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The Effect of Angle of Attack on Pressure Drag from a Cam Shaped Tube

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***Abstract*—**The pressure drag from a cam shaped tube in cross flows have been investigated experimentally using pressure distribution measurement. The range of angle of attack and Reynolds number based on an equivalent circular tube are within $0 \le \alpha \le 360°$ and $2\times10^4 < Re_{eq} < 3.4\times10^4$, respectively.

It is found that the pressure drag coefficient is at its highest at $\alpha=90°$ and 270° over the whole range of Reynolds number. Results show that the pressure drag coefficient of the cam shaped tube is lower than that of circular tube with the same surface area for more of the angles of attack. Furthermore, effects of the diameter ratio and finite length of the cam shaped tube upon the pressure drag coefficient are discussed.

***Keywords*—**Pressure Drag, Cam Shaped, Experimental.

I. Introduction

THE optimization of industrial processes for maximum utilization of the available energy has been a very active line of scientific research in recent times. Many industrial applications require the use of heat exchangers with tubes shape, circular or non-circular [1]-[8]. Major objectives in the design of these heat exchangers could be reduction of pressure drop and fouling.

Ota et al. [1] investigated experimentally the thermal performance of a single elliptical cylinder with an axis ratio (major axis to minor axis) of 2 in a flow of air having Reynolds numbers of 5000 to 90000 with angles of attack from 0 to 90° where the Reynolds number is based on the major axis. For air flow parallel to the major axis, they found that the Nusselt number for the elliptical cylinder was higher than that obtained for a circular cylinder from an empirical correlation. For more than one tube or for a bank of tubes, Merker and Hanke [2] found experimentally the heat transfer and pressure drop performance of staggered oval tube banks with different transversal and longitudinal spacings. The oval tube axis ratio was 3.97. They showed that an exchanger with oval-shaped tubes had smaller frontal areas on the shell-side compared to those with circular tubes. Ota and Nishiyama [3] investigated experimentally the flow around two elliptical cylinders with axis ratio of 3 which were in a tandem arrangement. The static pressure distribution on the surface was measured and the drag, lift, and moment coefficients were evaluated for a range of angles of attack and cylinder spacings.

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Heat transfer and pressure drop from an airfoil in cross flow was reported by Prasad et al. [4]. Their aerofoil test section was the NACA-0024 and they concluded that this shape gives lower values of C_f /St compared to the circular tube.

Badr [5] reported the forced convection heat transfer from a straight isothermal tube of elliptic cross-section placed in a uniform air stream. In this study, the Reynolds number range was $20<Re<500$ and angles of inclination was $0°<\alpha<90°$. The tube axis ratio varies between 0.4 and 0.9. His results also show that the rate of heat transfer reaches its maximum value at $\alpha=0°$ while the minimum occurs at $\alpha=90°$.

For evaporatively cooled heat exchangers, Hasan and Sirén [6] showed that a bank of wet oval tubes has a better combined thermal-hydraulic performance than corresponding circular tubes.

Matos et al. [7] studied the numerical and experimental heat transfer rate between staggered arrangements of circular and elliptic of finned tubes bundle and external flow. They have reported that the optimal elliptic arrangement exhibits a heat transfer gain of up to 19% compared to the optimal circular tube arrangement. The results illustrate that the heat transfer gain and the relative total mass reduction of up to 32% show that the elliptical arrangement has the potential to deliver considerably higher global performance and lower cost.

Bouris et al. [8] proposed tube cross-section was a parabolic upstream shape and a semi-circular one downstream. They carried out experiments and numerical simulations on the novel tube bundle heat exchanger for studying the thermal, hydraulic and fouling characteristics. Their results indicate that they attain higher heat transfer levels with a 75% lower deposition rate and 40% lower pressure drop.

In the previous studies, a non circular tube with cross-section similar to a cam was used in a heat exchanger for reducing of pressure and fouling [1]-[8].Therefore, the pressure distribution around a cam shaped tube at different angles of attack is important. In this study, the pressure distribution around this tube at $0 \le \alpha \le 360°$ has been investigated experimentally.

