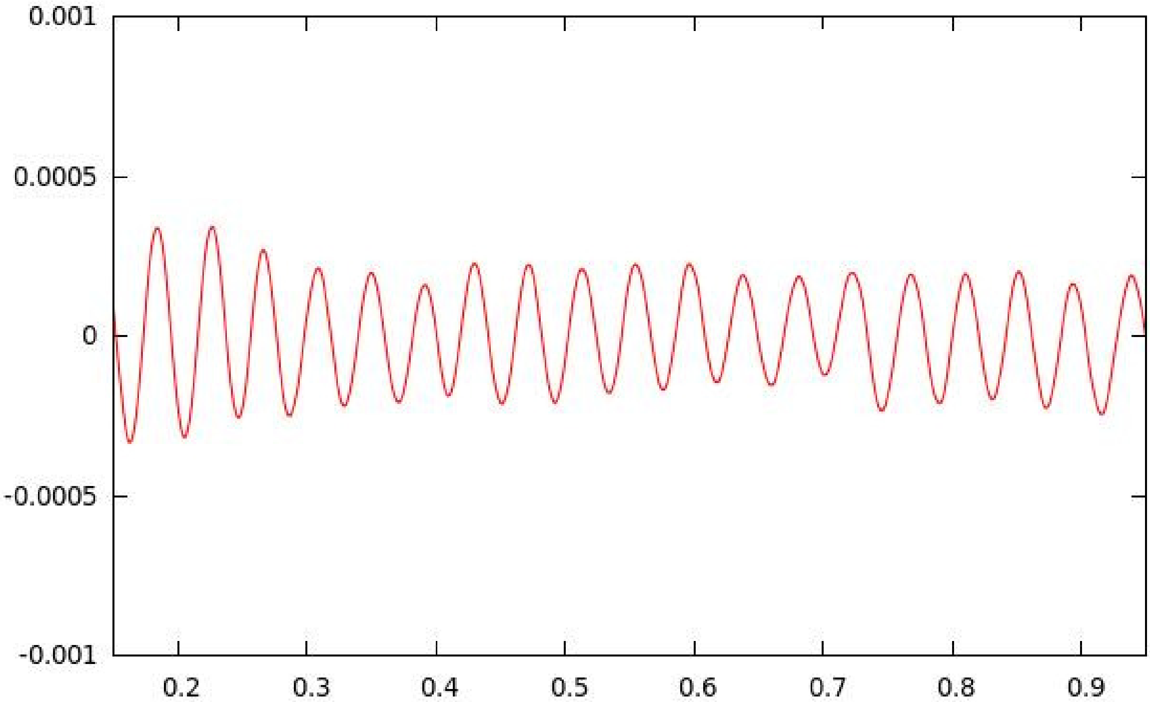

Figure 6. Motion of free tube
Upstream velocity 1.77 m/s

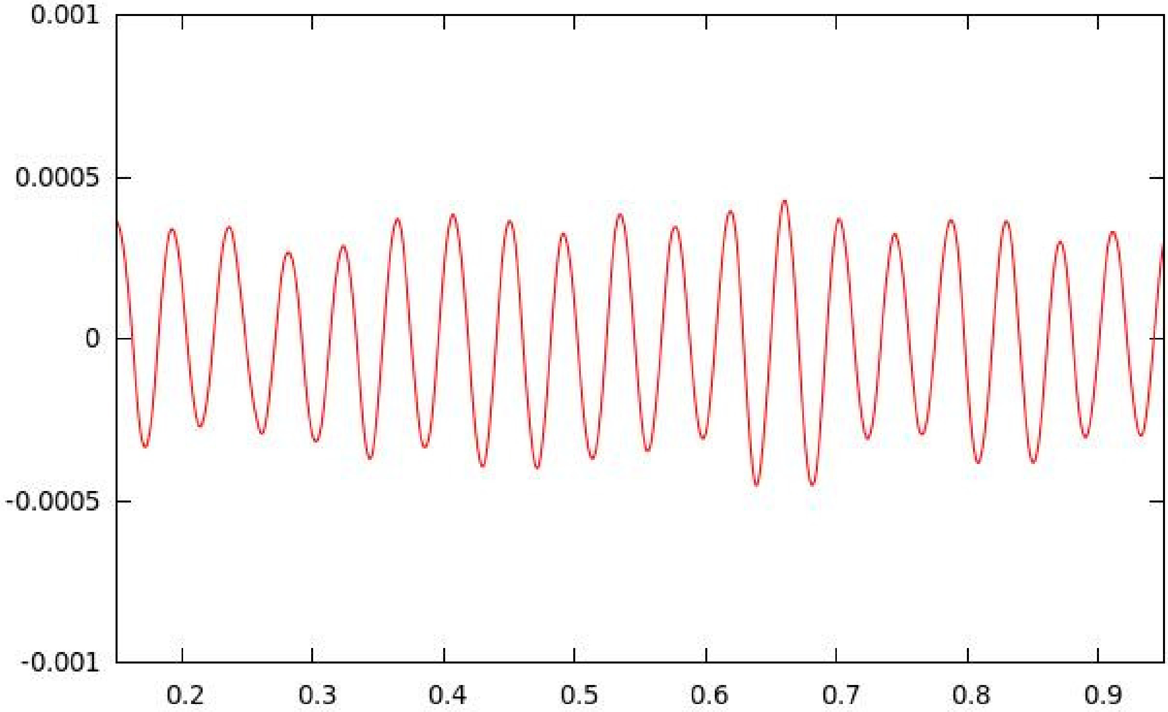

Figure 7. Motion of free tube
Upstream velocity 2.21 m/s

The calculated results for the amplitude of vibration (rms) for the situation with the central tube free to move and the others fixed can be seen on Tab. 3.

Table 3. Calculated amplitude of vibration

Free upstream velocity (m/s)	Pitch velocity (m/s)	Amplitude of vibration-peak to peak (mm)
1.61	5.9	0.44
1.77	6.5	0.44
2.21	8.1	0.70

The comparison between calculated amplitudes and measured amplitudes can be seen on Tab. 4.

Table 4. Comparison between calculated amplitudes and measured amplitudes

Free upstream velocity (m/s)	Amplitude - experimental (mm)	Amplitude -calculated (mm)	Difference-(%)
1.61	0.38	0.44	15,8
1.77	0.40	0.44	10,0
2.21	1.00	0.70	-30,0

For velocities 1.61 m/s and 1.77 m/s the calculated amplitudes are greater than the experimental ones, for velocity 2.21 m/s the converse occurs. To verify if this fact (calculated values smaller than experimental ones for relatively low velocities and greater than experimental values for relatively high velocities) is a tendency for the chosen approach (turbulence model, mesh discretization, …), there is need for more simulations.

The difference of 30% between calculated and measured amplitude for the velocity 2.21 m/s , although big, is acceptable for such situation.

5. CONCLUSION

