The Effect of Holes Number in Cylindrical Samples on the Forced Convection Heat Flow

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Abstract—**In this article, an experimental study was conducted on the effect of side holes in circular cylinders on the forced convection heat transfer process. Three circular cylindrical samples were made of aluminum. Sample No.1 without side holes, sample No.2 with two side holes, and sample No.3 with four side holes. These cylindrical samples were placed after being heated in an air duct (working section) and the position of samples in an air duct are same. Air laminar cross-flow was applied to the cylindrical samples at different velocities while observing their temperature drop. The results showed that the perforated cylinders increase the rate of heat dissipation compared to non-perforated cylinder at all air flow velocities and that the largest rate of heat dissipated was in the sample NO.3 by (24.8573 W) at temperature drop (10˚C) and air flow velocity (24.6688 m/s). Also Nusselt number was calculated at Reynolds number range (7435-20697), where it become discovered that Nusselt number will increase with the Reynolds number in all cylindrical samples. Empirical relationships for Nusselt number with Reynolds number and Prandtl number had been get it for the three circular cylinders and liken with relationships of circular cylindrical forms exist in other references. These Empirical relationships given acceptable constants values.**

Index Terms—**heat transfer, forced convection, circular cylinder, Reynolds number, Nusselt number**

I. Introduction

It is widely known that the metal of a hot cylinder cools faster when it is placed in front of a fan than compared to exposing it to still air. This is due to the fact that the heat is transferred away; this process is called convection heat transfer. The term convection offers the reader an intuitive perception regarding the process of heat transfer; nevertheless, this perception must be expanded so that an adequate analytical treatment to the problem can be reached. For example, it is known that when air blows over a hot cylinder the velocity influences the heat-transfer rate, however does the cooling process is influenced in a linear way; i.e., doubling the velocity will also make the heat-transfer rate double? Correspondingly, if the weight, or surface area of the cylinder changes, in what manner will it affect the heat transfer process? All these questions could be answered by using a rather basic analysis for cylinder [1] [2].

The circular cylinder can be used as fins to heat dissipation [3, 4]. For example, the pin fins can be made from circular cylindrical samples and which have the advantage of heat dissipating much more than the straight fins [5]. Pin fins have many industrial applications, including they are used as a heat sink in (CPU) of smart devices [6]. In general, improving the heat dissipation process from fins leads to an improvement in the performance of the applications associated with these fins [7]. Where a many researchers resort to improving heat dissipation from the fins by using different techniques and methods such as changing the geometry of the fins, changing the dimensions of the fins, perforating the fins or changing the working fluid has contact with surfaces of the fins, etc. [8] [9] [10]. Therefore, this article presents one of the methods for improving the heat dissipation of circular cylindrical samples in experimentally by using the perforation technique.

Many researchers have studied these subjects in the past. [11] Presented an experimental study of the effect taking place when the external shape of the cylinder is changed on the time rate of the heat transfer in forced convection through the cooling process. It was found that changing the shape of the cylinder effects the heat transfer process and that the Nusselt No. is directly proportional to the Reynolds No. for all cases. In addition, it obtained empirical relationships for Nusselt No. with Reynolds No. and Prandtl No. for cylindrical shapes and at Reynolds No. range (4555-18222), and the constants values of the experimental relationships were acceptable. [12] Presented a large vortex simulation of forced convection heat transfer in flow around finite-height circular cylinder installed on a specific surface. This study was made for a cylinder with an aspect ratio of 2.5, a Reynolds NO. based on a cylinder diameter of 44000 and a Prandtl No. of 1. It was found that the heat transfer coefficient is strongly affected by the free end of the cylinder. [13] Presented a numerical study of the effect of forced convection on the pin fins solid and perforated. It was found that the perforated pin fins have higher heat dissipation as compared to solid pin fins. Moreover, it was found that there is an increase in heat dissipation with the increase in the number of holes when comparing one, two, and three holes. [14] Presented an experimental study of forced convection heat transfer for laminar flows on cylinders (it has a heater) with different of cross section shapes in duct contains glass balls as a porous media. It was found that that Nusselt No. increases

