Numerical Simulation of Vortex Induced Vibration and Related Parameters in Cross Flow Shell and Tubes Heat Exchanger: A Review

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Abstract-This paper presents a brief review of studies on cross flow induced vortices in downside of tubes which leads to vibration. Two types of vibrations have been studied for tubes in cross flow: first vibration of the tube due to vortex shedding which is important primarily in cross flow but this vibration disappears in slug flow or froth flow regions which are important in numerous heat exchangers, secondly fluid elastic excitation which is most dangerous mechanism in heat exchanger tube bundles. The paper also presents the other parameters such as temperature variation on tube, pressure effect, lift and drag generation and their influence on heat exchanger tubes, different models comparison and tube size effect of tubes for vortices.

Keywords-Resonance, Slug Flow, Vortex Shedding, Fluid Elastic Excitation, Lift Coefficient

I. INTRODUCTION

The shell and tube heat exchangers have high surface area and volume ratio among all other types of heat exchangers and are easy to manufacture. Flow induced vibrations is a phenomena that can be found in many engineering fields such as aircraft wings, turbine blades, shell and tube heat exchangers, power transmission lines, centrifugal pumps, hydraulic gates and valves.

Turbulent buffeting is one the main cause of the tube excitation in heat exchangers. Vibration at or close to shedding frequency has a strong effect on the wake. Vorticity is a constant and discrete phenomenon. The important parameter defining the vortex shedding is Strouhal number. Strouhal number is the constant number between the frequency of vortex shedding and free flow velocity of the fluid. Fluid-elastic instability is by far the most hazardous excitation mechanism and the mainly general source of tube collapse.This instability is distinctive of self-exited vibration in that it results from the relations of tube motion and flow. The main reason behind acoustic resonance is that some flow excitation (possibly vortex shedding) having a frequency, which equals with the natural frequency of the heat exchanger cavity.

CFD is the simulation of systems concerning fluid flow, transfer of heat and coupled phenomena such as chemical reactions by means of computer-based simulation. The current paper presents the review of past papers of flow over tubes and cylinders creating vortices and vibration in the tubes.

A. Nomenclature

fvs	Frequency of vortex shedding
U_∞, U	Free stream flow velocity (m/s)
d	Diameter of tube (mm)
St	Strouhal number
Re	Reynolds number
T/D	Transverse pitch to dia ratio
P/D	Pitch to diameter ratio
L	Tube length (m)
λn	Frequency factor
ρ_m	Tube material density (kg/m3)
ρ_w	Water density (kg/m3)
γ	Bending stiffness (N/m)

B. Abbreviations

CFD	Computational fluid dynamics
FFT	Fast Fourier Transform
FIV	Flow induced vibrations
LES	Large Eddy simulations
FDM	Finite difference method
FVM	Finite volume method
FEM	Finite element method
DNS	Direct numerical simulation
RANS	Reynold's average navier stroke model

II. REVIEW

A brief review of the work done by various previous researchers has been presented here.

2.1 Fluid Elastic Excitation

Fluid-elastic instability is the most hazardous excitation method in heat exchanger tubes and the most ordinary reason of tube fracture. When the tubes vibrate forces generated and these forces have a linked with fluid-elastic instability. The fluid-elastic instability is characterized as the feedback mechanism between fluid forced and the structural motion [i]. A small displacement in structure due to instability effects the flow pattern, creates a change in fluid forces. This results to an auxiliary displacement of tubes and so on. If this displacement increases, the significant phase difference started to occur, leading to the fluid-elastic instability. There are three different ways in which energy is extract by cylinder from flow. These are

1. There must be difference in phases of cylinder displacement and fluid force generated.
2. There should be at least two degree of freedom phase difference between cylinder and flow
3. Since the fluid force is hysteretic due to non - linearities and its magnitude depends on the direction of cylinder motion.

A substantial hypothetical and experimental research has been undertaken in the past three decades to enter at a secure and consistent design criterion against fluid-elastic instability. The topic has been discussed on ordinary basis from time to time by different researchers focusing on tube failure caused by fluid elastic instability [ii, iii, iv, v].

