FORCED CONVECTION HEAT TRANSFER FROM THREE DIMENSIONAL BODIES IN CROSS-FLOW

M. A. Abd-Rabbo*, N. S. Berbish, M. A. Mohammad* and M. M. Mandour***.**

* Mechanical Engineering Department, Faculty of Engineering, Al-Azhar University.
** Mechanical Engineering Department, Faculty of Engineering Shoubra, Benha University.
*** Research Student.

ABSTRACT

In the present work, the heat transfer characteristics around a single horizontal heated cylinders with different cross-sections (circular, square, rectangular, diamond and elliptical) in cross flow were studied experimentally. Experiments were carried out under uniform heat flux condition, with air as a working fluid. The tested cylinders had approximately the same total surface area of $A_s \approx 0.015\ m^2$ and a length of 200 mm. The Reynolds number based on the upstream mean velocity and the equivalent hydraulic diameter, D_h, was ranged from 2200 to 22000. The results showed that, the average Nusselt number of the tested cylinders was increased with increasing Reynolds number. Highest Nusselt number was obtained for elliptic cylinder. Also, it was observed that the average Nusselt number of circular cylinder was the lowest value when compared with those for the other tested cylinders. Moreover, the present results were found to be in good agreement with the previously published experimental results.
Finally, empirical correlations for the average Nusselt number of the tested cylinders were obtained as a function of Reynolds number.

KEYWORDS: Heat transfer, Forced convection, Circular cylinder, Non-circular cylinders, Local and average Nusselt numbers, Cross-flow.

1. INTRODUCTION

Forced convection heat transfer from 3-D bodies like cylinders, spheres, cubes ….etc is very important in a number of industrial fields. In our present study, we will focus on the cylinders because they are the most widely used in the modern heat transfer applications such as heat exchangers, air coolers and heaters, forced air or water condensers, evaporators and the rating of the electrical conductors. Most of available researches had a major focus of heat transfer applications involving external flows around various bodies situated in cross-flow. These bodies may include cylinders of circular or non-circular cross-section, spheres, or plates. A great deal of effort has been conducted experimentally and theoretically around circular cylinder. On the other hand, for non-circular cylinders, relatively little modern information exists. For example, in virtually heat transfer textbook [1–2], there is a table of results for a group of non-circular.

Numerous studies have attempted to correlate the average heat transfer by forced convection from a circular cylinder in cross-flow. Morgan, [3] recognized many of notes affected heat transfer characteristics especially the blockage of the wind tunnel, turbulence intensity, and thermal properties. Churchill and Bernstein, [4] developed a correlation for forced convection heat transfer from circular cylinders for infinite circular cylinder. i.e. L»D. They concluded many reasons for the limitations of experimental work in this field. The most important limitations are: the use of different and undefined thermal boundary conditions, significant variation in physical properties between the surface and free stream around the surface and the influence of natural convection at very low Re. Zukauskas and Ziugzda, [5] published a study on heat transfer from a circular cylinder in air, water and oil. The effect of Re and Pr on both local and average heat transfer were reported. Ahmed and Yovanovich, [6] studied experimentally the forced convection heat transfer from different body shapes in range of $10^4 \le Re \le 10^5$ and Pr = 0.71. They developed an empirical correlation valid for wide Re range of $0 \le Re \le 10^5$ and the factor of turbulence intensity, Tu. Afify and Berbish, [7] studied experimentally the flow and heat transfer characteristics around a circular cylinder in three and four staggered cylinders in a cross-flow. Also, a single cylinder in cross-flow was studied in a range of Reynolds number of $0.5 \times 10^4 \le Re \le 5.0 \times 10^4$. Sparrow et al, [8] collected correlations for average forced convection heat transfer from all standard textbooks. These correlations included (circular cylinder, non-circular cylinders, plates and sphere) in cross-flow.

On the other hand, all of the available information for non-circular cylinders is in the form of a power-law relationship between the Nusselt and Reynolds numbers. The various cross-sections of the non-circular cylinders include the square, diamond, rectangle and ellipse.

For square cylinder, a few previous studies investigated experimentally forced convection heat transfer from it. The previous experimental correlations of the square cylinder with respect to the free stream flow are illustrated in Table (1).

Reiher, [9] and Hilpert, [10] examined heat transfer forced convection from square cylinder experimentally in different orientations using opposing flow and assisting flow. Igarashi [11] also examined this problem experimentally. He used three cylinders of L/W = 10, 7.5, 5 and L = 0.15 m, and the turbulence level in the working section was 0.5% within a range of Reynolds number of $5.6 \times 10^3 \le Re_w \le 5.6 \times 10^4$. Zukauskas and Ulinskas, [12] investigated an empirical correlation for the average Nusselt number for forced convection heat transfer from square cylinder in cross flow as a function of Reynolds and Prandtle numbers within a range of Reynolds number of $5 \times 10^3 \le Re \le 10^5$. Oosthuizen and Bishop, [13] investigated experimentally and numerically mixed convection from square cylinders using opposing flow and assisting flow. They examined this problem using the heat transfer transient technique. Ahmed and Yovanovich, [6] studied experimentally forced convection heat transfer from square cylinder with L/W = 9.12 and W = 0.017 m within the range of Reynolds number $1 \leq Re \leq 10^5$ and the factor of turbulence intensity, Tu, considered. More recently, Breuer et al, [14] investigated numerically the low Reynolds number flow past a square cylinder placed in a channel with a parabolic inlet profile. They contrasted the predictions of two numerical schemes, namely, the lattice-Boltzmann and the finite volume method.

Table (1): Empirical correlations of average Nusselt number for square cylinders in cross flow for Pr = 0.71, $Nu_w = C\, Re_w^n$.