II. Experimental Apparatus

Test section includes a single cam-shaped cylinder located at a distance of 10 cm in front of an open wind tunnel outlet with diameter 24 cm, (Fig. 1). The test cylinder is mounted horizontally perpendicular to the flow direction. The cross section profile of the tube comprised some parts of two circles with two line segments tangent to them. It is made of a commercial copper plate with 0.3 mm thickness and a length of 12 cm. Three test cylinders were applied to investigate the effect of cylinder dimensions on flow characteristics. These three tubes have identical diameters equal to d=1.2 cm and D=2.2 cm but, with three different distances between their centers, l=1.1, 2.9 and 6.6 cm, (Fig. 2).

The surface of each tube was covered with 20 holes (1 mm in diameter) drilled to measure the static pressure on the tube surface by a dial manometer.

A pitot static tube is used to measure the free stream velocity in front of the frame cross section. The air velocity varied from 12 to 22 m/s by controlling a variable speed motor.

The angle of attack was varied from $0 \leq \alpha \leq 360°$ in order to clarify variations of the flow characteristics of the tube . In the present paper, α is angle between the major axis of the cam shape tube and the direction of the upstream uniform flow. The angle of attack has positive values on clock wise rotation.

III. Experimental Technique

To estimate the pressure drag of the cam shaped tube compared to that of a circular tube with various cross sections, it is important to select an appropriate reference length. D_{eq} is the diameter of an equivalent circular tube whose circumferential length is equal to that of the cam-shaped tube. Based on Fig. 2, the equivalent diameter is obtained by $D_{eq}=P/p$ where P is perimeter of cam shape tube. The L/D_{eq} ratios for three tubes are 4.85, 3.36 and 2.03 respectively. This ratio has not effects on drag coefficient for $L/D_{eq}=\infty$ so the effect of this ratio on this coefficient for first, second and third tube is 38.3%, 39.7% and 43.3%, respectively [9]. In the present paper, however no corrections were made for L/D_{eq} effects.

The pressure drag coefficient C_D is determined experimentally from pressure distribution over the cam shaped-tube surface, including the large and small circles as well as two tangent lines between them as follows.

$$C_D = \frac{1}{D_{eq}} \oint C_p \cos\psi \, ds = \frac{1}{D_{eq}} \left\{ \sum_{i=1}^{20} C_{p,i} \, Cos\psi_i \Delta S_i \right\} \quad (1)$$

The pressure distribution on the cam shaped is expressed in dimensionless form by the pressure coefficient, $C_{p,i}$.

$$C_{p,i} = \frac{P_i - P_\infty}{0.5 \rho U_\infty{}^2} \quad (2)$$

Where P_i is the static pressure measured by a manometer at the location of the holes drilled on the tube surface. P_∞ and U_∞ are the pressure and velocity of the air free stream respectively and ρ is air density.

As shown in Fig.2 ψ is different for each of the holes. This angle denotes the angle between the normal vector on the tube surface and free stream. The angle ψ is changed with variation of angle of attack. S denotes the surface distance from leading edge of the cylinder and ΔS_i represents a length on the tube perimeter belong to each hole. The pressure drag coefficient uncertainties are about 10.4 to 12.8 percent for $0 \leq \alpha \leq 360°$

IV. Results and Discussion

A single circular tube with diameter of 2.47 cm and length of 12.5 cm is tested before testing the cam shaped-tube, to verify the data-taking process and to check the related equipment setup. Fig.3 compares the present results with the results of White [10]. The difference between the present results and that of curve-fit formula by White is about 1-2 percent. It can, therefore, be concluded that the set up can be used for measuring pressure drag from a cam shaped tube.

