THE EFFECT OF THE SEPARATION DISTANCE OF THE EXTERNAL BODY ON NATURAL CONVECTION REDUCTION FROM A HORIZONTAL CIRCULAR CYLINDER

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ABSTRACT

Natural convection heat transfer from a horizontal circular cylinder has been experimentally examined to study the effect of the presence of an external body in the way of the air on the heat transfer results. The experimental setup consists of an aluminum cylinder as test section with 28 mm inside diameter and 450 mm heated length, which is subjected to a constant wall heat flux boundary condition. The Rayleigh number in this investigation was ranged from $1.08*10^5$ to $5.8*10^6$. Four external bodies have been used with different separation distances parameter (L/D) 1.155, 1.44, 1.77 and 2.0. The results have shown a considerable percentage of heat transfer reduction when the separation distance (L) is greater than 1/3 of the cylinder diameter while the heat transfer process suffers appreciable reduction as the separation distance (L) is less than 1/3 of the cylinder diameter. It was concluded that there is no an appreciable effect on the heat transfer reduction when the separation distance parameter (L/D) is greater than 1.77. The average Nusselt numbers were correlated with the Rayleigh numbers with empirical correlations. The results were compared with the results of a free horizontal cylinder without external body presence.

Keywords: *External Body, Horizontal Circular Cylinder, Natural Convection Reduction, Separation Distance Effect*

1. INTRODUCTION

Thermal convection heat transfer is the process by which heat transfer takes place between a solid surface and the fluid surrounding it. If the motion of fluid is due to solely the action of buoyancy forces arising from the density variations in the fluid owing to the temperature difference between the fluid and the contacting surface, this case called natural or free convection [1]. Natural convection heat transfer from a single horizontal cylinder has been intensively investigated in the past, as witnessed by extensive review [2]. There are numerous applications, however, where heating (or cooling) is accomplished by the use of two or more horizontal cylinders. Examples of such applications, include space heating (e.g., baseboard heating), heating of oils, and heating or cooling of fluids in process plants.

The research described here is concerned with the natural convection interaction between horizontal cylinders, with specific consideration has been given to a pair of horizontal cylinders placed along and parallel to the other. Although natural convection from a horizontal cylinder has been intensively studied, limited papers have been published on natural convection heat transfer with the external body presence.

Farouk and Guceri [3] studied theoretically natural convection using a combined polar and cartesian drawing both laminar and turbulent flow ranges. They observed that the heat transfer characteristics were strongly dependent on the length of the cylinder as well as the Rayleigh number. Lieberman and Genhen [4] investigated natural convection from a horizontal cylinders array. They determined the effects on heat transfer and on the induced flow and temperature field. Marsters [5] performed experiments using three cylinders under the conditions of constant wall heat f1ux. It was observed that the heat transfer rate decreases with decreasing cylinders spacing due to interference of the buoyant flow from the preceding cylinders when the cylinders spacing was small.

Sparrow and Niethammer [6] conducted experiments on heat transfer from a pair of heated horizontal cylinders situated one above the other in a vertical plane. It was found that the upper cylinder Nusselt number takes on a maximum value as a function of separation distance. The enhancement or degradation of the upper cylinder Nusselt number relative to that for a single cylinder was strongly dependent on the separation distance. Tokura *et al.* [7] studied experimentally free convection from a cylinder array in a vertical line to examine the effect of two parallel plates enclosing the array as a heat transfer promoter. It was concluded that the heat transfer rate at downstream cylinders exhibits low values when the spacing of cylinders is small. Karvinen and Kauramaki [8] studied the effect of orientation related to vertical line, on free convection from a horizontal cylinders array immersed in water at constant wall temperature boundary condition. It was observed that the heat transfer rate of the first cylinder remains constant and equal to that of a single cylinder while the heat transfer decreases below the result of single cylinder in an infinite medium cylinders are very closely situated.