Eulerian porous medium formation was developed to model the fluid structure interaction of tube bundle [vi]. They results that porous medium model is used to represent the two way coupling which is assessed by comparing its predictions to DNS predictions of Laminar cross flow.

2.2 Vorticity Excitation

There are series of vortices produced across the tube as the fluid passes the tube and flow divides from the opposite sides of the tube. This shedding of vortices produces discontinuous forces, which arise more commonly as the free stream velocity increases. For a single cylinder, f_{vs} frequency of vortex shedding is given below by dimension less Strouhal number.

$$f_{vs} = \frac{StU}{d_o} \tag{1}$$

Locked-in phenomena occur in tubes when frequency of vortex shedding becomes equal to the natural frequency of of tubes vibrating freely even when we increase the free stream velocity [vii].

The value of Strouhal number becomes a constant of about 0.2 for a single cylinder [viii]. The accurance Vortex shedding for the ranges of Reynolds number 100 < Re <5x105 and > 2 x 106 while it dies out in-between. The gap is due to a transfer of the flow division point in vortices in the transitional trans-critical Reynolds number range. There is an excitation in the tubes when vortex shedding frequency matches with the natural frequency of the tubes.

Reference [ix] by simulating a circular cylinder found that by contrasting the flow at low Reynolds's number could generate the vortex shedding. There is a very wide wake when the flow is passed through a cooled cylinder due to more influence of the fluid which is ambient. A plot that clearly demarcated zones of the vortex shedding of Reynolds's number against Strouhal number is shown in Fig. 1.

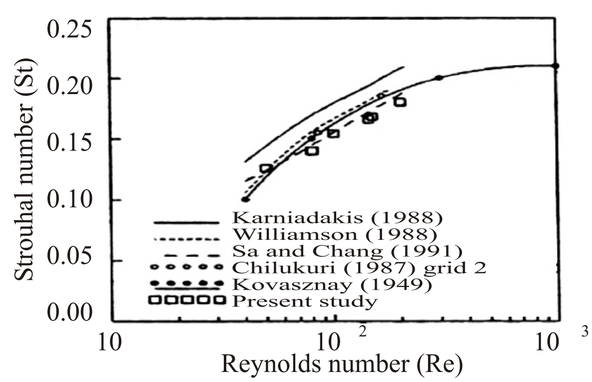


Fig. 1. Comparison of Strouhal number against Reynolds number. [ix]

Flow induced vibrations were investigated [x] by vortex shedding phenomena in underwater cylinder that leads to the damage in nuclear power plant components. Various numerical simulations and experiments have been conducted to predict the vibration phenomena. Three tests have been carried out including flow past a rigid circular cylinder, inline oscillations of the circular cylinder and flow induced vibrations with unidirectional motion to prove the projected numerical methods.

Reference [xi] studied the vortex shedding characteristics and the drag force acting on the circular cylinder attached with the splitter plate. The splitter plate is forced to oscillate harmonically at the Reynolds number of 100. The Fig. 2 presents the geometry and kinematics of the cylinder and the splitter plate.

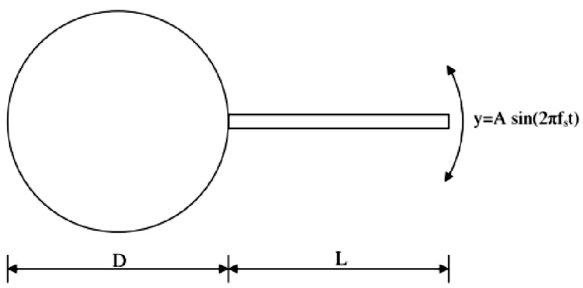


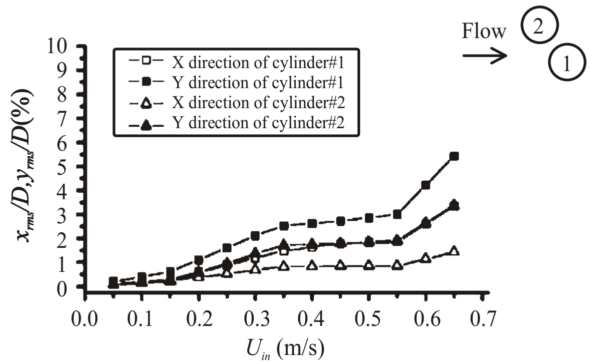
Fig. 2. Geometry of the cylinder and the splitter plate [xi]

Careful observation suggests that there are three patterns of vortex shedding observed in the wake of circular cylinder which mainly depends on the frequency and the amplitude of vibration of the oscillator plate, normal shedding, chain of vortices and shedding from the splitter plate. The results suggest that the shorter splitter plate with obligatory oscillations can be used to suppress vibrations.