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with the increase in Reynolds No. at constant heat flux and the best improvement in heat transfer by forced convection was when using circular cylinder in porous media. [15] Presented a study of heat transfer by forced convection of a circular cylinder with flexible fin in laminar flow and investigated numerically. It was found that the fin improves the heat transfer process from the circular cylinder by 11.07% as a maximum. [16] Presented an experimental study to enhance heat sink by perforated pin fins (circular cross section) under forced convection. It was found that the temperature drop at maximum power (250 W) was (300-55 ℃) for the fins without perforated and (300-38 ℃) for the fins with perforated. [17] Presented a numerically study of forced convection heat transfer on a circular cylinder in the presence of an electric field. It was found that the Ion wind can increase the local Nusselt NO. and average Nusselt NO. [18] Presented a non-isothermal 3D CFD model for the purpose of studying the thermal performance of a heat sink with perforated cylindrical fins as shown Fig. 1. It was found that the perforated cylindrical fins increase the rate of heat dissipation and provide a sufficient and cheap improvement in the thermal transfer compared to non-perforated cylindrical fins. [19] Presented a numerically study of the thermal performance of an isothermal horizontal cylinder with different cross sections in cross-flow by using the software Fluent™ (Version 18.2). It was found that the average Nusselt NO. depends on the Reynolds number and also on the orientation of the cylinder.

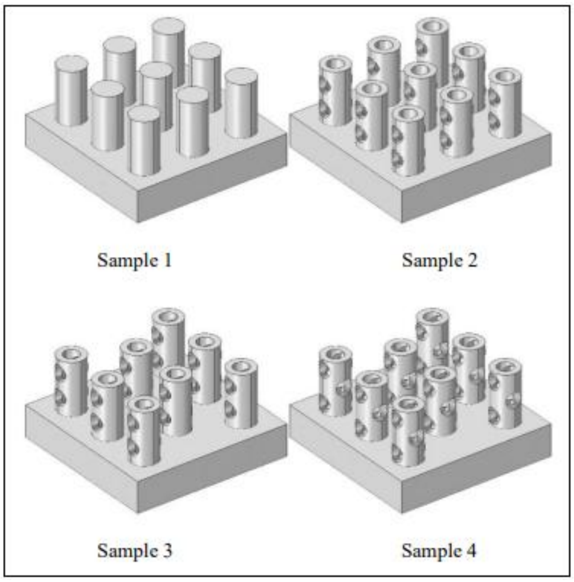


Figure 1. Four designs of pin fins as the heat sinks [18].

It is clear from what was presented that the process of heat transfer by forced convection of cylindrical shapes is affected by many factors and variables. In this article, some of those factors effecting heat dissipation from a circular cylinder will be investigated. Additionally, the focus in this study will be around the effect of increasing the number of holes on the heat transfer process.

II. Experimental Work

For the purpose of data gathering, a cross-flow heat exchanger (Model TE.93/A, Plaint Engineers, England) was used. The setup of the experiment is shown in Fig. 2.

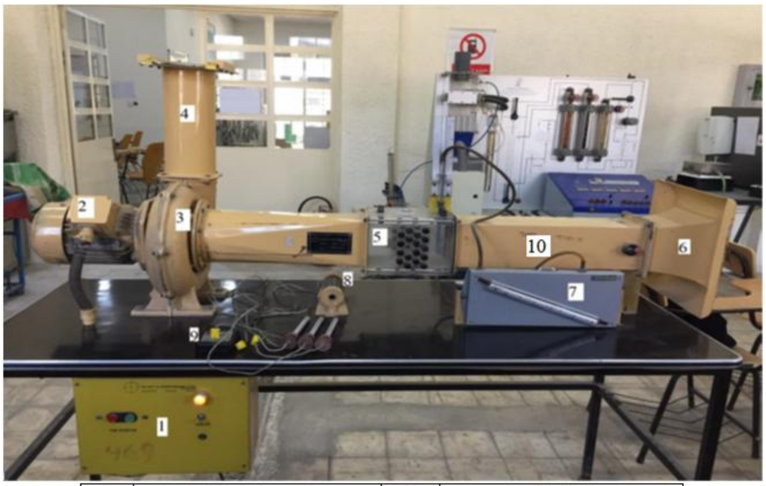
Three cylindrical test samples with a circular section were manufactured from aluminum alloy 2024. Aluminum alloy 2024 was chosen due to its excellent thermo-physical properties, appropriate cost, and the easiness to manufacture samples from it. The values of thermo-physical properties (density and specific heat) were obtained from the source equipped for this alloy as listed in Table I. All cylindrical samples are equal in length (125 mm) and diameter (12.15 mm). The difference between cylindrical samples is that sample No.1 without side holes, sample No.2 with two side holes, and sample No.3 with four side holes. The diameter of one hole is (5 mm), the distance between hole and hole is equal, and all the holes are pierced. The effective surface area of each of the cylindrical samples was calculated based on the effective dimensions of the cylindrical samples, and the mass of each cylindrical sample was calculated based on its size and density. Each cylindrical sample was provided with a type K thermocouple in order to measure temperature of the cylinder, as shown in Fig. 3.