Sparrow *et al.* [9] measured Nusselt numbers for an in line array of short horizontal cylinders that were affixed to a convectively participating vertical plate. It was found that the extent to which a given cylinder in the array was affected by cylinders situated below, it depended on the Rayleigh number, with enhanced heat transfer coefficients being more likely at higher Rayleigh numbers. Yüncü and Batta [10] studied numerically laminar natural convective heat transfer in air from a pair of equitemperature horizontal cylinders

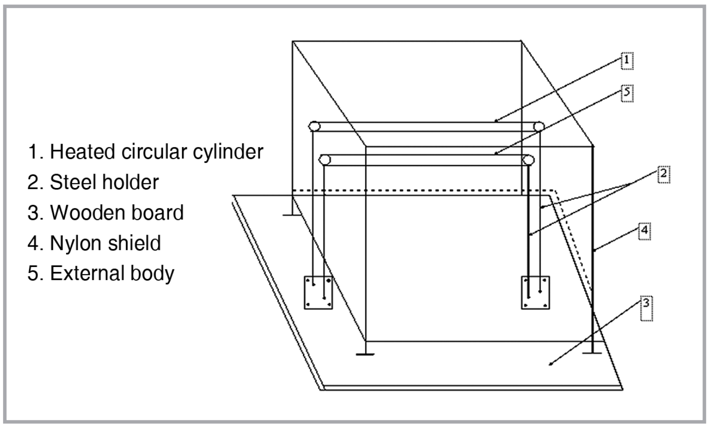

Figure 1: Schematic view of the experimental setup

placed one above the other in a vertical plane. A finite difference scheme based on the integration of the governing equations over finite cells was used. The effect of center-to-center separation distance between the cylinders on heat transfer from the upper cylinder was considered. Razelos [11] carried out an experimental investigation to study the natural convection interaction between a pair of horizontal cylinders located directly one above the other. It was found that the presence of the upper cylinder has a negligible effect on the heat transfer rate from the lower cylinder. It was also observed that the maximum enhancement of the heat transfer from the upper cylinder depends strongly on the temperature imbalance (T1/ T2) and weakly on the Rayleigh number value.

The purpose of this work is to: (i) investigate experimentally the heat transfer process from a single cylinder with the existence of an external body in a form of circular cylinder of same diameter as the working cylinder placed along and parallel to it with four different separation distances, (ii) propose empirical correlations for each case study and to compare the results with the available literature, and (iii) predict the percentage of the convection heat transfer reduction as the separation distance decreases.

2. EXPERIMENTAL SETUP AND PROCEDURE

The experimental apparatus is schematically illustrated in Figure 1. It is designed and constructed to investigate the natural convection heat transfer from a horizontal circular cylinder. The apparatus consists of a horizontal cylindrical test section supported by a steel holder. This holder was 600 mm high and is fixed on a wooden board. The heated cylinder was protected from the effect of external currents by nylon shields open at the top and permitting a free flow of air from the bottom to be entered. The conduction heat transfer from the cylinder to the holder could be reduced by using a layer of fiber glass insulation with thickness of 14 mm between the holder and the teflon ends of the horizontal cylinder. The present paper is an attempt to study the external body effects, therefore, experiments were conducted using a circular cy1inder having the same inside diameter as the working cylinder fixed along and parallel to the heated cylinder as shown in Fig. 1. The circular cylinder was made of aluminum with inner diameter of 28 mm and outer diameter of 30 mm with length of 450 mm.

2.1 HEATING ELEMENTS AND THERMOCOUPLES

The electrical heater consists of a heating coil 0.25 mm in diameter nickel-chrome wire (Omega NI60-010) with effective length of 420 mm. The heating coil was covered by a Pyrex glass tube and the ends connected to two ceramic pieces fixed to the Pyrex glass tube. The heater was covered by an asbestos layer with thickness of 3 mm. The heater with the asbestos layer was inserted inside the circular cylinder while the annular space between the heater and the inside cylinder surface was filled with asbestos powder to avoid convection from the heater to the air gap as shown in Figure 2. In order to have the heater central within the cylinder and to avoid horizontal movement of the heater inside the cylinder, two teflon flanges bolted at the ends of the cylinder. The inner diameter of the flanges is greater than the diameter of the heater ceramic which leaves an annular space at the ends of the cylinder through which the thermocouples wires passed.