Author	C	n	Re_w
Reiher, [9]	0.149	0.691	1960-6000
Hilpert, [10]	0.085	0.675	3900-78500
Igarashi, [11]	0.14	0.66	5600-56000
Oosthuizen and Bishop, [13]	0.281	0.57	300-5000

The diamond configuration is, in truth, the square cylinder rotated by 45^o so that one of the corners thrusts forward. The most of available information for the average Nusselt number for the diamond cylinder in cross-flow has been brought together in Table (2).

Table (2) Forced convection Nusselt Number for diamond cylinders in cross flow for Pr = 0.71, $Nu_w = C\, Re_w^n$.

Author	C	n	Re_w
Reiher, [9]	0.238	0.624	1960-6000
Hilpert, [10]	0.201	0.588	3900-78500
Igarashi, [11]	0.27	0.59	5600-56000
Oosthuizen & Bishop, [13]	0.414	0.537	300-5000

The literature on forced convection heat transfer from rectangular cylinders in cross-flow showed a little number of experimental investigations. Igarashi, [15] studied fluid flow and heat transfer around rectangular cylinders, of aspect ratios ranged from 0.33 to 1.5 within Reynolds number range of $7.5 \times 10^3 \leq Re \leq 3.75 \times 10^4$. The data presented in terms of Nusselt–Reynolds power-law representations.

The increasing interest in developing compact and highly efficient heat exchangers has motivated researchers to study flow and heat transfer from tubes of non-circular cross-sections. Special attention was focused on tubes of elliptical cross-section, not only to increase heat transfer rates but also to reduce the pressure drop across the heat exchanger. Heat transfer from elliptical cylinders in cross-flow has been examined by many investigators. Ota et al, [16] studied experimentally the heat transfer and flow around an elliptical cylinder of axis ratios 1/2 and 1/3, the angle of attack varied from 0^o to 90^o for Reynolds number range of $2.5 \times 10^3 \leq Re \leq 4.5 \times 10^4$. Their results show that, the maximum values of heat transfer coefficients were at angle of attack from 60^o to 90^o over the whole Reynolds number range studied. The heat-transfer coefficient of an elliptical cylinder is higher than that of a circular one with equal circumference. Kondjoyan and Daudin, [17] investigated experimentally the effect of free stream turbulence intensity on heat and mass transfer at the surface of a circular cylinder and an elliptic cylinder of axis ratio 1/4. They found that the effect of turbulence intensity appeared to be as important as the influence of velocity and seemed to be independent of the pressure gradient and of the degree of turbulence isotropy. Khan et al, [18] employed an integral method of boundary-layer analysis to derive closed-form expressions for the calculation of total drag and average heat transfer for flow across an elliptical cylinder under isothermal and isoflux thermal boundary conditions. Three general correlations, one for drag coefficient and two for heat transfer, had been determined. Abdel Aziz et al, [19] conducted an experimental investigation about the heat transfer characteristics and flow behavior around single and two elliptic cylinders with axis ratio of (1/2), zero angle of attack and at a range of Reynolds number $3.5 \times 10^3 \leq Re \leq 4.5 \times 10^4$. Berbish, [20] carried out an experimental and numerical studies to investigate forced convection heat transfer and flow features around the downstream elliptic cylinder in four staggered cylinders in cross-flow. It is found that the average Nusselt number for the single elliptic cylinder is higher than that for the circular cylinder. Also, the average Nusselt number of the downstream cylinder in four staggered arrangement is higher than that of the single elliptic cylinder.

The present work aims to study the heat transfer characteristics around a single horizontal heated cylinder with different cross-sections (circular, square, diamond, rectangular and elliptic). The experiments are carried out in an open circuit, specially built and designed for the present research work. The examined cylinders have the same surface area, $A_s \approx 0.015$ m^2 and a length of 0.2 m with zero angle of attack to the upstream uniform flow within a range of Reynolds number of $2.2 \times 10^3 \leq Re \leq 2.2 \times 10^4$. Also, the rectangular and the elliptic cylinders examined have an axis ratio of 1:2.

2. EXPERIMENTAL SETUP, INSTRUMENTATIONS AND PROCEDURES

The experimental setup employed in the present investigation is an open-loop air flow circuit as shown schematically in fig. (1). It is designed to give air flow across a heated horizontal cylinder. It mainly consists of a centrifugal blower, air passage, test section, and measuring instruments. A centrifugal type air blower is driven by an alternating electric current motor of 3.0 hp capacity, is used to supply the required air flow, which is controlled by air-gate valve. The air blower delivery section is a circular tube of 72 mm diameter and the intake is a circular section of 160 mm diameter. The air gate valve is an aluminium disk and is fixed on a rotating shaft at the delivery side of the blower. Various values of Reynolds number based on hydraulic diameter of the tested cylinder are utilized in the experiments which ranged from 2200 to 22000. Air passes through a circular/square transition duct of 430 mm length with a square section of (200 * 200 mm). After which air flows through upstream duct and then flows through straightener (honey comb) of a size (200*200*200 mm) before reaching the test section as shown in fig. (1). The honey comb shown in fig. (2), makes the flow uniform at the inlet of the test section. The test section of the wind tunnel is 200 mm wide, 200 mm height and 1500 mm long. The four sides for each of the upstream and test section are made from 1.5 mm mild steel sheet. Also, there is a rectangular opening (130 * 200 mm) made from 3 mm heat glass sheet and is located at the middle of the test section top side. The rectangular opening is used for adjusting and fixing the tested heated cylinders horizontally at the centre of the test section. Horizontal heated cylinders made of polished copper with different cross-sections (circular, square, diamond, rectangular and elliptical) are examined. The tested cylinders have nearly the same surface area of A_s = 0.015 m^2 and 200 mm length. A cartridge heater of 16 mm diameter is used to heat the copper tested cylinders with constant heat flux condition, as shown in fig. (3). Both sides of the heated cylinders are insulated to minimize the axial heat loss. Eight thermocouples made of Nickel-Chromium, K-type (0.2 mm wire diameter) are distributed circumferentially, embedded on the cylinder surface of the central section, to measure the surface temperature of the heated tested cylinder, as shown in fig. (3). The thermocouple hot junctions are embedded in slots at a depth of 0.5 mm from the heated cylinder outer surface, covered with conductive material and then smoothed. The average upstream air temperature entering the test section is measured by using two thermocouples located at the centreline of the wind tunnel. Digital turbine air flow meter with a minimum reading of 0.01 m/s was used to measure the air velocity inside the duct at inlet to the test section. Also, the digital turbine air flow meter is checked by using pitot tube. A digital thermometer with a minimum reading of 0.1 ^{o}C is employed for all the temperature measurements. The tested heated cylinders are internally heated by cartridge heater of 150 Ω total resistance. The power consumed in the heater is measured with digital multimeter to measure the voltage and the resistance. The present setup was designed with the facility of changing the tested heated cylinder with different cross sections. The thermophysical fluid properties were based on the average upstream air temperature. The experimental data are based on the equivalent hydraulic diameter, D_h, of the tested heated cylinders. The tested heated cylinders have nearly the same surface area of A_s = 0.015 m^2, and the hydraulic diameter, D_h, is calculated as follows:

