EXPERIMENTAL STUDY OF RADIATION HEAT TRANSFER OVER VERTICALLY PLACED CIRCULAR DISKS

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***Abstract*— The radiation heat transfer over vertically placed circular disks under vacuum and air medium were experimentally investigated. Two type's disks black and grey were considered for the study, which were placed vertically inside a heated chamber called an oven. A constant temperature was imposed inside the chamber. The chamber was partially vacuumed to prepare vacuum medium by controlling the air pressure with -0.8 to 0.6 bar. To understand the heat transfer, time requirement to obtain certain temperatures and heat transfer coefficient were calculated. Correlation between temperature and heat transfer coefficient were also analyzed. The findings highlighted that black disk provided the highest heat transfer coefficient and the lowest time requirement to achieve a certain temperature. Polynomial relationships between temperature and heat transfer coefficient for black and grey disks with R^2 less than 1 were obtained through the trendlines.**

***Keywords*— radiation heat transfer, heat transfer coefficient, temperature, polynomial relations, black disk and grey disk.**

I. INTRODUCTION

In various engineering application the combined impact of radiation and natural convection heat transfer is necessary. Many electronic devices, such as laptops and mobile phones, can benefit from natural convection combined with radiation as a dependable source of cooling. Cooling such gadgets can help them last longer by reducing battery consumption.

Over several decades, scientists and engineers have been working on solving problems related to heat transfer by applying different strategies involving design improvement and optimization. In 1884 Boltzmann turned his attention to the subject of thermal radiation, which had been attracting increasing attention since G Kirchhoff showed the relation between emittance and absorptance, in 1860. By 1879, another Austrian, Josef Stefan, had shown experimentally that the heat radiated from a hot, thermally black object, should rise with the fourth power of its absolute temperature Boltzmann used a very clever heat engine argument to prove that this was exactly true. In the 1960s, there was a growing trend to publish solutions for non-existing problems, which caused widespread concern. During the 1970s, researchers went in a very different direction, which led to some very good results. Heat exchanger analysis was overlooked during the 1960s while researchers significantly increased the number of, analytical methodologies, and design concepts in this field.

Various electronic components, such as laptops, cell phones, etc., can be effectively cooled by the combination of natural convection and radiation. Cooling these gadgets can reduce their power consumption and extend their battery life. A lot of research has been done on steady-state natural convection heat transfer from a horizontal cylinder under conditions of constant temperature or constant heat flux (Sadeghipour and Asheghi, 1994; Hatton *et al.*, 1970; Weder, 1968). They investigated the influence of cylinder orientation and distance between cylinders for optimal convection heat transfer. Morgan (1975) published a review on natural convection from smooth, circular cylinders in which he documented numerous experimental and numerical results under various flow and heating settings, as well as several correlations. The effect of heat transmission on the angular and radial velocity around a cylinder in air was studied by Kuehn and Goldstein (1980), for Rayleigh number ≤107. In addition, Saitoh *et al*. (1993) used finite difference methods to analyze the numerical convection heat transfer from a cylinder when it was placed in air. Kuehn and Goldstein (1980), Qureshi and Ahmed (1987), Chouikh *et al.* (1998) and Cesini *et al.* (1999) have all demonstrated that the heat transfer is greatest towards the bottom of the cylinder and diminishes above. The decrease in heat transfer attributes to an increase of the thermal boundary layer thickness and heat transfer.

Numerous research have been conducted on laminar and turbulent natural convection or mixed convection heat transfer coupled with radiation heat transfer on vertical walls and in enclosures (Chouikh *et al.*, 1998; Cesini *et al.*, 1999). A number of researchers (Talabani *et al.*, 2013; Zeyghami *et al.*, 2015; Zhao *et al.*, 1992) have studied the influence of thermal radiation on natural convection for a cylinder. Novotny and Kelleher (1967) investigated the laminar free convection of an absorbing, emitting gas at the stagnation point of a horizontal cylinder. Hossain *et al.* (1998) also investigated the influence of radiation on free convection from an isothermal vertical cylinder and mixed convection from a horizontal cylinder.

