World Applied Sciences Journal 34 (9): 1230-1237, 2016
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2016.34.9.188

The Best Gap Length between the Black Hot Pot and Glass Bowl for the Used Greenhouse in Solar Cooker

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Abstract: The performance of solar equipments is depending on a lot of parameters. One of them is the heat losses from absorber to surrounding. Greenhouse is the best guard for absorber black pot at solar cooker from heat loss. In this paper, the heat loss from hot absorber surface to enclosure air between black pot and glass bowl was studied to obtain the best distance between them according to convection heat losses. The selected black pot and glass bowl are concentric spheres. It will be study by using a fixed black pot outer diameter (250 mm) and much different glass bowls dimensions. The gap length between black pot and glass bowl a length will be start from 1 mm to 50 mm with step 1 mm. Theoretical analyses are performed by using a computer program. The theoretical studied shows that best gap length was 13mm to obtain lowest theoretical convection heat losses. The effect of the gap length, temperature differences ΔT, Nusselt number and the Rayleigh number on average heat transfer coefficients are investigated within a range of ($1 \le \delta \le 50$) mm, ($4\pi 135^2 \le A_o \le 4\pi 185^2$) mm^2, ($5 \le \Delta T \le 55$) °C with step 5°C and $0.05354 \le Ra_\delta \le 1.588 \times 10^6$.

Key words: Solar Energy · Thermal Performance Analysis · Greenhouse

INTRODUCTION

Using the solar energy applications will be become very important, because the traditional fuel prices became more expensive. But a large amount of this energy is lost by different methods and doesn't useful of it. Heat losses can have overwhelming impacts on performance. Lamminer ntural convection in the enclosed region is currently of some interest to designers of solar equipments. In an effort to protect performance of the solar equipments from decreasing. Heat transfer by covection within these sealed enclosures would be of great benefit, providing quick and easy to use design tools for preliminary design tasks such as parametric studies and trade off analysis.

During the operation of cooking, many types of top losses are found. A radiation loss is between the cook pot to the inner glass cover "bowl". The biggest loss is the natural convection heat loss between the surface of cook pot and air of inclosed space. So, convection heat losses will be studied in this paper.

Theoretical study of heat transfer by natural convection across air layers between a black hot pot and a cold glass bowl has been carried out. A lot of the investigations on heat transfer by convection have been carried out in annular space between concentric spheres. Then, the natural convection heat loss across air layers between black pot and glass bowl is of special interest to the designers of solar cookers. One of the most important parameters in the development of analytical prototypes is the availability of experimental data.

Reduction of heat loss from the absorber black pot through the air layers improves cooker efficiency. It is anticipated that the expertness learned during the development of a natural convection prototype for the concentric spheres will be directly applicable to more difficult enclosure geometries. Theoretical accurate results are very important in order to reveal trends, such as limiting cases or transition behavior and for the validation of completed prototypes. The current investigation contains only the best gap length between the black hot pot and glass bowl for greenhouse used in solar cooker.

Recently, Horg Wen Wu, *et al*., [1], are studied the effect of the fluid viscocity in natural convection of a different temperature between vertically eccentric annuli. Also they used BDF technique, Brinkman- Darcy-Forchheimer, to simulated the fluid transfer and heat transfer inside the porous field.

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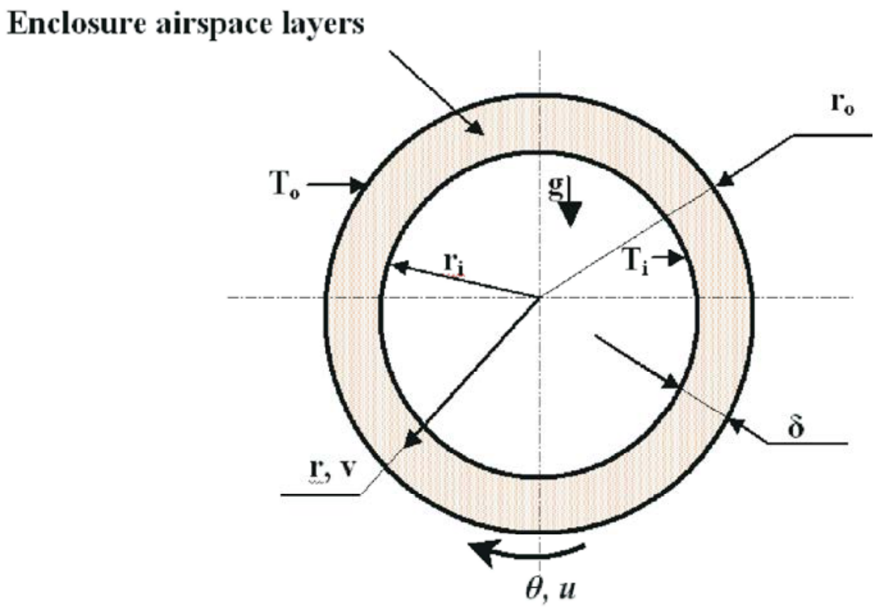