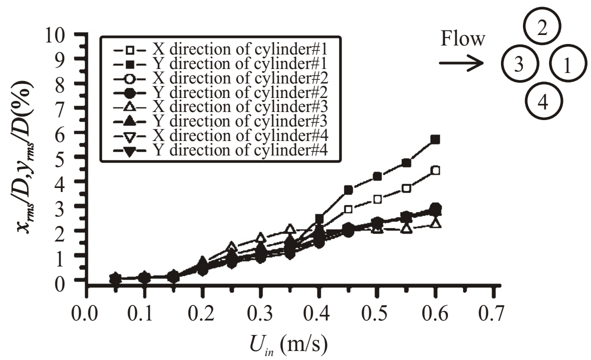
A numerical technique was used, called hybrid discrete vortex method, to simulate flow around circular cylinder in a planar oscillatory flow [xii]. Number of techniques is examined for estimating the forces on the cylinder. The comparison of different techniques shows that the Wu's method gives more accurate predictions in which surface pressure is predicted more perfectly than other numerical techniques.

Same discrete vortex method was used [xiii] to investigate the hydro elastic interaction between oscillating cylinder and the fluid forces. The calculations are compared with the results obtained by the quasi-steady theory. The results show that transition of vibration mode occurs with the varying reduced velocity.

A single cylinder can show a large amplitude response even with a small velocity change. There is a certain vibration of the cylinder in elliptical orbits beyond the critical value [xiv]. The displacement in different cylinders with respect to velocity is shown in Fig. 3.



(a)



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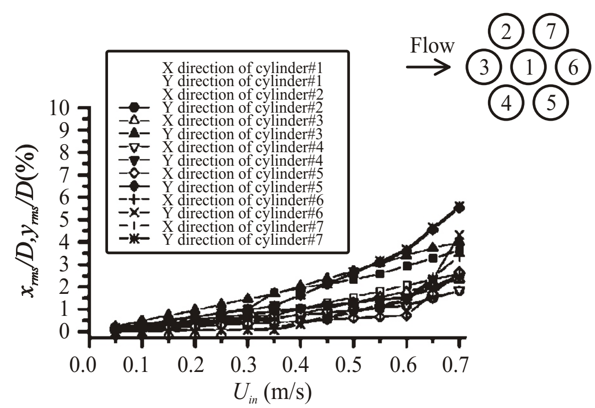


(c)

Fig. 3. (a), (b), (c) Displacement in different cylinders with respect to velocity [xiv]

Reference [xv] were the first who results analytically the vortex shedding frequencies in in-line tube bank in which he introduced different tube spacing and results that tube spacing has major effect on Strouhal number.

There exist vortex shedding in two cylinders when we arrange them parallel and perpendicular to free stream velocity [xvi, xvii].

Reference [xviii] carried out research on the turbulence response of the tubes due to excessive vibrations in many industries. They concluded the response of the tube, impact ratio and contact ratio in non-dimensionless form. There is a decrease in root mean square impact forces due to increase in support clearance which is a permanent level of excitation and centered tubes. Also there is a reduction in raise reaction of the tube for a series of clearances.

A numerical simulation was performed [xix] on two side by side tubes at different transverse gap ratio and results that at Re = 100 and Thickness/Diameter= 1.5 there is a biased flow pattern which is bi stable behind both cylinder. At different flow pattern and different flow velocities a wide and thin wake section develops behind each of the cylinders. Fig. 4 shows the flow characteristics of two side by side cylinders.