$$\mathbf{D_h = 4\ A_c/P} \qquad \textbf{(1)}$$

Where A_c & P are respectively, the cross sectional area and the perimeter of the tested heated cylinder.

The hydraulic diameter, D_h, for the present tested cylinders are calculated using equation (1) and listed in Table (3).

Table (3): The hydraulic diameter for the tested cylinders.

The tested cylinder	The hydraulic diameter
Circular cylinder	$D_h = [4(\pi D^2 /4)]/ \pi D = D$
Square cylinder	$D_h = 4W^2/4W = W$
Rectangular cylinder	$D_h = 4ab/[2(a+b)] = 2ab/(a+b)$
Elliptic cylinder	$D_h = [2(\pi-(\pi-2)e^3)](c/2)/ \pi$

Where:

W is the side length of the square section.

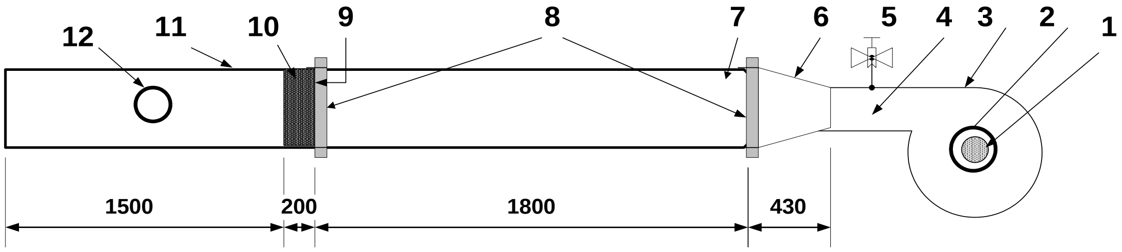
a, b are the dimensions of the rectangular cross section.

e is the eccentricity which is given by:

$$e = \sqrt{1-\left(\frac{d}{c}\right)^2} \qquad \textbf{(2)}$$

c & *d* is the major and minor axis length of the elliptic section, respectively.

Note: The present rectangular and elliptical cylinders have the axis ratio of ($\frac{1}{2}$) with zero angle of attack with the upstream flow.



1- Electric Motor. **2- Blower intake.**
3- Centrifugal air blower. **4- Delivery outlet.**
5- Air gate valve. **6- Convergent/ divergent section.**
7- Upstream section. **8- Flanges.**
9- Rubber sheet. **10- Honey comb.**
11- Test section. **12- Tested cylinder.**

Figure (1) The experimental set-up.

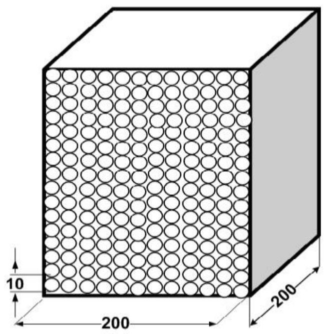


Figure (2): Honey comb.

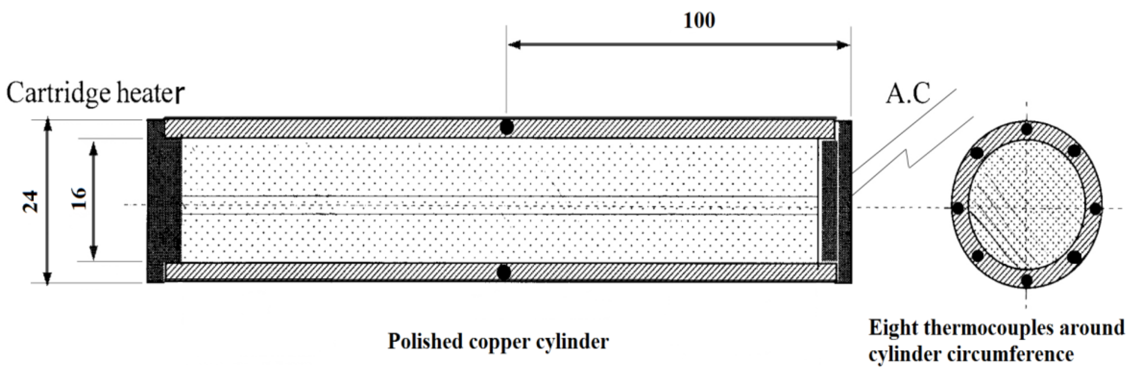


Figure (3): Details of the tested cylinder.