Fig. 1: Natural convection in annular space between concentric spheres.

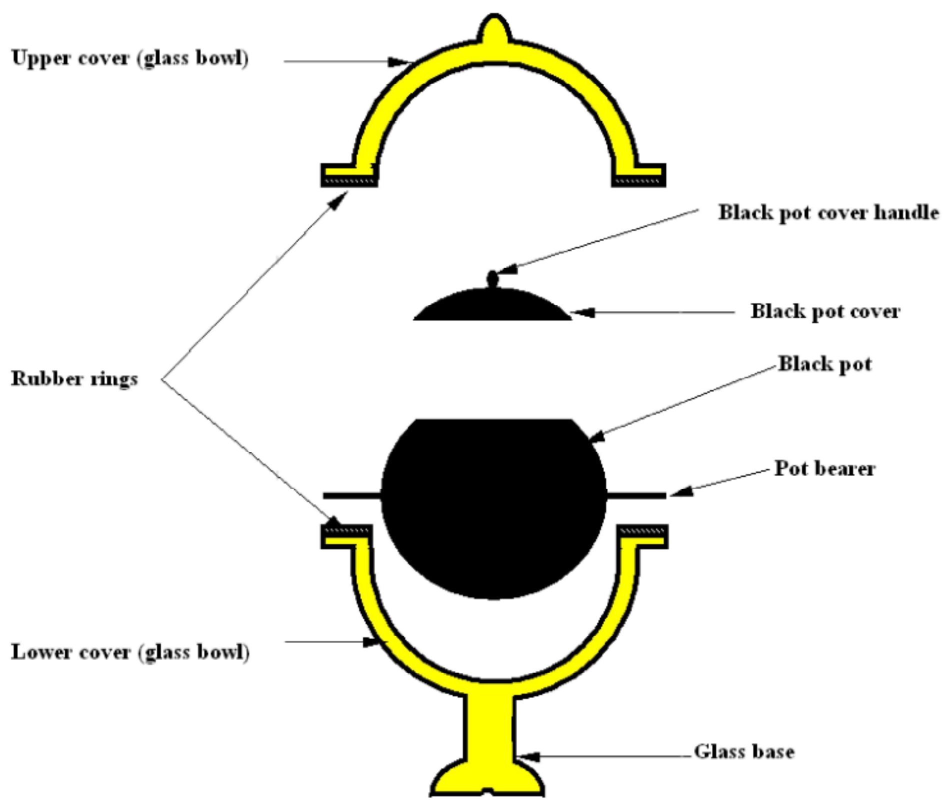

Fig. 2: Illustration drawing of the black pot and glass bowls

The heat transfer by natural convection through the concentric spheres was study from Weber *et al*. [2], Bishop *et al*. [3], Powe *et al*. [4] and Scanlan *et al*. [5]. Scanlon *et al*. [5], performed a lot of experiments on heat transfer by convection through concentric spheres and they indicated the experimental correlation as a functions of the effective thermal conductivity. And also Scanlon *et al*. [5], performed a lot of experiments for water and silicon oil filled spherical enclosures, with $4.7 \leq pr \leq 4148$ for five diameters and ratios ranging from

