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Flow and heat transfer behaviour across circular cylinder and tube banks with and without splitter plate

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Abstract: This paper describes the passive flow control of fluid in the downstream direction of the circular tube and in tube banks by means of splitter plate. Heat transfer and pressure drop depend on complex flow pattern of fluid in tube banks, whereas pressure drop linked directly with the fluid pumping capacity. A primary focus is to review experimental, analytical and numerical works that had been carried out to study the effect of longitudinal and transverse tube spacing, Reynolds number, stagnation point and surface roughness on wake size and vortex shedding.

Index Terms: Circular cylinder, Splitter plate, Tube banks, Cross flow, Heat transfer, Vortex shedding

I. INTRODUCTION

A heat exchanger is a device built for efficient heat transfer from one medium to another. The media may be separated by a solid wall, so that they never mix. Tube bank is the crossflow tubular heat exchanger and consists of multiple rows of tubes. One fluid passing through the tubes and other is passing across the tubes as shown in Figure 1. Tube banks arrangement include the in-line and the staggered arrangements. Cross flow tubular heat exchanger are found in diverse equipment as economizer, waste heat recovery, evaporator of an air conditioning system to name but few.

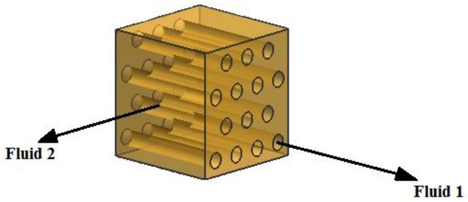

Figure 1.Cross Flow Tube Banks

Heat Exchanger involve several important design consideration which include thermal performance, pressure drops across the exchanger, fluid flow capacity, physical size and heat transfer requirement. Out of this following consideration, determination of pressure drop in a heat exchanger is essential for many applications because the fluid needs to be pumped through the heat exchanger. The fluid pumping power is proportional to the exchanger pressure drop. In tube banks, the heat transfer and pressure drop characteristic depend upon the flow pattern of fluid. The fluid flow converges as the minimum area occurs between the tubes in transverse row or in a diagonal row which makes the flow pattern very complex.

Passive control is one of the flow control techniques for reducing the aerodynamic drag exerted on a bluff body. It controls the vortex shedding by modifying the shape of the bluff body or by attaching additional devices in the flow stream. Passive control can achieve by use of splitter plate, small cylinder and base bleed method. Roshko (1954) was one of first investigator to study the influence of splitter plate on vortex shedding. Splitter plate is the longitudinal fins, built-in with the tubes as shown in Figure 2. Gerrard (1966) explained the flow mechanism across a circular cylinder. H. Akilli (2008) and E. A. Anderson (1997) also studied flow behaviour with splitter plate with different configuration. Flow across circular cylinder was explained by John H. Lienhard (23).

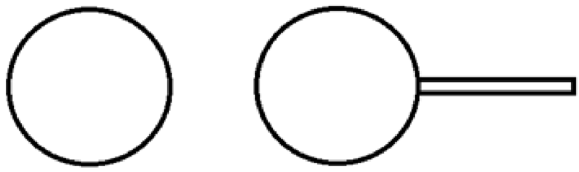

Figure 2. (a) Circular Cylinder (b) Circular Cylinder with Splitter Plate

II. EFFECT OF SPLITTER PLATE ON FLOW AND EAT TRANSFER BEHAVIOUR AROUND CIRCULAR CYLINDER

Roshko (1954) carried out an experimental investigation of circular cylinder by placing a splitter plate in the downstream direction of the wake at Re = 14,500. It was observed that flow pattern changes. When the length of splitter plate was 5D, the vortex shedding completely disappeared and pressure drag was significantly reduced. Moreover when the splitter plate was detached and move 3.85D downstream from the cylinder exhibits the shedding frequency become minimum and the base pressure was maximum. A splitter plate of length 1D did not inhibit formation of vortices but changed the shedding frequency slightly

Gerrard (1996) conducted experiments to studied the formation region behind circular cylinder at Re = $2x\ 10^4$. It was found that the Strouhal number decreased when the length of the splitter plate was smaller than d, but it increased for d<l<2d. Addition of splitter plate increased the production of circulation at the rear of the cylinder, as a result the vortex strength in the early stage of growth decreased. The effective formation-region length was the distance from the plate to the end of the region. It was found that when the vortex was growing close behind the plate, there was a large cross-flow velocity produced near the plate, assist the shedding process and increase the frequency.

J.Y. Hwang et al. (2003) numerically studied flow induced forces on a circular cylinder using detached splitter plate for laminar flow. A splitter plate with the same length as the cylinder diameter was placed horizontally in the wake region. Suppressing the vortex shedding, the plate significantly reduced drag force and lift fluctuation, there existed an optimal location of the plate for maximum reduction. However, they sharply increase as the plate was placed further downstream of the optimal location.