Twenty eight 0.15 mm chromel-constantan insulated E-type thermocouples (Omega TF-E-30) were used with extension wire (Omega EXPP-E-20) for relaying the information to the data acquisition system. The thermocouples were attached to the outside of the cylinder wall with an epoxy adhesive (Omega bond 101) with high thermal conductivity and electrical resistivity as shown in Figure 2. Thermocouples were fixed on the external surface by making holes of 1.2 mm in diameter drilled in the wall and the

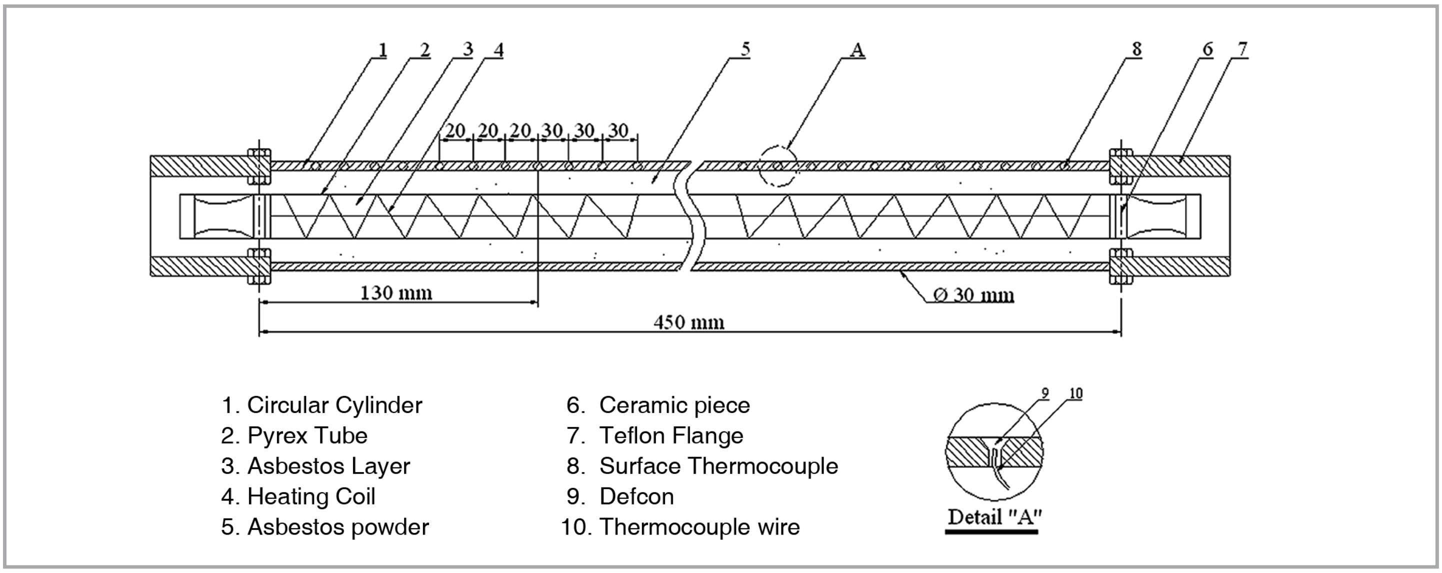

Figure 2: The construction of the heated circular cylinder

measuring junctions of the thermocouples were inserted from inside and soft soldered to the cylinder surface. The surface was cleaned and polished carefully then electroplated by nickel to minimise the radiation from the cylinder surface. The ambient temperature was measured by means of a thermocouple hung in the air far away from the cylinder. Eight chromel-constantan insulated (E-type) thermocouples were fitted around the cylinder circumference at two cylinder cross-sections and another six thermocouples were fixed at the middle of the external body to measure the mean temperature. The calibration of thermocouples and thermocouple probes showed that they were accurate to within 0.2°C.

