Analysis of Entropy Generation for Horizontal Heated Cylinder by Natural Convection and Radiation

Louay Abd Al-Azez Mahdi
Energy and Renewable Energies Technology Center, University of Technology -Iraq

Mohammed A. Fayad
Energy and Renewable Energies Technology Center, University of Technology -Iraq

Miqdam T. Chaichan
Energy and Renewable Energies Technology Center, University of Technology -Iraq

https://doi.org/10.5109/6792884

出版情報：Evergreen. 10 (2), pp.888-896, 2023-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Analysis of Entropy Generation for Horizontal Heated Cylinder by Natural Convection and Radiation

Louay Abd Al-Azez Mahdi[1], Mohammed A. Fayad[1], Miqdam T. Chaichan[1*]
[1]Energy and Renewable Energies Technology Center, University of Technology -Iraq

E-mail: Miqdam.t.chaichan@uotechnology.edu.iq

(Received March 16, 2023; Revised April 16, 2023; accepted April 23, 2023).

Abstract: Because of the complexity involved, most researchers avoid studying the entropy generation due to both convection and radiation. In this study, the heat transfers from the horizontal heated cylinder by natural convection and radiation and the entropy generation is the case study and the ability to combine of these two heat transfer methods depending on the thermodynamic principles. Three heating horizontal cylinders were used during this study. The results indicated that the natural convection is effective parameter to produce the entropy generation when the ratio of Ra/Ra, opt lower than 1 and the Ns increased slightly to 3 at Ra/Ra, opt=0.001, but when the radiation is the effective parameter to produce the entropy generation that is done when Ra/Ra, opt higher than 1 and the Ns increases to 200 at Ra/Ra, opt=1000.

Keywords: Thermal system; entropy generation analysis; natural convection; radiation; horizontal cylinder

1. Introduction

Climate change and the ozone layer depletion are the most direct threats to humanity[1) 2)]. Increasing levels of greenhouse gases in the troposphere have been caused by human activities such as burning forests, clearing agricultural lands, and using fossil fuels excessively[3)]. On a national scale, most studies estimate that 35% to 49% of the energy used for comfort conditions in residential and industrial buildings goes towards providing comfort[4) 5) 6)]. Residential, commercial, and industrial refrigeration systems are widely used to remove heat from a variety of processes. All fields and applications use heat exchange processes[7) 8)]. Heat exchanges in all system in the three known styles: conduction, convection and radiation [9) 10)]. In all this processes entropy changes according to Newton's 2nd low[11)].

Entropy is a thermodynamic property which is just a measure of the magnitude of molecular disturbance inside a thermal system. The high-grade molecular perturbation system has an extremely high entropy generation[12)]. On the other hand, the thermal system with a very low level of molecular disruption has a very low generation of entropy. The first law of thermodynamics defined yield as the ratio of labor power to the total heat entering the system which does not provide a lot of information about the efficient use of available energy (irreversibility)[13)]. In a heat system, particular attention should be given to improving energy efficiency by analyzing lost energy which can be evaluated under the second law of thermodynamics. The second law of thermodynamics can be applied to investigate irreversibility in terms of how quickly entropy occurs where the distributed energy is commensurate with the production of the entropy[14)]. One of the key features of entropy generation analysis is that it is more attractive than conventional approaches to energy balance. Entropy generation analysis can be used for any type of energy conversion process.

Natural convection from horizontal cylinder was experimentally studied and the correlation with non-dimensional groups presented by[15) 16) 17) 18) 19) 20)].

Previous studies by Churchill et al.[21)] and Morgan[22) 23)] used the data to found experimental correlations depend on non-dimensional groups Nu and Ra. The natural convection from horizontal cylinder also studied numerically by Merkin and Pop[24)], CHOUIKH et al.[25)], Miana et al.[26)], Sebastian and Shine[27)], Sedighi and Aghighi[28)]. Experiment and numerical study for natural convection from horizontal cylinder were presented by[29) 30) 31)]. The computational fluid dynamics (CFD) also used to study the free convection above a heated horizontal cylinder as mentioned by[32) 33)34)]. The entropy generation by natural convection from horizontal cylinder was examined by [35) 36) 37) 38) 39) 40) 41)42)]. The entropy generation by radiation from horizontal cylinder and surfaces was studied by [43) 44) 45) 46) 47)].