Figs. 4(a)–4(c) depicts the effect of l/D_{eq} on pressure coefficient against S/D_{eq} on the upper and lower parts of the cam-shaped tube surface for three different values of l/D_{eq} =0.4, 0.8 and 1.1 and α=0°, 120° and 270° degree. The positive and negative values on the abscissa indicate the measured distance along the upper and lower parts of the cylinder surface, respectively. The free stream velocity is the same for three angles and is equal to U_∞=15 m/s. In Fig. 4(a), the trend of curves is similar for three values of l/D_{eq}=0.4, 0.8 and 1.1 and discrepancy among them is limited in the range of $-0.5<S/D_{eq}<0.5$. This treatment will intensively continue in Figs. 4(b) and 4(c) for α=120° and 270°, respectively. For α=0° at l/D_{eq}=0.4, the flow separates at about $S/D_{eq}=\pm0.75$and the pressure inside the separated flow region is constant. At l/D_{eq} =0.8 and 1.1 these points are at about $S/D_{eq}=\pm$ 0.85 and $\pm$ 0.5 and reattach onto the surface at about S/D_{eq}=1.3 and 0.8, respectively and subsequently at turbulent boundary layer develops downstream. Such a feature of pressure distribution around the surface causes to decrease the drag. The results show that the trend of the pressure coefficient is nearly similar to the one produced by the perfect fluid theory around a circular tube. While the angle of attack increases from α=0° to 120° degree, the maximum pressure coefficient shifts towards the negative values of the abscissa, (Fig.4(b)). In other words, the lower part becomes more effective near the leading edge in comparison to the upper part. This is probably due to wake formation on the upper region. By increasing more the angle of attack from α=120° to 270° degree, in this case, the maximum pressure coefficient shifts towards the positive values of the abscissa, (Fig.4(c)).

Fig. 5 exhibits variation of average pressure drag coefficient of cam-shaped tube against α for l/D_{eq}=0.5 in the range of $2\times10^4< Re_{eq}<3.3\times10^4$. The shape of all curves is almost the same and repeated every other 150º degree so that the overall relation between variables can be expressed by the least squares curve fitting method as:

$$C_D = A + B \sin(C\alpha) \quad (3)$$

Where A, B and C are constants and their values are about 0.76, -0.42 and 2.4 respectively. In this figure the average drag coefficient of the cam-shaped with l/D_{eq}=0.4 and circular cylinder [9] with same circumference length of cam shaped have been compared. It is clear that in some ranges of the angles of attack C_D for cam-shaped cylinder is higher than that of the circular cylinder. The maximum and minimum values of the average drag coefficient are about C_D=0.9 and C_D=0.4 respectively and their occurrence are at different

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angles. The reason could be explained by external flow configuration which involves the cam-shaped cylinder in cross flow where the cylinder is under the angles of α=30º, 90º, 180º, 270º and 330º.

Now, for example, consider the fluid mechanics of the situation at α=180º in cross flow. Under $2\times10^4 < Re_{eq} < 3.3\times10^4$, the laminar boundary layer is formed over the most part of the tube surface and separation is delayed thereby, reducing the extent of wake region and the magnitude of the form drag. In other words, the pressure differential in the flow direction resulting from formation of the wake is low compared to the boundary layer surface shear stress (friction drag) and causes a low pressure drag coefficient.

Fig. 6 shows the effect of slenderness of the cam-shaped tube on the pressure drag coefficient against the angles of attack. It appears that the discrepancy between the drag coefficient of the cam-shaped tube with an equivalent circular tube increases monotonically as l/D_{eq} increases. The drag coefficient has minimum value of C_D=0.1 for l/D_{eq}=1.1 and it occurs at α=0º or 180º degree.

There are end effects that might influence the flow characteristic over the tube. Fig. 7 shows the effect of L/D_{eq} on the pressure drag coefficient for different attack angles. It appears that when L/D_{eq} increases the pressure drag coefficient approaches a constant value. There is a minimum value for L/D_{eq} where beyond that the influence of the end effects can be neglected. This value is about $L/D_{eq}>5$. Solid line in the figure shows the variation of C_D for a circular tube with L/D_{eq}, where its circumference length is the same as the cam shaped tubes perimeter. As it is shown this coefficient is not changed after $L/D_{eq.}>4.5$.

V. Conclusion

Pressure distribution has been carried out on a cam shaped tube in cross flow. The angle of attack is varied 0º<α<360° over the $2\times10^4 < Re_{eq} < 3.4\times10^4$.

The experiments aimed to ascertain the effects of the angle of attack and l/D_{eq} over pressure drag. These Results show that pressure drag for a cam shaped tube is maximum at about α=90° and 270°.