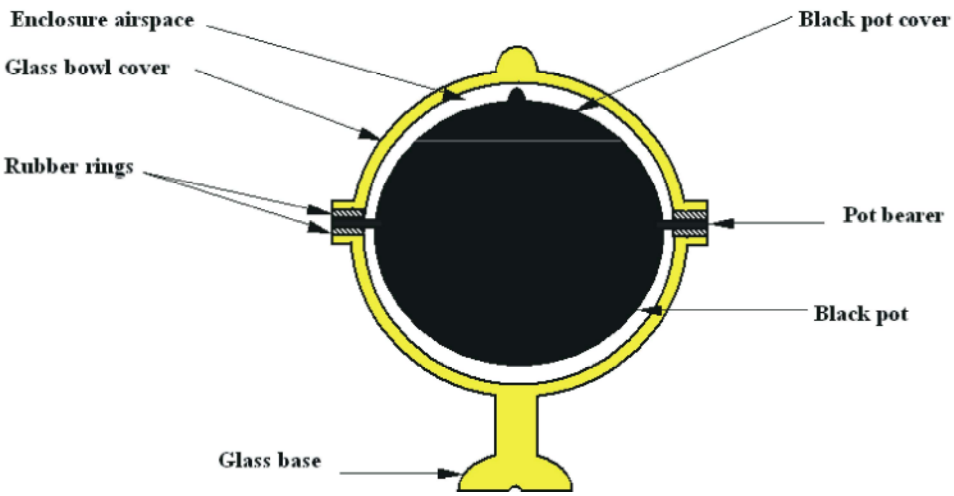

Fig. 3: Greenhouse enclosure airspace

d_o/d_i = 1.25 to 2.81. The results do not obtain the best gap length between the concentric spheres to reduction the heat loss from the absorber black pot through the air layers improves cooker efficiency.

Weber *et al*. [2] repeated the Scanlan's experiments for a gap between vertically eccentric spheres. The studies from [6] to [15], there are no exeprimental data in the current investigation for the best gap length between the black hot pot and glass bowl for greenhouse used in solar cooker.

In the current investigation is underway to develop theoretically based modeles to predict convective heat transfer in these solar equipments. The objective of this investigation is to study free convection heat transfer in confined air by a outer surface of black hot pot and an inner surface of cold glass bowl. The studies for obtained the best distance between them. Also, the objective of the current investigation is to study the condition from the lamminar boundary layer flow limit to the conductive limit when the inner surface of boundary air layer is hot and constant surface area and outer of this layer is cold.

Problem Definition: Natural convection in the gap between concentric spheres is very difficult. The only practical approach to analyze the problem is by numerical solution. The physical prototype of natural convection in annular space between the black pot and glass bowl (as a concentric spheres) is shown in Figures (1) to (3).

Since the problem is axis of symmetry for which the Eckert number can be taken as zero, one can write the simplified constant property energy equation in the spherical coordinate system (r, θ, φ) as follows:

$$\rho C_p\left[v_r\frac{\partial T}{\partial r}+\frac{v_\theta}{r}\frac{\partial T}{\partial\theta}+\frac{v_\varphi}{r\,sin\theta}\frac{\partial T}{\partial\varphi}\right]=K\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2 sin\theta}\frac{\partial}{\partial\theta}\left(sin\theta\frac{\partial T}{\partial\theta}\right)+\frac{1}{r^2 sin^2\theta}\frac{\partial^2 T}{\partial\varphi^2}\right] \tag{1}$$

were r, θ, φ are the spherical coordinates and the governing equations are [16]:

$$\frac{u}{r}\frac{\partial u}{\partial\theta}+\frac{\partial v}{\partial r}+\frac{v}{r}=0 \tag{2}$$

$$\frac{1}{r}\frac{\partial u}{\partial\theta}+v\frac{\partial v}{\partial r}+\frac{uv}{r}=-\frac{1}{\rho r}\frac{\partial p}{\partial\theta}+v\left(\frac{1}{r^2}\frac{\partial^2 u}{\partial\theta^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial r^2}-\frac{u}{r^2}+\frac{2}{r^2}\frac{\partial v}{\partial\theta}\right)-g\beta\left(T-T_{ref}\right)\sin\theta \tag{3}$$