Several studies in literature investigated the combined effect of thermal radiation and natural convection heat transfer in an enclosure or flat wall. However, the experimental study of radiation and natural convection heat transfer over circular disk under vacuum and air medium is limited in literature. As a result, none of the known correlations are capable of accurately predicting the heat transfer that occurs around the heated disk. The radiation effects from vertically placed horizontal cylinders under a constant temperature condition have not yet been examined, which motivates the current work. Moreover, the relationship between temperature and heat transfer coefficient was not properly evaluated in literature. The literature also reported several evaluations for steady-state and transient natural convection heat transfer from discrete heat sources in vertical rectangular channel (Bhowmik and Tou, 2005; Bhowmik *et al.*, 2004), and this fundamental arrangement has not been explored for radiation heat transfer. The current experimental work analyzes the process of cooling a heated disks (black and grey) that is positioned vertically inside a heated chamber (oven). The cooling is achieved by the radiation heat transfer which. This study also analyzes the effect of the time, temperature and the heat transfer coefficient on the disks circumference, under vacuum medium. Finally, a correlation equation for predicting the heat transfer characteristics around the disk is showed through trendlines.

II. METHODS

A. Experimental Set-up and Procedures

The experimental setup consists of a heated chamber which is an oven with outside tength 15cm and height 14cm, mounted at the top of the circular cylinder of 26cm, as shown in Fig. 1(a). The chamber is made by aluminum at outside. Inside the chamber, constant temperature is maintained. The black or grey disk is placed vertically at the middle of the chamber with the help of a rod which is covered by a cylinder. The disk is placed at the middle of the chamber so that heat from all side can be flown to the disk. The black disk and grey disk are attached with a rod Ktype thermocouple. The temperature of oven and bodies are obtained from the monitor of the device.

All experiments are conducted without inlet velocity in to the test section. Two circular plates one is black and another one is grey was investigated under vacuumed and air medium. The dimensions of the plates were constant. The temperature of the chamber was maintained 240°C to perform the experiment. The time required to gain 70°C to 190°C by the bodies were measured.

At the beginning of the experiment to stabilize the temperature of the cold heat exchanger, cooling water was turned on. Then the sample cylindrical rod with black body/grey body was placed "up" position. During calculating only radiation heat transfer to stop heat transfer by natural convection, partial vacuum was made inside the oven using the vacuum pump by controlling the pressure -0.8 to -0.6 bar. After switching on, to stabilize the temperature overall 30 minutes were required. The thermal properties of the black and grey disks is provided in Table 1.

B. Experimental Data Analyses

The rate of radiation heat transfer between these two surfaces is given by

$$Q = \varepsilon A_s \sigma (T_e^4 - T^4) \qquad (1)$$

where, A_s is area of the black/grey body, ε is the emissivity, T is the surface temperature of the black/grey body, T_e is the chamber temperature and σ is the Boltzmann constant.

Table 1: Thermal properties of Black and Grey bodies

Properties	Black Disk	Grey Disk
Mass of body, M	1.2 gm	1.16 gm
Specific heat, S	386 J/kg ^{0}C	415J/kg ^{0}C
Surface area, A_s	2 cm ^{2}	2 cm ^{2}
Emissivity of surface, ε	ε < 1(ε = 1)	ε = 0.935