Dims in mms.

The input electrical power, Q, is adjusted using a voltage regulator. It is calculated from the resistance of the cartridge heater, the voltameter and the ammeter readings. The steady state condition is reached after 2:2.5 hours, the surface temperatures of the heated cylinders, $T_{s,\theta}$, and the upstream air temperature, T_∞, were measured using the calibrated thermocouples and the digital thermometer. The local heat transfer coefficient, h_θ and the corresponding local Nusselt number, Nu_θ, are calculated, respectively, as follows:

$$h_\theta = \frac{Q}{A_s(T_{s,\theta} - T_\infty)} \quad \textbf{(3)}$$

$$Nu_\theta = \frac{h_\theta D_h}{K_a} \quad \textbf{(4)}$$

Also, the average Nusselt number over the whole circumference of the heated cylinders, Nu, is calculated from integration of the local Nusselt number; as:

$$Nu = \frac{hD_h}{K_a} \quad \textbf{(5)}$$

Moreover, the Reynolds number based on the hydraulic cylinder diameter, Re, is calculated as follows:

$$\mathrm{Re} = \frac{\rho_a U_\infty D_h}{\mu_a} \quad \textbf{(6)}$$

- The thermophysical properties of the air are evaluated at the average upstream air temperature, T_∞.

The uncertainty of the heat transfer coefficient or Nusselt number is estimated to be about ±3.8%. Also, uncertainty of about ±0.42% is found in measuring the flow velocity or reported Reynolds number.

3. RESULTS AND DISCUSSION

Forced convection heat transfer from the heated cylinders with different cross-sections (circular, square, diamond, rectangular, elliptic) are investigated experimentally within the Reynolds number range of $2.2 \times 10^3 \leq Re_{Dh} \leq 2.2 \times 10^4$. The dimensionless coefficients, Nu and Re numbers have been calculated based on cylinder hydraulic diameter, $\mathbf{D_h} = \frac{4A_c}{P}$. The experiments are carried out at constant heat flux condition using air as a working fluid.

3.1 Temperature difference

The variation of the local temperature difference, ΔT, versus θ measured from stagnation point at different Reynolds numbers for tested circular, square, diamond, rectangular and elliptic cylinders are indicated in figures 4, 5, 6, 7 and 8, respectively.

These figures showed that the local temperature difference is decreased with the increasing of Reynolds number. For circular, diamond, rectangular and elliptic cylinders, it is observed that the local temperature difference is decreased monotonically with increasing angle θ, from $\theta = 0^o$ (stagnation point) until $\theta = 90^o$ for each upper and lower sides of these tested cylinders and then ΔT is decreased until $\theta = 180^o$, as shown in figures 4, 6, 7 and 8, respectively.

For square cylinder, it is found that the local temperature difference, ΔT, is increased with increasing angle θ, from $\theta = 0^o$ to $\theta = 135^o$ and after that, ΔT is decreased until $\theta = 180^o$, as shown in figure 5. Also, it is clear that the symmetry of the local temperature difference distribution on the upper and lower surfaces of the tested cylinders is satisfactory at all the Reynolds number.

3.2 Local heat transfer

The influence of Reynolds number on the local Nusselt number distributions around the whole circumference of the heated tested circular, square, diamond, rectangular and elliptic cylinders is indicated in figures 9, 10, 11, 12 and 13, respectively. The local Nusselt number, Nu_θ, is plotted versus the angle, θ from the leading edge ($\theta=0^o$) to the trailing edge. Generally, these figures showed that the local Nusselt number is increased with the increasing the Reynolds number. Also, it is noticed that the symmetry of the local Nusselt number distribution on the upper (positive θ) and lower (negative θ) surfaces of the tested cylinders is satisfactory at all the Reynolds numbers. It is found that the local Nusselt number reaches a maximum at the upstream stagnation point ($\theta = 0^o$) and steeply decreases on both sides of the tested cylinders with increasing angle, θ, due to the development of the laminar boundary layer and subsequently reaches a minimum near the separation point. However, the flow separates (minimum local Nusselt number) at about $\theta=90^o$ for circular, diamond, rectangular and elliptic cylinders as shown in figures 9, 11, 12 and 13, respectively. For square cylinder, the separation occurs at ($\theta = 135^o$) as shown in figure 10. For all tested cylinders, it is observed that the local Nusselt number, Nu_θ, begins to increase slightly at the rear part of the cylinder downstream of the separation points except the rectangular cylinder. For the rectangular cylinder, the local Nusselt number, Nu_θ, is highly increased from $\theta = 90^o$ (separation point) to $\theta =135^o$ and then slightly decrease until $\theta = 180^o$ as shown in figure 12. Moreover, it may be reasonable to consider that the whole tested Reynolds number range is included within the subcritical flow regions, since the heat transfer distribution shows no essential change with Reynolds number [16, 19, 20].
Finally, it is found that the local Nusselt number, Nu_θ, begins to increase slightly downstream of the separation points near the tested cylinder trailing edge, due to turbulent periodic vortices which alternately shed on both sides of the cylinder rear surface [21].

3.3 Average heat transfer

The average Nusselt number for a single cylinder with cross-section of circular, square, diamond, rectangular and elliptical, in cross-flow of air is calculated using the present experimental data and within Reynolds number range of $2.2 \times 10^3 \leq Re_{Dh} \leq 2.2 \times 10^4$. It is found that the average Nusselt number increases with increasing of Reynolds number. A correlation between average Nusselt number and Reynolds number can be deduced in the form of, $Nu = C\, Re^n$, Where the values of the constants (c,n) are obtained by the curve fitting, based on the least squares method using the present experimental data.