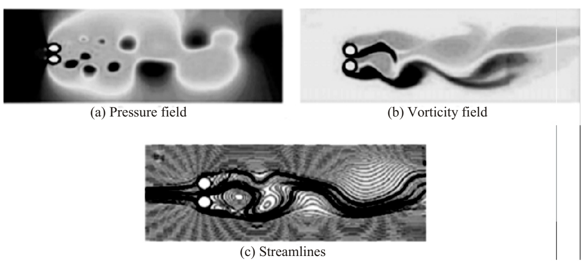


Fig. 4. Flow characteristics of two side by side cylinder at Re =100 T/D =1.5 tU/D = 65. [xix]

A simulation was performed for the flow behavior in a tube bundle and viewed that in the flow bundles [xx], when we know about the flow structure it can support in alleviating tribulations which are related by noise and vibrations induced by flow technique.

Analysis of fleeting flow behavior in the bundle of tubes with rounded and quadratic cross sections at dissimilar Reynolds numbers depends upon the inlet velocity and at different angle of attack. Results describes that a lean shear layers on the edge is resolved which becomes unsteady and this may result in the formation of co and contradict revolving vertices [xxi].

Research on surface vorticity method describes that while the tubes are fixed or rigid, stream in the region of the tubes is in ordinary pattern in a path around the tubes [xxii] as shown in Fig. 5.

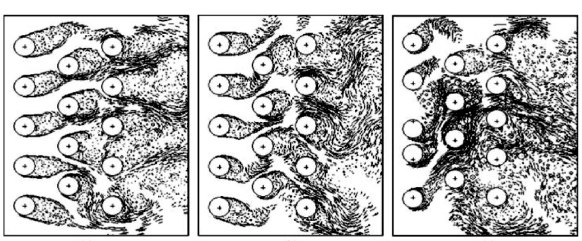
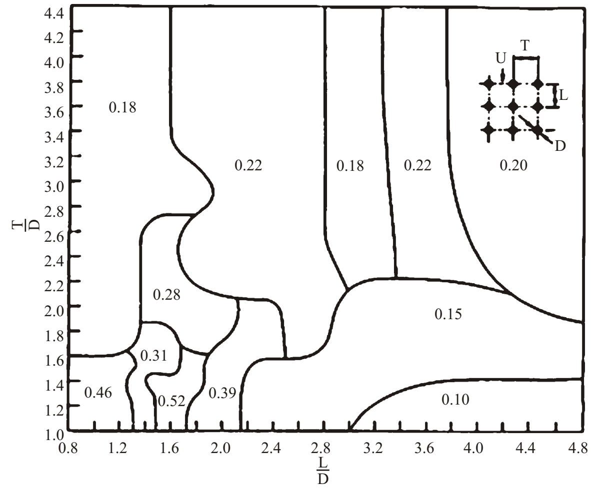
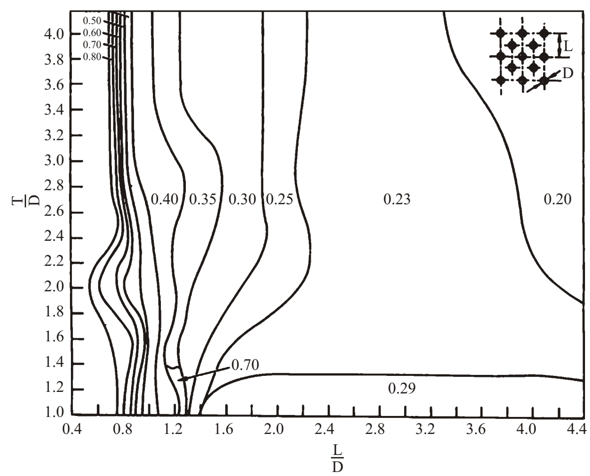


Fig. 5. Vorticity map of rigid and flexible cylinders (A) Rigid; (b) Flexible at SG =1.29, M =10 9; (c) Flexible at SG =0.516 , M=4. [xxii]

For tube banks strouhal number is not a unique value but changes with the pitch between the tubes [xxiii, xxiv]. Typical values for Strouhal number in-line and staggered tube bundle geometries are given in Fig. 6.