The conduction and radiation heat exchange between the working cylinder and the holder and the external body were carefully treated and deducted from the input power. The radiation heat transfer between the surface of cylinders and the ambient walls can be calculated using the same method as outlined by Marsters [5] by assuming that the emissivity of the cylinder surface is already known. An emissivity of 0.04 was employed for the polished surface of aluminum tubes. The calculated contribution of the radiative heat transfer to the total proved to be less than 6 %.

2.2 EXPERIMENTAL PROCEDURE

The input electric power is regulated by an AC power variac and measured by a digital wattmeter with a resolution of 0.01 W. The heat transfer measurements at uniform wall heat flux boundary condition were carried out by measuring the local surface temperatures at all stations along the axis and the circumference of the cylinder. The data acquisition system used for the temperature measurements consisted of an Electronic Controls Design model 7200 data logger with 50 input channels interfaced with a personal computer.

Four cases of the separation distance parameter (L/D) 1.155, 1.44, 1.77, and 2.0 were used in the present work. The readings of all thermocouples were taken by a precalibarted digital temperature recorder capable of reading 0.01°C via a multi-switch connected to the data acquisition system interfaced with a personal computer. The steady state condition for each run was achieved after approximately 4 hours. The steady state is considered to be achieved when the temperature reading of each thermocouple did not change by more than 0.5 °C within 30 minutes. Once the steady state condition is established, the readings of all thermocouples, the input power and the inlet and outlet bulk temperatures are recorded.

2.3 UNCERTAINTY ANALYSIS

The accuracy of experimental results depends upon the accuracy of the individual measuring instruments and the manufacturing accuracy of the circular cylinder. The accuracy of any instrument is also limited by its minimum division (its sensitivity). The calculation of the error, precision, and the general validity of the experimental measurements were carried out. The probable errors in the experimental data are those some uncertainty values. This uncertainty is substantially depending upon the circumstances of experiment. In fact, the magnitude of the experimental error is always inconsistent.

In the present work, the uncertainties in heat transfer coefficient (Nusselt number), and Rayleigh number were estimated using the method outlined by Moffat [12]. The measurements are combined to calculate particular results, which are desired. Therefore, it should be informed that the uncertainty in the final result is due to the uncertainties in the measurements. Since the values of the errors in the measuring parameters may be positive or negative, then the absolute values are considered to obtain the maximum absolute uncertainty.

For a typical experiment, the total uncertainty in measuring the heater input power, temperature difference (T_s-T_o), the heat transfer rate, and the circular cylinder surface area were ± 0.22 %, ± 0.11 %, ± 1.1 %, ± 1.3 % respectively. These were combined to give a maximum error of 2.12 % in heat transfer coefficient (Nusselt number) and maximum error of 2.23 % in Rayleigh number.

2.4 DATA ANALYSIS METHOD

The heat transfer process for air flow from a horizontal circular cylinder when its surface was subjected to a constant wall heat flux boundary condition can be analysed as follows:
The total input power supplied to cylinder can be calculated as:

$$Q_t = I^2 . R \tag{1}$$

The convection heat transferred from the cylinder surface is:

$$Q_{conv.} = Q_t - Q_{cond.} \tag{2}$$

Where $Q_{cond.}$ is the total conduction heat losses (lagging and ends losses). The convection heat flux can be represented by:

$$q_{conv.} = \frac{Q_{conv.}}{\pi . D . L} \tag{3}$$

The convection heat flux was used to calculate the local and average heat transfer coefficient as:

$$h_x = \frac{q_{conv.}}{T_{sx} - T_0} \tag{4}$$

Where T_{sx} is the local surface temperature; T_0 is the ambient air temperature from the laboratory environment (which was ranged from 35 - 38 °C at the days of the experiments).
All the air properties were evaluated at the mean film temperature as reported by Incropera and DeWitt [13].