For circular cylinder (L/D = 8.3 and D = 0.024 m), the average Nusselt number is calculated from the present experimental data and is correlated as a function of Reynolds number as follows:

$$\mathbf{Nu = 0.23\, Re^{0.594}} \qquad \mathbf{(7)}$$

This correlation is valid within the range of Reynolds number from 2200 to 22000 with a maximum deviation of about ± 3%. The present correlation (i.e. the approximate solution of the present study), eq. (7), is compared with the correlation proposed by Churchill and Bernstein, [4], Zukauskas and Ziugzda, [5], Afify and Berbish, [7] and Sparrow et al, [8], and good agreement is found as shown in figure (14). Also, it is noticed from figure (14) that, there is a little difference between them and this may be attributed to the change in operating conditions. The good agreement between the present experimental results of a single circular cylinder and the previous published correlations, ensures the reliability and the validity of the present experimental set-up and the method of calculations.

For square cylinder (L/W = 8.3 and W = 0.024 m), Figure (15) presents the average Nusselt number which is correlated utilizing the present experimental data as a function of Reynolds number, as follows:

$$\mathbf{Nu = 0.125\, Re^{0.68}} \qquad \mathbf{(8)}$$

This correlation is valid within the range of Reynolds number from 2200 to 22000 with a maximum deviation of about ± 1.5%. The present correlation, eq. (8), is compared with correlations of the previous works such as Rieher, [9], Hilpert, [10], Igarashi, [11] and Bishop, [13]. It is observed that there are differences between Rieher, [9], Hilpert, [10] and Bishop, [13], this is reflected in a scatter between the presented data which may be a reason of the turbulence intensity, the high temperature difference between the surface temperature and the ambient temperature, influence of radiation, free convection, calculation of thermal properties or any other reason. One concludes it is difficult to justify the difference between them. It is also observed that the present study is in a good agreement with the experimental correlation obtained by Igarashi, [11] since the present study is higher by 7.5%.

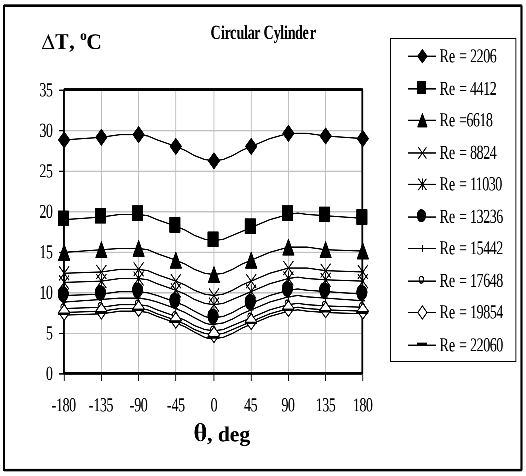


Figure (4): Variation of the local temperature difference versus θ from stagnation point for a single circular cylinder.

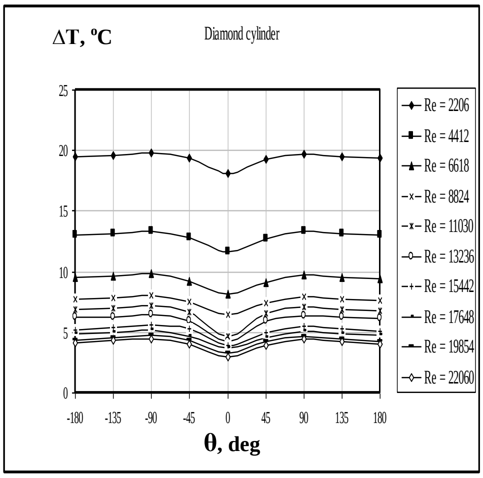


Figure (6): Variation of the local temperature difference versus θ from stagnation point for a single diamond cylinder.

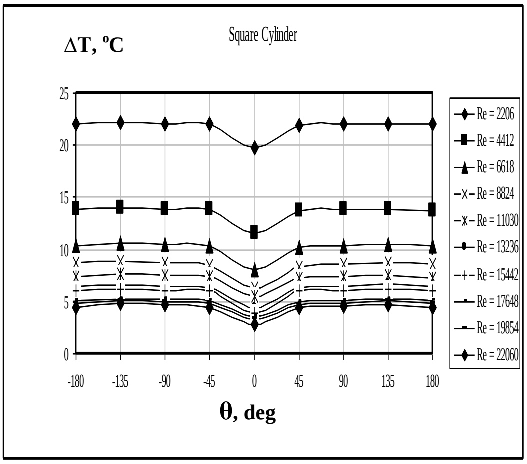


Figure (5): Variation of the local temperature difference versus θ from stagnation point for a single square cylinder.

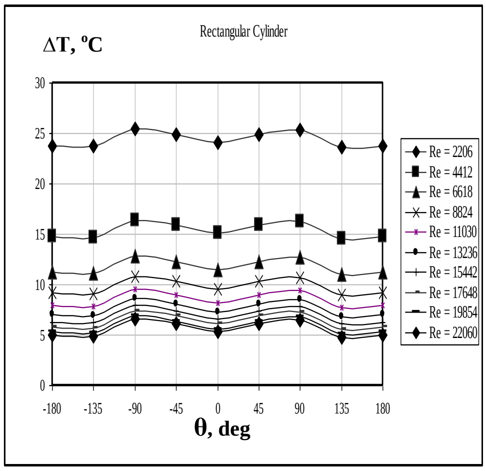


Figure (7): Variation of the local temperature difference versus θ from stagnation point for a single rectangular cylinder.