(a)



(b)

Fig. 6. (a) Strouhal numbers for in-line tube banks (b) Strouhal numbers for staggered tube banks [xxiii,xxiv]

Reference [xxv] have results numerically the effect of space between tubes on the vortex shedding of streamline flow over the inline tube array. The study consists a six row in-line tube bank having P/D = 8, with Navier-Strokes continuity equation based unstructured code. They wrote the incompressible navier-strokes equation in tensorial Cartesian form as given in equation (2) and (3)

$$\delta u_i / \delta x_i = 0 \quad (2)$$

$$\delta u_i/\delta t + \delta u_i u_j/\delta x_j = - \delta p/\rho \delta x_i + \nu \delta^2 u_i / \delta x_j \delta xj \quad (3)$$

A significant spacing range between 3.0 and 3.6 is identified at which displacement is maximum for the mean lift and drag coefficients. Also at critical spacing, there is 180° phase difference in the shedding cycle between succeeding cylinders and the vortices travel a distance twice the tube spacing within one period of shedding.

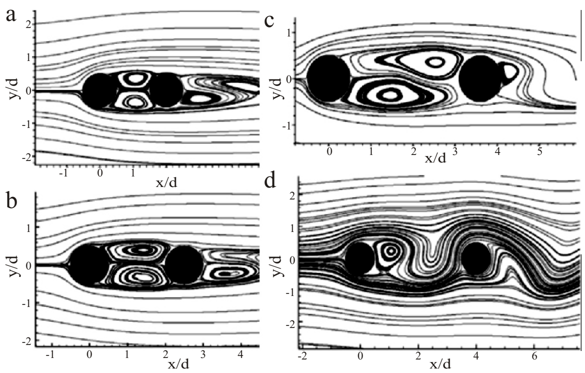


Fig. 7. Instantaneous response of two in line cylinders in tandem arrangement: (a) s=2, (b) s=2.5, (c) s=3.6 and (d) s=4.0. [xxv]

The review and summary of the basic results and discoveries associated to vortex induce vibrations with meticulous prominence to vortex dynamics and energy transfer that give rise to vibrations. They given the importance of mass and damping and the concept of "critical mass", "effective elasticity" and the liaison between force and vorticity. They results that that as the vibrating structural mass decreases, velocity stream (non-dimensional) having large amplitude vibration rises [xxvi].

The results of simulation in relation among vortex shedding and acoustic resonance in boiler plant for tube banks to illuminate the interactive properties of vortex shedding and acoustic resonance. At the Reynolds number range (1100-10000) it is observed that there is sporadic velocity fluctuation due to vortex shedding in tube banks [xxvii]. A review stated that it is important to control vibrations induced by vortex shedding in realistic applications where active or passive control could be applied [xxviii].

Simulation results on vortex shedding relative with the acoustic resonance in staggered tube banks and examine three Strouhal number (0.29, 0.22 and 0.19). The vortices of 0.29 and 0.22 components on the other hand occasionally originated [xxix].

The discussion and overviewed procedures and recommended design guidelines for periodic wave shedding in addition to other flow induced vibration considerations for tube bundles concludes that the variable forces due to sporadic gesture shedding depends on the number of considerations like numerical configuration of tube bundles, its position Reynolds number, turbulence, density of fluid and pitch to diameter P/D ratio [xxx].

Reference [xxxi] tested different tube arrays and apply numerical method to different industry devices. Transient flow behaviour with tubes of circular, square and twice cruciform at different Reynolds number using different angles of attacks is studied. Results show that at high Reynolds no Re > 500 two dimensional effects are less important than three dimensional and it becomes necessary to us to simulate the detailed three dimension devices.

By using the URANS model show that flow is instable across tube bundles and there is a high pressure on the tube which is on the inlet flow of water and these results are taken from the distribution of pressure around the tubes [xxxii].

Turbulent flow computation in the cylinder arrays shows that there is a different flow regimes in line and circular cylinder even at same Reynolds's number. There is a different vortex form and a jet shear layer of vortices is present in the inline cylinder. In the rotated array vortices are generated by periodic shedding off the boundary. Due to these vortices rotated cylinder arrays have higher lift and drag coefficient [xxxiii].

Simulate the fluid structure interaction in a tube array shows that cylinder spontaneously displays an oscillatory motion which first corresponds to vortex induced vibration associated to a lock-in mechanism for low values of the reduced velocity and secondly develops Movement Induced Vibration, MIV, for higher values of the reduced velocity [xxxiv].