TABLE I. Thermo-physical and Geometrical Data for the Three Tested Cylindrical Samples.

Cylindrical Sample number	material	mass (kg)	effective surface area (m^2)	Density (kg/m^3)	Specific heat (J/kg.˚C)
1	Aluminum alloy 2024	0.040145	0.004771	2770	875
2	Aluminum alloy 2024	0.038823	0.005074	2770	875
3	Aluminum alloy 2024	0.037501	0.005377	2770	875

The test process is done by heating the cylindrical sample in the electric heater to a specific temperature that is read by digital thermometer. Then the cylindrical sample is placed in the working section and the centrifugal fan is turned on in order to intake the air (working fluid), which passes around the surface of the cylinder in a cross flow and cools the cylindrical sample as in Fig. 4. The cooling process is observed by recording the cooling time by watch timer when the temperature of the cylindrical sample falls every (10 ℃). The ambient air temperature is recorded by the mercury thermometer.

Inlet air flow is controlled by throttle opening, air flow can be sensed by Pitot tube and calculate its velocity with the help of inclined manometer. The process is repeated for each of the three cylindrical samples and for more than air flow velocity, noting that the location of the cylindrical samples in the working section is fixed for all cases.



1	**Control panel**	6	**Air inlet**
2	**Electric motor**	7	**Inclined manometer**
3	**Centrifugal fan**	8	**Electric heater**
4	**Throttle opening**	9	**Digital thermometer**
5	**Working section**	10	**Air duct**
There is also: **Mercury thermometer**, **Watch timer**			

Figure 2. The experimental setup.

Note that, according to the operating conditions and previous studies in the experimental setup [11], the dimensions of the samples and measurement devices were chosen, as well as the preparation of the readings table as shown in Table II.

The temperature of cylinder was considered constant from the center to the surface due to the small diameter of the cylinder. That is, the temperature gradient is negligible.

TABLE II. Template of the Readings Table

Number of Samples	
Temperature of Cylinder (˚C)	Cooling Time (s)
max.-x	x
x	x
x	x
x	x
x	x
x	x
min.-x	x
Ambient Temperature = x It must be less than min. temperature of cylinder	
Liquid head in manometer = x cmH_2O The liquid head value determines the air flow velocity	

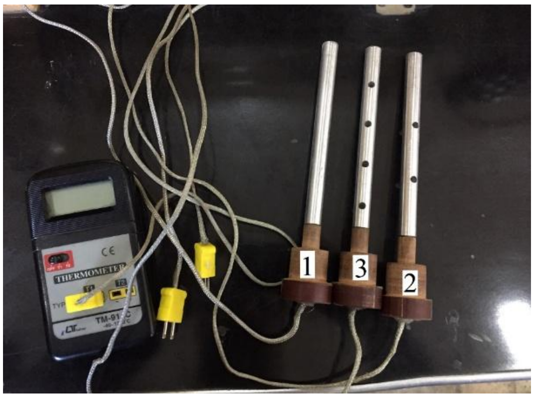


Figure 3. Test samples.

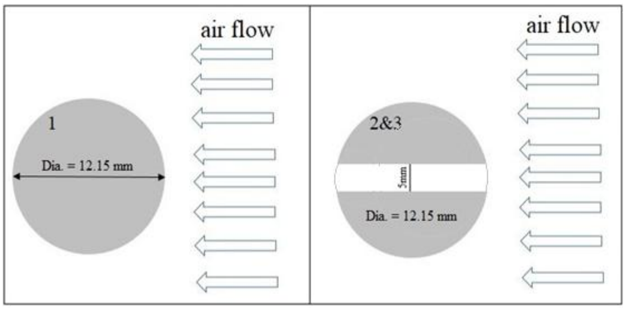


Figure 4. Direction of air flow with cylinder (cross-flow).

III. Theoretical Analysis

The rate of heat loss from cylinder to air is given by [20]:

$$q = h\, A_s\, (T - T_a) \tag{1}$$

where: q: rate of heat loss (J/s), h: heat transfer coefficient ($J/s.m^2.^\circ C$), A_s: effective surface area of cylinder (m^2), T: temperature of cylinder (˚C), T_a: temperature of air (Air ambient temperature) (˚C).