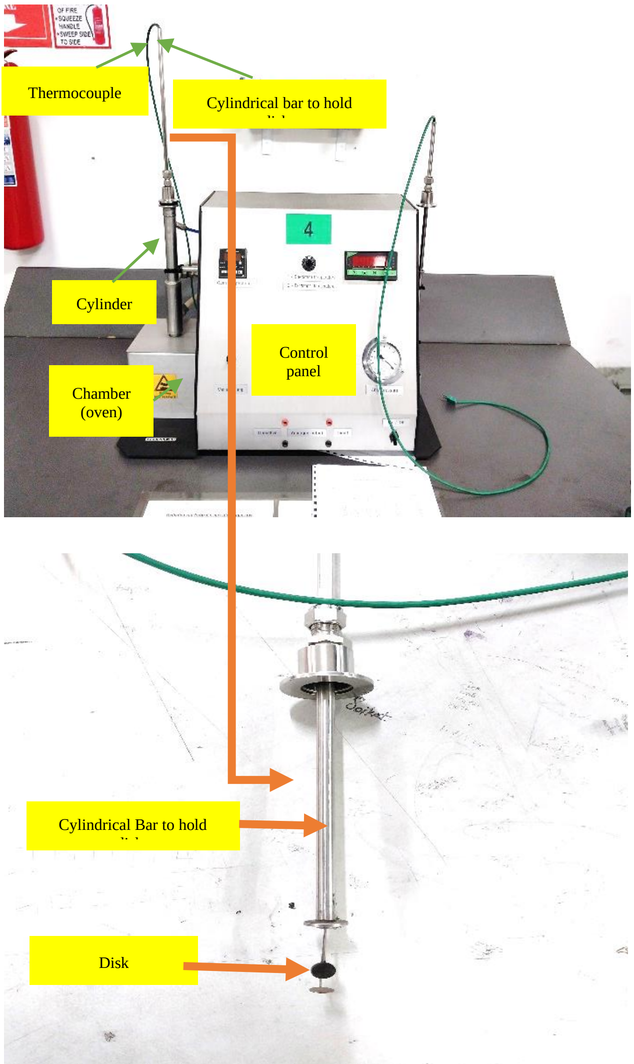

Figure 1: Experimental rig of the study.

The Boltzmann constant σ can be identified from the following equation and verify with standard value.

$$\sigma = \frac{MC\left(\frac{dT}{dt}\right)}{A_s(T_e^4 - T^4)} \frac{W}{m^2}.K^4 \qquad (2)$$

where, M is the mass and C is the specific capacity of the black/grey body.

The radiative heat transfer coefficients can be obtained as follows:

$$h_r = \varepsilon\sigma \frac{T_e^4 - T^4}{T_e - T} \qquad (3)$$

where, K is the thermal conductivity of the fluid inside the chamber and L_y is the characteristic length of the radiative surface (black/grey).

C. Experimental Uncertainty Analyses

The uncertainty associated with each measurement technique is measured with the policy on uncertainty (Jong *et al.,* 1993). Heat loss due to conduction is minimized by the design of the equipment and assumed to be unaffected by the conduction from the cylinder. However, only the combined effect of convection and radiation heat transfer, which are occurred in air medium from heated chamber, is considered. The uncertainty of the temperature measurements is calculated and found to be less than 1% that provides the uncertainties of Nu and h are about 6.5% and 3.5%, respectively. These values are based on the assumption of negligible uncertainty in the relevant fluid properties.

D. Experimental validation

For validating the experimental results, the Stefan-Boltzman law was checked with experimental data by using the equation 2. The standard theoretical value of Stefan-Boltzman constant is 5.67×10^{-8} $\mathrm{W/m^2.K^4}$. by using the experimental data in equation 2, 6.09×10^{-8} $\mathrm{W/m^2.K^4}$ value was obtained for the Stefan-Boltzman constant which provided good agreement with theory within below 10% error.

III. RESULTS

The findings of the experimental study mainly describe the time requirement and heat transfer coefficient for different oven temperature for black and grey disks to understand the heat transfer relationship. Under vacuumed condition in the chamber, only radiation heat transfer is occurred over black and grey bodies. Inside the chamber to achieve, the temperature from 70°C to 190°C by grey and black bodies the required time is presented in Fig. 2. For both black and grey disk time requirement to obtain desired heat is increasing with rise in temperature. To increase temperature 120°C for black disk 182.03s was required whereas for grey disk the required time was 402.42s. According to Boltzmann's law, the heat transfer capability of black disk is higher compared to grey disk therefore within a short time black disk obtained 70°C to 190°C temperature whereas grey disk needed 55% more time compared to black disk to achieve the desired temperature.