$$T_{fx} = \frac{q_{conv.}}{T_{sx} - T_0} \tag{5}$$

Where T_{fx} is the local mean film air temperature.
The local Nusselt number (Nu_x) can be determined as:

$$Nu_x = \frac{h_{x.} D}{K_x} \tag{6}$$

The average values of Nusselt number ($\overline{Nu}$) can be calculated as follows:

$$\overline{Nu} = \frac{1}{L} \int_0^L Nu_x \ dx \tag{6}$$

The average values of the other parameters can be calculated as follows:

$$\overline{T_f} = \frac{\overline{T_s} + \overline{T_0}}{2} \tag{8}$$

$$\overline{Gr} = \frac{g \ \beta \ D^3 (\overline{T_{sx}} - \overline{T_0})}{v^2} \tag{9}$$

$$\overline{Ra} = \overline{Gr}.\ Pr \tag{10}$$

Where: $\beta = 1/(273 + \overline{T_f})$, All the air physical properties (ρ, μ, ν and κ) were evaluated at the average mean film temperature ($\overline{T_f}$).

3. RESULTS AND DISCUSSION

A total of 55 runs were performed for covering both free horizontal cylinder and horizontal cylinder with an external body in which the separation distance parameter (L/D) equals to 1.155, 1.44, 1.77, and 2.0. The Rayleigh number was ranged from 1.08 x 10^5 to 5.8 x 10^6. The effect of the separation distance parameter (L/D) on the surface temperature variation and on the heat transfer reduction are described and presented in this section. The average heat transfer empirical correlations, also in this section, are proposed, presented for the horizontal circular cylinder with the external body presence and compared with the empirical correlation of a free horizontal circular cylinder.

3.1 SURFACE TEMPERATURE

The variation of the temperature difference between the surface and the air along the cylinder may be affected by many variables such as the heat flux and the separation distance parameter (L/D). This variation of temperature difference (T_s – T_o) versus the dimensionless axial distance (X/D) along the cylinder is plotted in Figures 3-5 for selected runs for a free horizontal cylinder and for a horizontal cylinder with the existence of an external body.

It can be seen from these figures that the variation of the temperature difference ($T_s – T_o$) for all cases under consideration exhibits the same general shape and show a constant temperature region at the middle of the cylinder and this value decreases gradually towards the cylinder ends. This reduction is due to the axial conduction in the cylinder and the conduction between the cylinder and the holder. Therefore, to reduce the effect of end conduction, the calculation of heat transfer coefficient was based on the mean temperature of the middle region. It was observed that the variation of the temperature difference decreases as the separation distance parameter (L/D) increases for same heat flux.

It was found that the readings of thermocouples of each cross-section are the same in all rest runs (i.e. experiments under the same conditions were conducted periodically to ensure the repeatability of the results and the difference between the duplicated experimental runs was within $\pm$ 2 %). This also means that the materials of the cylinder were of high thermal conductivity that the whole surface temperature over the entire cross-section to be uniformed. Therefore, it was accurate enough to consider the

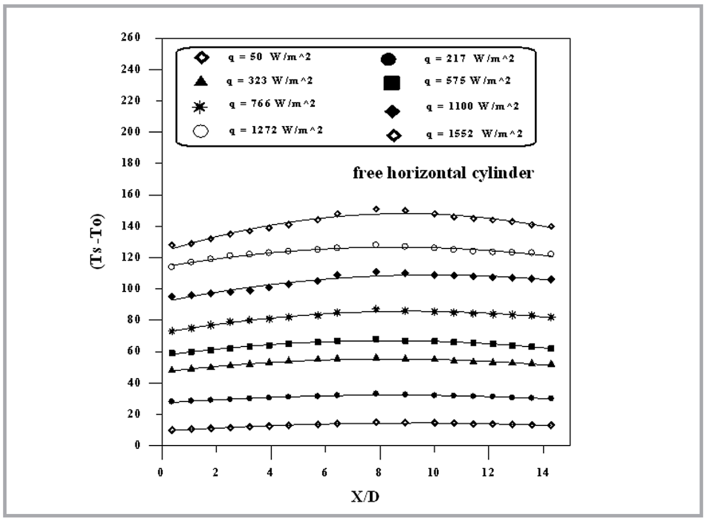

Figure 3: Variation of the temperature difference along the cylinder distance for a free horizontal cylinder