The obtained results show that the use of CFD simulation for estimating the amplitude of vibration for tube banks at the fluidelastic instability regime is promising, but it requires a lot more simulations (and respective comparison to experimental data) considering several geometries and several fluids before considering it as a consolidated tool for such situations.

6. REFERENCES

Dombard, J. and Iaccarino, G., 2012. “Sensitivity analysis to the normal grid-resolution in a turbulent channel flow using large-eddy simulations”. *Annual research briefs 2012*, Center for turbulence research

Grover, L.K. and Weaver, D.S., 1978. “Cross-flow induced vibration in a tube bank – turbulent buffeting and fluid elastic instability”. *Journal of sound and vibration*, Vol. 59 (2), p. 263

Khushnood, S., 2012. “Cross-flow induced vibration in heat exchanger bundle –a review”. In *Nuclear power plants* – edited by Chang, S.H.

Paidoussis, M.P., 1981. “Fluidelastic vibration of cylinder arrays in axial and cross flow: state of the art”. *Journal of sound and vibration,* Vol. 76 (3), p. 329

Schroder, K. and Gelbe, H., 1999, “Two- and three-dimensional CFD-simulation of flow-induced vibration excitation in tube bundles”. *Chemical Engineering and processing*, Vol. 38, p. 621

Weaver, D.S. and Grover, L.K., 1978. “Cross-flow induced vibration in a tube bank – vortex shedding”. *Journal of sound and vibration*, Vol. 59 (2), p. 277

Williams, E., Gerber, A. and Hassan, M., 2004. “Simulation of cross flow induced vibration”. In *International ANSYS conference* <http://www.ansys.com/staticassets/ansys/staticassets/resourcelibrary/confpaper/2004-int-ansys-conf-137-pdf>

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