Analysis of the flow induced vibration of PWR steam generator used the fully coupled model of fluid dynamics and structure for the fluid structure problems and results that single tube gives more vibration as compared to bundles [xxxv].

2.3 Temperature Distribution And Heat Transfer Around Tubes:

Reference [xxxvi] reviewed that different arrangement of heated rod bundles found the introduction of different distribution of the temperature at the wall of the rods and its value depends upon the structure of the geometry. When conditions of the flow are the same, the flow which is on the downside of the rods is at higher wall temperature than the flow which is on the upper side. Also there is a smallest temperature of the wall at hexagonal geometry frame.

Research finds that there is an increase in heat transfer at high air velocity and decrease in pressure loss in the layer with delta winglet eddy generators [xxxvii].

2.4 Pressure Creation And Fall On Tubes

Research on the effect of increasing and decreasing baffle cuts on the pressure drop results that decrease the baffle plates cut, pressure drop across the heat exchanger decreases. They pointed out that this effect is due to baffle plate length the fluid crossing it [xxxviii]. A research on plate fin heat exchanger to calculate the pressure fall break up of stainless steel heat exchanger calculated that the actual case has almost sixteen percent higher drop in pressure than ideal one which has a jagged curved at the inlet channel of heat exchanger [xxxix].

Reference [xl] performed a numerical study and concluded that there is a wake switching effect and rotatory eddy flaking in a tube bank which is to be staggered. They concluded that there is a spontaneous develops in the transient flow. Due to transient nature, pressure related quantities have a large shock. Also there is a large fluctuation of pressure acting on tube walls which is to be due to triode like effect. Reference [xli] carried our research on simulation of flow of fluid for the reduction of pressure drop across polymer tube bundles. Results shows that to make the streamline cylinder more slender there is a increase in the drag reduction. They results that there is a significant reduction in pressure drop when we use elliptical cylinder instead of circular cylinder.

Reference [xlii] carried out research that how pressure is drop in rheological and algebraic forms in the tubes. Their simulation describes that velocity is high in the centre of the tubes away from the walls. Due to the low additional stress point there is a low twisting rate occurs in the tubes.

Reference [xliii] carried out research on the different inlet velocity and oscillatory flow past a cylinder and concluded that there are several computational aspects at Reynold = 160. Results describes that there is a decrease in moment domain of nusselt number and root mean square values while increase in time domain drag coefficient with the increase in temperature values at the surface.

The investigation of turbulent flow crosses the heat exchanger tubes flow velocity in near wall passages have higher velocity and higher temperature. They results that heat transfer coefficients are lower near to wall tubes as compared to other tubes [xliv].

2.5 Effect of Size of Tubes

Reference [xlv] perform a numerical evaluation of heat exchanger and views that by alternating the sizes of the tube, there is a repression of the eddy flaking mechanism. The configuration of unequal cylinders that has been placed longitude and transverse pitches les to a raise in heat transfer.

A research on helically coil tubes find that there is a vibration and freeting wear which is due to potential flow. They concluded that by increasing the diameter of coil or the number of turns of the coil there is a reduction in normal frequency. The response of the amplitude to the highly disorder vibration induces by flow increases as the space rate or diameter of the coil increases [xlvi].

A research on the two phase bubby flow views that bubble trajectory in tube rods depends on the size of the bubble and the geometry of the rod [xlvii].

Reference [xlviii] concluded that at Re = 100 over cylinder and Length/Diameter = 2.5 in between the cylinders, there is no vortices on upstream cylinder shed and the cut off coating from the cylinder separation are going to reattach on the face of the downstream one. There is a decaying trend due to viscosity in the lift coefficient which is used to stabilize the flow. When we increase the Reynolds no and L/D ratio there is a more unstable behavior of flow.

Reference [xlix] using a number of techniques to find the cylinder forces and reviews that pressure which acts on the cylinder is considered by using the ordinary vortices slope at the surface with the use of Poisson's equation.

Reference [l] shows the Uncertainty reduction of the heat exchanger tubes along with the different complex issues which are responsible for the stability analysis. They actually gives us a review of real flows which are subjected to turbulent as well as vortex shedding.

Reference [li] pointed out that the turbulence is responsible to reduce the fluid flexible stable boundary and these stable boundary is defined by an unsteady divergence.