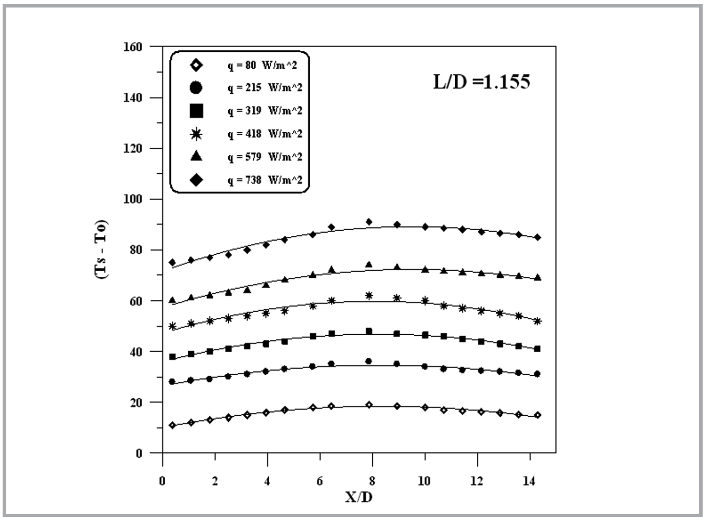

Figure 4: Variation of the temperature difference along the cylinder distance with external body (L/D=1.155)

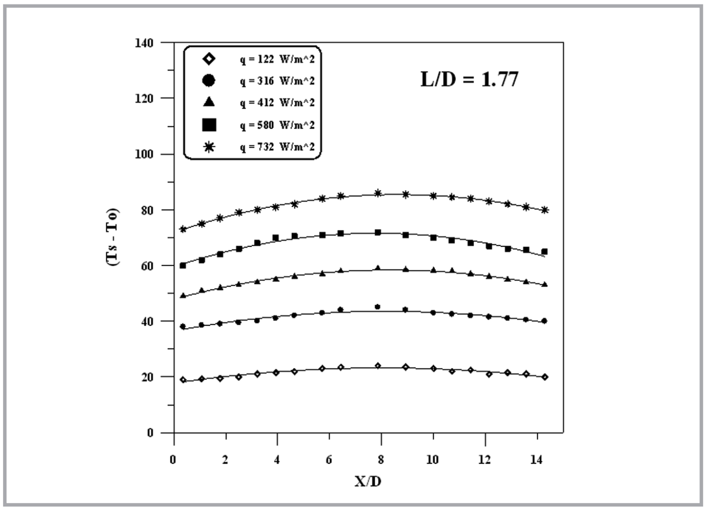

Figure 5: Variation of the temperature difference along the cylinder distance with external body (L/D=1.77)

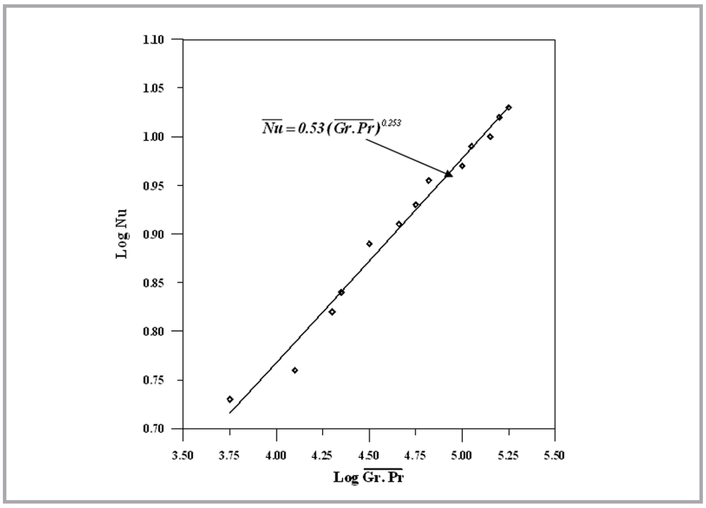

Figure 6: Variation of the average Nusselt number with the average Rayleigh number for a free horizontal cylinder

thermocouples readings installed at the top of the cylinder to be the average surface temperature.