In a period of time (dt) the temperature drop (dT) is given as [21]:

$$q = m\, cp\, \frac{dT}{dt} \tag{2}$$

where: m: mass of cylinder (kg), cp: specific heat of cylinder (J/kg.˚C), t: time (s)

Combining equations (1) and (2) and eliminating q give the following:

$$\frac{-dT}{(T - T_a)} = \frac{h\, A_s}{m\, cp}\, dt \tag{3}$$

Integrating equation (3) from cylinder temperature at zero time to cylinder temperature at to an indefinite time (t) gives:

$$\mathrm{Ln}(T - T_a) - \mathrm{Ln}(T_o - T_a) = \frac{-h\,A_s}{m\,cp}\,t \quad (4)$$

where: T_o: cylinder temperature at time (t) = 0.

The plot of Ln (T-T_a) against (t) yields a straight line of slope (M) as:

$$M = \frac{-h\,A_s}{m\,cp} \quad (5)$$

From which the heat transfer coefficient (h) is calculated as:

$$h = \frac{-M\,m\,cp}{A_s} \quad (6)$$

The Reynolds number of air flow is determined using the following relation [1]:

$$Re = \frac{\rho_a\,u_a\,d}{\mu_a} \quad (7)$$

where: Re: Reynolds number,ρ_a: density of air (kg/m^3), u_a: velocity of air inside duct (m/s), d: diameter of cylinder (m), μ_a: viscosity of air (kg/m.s).

The air velocity inside the air duct is calculated:

$$u_a = \sqrt{\frac{2\,\rho_w\,g\,H_w}{\rho_a}}\ x\ \frac{10}{9} \quad (8)$$

where: ρ_w: density of water (kg/m^3), g: ground acceleration (m/s^2), H_w: head tube connected to an inclined water manometer (m).

The Prandtle number is determined from the eq. [22]:

$$Pr = \frac{\mu_a\,cp_a}{k_a} \quad (9)$$

where: Pr: Prandtle number, cp_a: specific heat of air (J/kg.˚C), k_a: thermal conductivity of air (J/s.m^2.˚C).

The fully developed Nusselt number is evaluated by [1]:

$$Nu = \frac{h\,d}{k_a} \quad (10)$$

The experimental Nusselt number is calculated as [23]:

$$Nu = CR_e^n\,Pr^{0.3} \quad (11)$$

The constants (C) and (n) can be determined through the relation between the graphs Log (Nu/Pr$^{0.3}$) & Log (Re) as shown in Fig. 5.

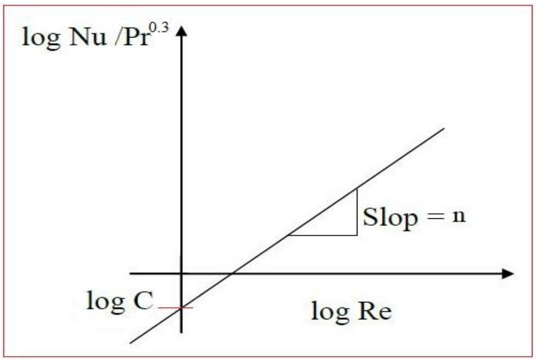


Figure 5. Empirical relation between (Log Re) & (Log Nu/Pr0.3).

IV. Results and Discussion

The experimental results were obtained after applying a forced convection on the cylindrical samples. Four air-flow velocities (24.6688, 20.0606, 14.6948 and 8.8613 m/s) were used in test. The ambient temperature recorded was (15 ℃), the maximum temperature of cylinder chosen in the test was (80˚C) and the minimum temperature of cylinder in the test was (30˚C).

Fig. 6 shows the relationship between temperature and cooling time for cylindrical sample No. 1 (without side holes) at different air velocities. It can be seen that when the air velocity around the cylindrical sample increases, the cooling time decreases. The reason for this is due to the increase in heat transfer coefficient when increasing the air flow velocity, which leads to transfer of heat lost from the cylindrical sample to the air in less time when same difference between the temperatures of cylinder (80˚C-30˚C).

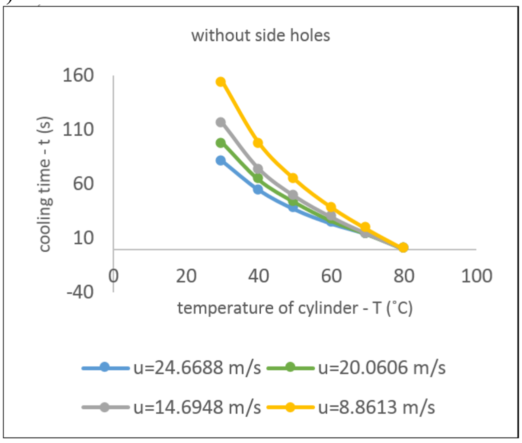


Figure 6. Relationship between temperature of cylinder and cooling time for cylindrical sample No.1 at different air velocities.