H. Akilli et al. (2008) investigated experimentally passive control of vortex shedding by splitter plates having L/D ratio (0.2 to 2.4) attached on the cylinder base in shallow water flow at Re = 6300. In this study, the length of the splitter plate was varied from in order to see the effect of the splitter plate length on the flow characteristics. Instantaneous and time-averaged flow data clearly indicated that the length of the splitter plate has a substantial effect on the flow characteristics. They found the flow characteristics in the wake region of the circular cylinder sharply changed up to the splitter plate length of L/D=1.0 and above this plate length, small changes occurred in the flow characteristics.

A. Fage et al. (1930) carried out experimental investigation to determine effect of turbulence and surface roughness on the drag of the circular cylinder. It was seen that as the surface was made rougher, the fall in drag coefficient occurred at a lower valve of Reynolds number and that this fall gradually dies away. There was an indication that if the roughening had been continued, a surface would eventually have been obtained for which there would be no fall in drag. From this, it may be concluded that increase in roughness further retards the flow in boundary layer over the cylinder and causes the stagnation point to shift further upstream. They also concluded the region $\theta = (+\ 37.5^o$ to $+100^o)$ was very sensitive to surface roughness, since it include those parts where the flow separates from the surface.

Schmidt et al. (1943) conducted experimental analysis over the circumference of a heating cylinder having different diameter (50, 100, 250) at Re= 5000-426000. They explained effect of surface projection on the heat transfer of circular cylinder. It was observed that starting from the stagnation point the heat transfer coefficient dropped to a distinct minimum close before angle 90^o forward stagnation point and then rises again, which increases to higher value as Reynolds number increases. Furthermore, they concluded that minimum pressure distribution lies before the minimum heat transfer coefficient.

P. A. R. Ribeiro et al. (2004) developed a numerical simulation for bluff-body vortex shedding suppression at Re = 100 and 160 using Finite Difference method. As attached plates perform great changes on the shedding frequency depending on the length, the use of splitter plate to control bluff-bodies' vortex shedding shows to be great efficiency.

E. A. Anderson et al. (1997) investigated 2 and 3-dimensional flow configuration of splitter plate effect on the circular cylinder wake. Result of flow visualization showed that shear layer characteristics such as circulation strength, ability to entrain fluid, and length had significant effect on the Karman shedding frequency at subcritical Reynolds number between 2700 to 4600. The variation in strouhal number over the range of l/d = 0 to 1.75 was divided into four distinct regions where within each region a different flow phenomenon dominated the selection process of the shedding frequency.

S. Tiwari et al. (2005) obtained a three dimensional model to study the heat transfer behaviour of a circular tube in cross-flow configuration with different length of wake splitter plate at Re = 500, 1000, 1500. The splitter plate of chord length 2H (height of the tube) causes the vortex to clear off the plate. As the chord length of the plate increases, vortices moves towards the plate and roll over the edge i.e. presence of splitter plates delayed the flow separation which decreased the total drag and therefore reduction in pumping power. In front of the tube, there was a sudden increase in Nusselt number. The reason for the abrupt increase in Nusselt number can be attributed to the formation of horseshoe vortices. The spiralling motion of the horseshoe vortices brings about better mixing and the heat transfer in this region was enhanced significantly. The Nusselt number was low in the wake region. The separated dead water zone where fluid recirculates with low velocity causes poor heat transfer. The splitter plate creates a streamlined extension of the circular tube, which also brings about enhancement of heat transfer. A reduction in the size of wake zone was observed. Narrowing of the wake zone reduces convective heat transfer from the tube surface but the splitter plate itself generates an extra fin area for conduction. One would expect the value of viscous drag coefficient to increase with increasing chord length of the splitter plate. However, the counter rotating vortices diminish the effect of viscous drag on the chord of the splitter plate i.e. total drag decreases.

S. E. Razavi et al. (2008) carried out numerical investigation of flow and heat transfer around circular cylinder in the range of 20 < Re < 1000 by finite volume method. It was concluded that splitter plate streamlined the flow around the cylinder and accordingly decreased the pressure drag causing the significant reduction in overall drag. The heat transfer decreased from the cylinder surface, while placing the splitter plate increased the total heat transfer.

III. EFFECT OF SPLITTER PLATE ON FLOW AND HEAT TRANSFER BEHAVIOUR AROUND SQUARE CYLINDER

Said Turki (2008) conducted a numerical study to examine a passive control of flow by introducing a splitter plate behind a square cylinder inside a horizontal channel. At 110<Re<200 and for affixed blockage ratio β= h/H=1/4. The effect of splitter plate length and its location in the wake region on the Strouhal number and the drag and lift coefficient were analyzed. It was found that critical length of the splitter plate, characterizing the suppression of the vortex shedding, increases as the Reynolds number increase and it can be correlated by the linear relationship: Lc = 0.0366R – 3.3184. For L<Lc, the

splitter plate significances reduces the lift and the drag fluctuation.