To measure the heat transfer rate, the heat transfer coefficient was calculated under vacuumed conditions for both black and grey disk and presents in Fig. 3. The figure presented that with increase in temperature both black and grey disk provided enhancement in heat transfer coefficient in polynomial order. The results indicated that black disk provided better heat transfer rate compared to grey disk. In details, black disk showed maximum heat transfer coefficient 32.09 $W/m^2.K$ while grey disk showed maximum heat transfer coefficient 17.40158 $W/m^2.K$ at a constant temperature 190°C. However, to rise the temperature from 70°C to 190°C both black and grey disk showed 70.1% enhancement in heat transfer coefficient. Due to the highest absorption and emission, capacity of black disk the highest heat transfer coefficient compared to grey disk was observed. Additionally, the mass of the grey body is lower and specific heat is higher compared to black body which also responsible for the heat transfer of black disk.

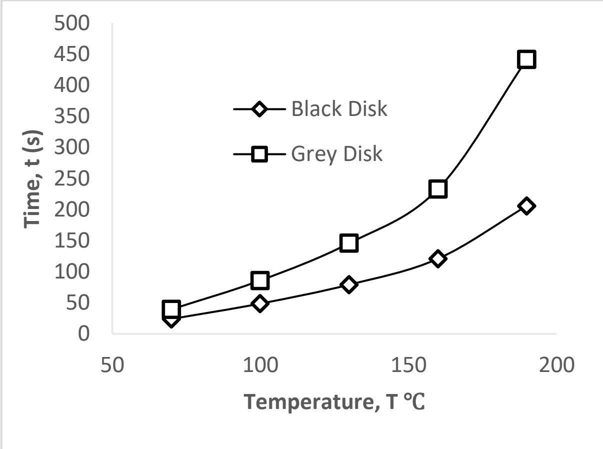

Figure 2: Time requirement to rise temperature from 70°C to 190°C

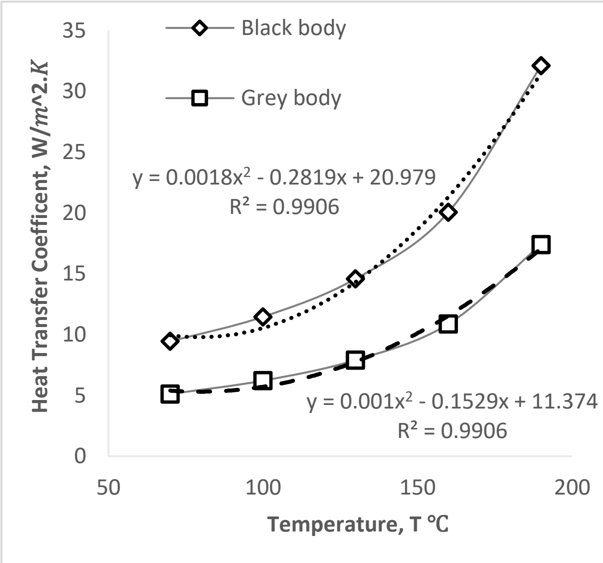

Figure 3: Variation of heat transfer coefficient with Temperature

To understand the correlation between heat transfer coefficient and Temperature trend lines are plotted for the black and grey disk wherein polynomial trend lines are perfectly suited for both bodies with o.9906 R^2.

Through polynomial trend lines the obtained correlations are as follows-

$$y = 0.0018x^2 - 0.2819x + 20.979 \text{ for black body;}$$

$$y = 0.001x^2 - 0.1529x + 11.374 \text{ for grey body}$$

The minimum and maximum heat transfer coefficient was obtained at temperature 70°C and 190°C, respectively which is presented in Fig. 4. Due to the increase in temperature, the heat transfer coefficient also enhance accordingly. To gain temperature from minimum to maximum, the requirement of time is presented in Fig. 5. In oven, it was taken 23.86s to gain 70°C and 205.89s to gain 190°C for black body which reflects that to obtain maximum heat transfer, maximum time is also required.