The same behavior in Figs 7 and 8, which show the relationship between the temperature and the cooling time of the cylindrical sample No. 2.3, respectively, at different air velocities. Also can be seen that when the air velocity around the cylindrical sample increases, the cooling time decreases.

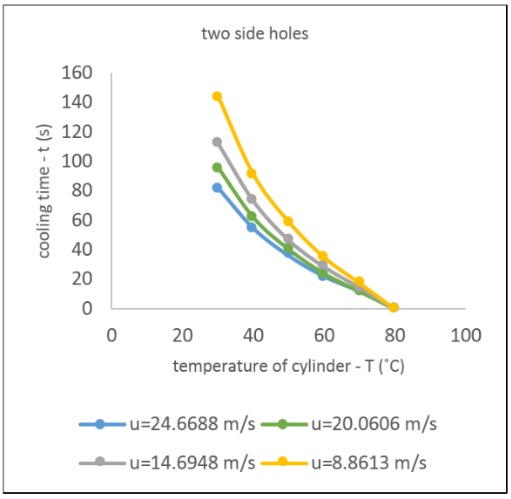


Figure 7. Relationship between temperature of cylinder and cooling time for cylindrical sample No. 2 at different air velocities.

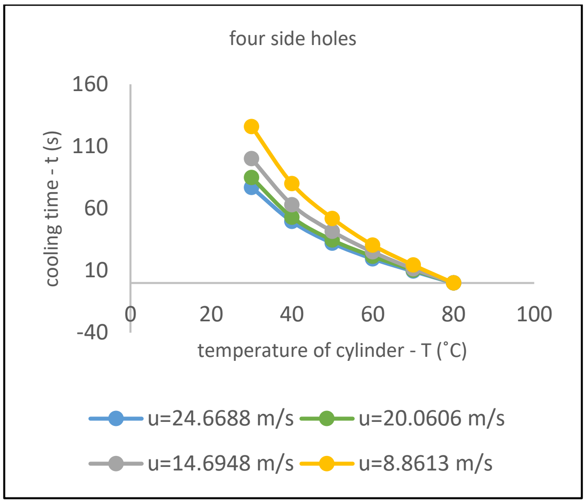


Figure 8. Relationship between temperature of cylinder and cooling time for cylindrical sample No.3 at different air velocities.

Figs 9, 10, 11 and 12 show the relationship between temperature and cooling time for the three cylindrical samples at the velocity of air flow (u = 24.6688 m / s), (u = 20.0606 m / s), (u = 14.6948 m / s), (u = 8.8613 m / s), respectively. It can be seen that the cooling time of cylindrical sample No. 3, which is less than the cooling time of cylindrical samples No. 1 and No. 2 at all air velocities, although a heat transfer coefficient for cylindrical sample No. 3 is less than a heat transfer coefficient for cylindrical samples No. 1 and 2 at some air velocities. The reason for this is due to an increase in the effective surface area of the cylindrical sample No. 3 resulting from the four side holes through which air passes. Also it can be seen that the difference between the cooling time of the three cylindrical samples increases as the air velocity decreases, especially between the cylindrical sample No. 1 and the cylindrical sample No. 3. The reason for this is that the air velocity decrease leads to the air disturbances decrease. This means that the air vortices will be reduced at entrance to the hole, which means that more air will enter the holes. That leads to cooling cylindrical samples with side holes in less time compared to the cylindrical sample without side holes when same the air flow velocity.

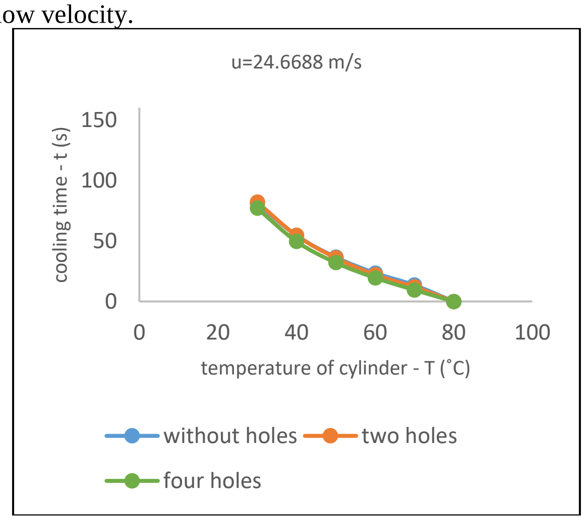


Figure 9. Relationship between temperature of cylinder and cooling time for three cylinder samples at (u=24.6688 m/s).