3.2 AVERAGE HEAT TRANSFER CORRELATION

The heat transfer in this case depends on the variables Nusselt, Grashof and Prandtl numbers as shown:

$$Nu = C\,(Gr.\,Pr)^n \qquad (11)$$

The relation between average Nusselt number $\overline{Nu}$ and average Rayleigh number $\overline{Ra}$ for free cylinder is plotted in Figure 6. The present results were correlated by the following formula:

$$\overline{Nu} = 0.53\,(\overline{Gr.\,Pr})^{0.253} \qquad (12)$$

It was found that the overall accuracy of the heat transfer results in the above correlation is 5 % greater than the correlation available in the literature of [14, 15]. In spite of that, the accuracy can be considered to be good enough to provide the basis of estimation of heat transfer rate in the case where the external body is present. Figure 7 shows the heat transfer empirical correlations for horizontal cylinder with the existence of external body and the four cases under consideration. The correlations for all cases and for free cylinder are plotted together. Table 1 demonstrates the variation of C and n values as the external body position changes with respect to the heated cylinder.

Table 1 the variation of C and n values with the external body position related to the heated cylinder.

Case Study	C	n
Free cylinder, Equation (12)	0.530	0.253
With external body (L/D = 2.0)	0.527	0.254
With external body (L/D = 1.77)	0.498	0.256
With external body (L/D = 1.44)	0.487	0.258
With external body (L/D = 1.155)	0.416	0.266

Figure 7 also shows that the present of the external body suppresses the convection current. The reduction in heat transfer rate as a result of external body existence is shown in Figure 8. When the percentage of reduction in heat transfer is plotted against the separation distance parameter (L/D), it reveals a sharp increase in the percentage of reduction as the (L/D) parameter less than 1.44 while the plot is approximately linear in the range greater than 1.44. Table 2 represents the variation of Nusselt number ratio (for the cylinder with external body to the free cylinder) with separation distance parameter (L/D).

Table 2 the variation of Nusselt number ratio (Nu_e/Nu_f) with the separation distance parameter (L/D).

Separation distance parameter (L/D)	(Nu_e/Nu_f)
with external body (L/D=2.0)	0.963
with external body (L/D=1.77)	0.945
with external body (L/D=1.44)	0.924
with external body (L/D=1.155)	0.857

It was inferred from the results presented, that the separation distance of the external body which reduces the natural convection heat transfer rate affects significantly the value of the heat transfer coefficient. Furthermore, the average heat transfer correlations developed in this study, in terms of average Nusselt number with average Grashof and average Prandtl numbers, can assist the designer to consider the effect of the convection currents if the separation distance (L) less than 1/3 of the cylinder diameter.

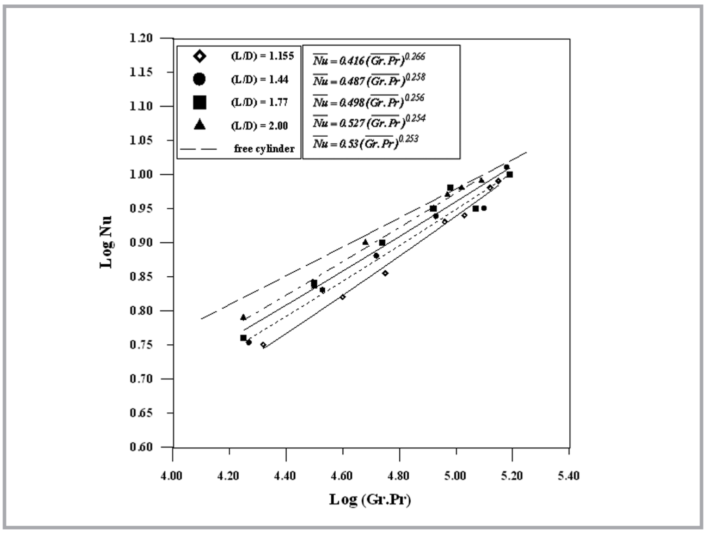

Figure 7: Comparison between natural convection from a free horizontal cylinder and a horizontal cylinder