In order to compare the available pressure drag values of cam shaped and circular cross-sections with same circumferential length, a Reynolds number based on the equivalent tube diameter has been defined. These comparisons have shown that cam shaped tubes give lower values of C_D than the circular cross-section for more of the angles of attack. Effects of the l/D_{eq} for a cam shaped tube with same d/D upon its C_D are also investigated. These results show that for tube with large l/D_{eq} this coefficient is minimum at α=0 and 180° and is maximum at α=90° and 270°.

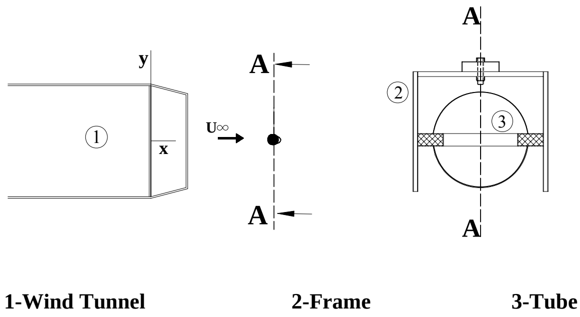


Fig. 1 Schematic diagram of experimental apparatus flow

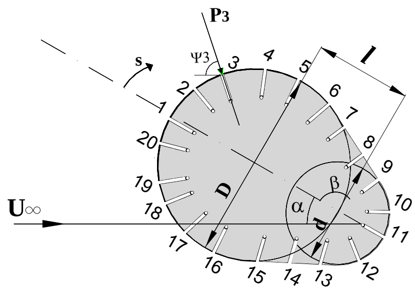


Fig. 2 Schematic diagram of a cam shaped tube

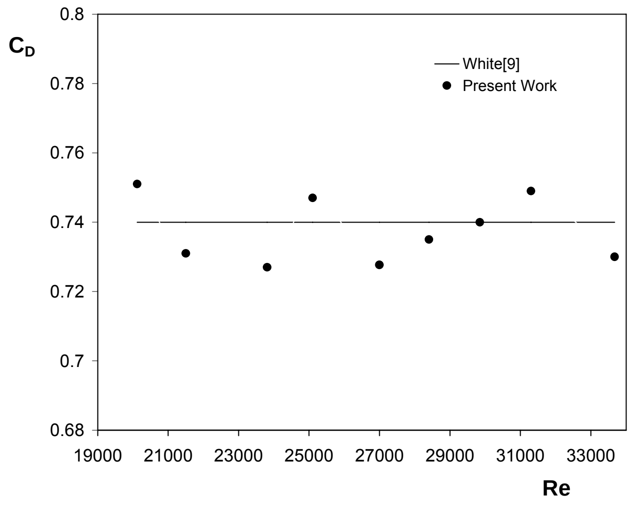
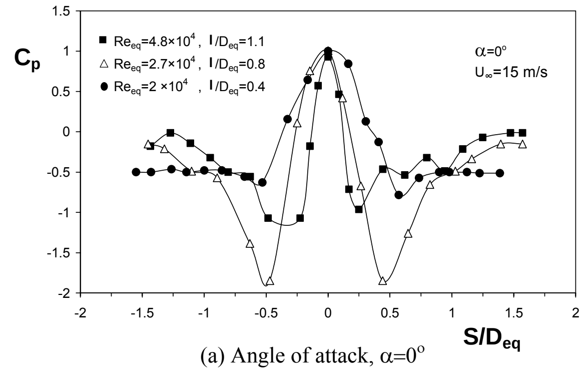
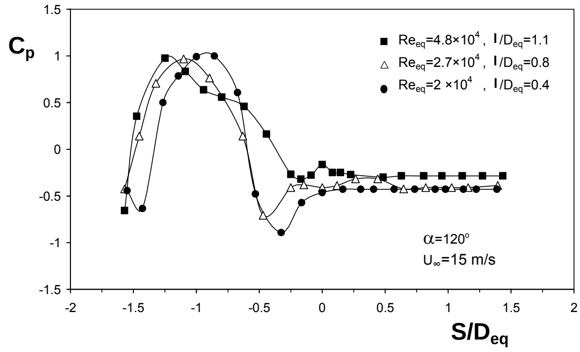