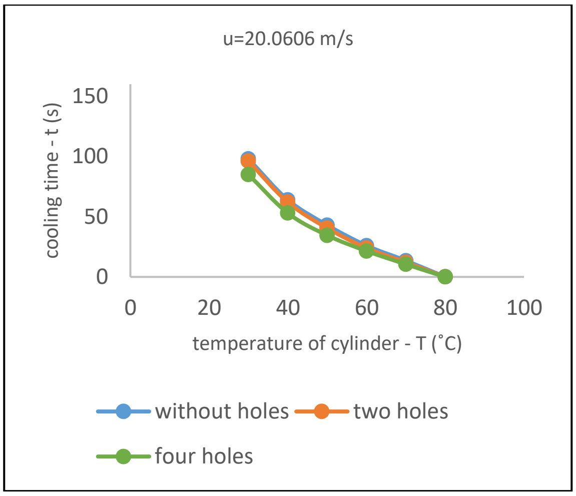


Figure 10. Relationship between temperature of cylinder and cooling time for three cylinder samples at (u=20.0606 m/s).

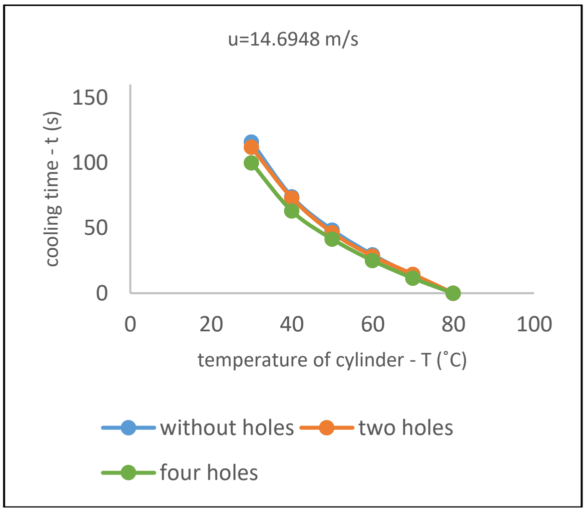


Figure 11. Relationship between temperature of cylinder and cooling time for three cylinder samples at (u=14.6948 m/s).

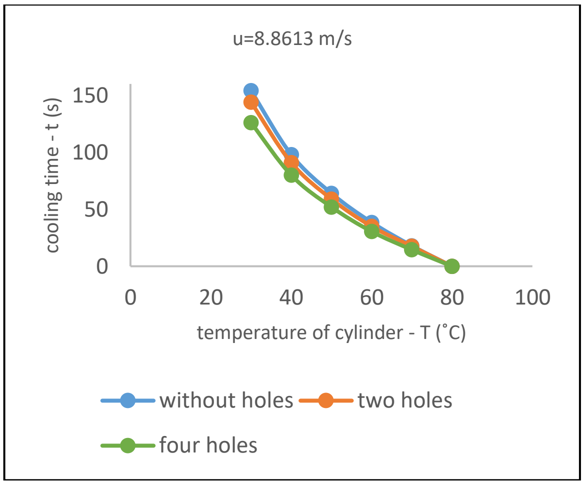


Figure 12. Relationship between temperature of cylinder and cooling time for three cylinder samples at (u=8.8613 m/s).

By making use of the relationship No. (2), rate of heat dissipated calculated at temperature drop of (10˚C). Fig. 13 shows the relationship between air-flow velocity and rate of heat dissipated for the three cylindrical samples. The results showed that the air-flow velocity significantly effects the rate of heat dissipated, as well as, increasing the number of holes lead to enhancement the rate of heat dissipated. The reason for the convergence of the behavior of the sample without holes and the sample with two holes in Fig. 13 is the difference in mass. That is, if the mass of the two samples is equal, then sample with two holes will give a greater rate of heat dissipated.

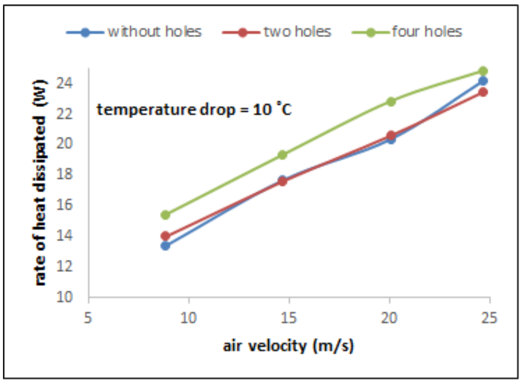


Figure 13. Relationship between air flow velocity and rate of of heat dissipated for three cylinder samples.