$$\frac{u}{r}\frac{\partial v}{\partial\theta}+v\frac{\partial v}{\partial r}-\frac{u^2}{r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+v\left(\frac{1}{r^2}\frac{\partial^2 v}{\partial\theta^2}+\frac{1}{r}\frac{\partial v}{\partial r}+\frac{\partial^2 v}{\partial r^2}-\frac{u}{r^2}+\frac{2}{r^2}\frac{\partial u}{\partial\theta}\right)-g\beta\left(T-T_{ref}\right)\sin\theta \tag{4}$$

$$\frac{u}{r}\frac{\partial T}{\partial\theta}+v\frac{\partial T}{\partial r}=\alpha\left(\frac{1}{r^2}\frac{\partial^2 u}{\partial\theta^2}+\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{5}$$

where, T_{ref} is a reference temperature and:

$$p_{eff} = p + \rho g \sin\theta + \rho \cos\theta \quad (6)$$

p_{ref} is the effective pressure. Equations (1) to (4) are subject to the following boundary conditions:

$$u = 0, \frac{\partial v}{\partial \theta} = \frac{\partial T}{\partial \theta} = 0, \quad at\ \theta = 0\ \ or\ \pi \quad (7)$$

$$u = v = 0,\ T = T_i,\ \text{at } r = r_i \quad (8)$$

$$u = v = 0,\ T = T_\infty,\ \text{at } r = r_0 \quad (9)$$

where, $T_i > T_o$ the total heat transfer rate through the enclosed region is determined at the inner boundary by Yovanovich as [17]:

$$Q = \int\int_{A_i} -k\frac{\partial\theta}{\partial n}dA\,, \qquad \theta = T(\vec{r}) - T_b \quad (10)$$

where, $T(\vec{r})$ is the temperature distribution adjacent to the inner boundary along an outer facing normal, T_b is the bulk fluid temperature in the enclosure.

The average heat transfer coefficient for the enclosure h is defined based on the average heat flux from the inner boundary and the overall temperature difference:

$$h = \frac{Q_{conv}}{A_i(T_i - T_o)} \quad (11)$$

and

$$Nu_\delta = \frac{h\delta}{k} \quad (12)$$

where, Nu_δ is the Nusselt number.

The Rayleigh number is defined using the same parameters:

$$Ra_\delta = \frac{g\beta\,(T_i - T_o)\delta^3}{\nu\alpha} \quad (13)$$

Purpose: The purpose of the analysis is to examine one of the thermal design parameters for greenhouse cook pots used in low-cost solar cookers. The analysis concentrates on methods of the heat losses by convection, so that it is obtained to the best gap length between hot black pot and glass bowl. The greenhouse is an important consideration in virtually all solar thermal systems because outdoor exposure and the consequential heat loss of this exposure is a necessary design consideration of such systems, especially in low-cost solar cookers.

RESULTS

According to Scanlon and *et al*. [5], the convection heat losses between the outer absorber surface of black cook pot and the inner glass surface of bowl Q_{conv} can be as follows:

$$Q_{conv} = \frac{4\pi\, k_e\, r_i\, r_o}{\delta}(T_i - T_o) \quad (14)$$

where K_e is the effective thermal conductivity and can be calculated by Scanlon and *et al*. [5]:

$$\frac{K_e}{K_{air}} = 0.228\,(Ra^*)^{0.226} \quad (15)$$

where: $1.2 \times 10^2 < Ra^* < 1.1 \times 10^9$, $0.7 < Pr < 4148$ and

$$Ra^* = \frac{g\beta\delta^4(T_i - T_o)}{\nu\alpha r_i} = Ra_\delta\left(\frac{\delta}{r_i}\right) \quad (16)$$