Reference [lii] reviewed that Spiral tube bundles are used in heat exchanger for the enhancement of the heat transfer and shows that in tube heat exchanger there is a significant effect due to cone angle and cross section and there is a little influence on the tube heat exchanger due to helical pitch. The inferior fluid flow turns into serious due to the raise of twist.

2.6 Formation of Lift and Drag on the Tube Bundles

Reference [liii] presented the Effect of Reynolds no on the drag and lift forces and results that there is a apparent periodic oscillations in lift coefficient. These oscillations are shown in Fig. 8.

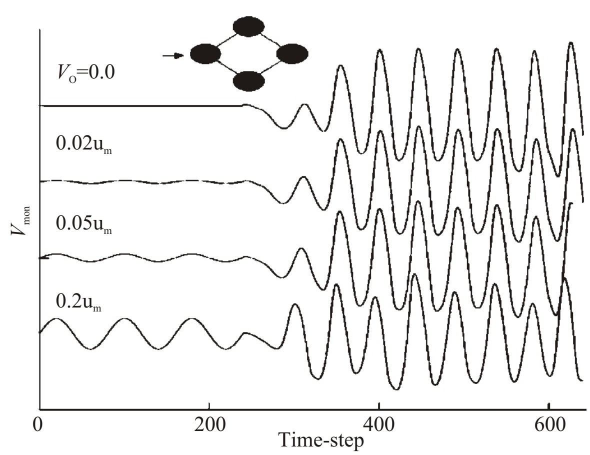


Fig. 8. Effect of Re on the lift coefficient. [liii]

Reference [liv] have perform a numerical study on the time proof of drag and lift forces, acting on the bundle of tubes and power spectral density. They concluded that it is possible to provide a mathematical approximation of the significant stream speed for the threshold of fluid flexible instability from the numerical results without using any results from experiment.

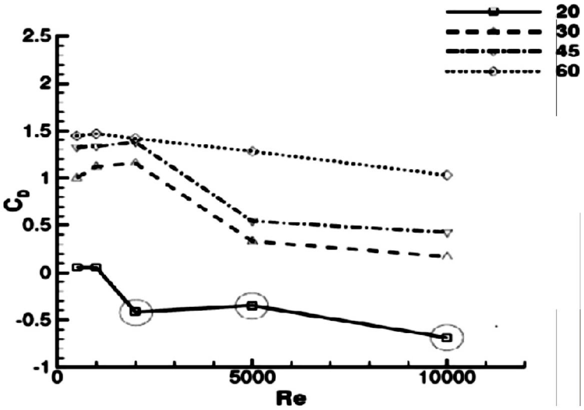


Fig. 9. Values of coefficient of drag at different Reynold's number. [liv]

Reference [lv] have performed the flow characteristics on staggered and non staggered tube bundles. The conservative forms incompressible energy, continuity and momentum equations which were used in their research are shown in equation (4), (5), and (6)

Continuity $$\frac{\partial y}{\partial t} + \nabla(\rho V) = 0 \qquad (4)$$

Momentum $$\rho\frac{DV}{Dt} = \nabla.\tau_{ij} - \nabla p + \rho F \qquad (5)$$

Energy $$\rho\frac{De}{Dt} + p(\nabla V) = \ (6) \qquad (6)$$

These equations are solved at every node of the the mesh for the drag and lift. The results shows that at high Reynolds number, the power range density results of the drag and lift forces are dissimilar on different tube rows are flooded onto a single curve.

A research on surface pressure measurement on the deformed tubes finds that when we integrate the exterior pressure allocation at a position which is at an angle, there is gradient in coefficient of lift and drag forces with respect to neighboring tube displacement and these parameters are free from Reynolds's number. They also concluded that tube spacing in the heat exchanger tubes effects the vortex shedding [lvi].

Reference [lvii] by using different method and set of laws to find the Navier stocks and continuity equations views that there is a critical spacing where average drag along with lift co-efficient for cylinders are maximum when cylinders are placed at last. By further increasing the spacing there is a decrease in force statistics.