By making use of the relationship No. (7) and No. (10), Reynolds number and the fully developed Nusselt number were calculated for the three cylindrical samples at all air velocities. The results showed that as Reynolds number increases, Nusselt number increases for all cylindrical samples, as shown in Figs 14, 15 and 16. The reason for this is that the increase in Reynolds number results from the increase in the air flow velocity around cylindrical samples, which in turn leads to an increase in a heat transfer coefficient, it that means increase in Nusselt number.

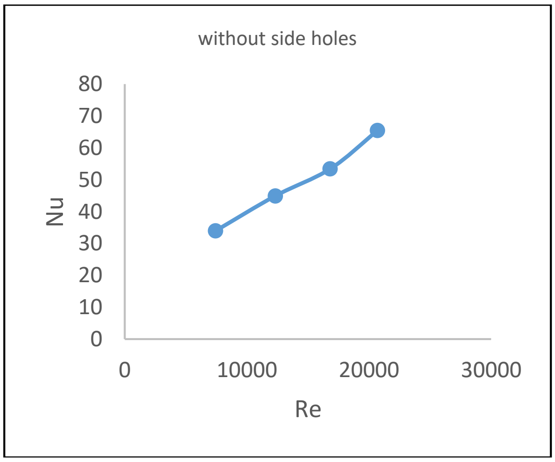


Figure 14. Variation Reynolds number with Nusselt number of cylindrical sample No.1.

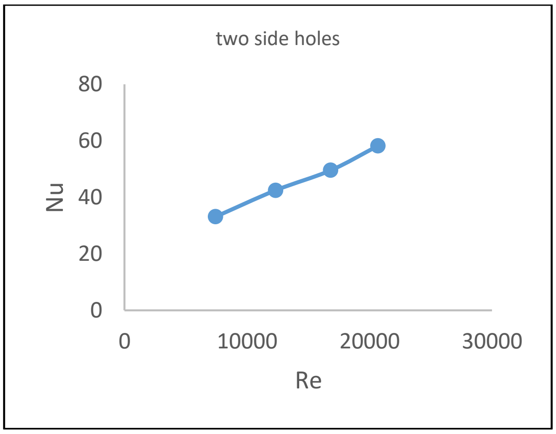


Figure 15. Variation Reynolds number with Nusselt number of cylindrical sample No.2.

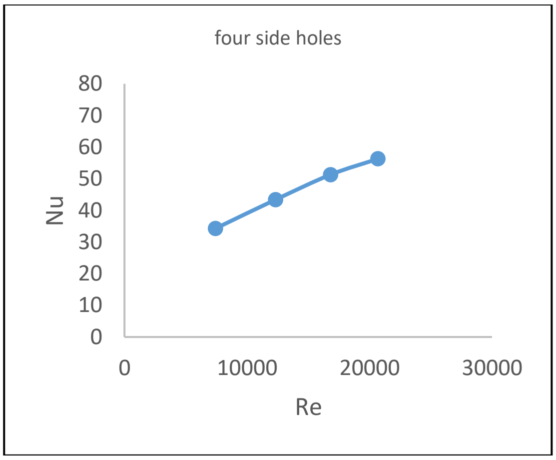


Figure 16. Variation Reynolds number with Nusselt number of cylindrical sample No.3.

By using the relationship No. (11) and Figs. 17, 18 and 19, The experimentally verified relation obtained for Nusselt No. with Reynolds No. and Prandtle No. was as follows:

$Nu = 0.1480 R_e^{0.6194} Pr^{0.3}$ For a circular cylinder without side holes (cylindrical sample No.1).

$Nu = 0.3045 R_e^{0.5363} Pr^{0.3}$ For a circular cylinder with two side holes (cylindrical sample No.2).

$Nu = 0.4879 R_e^{0.4892} Pr^{0.3}$ For a circular cylinder with four side holes (cylindrical sample No.3).