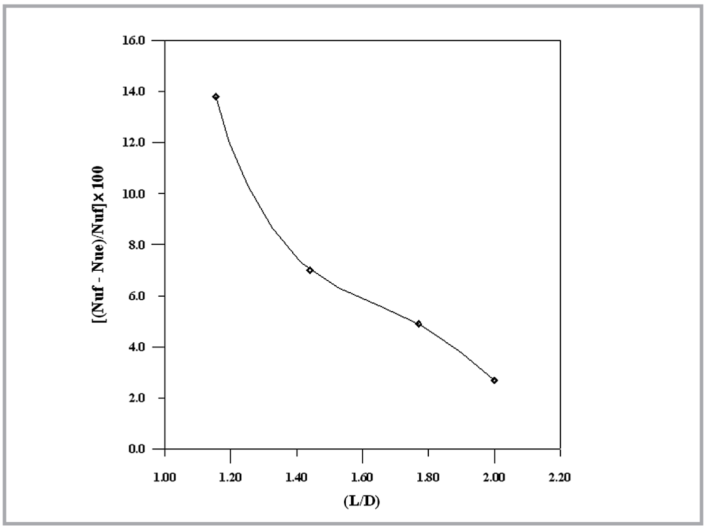

Figure 8: The variation of heat transfer reduction with the external body separation distance parameter

4. CONCLUSIONS

The heat transfer from a heated horizontal cylinder with the existence of an external body near it has been experimentally investigated. The reduction in heat transfer rate significantly depends upon the separation distance parameter (L/D) between the heated cylinder and the external body. It was found that the temperature difference between the surface and the air along the cylinder decreases as the separation distance parameter (L/D) increases. The results show a considerable percentage of heat transfer reduction when the separation distance (L) is greater than 1/3 of the cylinder diameter while the heat transfer process suffers appreciable reduction as the separation distance (L) is less than 1/3 of the cylinder diameter.

Therefore, care should be taken by the designer to superimpose both of the external body and the horizontal cylinder if the separation distance (L) is less than 1/3 of the cylinder diameter. Empirical correlations proposed for the four cases, to evaluate the average Nusselt number in terms of Rayleigh number, are agreeable with the previous works of Sparrow and Niethammer [6], and Tokura et al. [7], which indicate that the separation distance parameter (L/D) has an appreciable effect when it is less than a cylinder diameter, while Karvinen and Kauramaki [8] concluded that the effect of the first cylinder in an array is the same as of a single cylinder. ■

NOMENCLATURE

C	constant Equation (11)
C_p	specific heat at constant pressure (J/kg.°C)
D	cylinder diameter (m)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2.°C)
I	heater current (A)
κ	thermal conductivity (W/m.°C)
L	cylinder separation distance centre to centre (m)
L/D	separation distance parameter
n	constant Equation (11)
$Q_{cond.}$	conduction heat loss (W)
$q_{conv.}$	convection heat flux (W/m^2)
$Q_{conv.}$	convection heat loss (W)
Q_t	total heat input (W)
R	heater electrical resistance (Ω)
X	axial distance (m)

Greek

ΔT	temperature difference ($T_s - T_o$) (°C)
β	thermal expansion coefficient (1/K)
μ	dynamic viscosity (kg/m.s)
ν	kinematic viscosity (m^2/s)
ρ	air density (kg/m^3)

Dimensionless Group

Gr	*Grashof number*, $g\ \beta\ D^4 q\ /\ \kappa\ \nu^2$
Nu	Nusselt number, $h.D\ /\ \kappa$
Pr	Prandtl number, $\mu.Cp/\ \kappa$
Ra	Rayleigh number, $Gr.Pr$

Subscript

e	free cylinder with external body
f	free cylinder condition
o	ambient
s	surface
x	local

Superscript

— average

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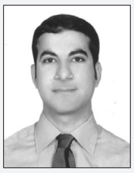

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