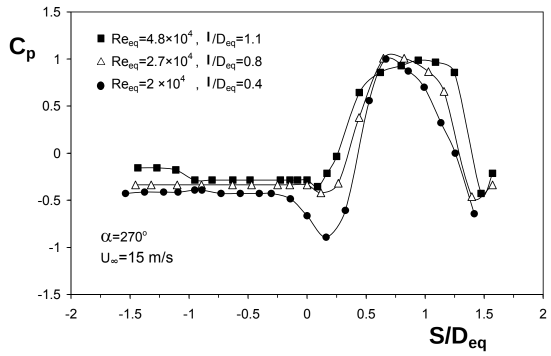
Fig. 3 Drag coefficient of a circular tube in cross flow



(a) Angle of attack, α=0°



(b) Angle of attack, α=120°



(c) Angle of attack, α=270°

Fig. 4 Pressure coefficient for three different l/D_{eq} and Reynolds number

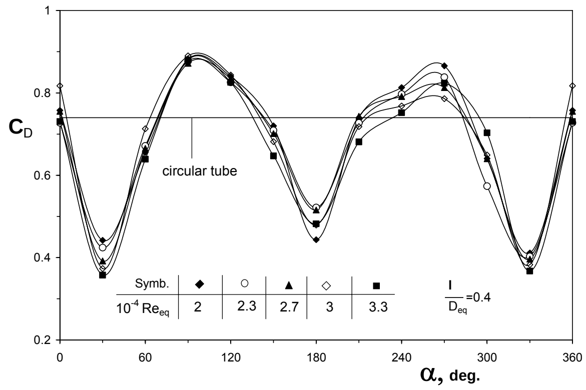


Fig. 5 Pressure drag coefficient of a cam-shaped and circular tubes versus angle of attack

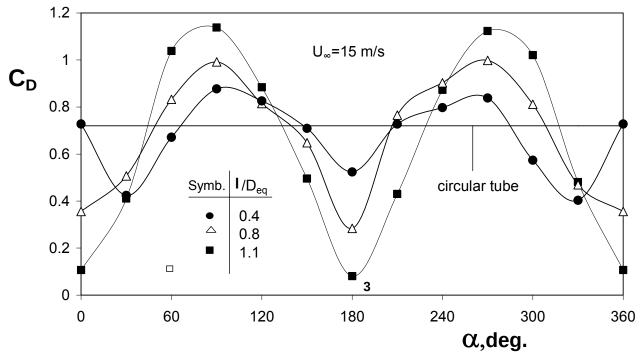


Fig. 6 Length to diameter ratio effects on the pressure drag coefficient of a cam-shaped tube

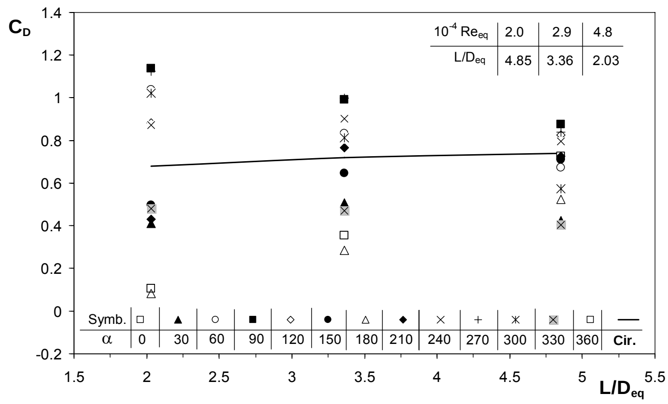


Fig. 7. Effect of L/Deq on drag coefficient for different angle of attack

NOMENCLATURE

A,B, C constant
C_D pressure drag coefficient
C_p static pressure coefficient
d small diameter
D large diameter
L cylinder length
l distance between centers
P pressure, circumferential length
Re Reynolds number, $U_\infty D/\nu$
S streamline coordinate
T temperature
U velocity

(i) Greek
α attack angle
β angle
Δ difference
ρ density
ν kinematic viscosity
ψ hole angle

(ii) Subscripts
cam cam-shaped cylinder
cir circular cylinder
eq equivalent
i hole number
∞ free stream

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