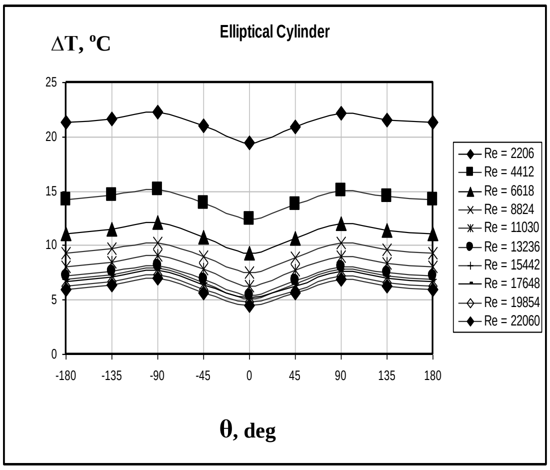


Figure (8): Variation of the local temperature difference versus θ from stagnation point for a single elliptic cylinder.

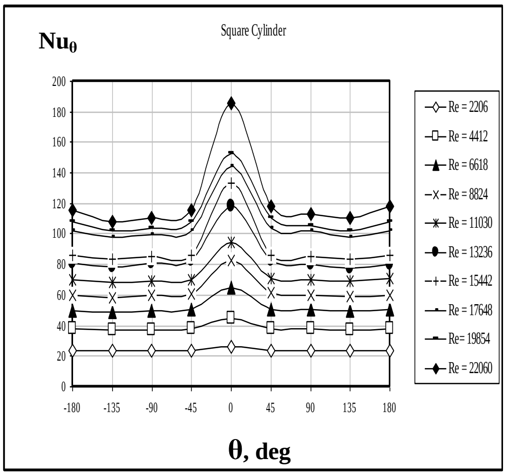


Figure (10): Variation of the local Nusselt number versus θ from stagnation point for a single square cylinder.

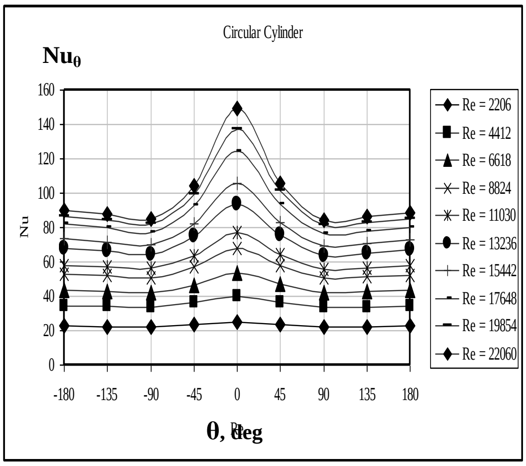


Figure (9): Variation of the local Nusselt number versus θ from stagnation point for a single circular cylinder.

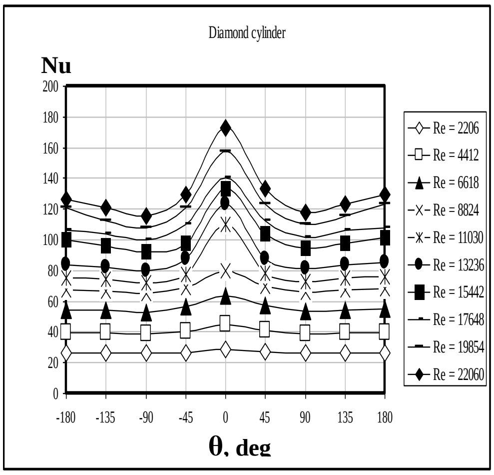


Figure (11): Variation of the local Nusselt number versus θ from stagnation point for a single diamond cylinder.

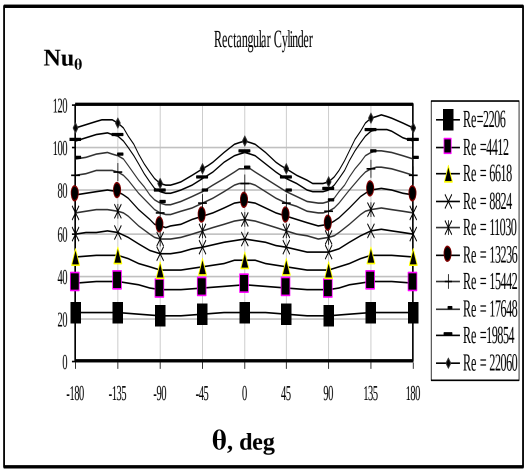


Figure (12): Variation of the local Nusselt number versus θ from stagnation point for a single rectangular cylinder.

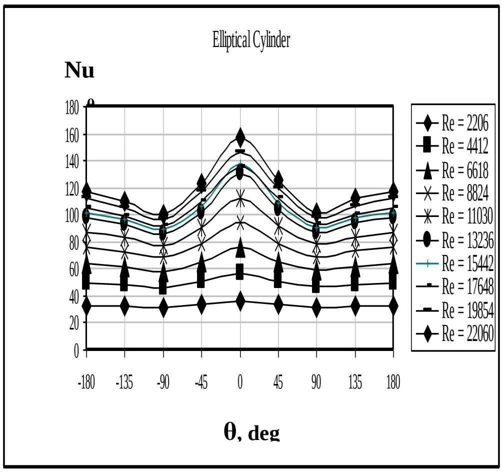


Figure (13): Variation of the local Nusselt number versus θ from stagnation point for a single elliptic cylinder.