Woe-Chul Park et al. (1997) numerically investigated of wake flow control by a splitter plate attached to the base of square cylinder. It was found that the splitter plate blocks the roll-up of the separated shear layer close to the base of the body, and lowers the velocity near the base, the drag of the body and the vortex shedding frequency. Interaction of separated shear layer was delayed until the end of the plate. Because of this, shorter splitter plate was more sensitive to wake flow forming low velocity region behind the cylinder. Both the drag and Strouhal number were significantly reduced by suppressing the vortex shedding in the wake.

IV. FLOW INDUCED VIBRATION MITIGATION USING ATTACHED SPLITTER PLATE

B. Stappenbelt (2010) conducted experimental investigation of vortex–induced vibration response of an elastically mounted rigid cylinder with a range of splitter plate ratio (l/d= 0 to 4) under reduced velocity interval of U_r = 3 to 60. For splitter plate ratios of l/D = 2.8 to 4, no significant vortex-induced and galloping type vibration were observed. It was only this region that vibration mitigation was realized.

Ibrahim Ayoub et al. (2008) also studied effect of splitter plate on vortex–induced vibration with splitter plate of length 3 to 3 diameters under the reduced velocity ranging from 0 to 0.35 and Reynolds number of range $1.0 \times 10^4 < Re < 7.5 \times 10^4$. Experimental results contradict some existing data, the amplitude of response increases dramatically with attached splitter plate. It was observed that amplitude of cylinder with splitter plate of length 0.5 to 1 diameters are up to 4 times larger than bare cylinders.

V. HEAT TRANSFER FROM TUBE BANKS

W.A. Khan et al. (2006) studied heat transfer from tube banks using analytical approach. It was concluded that the average heat transfer coefficients for tube banks depend on the longitudinal, transverse pitches, Reynolds number and Prandtl number. Compact banks (in-line or staggered) indicate higher heat transfer rates than widely spaced ones and the staggered arrangement gives higher heat transfer rates than the in-line arrangement. This was also supported by the further work of W. A. Khan (2007), where an optimal model of tube banks heat exchanger was developed using entropy generation minimization method. It was also demonstrated that the staggered arrangement gives a better performance for lower approach velocities and longer tubes, whereas the inline arrangement performs better for higher approach velocities and larger dimensionless pitch ratios.

S. Aiba et al. (1982) carried out an experimentally studied the heat transfer around tubes in-line tube banks. Measurements were conducted for seven cylinder spacing in the Reynolds number range from 10^4 to 6×10^4. The mean Nusselt number of the first cylinder varies considerably with the cylinder spacing but Nusselt no. did not show any essential variation with the cylinder spacing for second and farther downstream cylinder.

S. Aiba et al. (1982) also conducted experiments to investigate the heat transfer and flow around tubes in staggered tube banks in cross flow. The cylinder spacing examined $C_y/d \times C_x/d$ was 1.6x1.6 and 1.2x1.2 in the Re. no. range of 8600 to 3600 where C_x and C_y cylinder spacing along and normal to the upstream uniform flow direction and d was the cylinder diameter. In case of 1.6x1.6 the heat transfer rate for the third cylinder was the maximum. This may due to high velocity of the flow on coming to the third cylinder along with its turbulence intensity. In case of 1.2x1.2 the heat transfer rate of the first cylinder was extremely low. A very large velocity of the flow oncoming to the second cylinder produce a high heat transfer rate as compared to that in case of 1.6x1.6. Heat transfer rate was almost equal for both the cases of 1.2x1.2 and 1.6x1.6 at the same Reynolds number

E. Buyruk (1999) carried out an experimental study to investigate heat transfer and flow characteristics from one tube within a staggered tube bundle and within a row of similar tubes. The tube spacing examined S_t and S_l were 1.5 x 1.5 and 1.5 x 1.25 where S_t and S_l denote the transverse and longitudinal pitches respectively at Reynolds number 4.8×10^4. The influence of the blockage of a single tube in a duct and transverse pitch for a single tube row with Reynolds number range of 7960 to 47770 also investigated. Experimentations were carried out by varying blockage ratio from 0.131 to 0.843. It had been shown that the general shape of local Nusselt number distribution around the cylinder varies only slightly with blockage for blockage ratio was less than 0.5. When the blockage ratio was greater than 0.395, increasing blockage causes the minimum pressure and minimum Nusselt number to move to the downstream side of the cylinder. For the blockage ratio in the range of 0.668-0.843, there was a distinct change in the flow compared with the lower blockage cases. Local Nusselt number and static pressure are remarkably different. Due to the great acceleration of the flow minimum local static pressure values reached very low values. Changes in both longitudinal and transverse pitch were observed to have a noticeable influence on the velocity distribution around the tubes in a bank. For the staggered tube bundle geometry, the mean Nusselt number of the inner tubes becomes higher by increasing the transverse pitch and decreasing longitudinal pitch ratios.