The input data to the computer program were organized in different forms to give more flexibility to enter any combination of data. At first the computer program computes different parameters every δ= 1mm and ΔT=5°C, from (δ= 1 to 50 mm and the step is 1 mm) and (ΔT = 10 to 55°C and the step is 5 °C). Figures (4) shows the comparison between theoretical heat losses by convection with different gap lengths δ at ΔT = 55°C (*for example*). It is observed from this figure that the theoretical heat losses by convection Q_{conv} at different gap lengths δ is the lowest at δ = 13 mm. Figure (5) shows the variation of the theoretical convection losses, Q_{conv} with gap length δ at different temperature differences, ΔT=45, 50, 55°C. From this Figure, it is observed that the theoretical heat losses by convection Q_{conv} is the lowest at the same gap length, i. e. at δ = 13 mm. For concentric spheres and at small values of the gap length δ when Grashof number is less than 2000 ($Gr > 2000$), it must be, the heat transfer is a necessary by conduction, then Nusselt number is constant and equal one when $Gr > 2000$ and as shown in Figures (6) and (7). At this condition, it is a necessary, the effective thermal conductivity "K_e" equals the actual thermal conductivity K, where:

$$Nu_\delta = \frac{h\,\delta}{K} = \frac{K_e}{K} \quad (17)$$

and

$$Q_{conv} = \frac{4\pi\, k_e\, r_i\, r_o}{\delta}(T_i - T_o) \quad (18)$$

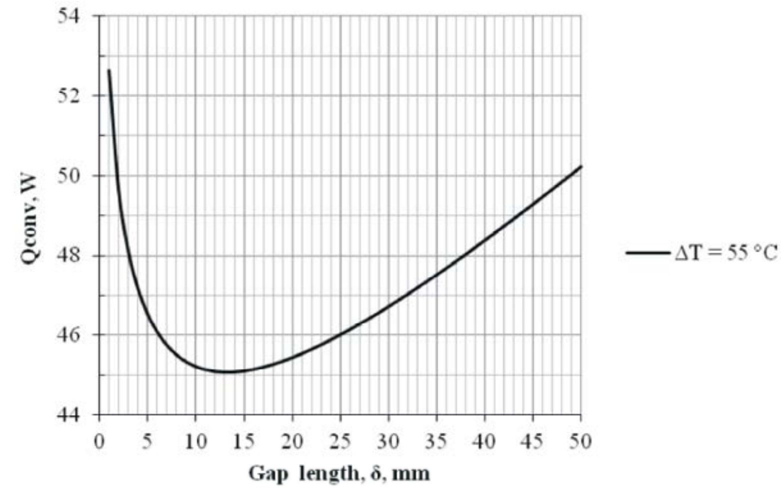

Fig. 4: Variation of the theoretical convection losses, Q_{conv} with gap length δ at temperature difference ΔT=55°C (for example)

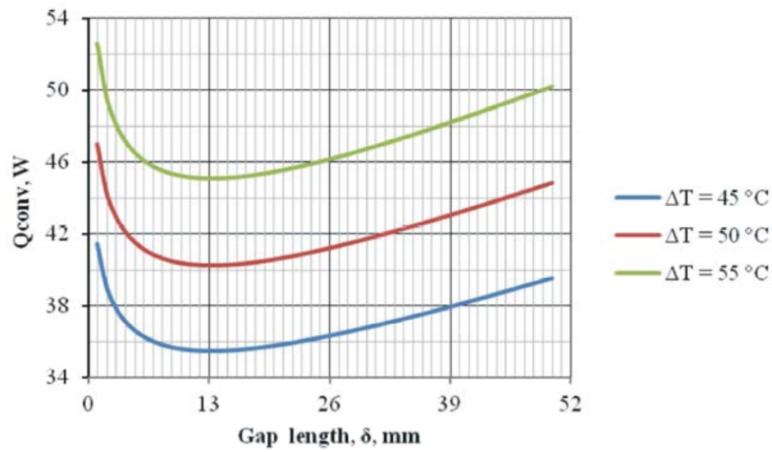

Fig. 5: Variation of the theoretical convection losses, Q_{conv}, with gap length δ at different temperature differences, ΔT=45, 50, 55 °C (for example)