For diamond cylinder (L/W = 8.3 and W = 0.024 m), Figure (16) shows the present experimental data of the average Nusselt number which is correlated utilizing the present experimental data as a function of Reynolds number, as follows:

$$Nu = 0.242\, Re^{0.61} \quad (9)$$

This correlation is valid within the range of Reynolds number from 2200 to 22000 with a maximum deviation of ± 5.5%. The present correlation, eq. (9) is compared with correlations of the previous works such as Rieher, [9], Hilpert, [10], Igarashi, [11] and Bishop, [13]. It is clear from the figure that, all of the data characterized by slopes that are virtually near to each other. It is also observed that the present study is in a good agreement with the experimental correlation obtained by Igarashi, [11], since the present study is higher by 8%.

For rectangular cylinder (major axis parallel to free-stream direction, a/b = 1/2 and L = 0.2 m), Figure (17) presents the present experimental data of the average Nusselt number for a single rectangular cylinder utilizing the present experimental data as a function of Reynolds number, as follows:

$$Nu = 0.122\, Re^{0.67} \quad (10)$$

This correlation is valid within the present range of Reynolds number with a maximum deviation of ± 5.3%. The present data compared with correlations of the previous work of Igarashi, [15]. It is observed that, the present study is in a good agreement with the experimental correlation obtained by Igarashi, [15] since the maximum deviation between them is nearly 8.7%.

For elliptic cylinder (major axis parallel to free-stream direction, c/d = 1/2 and L = 0.2 m), The correlation of the average Nusselt number related to values of Reynolds numbers is plotted in figure (18). Finally, the average Nusselt number for a single elliptical cylinder with zero angle of attack is correlated as follows:

$$\mathbf{Nu = 0.415\ Re^{0.566}} \qquad \mathbf{(11)}$$

This correlation was valid within the range of Reynolds number from 2200 to 22000 with a maximum deviation of about ± 8.4%. Comparisons between the present empirical correlation, Eq, (11) and the correlations proposed by the previous researchers such as Ota et al, [16], Khan, [18] and Abdel Aziz et al, [19]. It is observed that there is a little difference between the previous works of Ota et al, [16] and Khan, [18] with the experimental results of Abdel Aziz et al, [19], this may be attributed to the change in elliptic cylinder axis ratio. On the other hand, a fair agreement is found between the present correlation with the correlation obtained by Abdel Aziz et al, [19], with a maximum deviation about ± 10%. A satisfactory agreement in the above comparisons has confirmed that the experimental procedures employed are adequate and the results are reliable.

3.4 Comparison between the whole present correlations of circular and non-circular cylinders

The figure (19) shows a comparison of all tested bodies that in our present study. It is observed that elliptical cylinder parallel to the free-stream offers higher heat transfer rates than that of other objects that have the same characteristic dimension, D_h. The objects considered included cylinders whose cross-sections are: (1) circular, (2) square, (3) diamond and (4) rectangular. It also observed that, the square cylinder has higher heat transfer rates compared with circular, rectangular and "diamond at $Re_{Dh} \geq 12.5 \times 10^3$"cylinders. And diamond cylinder has higher heat transfer rates than which in circular and rectangular cylinders. Then the rectangular cylinder has higher heat transfer rate than which in circular cylinder. Therefore, in other words, it is worth to consider that circular and elliptical cylinders have respectively the lower and the higher rates of heat transfer for the pre-mentioned group of cylinders.

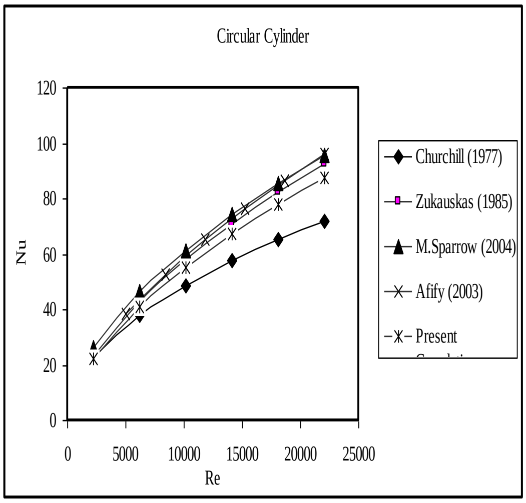


Figure (14): Variation of the Average Nusselt number versus Reynolds number for a single circular cylinder.

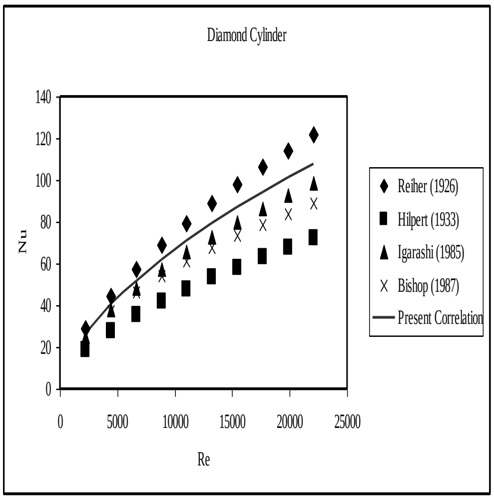


Figure (16): Variation of the Average Nusselt number versus Reynolds number for a single diamond cylinder.

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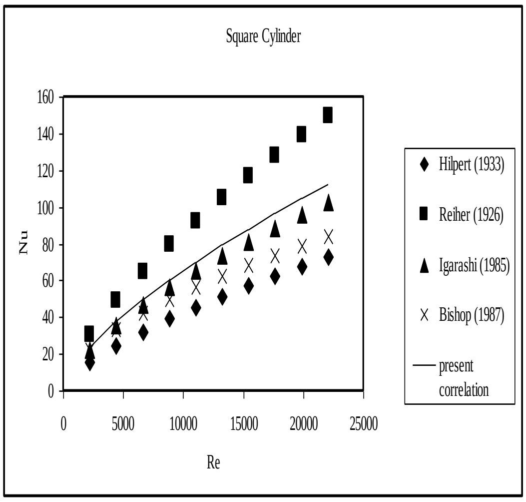

Figure (15): Variation of the Average Nusselt number versus Reynolds number for a single square cylinder.