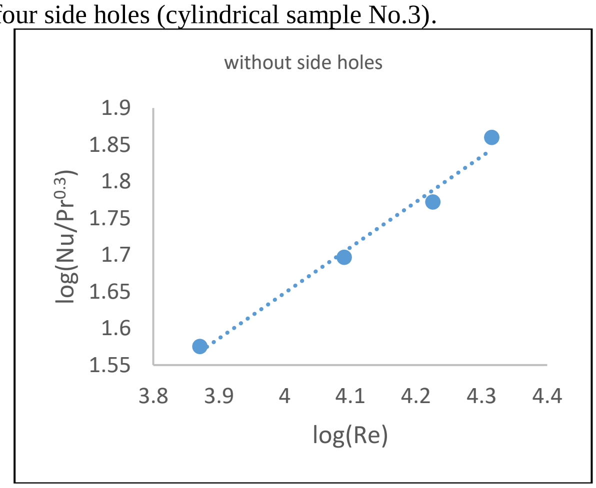


Figure 17. The empirical relationship between the (Log Re) and (Log $Nu/Pr^{0.3}$) for cylindrical sample No.1.

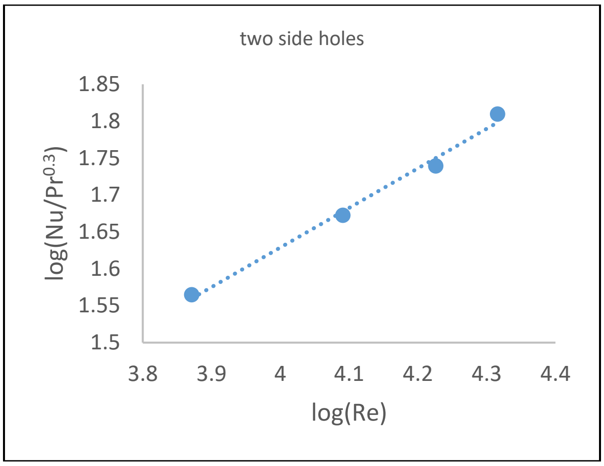


Figure 18. The empirical relationship between the (Log Re) and (Log $Nu/Pr^{0.3}$) for cylindrical sample No.2.

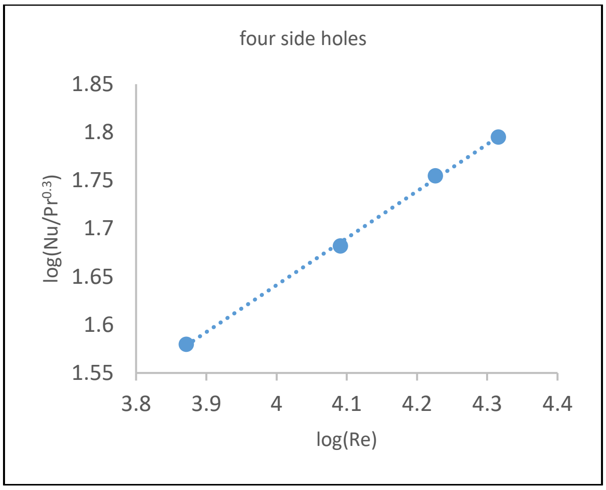


Figure 19. The empirical relationship between the (Log Re) and (Log $Nu/Pr^{0.3}$) for cylindrical sample No.3.

The relations of circular cylinders were found to be convenient compared to other researchers' relations such as those given by Zukauskas & Jakob [11] whose equation was as in the following:

$Nu = 0.1945R_e^{0.5920}Pr^{0.3}$ For a circular cylinder at Re (4000-40000).

Table III, shows the consonance between the equation derived from this research and the equation obtained from the reference [11]:

TABLE III. COMPARISON OF THE EXPERIMENTAL NUSSELT NUMBER FOR PRESENT CASE AND ZUKAUSKAS AND JAKOB [3].

sample number	Reynolds number &Prandtle number	Nu by Present case	Nu by Zukauskas and Jakob	Difference %
1	10000&0.7	39.9384	40.7801	2.06 %
2	10000&0.7	38.2222	40.7801	6.27 %
3	10000&0.7	39.6880	40.7801	2.67 %

V. CONCLUSION

An experimental study was conducted to find out the effect of increasing holes in circular cylindrical samples on the forced convection of the Reynolds Number ranged (7435-20697). The following can be concluded from this study:

- The air-flow velocity significantly effects the rate of heat dissipated. The number of holes in circular cylindrical samples also effects it. Both of these effects increase the rate of heat dissipated.
- Nusselt number is directly proportional with Reynolds number in all cases.
- Empirical relationships were obtained for the circular cylindrical samples, and it was found that they are in good comparison with the relations obtained by others.
- Further investigation should be carried out using more holes in the circular cylindrical sample.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The contributions of authors to this work are as follows:

Saif Ali Kadhim designed the samples, conducted the theoretical analysis, interpreted the results, and wrote the article. Osama Abd Al-Munaf Ibrahim supervised the experimental work. All authors had approved the final version.

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