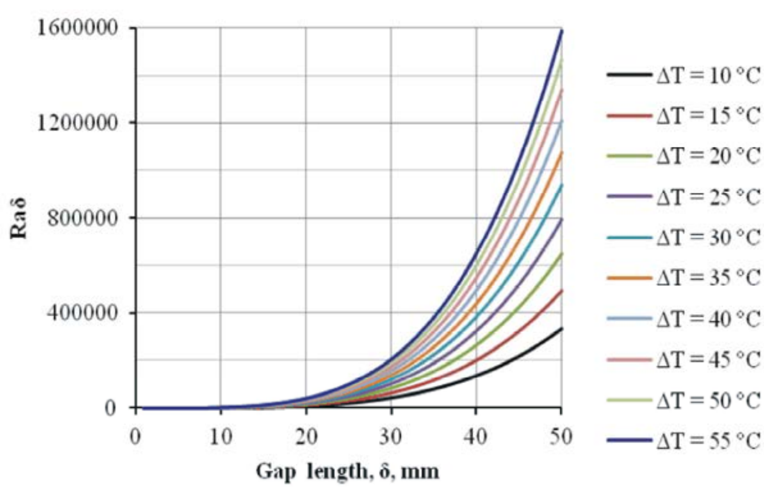

Fig. 6: Variation of the theoretical Rayleigh number, Ra_{δ}, with gap length δ at different temperature differences, ΔT

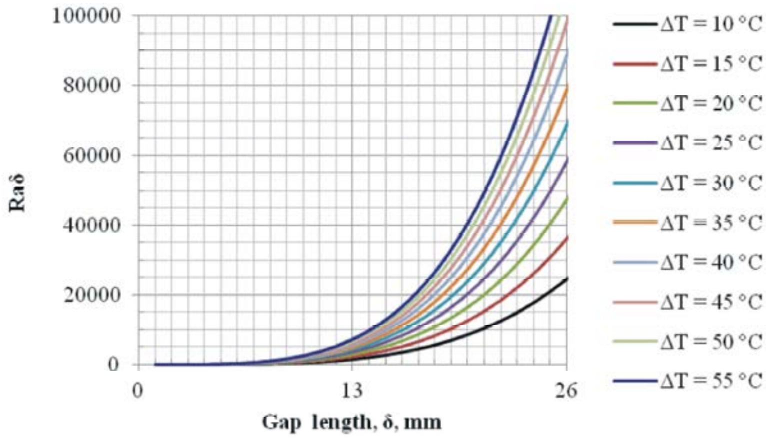

Fig. 7: Variation of the theoretical Rayleigh number, Ra_δ, with gap length δ (from δ=1 to 26 mm) at different temperature differences, ΔT

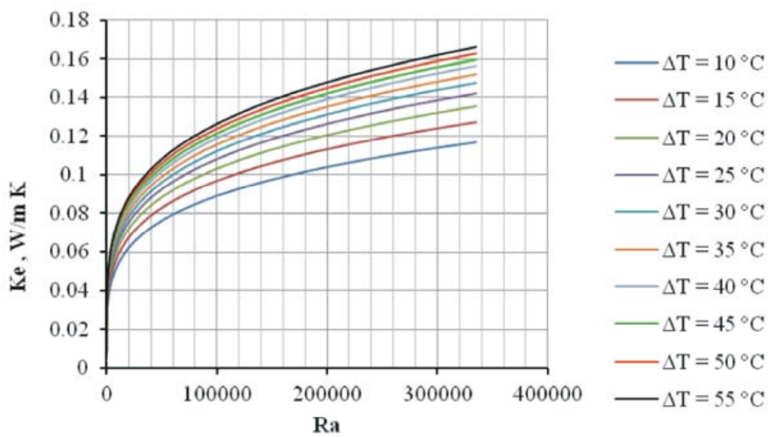

Fig. 8: Variation of the theoretical Rayleigh number, Ra_δ, with effective thermal conductivity K_e

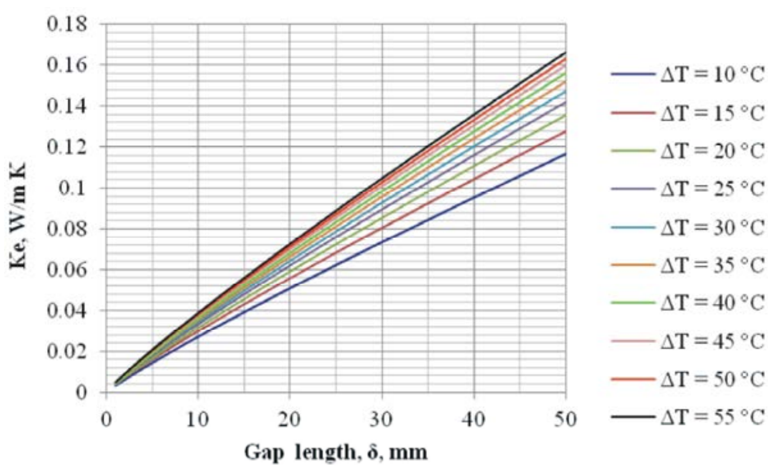

Fig. 9: Variation of the effective thermal conductivity K_e with gap length δ at different temperature differences, ΔT