E. Buyruk (2002) Heat transfer characteristic on tandem cylinder with (L/D = 1.13, 2, 3, 6) were also investigated at constant Re = 400. Laminar boundary layer region heat transfer of first cylinder was not affected by decreasing gap between the cylinders. Smaller gap between the cylinder results lower heat transfer rate on the downstream side of the first cylinder and upstream side of second cylinder. Such as when ratio L/D changed from to 3 to 1.13 then, impact point location changes from about 55^o to 70^o which decreases the rate heat transfer. Effect of Reynolds number (80,120,200) was investigated for inline and staggered tube banks with transverse and longitudinal pitch of 2 x 2. For the first cylinder it was seen that increase Reynolds number causes the heat transfer rates to increase and separation point moves upstream side of the cylinder. Heat transfer rate for second cylinder was relatively low comparing with the first cylinder, as second cylinder located in the wake of first cylinder that will block the direct effect of flow on the second cylinder. Increase in Reynolds number causes the impact point to move upstream of the second cylinder for inline arrangement. For staggered arrangement, local heat transfer coefficient of second cylinder front region was higher than the first cylinder front region due to effect of flow acceleration. Such as front stagnation value for second cylinder was nearly 60% higher comparing the Re=80case with Re=200 case.

S. Jayavel et al. (2008) numerically studied the heat transfer and pressure drop for flow past inline and staggered tube bundles. Three-dimensional computational codes were developed and apply to compare flow and heat transfer characteristics for inline and staggered arrangement of circular tubes in a tube bundle. A finite volume-based numerical investigation was carried out to study the flow and heat transfer for flow past inline and staggered arrangement of tube bundles confined in a rectangular channel. The investigation identify the range of Reynolds number in which staggered arrangement of tubes in a tube bundle provide more heat transfer causing less pressure drop compared with inline arrangement of tubes. However, at lower Reynolds numbers inline arrangement of tubes are found to be preferable due to heat transfer and smaller pressure drop.

Seong-Teon Yoo et al. (2007) experimentally investigated heat transfer characteristics for staggered tube banks in cross-flow using naphthalene sublimation technique. It was concluded that the variation of the local heat transfer coefficients was quite different from the first tube to the third tube, but they are similar afterwards. The average Nusselt number increases more than 30% and 65% on the second and third tubes, respectively, in comparison with that of the first tube. The local heat transfer coefficients on each tube increase except on the front part of first tube as the tube spacing decreases. Due to strong vortices the local heat transfer near the rear stagnation point of the first tube increases drastically with decreasing tube spacing. Consequently, the average Nusselt number on the first tube for the tube spacing of 1.75 and 1.5 was higher by about 25% and 45%, respectively than that for the tube spacing of 2.0. In the first and third tubes, dependence of average Nusselt number on Reynolds number was almost same regardless of the tube spacing.

VI. HEAT TRANSFER FROM TUBE BANKS WITH SPLITTER PLATE

Suzairin Md. Seri et al. (2011) carried out an experimental studies in the Reynolds number range 5 x 10^5 to 10^5 on a single cylinder with splitter plate laving length-to-tube diameter ratios (L/D = 0.5, 1.0, 1.5 and 2.0). Tube banks consisting of 12 rows and 3 tubes per row in equilateral triangle arrangements with transverse pitch to diameter ratio (a = 2), and longitudinal pitch to diameter ratio (b = 1.73). It was concluded that the local Nusselt numbers on the rear of a single tube are depressed when a splitter was attached to the tube. The reduction being greatest at rear stagnation but the Nusselt numbers rise steadily from base of the splitter plate towards the tip. In the first row of tube banks, heat transfer behaviour was similar to that of the single tube. The fin tip Nusselt numbers, at the middle to high range of the investigated Reynolds numbers, are higher than the forward stagnation point values. For all tube banks, Nusselt number at the rear stagnation point of any row was highest at the second row due to the greatest intensity of turbulence at this location. Heat transfer characteristics were studied for tubes with different L/D ratios under constant heat flux conditions. Tube banks with L/D = 1.0 yielded the highest heat transfer rates.

VII. CONCLUSION

This paper describes the influence of splitter plate on flow behaviour and heat transfer characteristic across cylinder and in tube banks. Vortex shedding and pressure drop mostly depends on Reynolds number and tube spacing. Addition splitter plate on a single cylinder can be attributed to the attenuation of vortex shedding in the wake and also reduced pressure drag significantly. Increase in total heat transfer can be also observed as a result of extra surface area generated by the splitter plate.

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