Numerical simulation on the triangular arrays of tubes results that the lift coefficient of the root mean square and the time average drag coefficient take their maximum charge for the time in position for the cylinder. In the wake of the cylinder volumetric portion of the gaseous phase has a greater value [lviii].

Reference [lix] describes that flow patterns has a great effect on the vibration of tubes and concluded that by using mathematical study we have an inflection phenomenon which occurs at a lower excitation frequency in case of two cylinder than at a single cylinder. There is a higher drag and root mean square values in oscillating cylinders than at stationary cylinders.

2.7 Comparison of Different Models

Research to compare the different technique reviewed that these techniques gives the results of LES models on a mesh which is to be fined with the DNS model shown a sensible conformity even with a course mesh. Also the results shown that the 2D RSTM model is physically irrational which produced strong vortex shedding in the tubes [lx]. Reference [lxi] carried out research on Characteristics of gas pass a cylinder pointed out that the rebound tendency of the particulate is suppress by the high reynolds's no of the gas flows . A research which gives us a well-built relationship of the coherent velocity fluctuations which is to be found from the extent of two point space point relationship. This results is very suitable when the value of the Reynolds no are taken to be higher and the systems which are more complex [lxiii].

TABLE I
TUBE NATURAL FREQUENCIES MACDUFF AND FEGLAR [lxiii]

Formula/Procedure	Conditions
$f_n = \left(\frac{1}{2\pi}\right)\frac{\lambda_n}{l^2}\left(\frac{EI}{m}\right)^{1/2}$ (Jones, 1970)	Straight beams /single span n is the mode number and λ_n is a frequency factor which depends upon the end conditions
$f_n = \frac{1}{2\pi}\lambda_n\left(\frac{1}{R\alpha}\right)\left(\frac{EI}{m}\right)^{1/2}$ (Archer, 1960)	Curved beams/ single span λ_n is a frequency factor R is the radius of curvature and α is the subtended angle
$f_n = 59.55\frac{C_u}{L^2}\left(\frac{EI}{M_e}\right)^{0.5}$ (TEMA Standards, 1978)	U-tube curved C_u is the first mode U-tube constant

Formula/Procedure	Conditions
Experimental/computer Program $f_n = \frac{(\beta_n L)^2}{2\pi L^2}\sqrt{\frac{EIg}{W}}$ (Lowery and Moretti, 1975)	Straight/multiple, free-free spans (1-5 span tests); idealized support conditions, $(\beta_n L)^2$ is eigen value
FEM in-plane and out of plane Experimental/analytical (Elliott and Pick, 1973)	Straight/curved
Beams immersed in liquids, air, kerosene, and oil (Jones, 1970)	Straight/simply supported/clamped
Out of plane: $f_n = 3.13\frac{\lambda_n}{R^2}\sqrt{\frac{C}{\gamma A}}$ $\lambda_n = \frac{n(n^2-1)}{\sqrt{1+kn^2}}$ (Ojalvo and Newmann,1964)	Clamped ring segments n is mode number; k is bending stiffness γ is specific weight; C is the torsional stiffness. A is cross-sectional area
Graphical in-plane and out of plane (Wambsganss et al., 1974)	Straight/curved, single span /multiple span
Analytical/experimental (Khushnood et al., 2000)	Straight tubes single/multiple spans with damped/ fixed boundaries, Experimentation on refinery research exchanger (in-service)
Plucking and transient decay (Simpson and Harlten, 1974)	Tubes were not fully straightened. Wind tunnel determination of fluid-elastic thresholds Tubes were found sensitive to temperature.

III CONCLUSIONS

1. Fluid-elastic instability is characterized as the feedback mechanism between fluid forced and the structural motion.
2. At Reynold's number of Re > 40 amplitudes of coefficient of lift begins to develop which generate vortex shedding in the tube.
3. When the tubes are fixed, stream in the region of the tubes is in ordinary pattern in a path around the tubes.
4. The value of Strouhal number changes as the pitch and tube diameter changes.
5. Hexagonal geometry frame has a smallest temperature of the wall as compared to other geometry arrangement.
6. Pressure drop across the heat exchanger decreases as we decrease the baffle plates cut.
7. Reduction in pressure drop is dependent on the geometry of cylinder, by using elliptical cylinder instead of circular cylinder there is a significant decrease in pressure drop.

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