The data are indicating by the smooth transition from conduction to convection dominated heat transfer that occurs as seen in Figures (6) and (7). But, when the Grashof number is more than 2000 ($Gr < 2000$), it must be, the heat transfer is a necessary by convection. At this condition, K_e is greater than K. The effect of gap length on the effective thermal conductivity K_e and the effect of Rayleigh number, Ra_δ, on the effective thermal conductivity K_e shows in Figures (8) and (9) respectively.

Equation [17] can rearrange as follow:

$$Q_{conv} = \frac{4\pi\, k_e\, r_i\,(r_i + \delta)}{\delta}(T_i - T_o) \qquad (19)$$

Point of Inflection: It observed that from Figures (4) and (5), the point of inflection occurs at gap length δ equals 13 mm due to:

- According to heat transfer principals

When the gap length δ is very small (one mm) so the air volume in an enclosure is very small also and the inner layer temperature is maximum which call forth conduction heat transfer through the enclosure air layers. But the gap length δ is continues to increscent and the air volume in an enclosure is increasing although the difference of temperature is constant, so the convection heat transfer is decreasing until the gap length δ equals 13 mm. After the point of inflection, the convection heat transfer is increasing based on two main criteria. First, because the air volume in an enclosure is increasing due to the gap length δ is continues to increscent. Second, the densities difference of enclosure air occurs. So, quickly convection currents occur from down to up which call forth the convection heat transfer is an increscent and as seen in Figures (4) and (5).

- According to mathematical principals

In Equation (18), the numerator and denominator have a gap length δ, so the quotient group has a point of inflection. This point is the lowest heat convection loss and at gap length equals 13 mm and as seen in Figures (4) and (5).

CONCLUSION

The aim of the research project is obtained the best distance between the black pot and glass bowl. The best gap length is 13 mm to obtain lowest convection heat losses.

Nomenclature of Symbols: Symbols used by others have been altered in all the formulas shown in this paper and have been listed alphabetically.

English Symbols

A = sphere surface area, m^2
C_p = heat capacity of water, J/kg K
d = diameter, m
= is form for expressing "derivative"
g = gravitational acceleration and equal 9.81 m/s^2
Gr = Grashof number, $g\delta^3\beta\,\Delta T/\,v^2$, dimensionless
h = heat transfer coefficient by convection, W/m^2K
K = Thermal conductivity, W/mK
Nu = Nusselt numbe, $h\delta/K$, dimensionless
p = air pressure, Pa
Pr = Prandtl number, $\mu Cp/K$, dimensionless
Q = heat transfer, W
r = radius, m
Ra = Rayleigh number, $g\delta^3\beta\,\Delta T/\,v\alpha$, dimensionless
T = temperature, K
ΔT = temperature difference, $=T_i$-T_o, K
u = angular velocity, rad/s
v = liner velocity, m/s

Greek Symbols

α = thermal diffusivity of air, m^2/s
β = thermal extended coefficient, K^{-1}
δ = gap thickness, = r_o - r_i, m
ε = effectiveness
μ = dynamic viscosity, N s /m2
ν = kinematic viscosity, m2/s
π = pi is the ratio of circumference of circle to its diameter and equals 3.14159
= in a angular measure π radians is equal to 180°
ρ = density, kg/m^3
σ = Stephen- Boltzmann constant = 5.67 ?10^{-8} W/m^2K^4
θ = angle, rad
◎◎ = partial differential

Subscripts

cond = Conduction losses
conv = convection losses
e = effective
encl = enclosure
g = glass bowl
i = inner boundary layers of air
o = outer boundary layers of air
rad = radiation losses
ref = reference
tot = total

Coordinates

r, θ, φ = spherical coordinates

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