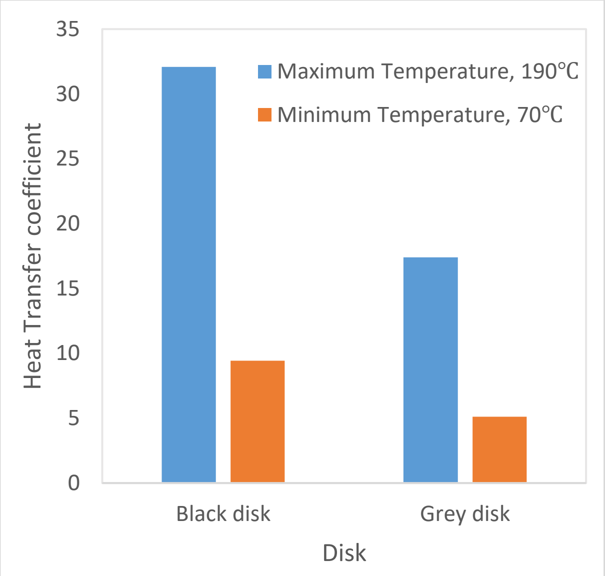

Figure 4: Heat transfer coefficient for maximum and minimum temperature.

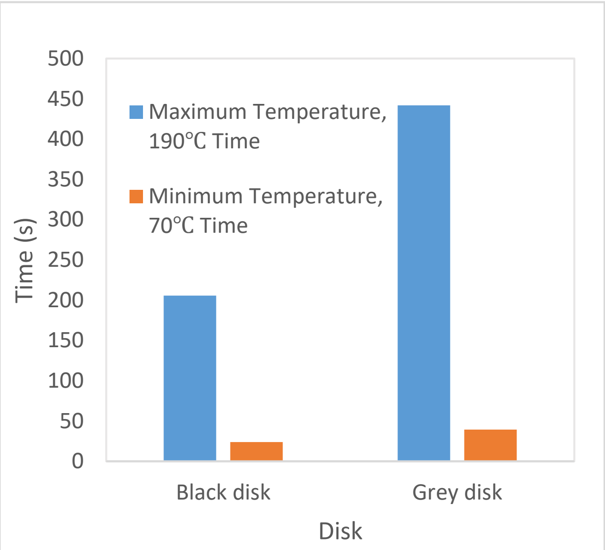

Figure 5: Time to gain maximum and minimum temperature.

V. CONCLUSIONS

The combined radiation heat transfer over vertically placed circular disks are experimentally investigated. To understand the heat transfer, time requirement to obtain certain temperatures and heat transfer coefficient were calculated. The key findings of the study are as follows-

1. Compare to grey disk, black disk required the lowest time to obtain 70℃ *to* 190℃ temperature at constant chamber temperature. To increase temperature 120℃, black disk required 182.03s and grey disk required 402.42s for vacuumed medium while for air medium the black disk required 152.41s and the grey disk required 184.55s time.
2. Black disk provided the highest heat transfer coefficient for both mediums. Moreover, air medium showed 49% and 99.97% higher heat transfer coefficient for black and grey disk respectively compared to vacuum medium.
3. The trendlines are showed polynomial relationships between temperature and heat transfer coefficient for black and grey disk under both mediums with R^2 less than 1.

ACKNOWLEDGEMENT

Authors are acknowledged Sub Assistant Engineer Md Nazmul Hussain from Heat Transfer Laboratory in Military Institute of Science and Technology, Bangladesh to assist in experimental setup and data collection.