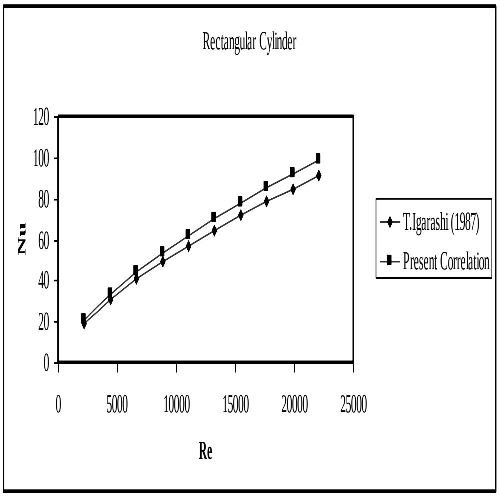

Figure (17): Variation of the Average Nusselt number versus Reynolds number for a single rectangular cylinder.

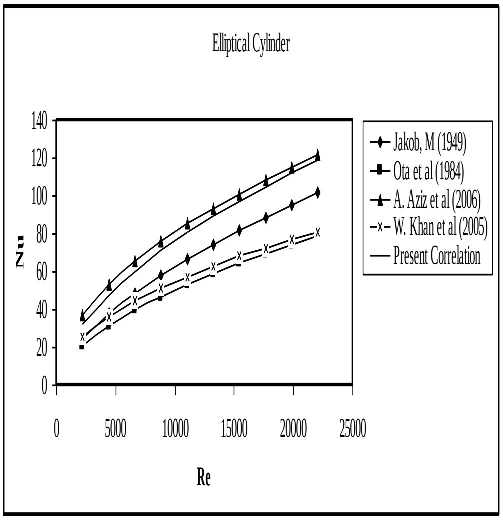

Figure (18): Variation of the Average Nusselt number versus Reynolds number for a single elliptical cylinder.

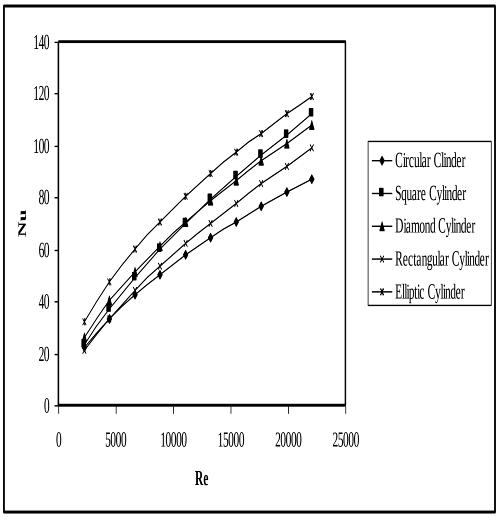

Figure (19): Present correlations of average Nusselt numbers for cross-flow heat transfer in air from (circular & non-circular) body shapes.

4.CONCLUSIONS

The forced convection heat transfer characteristics around cylinders with different cross-sections (circular, square, diamond, rectangular and elliptic) were studied experimentally with air as a working fluid and zero angle of attack. The examined cylinders were made of polished copper and heated under constant heat flux condition within Reynolds number (based on the upstream mean velocity and the equivalent diameter, D_h). An experimental set-up was designed and constructed for this investigation. The tested heated cylinders had approximately the same hydraulic diameter, D_h = 0.024 m and length of 0.2 m, and were taken individually as the heating surface. The results of the present study lead to the following conclusions:

1- The average Nusselt number for all body shapes increases with the increase of the Reynolds number.
2- Although the tested bodies have nearly the same total surface area & the same range of Reynolds number and the same power input, they differ significantly in the average heat transfer obtained.
3- The average heat-transfer rate from circular cylinder is the lowest when comparing with the other body shapes.
4- The average heat-transfer rate from the elliptical cylinder is the highest when comparing with the other tested cylinders.
5- Empirical correlations of the average Nusselt number for the tested cylinders obtained as a function of Reynolds number and the hydraulic diameter.

6- The local Nusselt number reaches a maximum value at the upstream stagnation point (the leading edge) and decrease steeply with θ increasing until reaches the separation point where the minimum value of heat transfer, then it increases again due to the development of laminar boundary layer and the flow reattachment.

NOMENCLATURE

A_c Cross-sectional area of heated cylinder, m^2.
A_s Surface area of heated cylinder, m^2.
L Cylinder length, m.
D Circular cylinder diameter, m.
W Square cylinder's side length, m.
a Rectangular cylinder's minor side length, m.
b Rectangular cylinder's major side length, m.
c Elliptic cylinder's major axis length, m.
d Elliptic cylinder's minor axis length, m.
D_h Hydraulic diameter, m.
P The perimeter of the tested cylinder, m.
e The eccentricity of the elliptic cylinder.
Q Total input power to the heater, W.
$T_{s,\theta}$ Local surface temperature of the body, ^oC.
T_∞ Ambient air temperature, ^oC.

K_a Thermal conductivity of air, W/m.°C.
Pr Prandtl number, Pr = $\mu a * C_{Pa} / k_a$.
h Average of heat transfer coefficient, $W/m^2.°C$.
h_θ Local heat transfer
N_u Average Nusselt number.
Nu_θ Local Nusselt number.
U_∞ Average velocity of air inside the test section.
μ_a Air dynamic viscosity, kg/m.s.
Re Reynolds number.

Subscripts

θ local angle in the axial direction.
∞ upstream flow.
a air.
s cylinder's surface.
c cylinder's cross-section.

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