NOMENCLATURE

A_s	area of the black/grey body
ε	emissivity,
T	surface temperature of the black/grey body
T_e	chamber temperature
M	mass
C	specific capacity of the black/grey body
σ	Boltzmann constant
K	thermal conductivity of fluid in the chamber
L_y	characteristic length of the radiative surface.

REFERENCES

Bhowmik, H. and Tou, K.W. (2004) Experimental study of transient natural convection heat transfer from simulated electronics chips. *Exp. Ther. Fluid Sci*. **29**, 485-492.

Bhowmik, H., Tou, K.W. and Tso, C.P. (2004) Water cooling study of natural convection heat transfer from simulated electronic chips during power-on transient period. *Proc. IEEE Semiconductor Thermal Measurement and Management Symposium*. 130-134.

Cesini, G., Paroncini, M., Cortella, G. and Manzan, M. (1999) Natural convection from a horizontal cylinder in a rectangular cavity. *Int. J. Heat Mass Tran*. **42**, 1801-1811.

Chouikh, R., Guizani, A., Maalej, M. and Belghith, A. (1998) Numerical study of the laminar natural convection flow around horizontal isothermal cylinder. *Ren. Energy*. **13**, 77–88

Hatton, A., James, D. and Swire H. (1970) Combined forced and natural convection with low-speed air flow over horizontal cylinders. *J Fluid Mech*. **42**, 17–31.

Hossain, M.A., Alim, M.A. and Rees D.A.S. (1998) Effect of thermal radiation on natural convection over cylinders of elliptic cross section. *Acta Mech*. **129**, 177-186.

Jong, H.K., Terrence, W., Simon, R.V. (1993) Journal of Heat Transfer Policy on Reporting Uncertainties in Experimental Measurements and Results. *ASME J. Heat Transfer*, **115**, 5-6.

Kuehn, T.H. and Goldstein, R.J. (1980) Numerical solution to the Navier-Stokes equations for laminar natural convection about a horizontal isothermal circular cylinder. *Int. J. Heat Mass Tran.* **23**, 971-979.

Morgan, V. (1975) The overall convective heat transfers from smooth circular cylinders. *Adv. Heat Transfer*. **11**, 199-269.

Novotny, J.L. and Kelleher, M.D. (1967) Free-convection stagnation flow of an absorbing-emitting gas. *Int. J. Heat Mass Trans*. **10**, 1171-1178.

Qureshi, Z. and Ahmad, R. (1987) Natural convection from a uniform heat flux horizontal cylinder at moderate Rayleigh numbers. *Num. Heat Tran*. **11**, 199– 212.

Sadeghipour, M.S. and Asheghi, M. (1994) Free convection heat transfers from arrays of vertically separated horizontal cylinders at low Rayleigh numbers. *Int. J. Heat Mass Transfer.* **37**, 103-109.

Saitoh, T., Sajiki, T. and Maruhara, K. (1993) Bench mark solutions to natural convection heat transfer problem around a horizontal circular cylinder. *Int. J. Heat Mass Tran.* **36**, 1251-1259.

Talabani, Z.J. and Mohammed, A.K. (2013) Thermal Radiation and Free Convection Heat Transfer from Horizontal and Vertical Cylinders in enclosed system. *Int. J. Adv. Engg. Sci. Tech*. **2**, 213-219.

Weder, E. (1968) Messung des gleichzeitigen Wärme- und stoffübergangs am horizontalen Zylinder bei freier Konvecktion. *Wärme Stoffübergangs.* **1**, 10–14.

Zeyghami, M. and Rahman, M.M. (2015) Analysis of Combined Natural Convection and Radiation Heat Transfer Using a Similarity Solution. *Energy Research J*. **6**, 64-73.

Zhao, Z., Poulikakos, D. and Rent, Z. (1992) Combined Natural convection and Radiation from heated cylinders inside a container. *J. Therm. Heat Tran*. **6**, 713- 720.

Received: July 26, 2022
Sent to Subject Editor: October 24, 2022
Accepted: February 9, 2023
Recommended by Subject Editor Gianfranco Caruso