The review studies for entropy generation were presented by Sciacovelli et al.[48)], which analyzed different types of engineering systems. Biswal et al.[49)] analyzed the entropy generation of natural convection in various cases and processes involving different practical applications.

Chen et al.[50] used the optimization of convective heat transfer processes to model a multi-objective optimization issue in the entropy-based approach and a constrained optimization issue in the entransy-based approach.

Morsli, S. et al.[51] study the entropy generation numerically for burner working with hydrogen- air. Said K. et al.[52] studied the entropy generation done by natural convection heat transfer for Square Cavity with different inclination. Zemani-Kaci et al.[53] numerically analyzed the natural convection for square cavity on side heated while the other cooled.

The wire on tube condenser is one of scientific interests in part of refrigerator thermal system. The thermal analysis for this type of heat exchanger includes the refrigerant inside the tube and the air outside the tube. The loss of available energy via the production of entropy on the air side is due to natural convection and radiation.

For the air side of the wire on tube condenser; trying to find simple relation depending on the thermodynamic principles between the natural convection and radiation entropy generation. It was started with the horizontal heated cylinder to find the relation and its limitations like the radiation entropy generation range and the natural convection entropy generation range. Also, the optimum working point between the radiation effect and natural convection effect. The previous works [35)- 39)] covered the forced convection and pressure drop entropy generation around horizontal cylinder and not cover the natural convection and radiation entropy generation.

In the literature review, most researchers avoid studying the mutual effects of convection and radiation heat transfer from different surfaces on entropy generation. A common reason for this avoidance is the complexity of describing the overlap value and the constant change in the proportions of influence. So, this study aims to examine the correlation between natural convection and radiation for a horizontal heated cylinder on its entropy generation. It is the first step towards analyzing the overlap between both modes and the direct effects it has on entropy generation

2. Entropy generation thermodynamic model

The entropy generation rate in steady state external flow for a control volume shown in figure (1) may be given as follows:

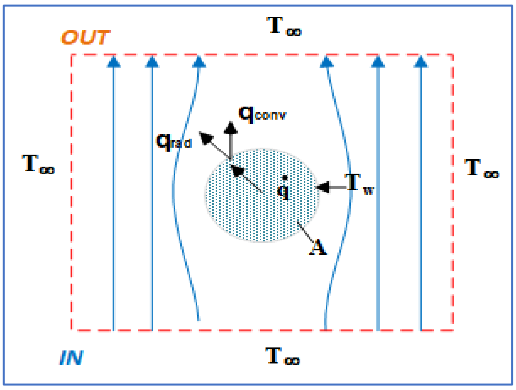

Figure 1 Control volume for entropy generation by natural convection and radiation.

Balancing for mass:

$$\dot{m}_{in} = \dot{m}_{out} \qquad (1)$$

Balancing for heat:

$$\dot{m}_{in} h_{in} - \dot{m}_{out}\, h_{out} + \iint q''\, dA = 0 \qquad (2)$$

Entropy generation balance:

$$\dot{S}_{gen} = \dot{m}_{out} s_{out} - \dot{m}_{in} s_{in} - \iint \frac{q'' dA}{T_s} \qquad (3)$$

The Gibbs equation [54)] is:

$$dh = TdS + VdP \qquad (4)$$

Applying Gibbs equation for the control volume in figure (1), equation (2) gives:

$$\dot{m}_{in} h_{in} - \dot{m}_{out}\, h_{out} = T_\infty(\, \dot{m}_{out} s_{out} - \dot{m}_{in} s_{in}) + \frac{\dot{m}_{in}}{\rho_\infty}\,(P_{out} - P_{in}) \qquad (5)$$

In natural convection, the second term for the pressure drop may be neglected due to low magnitude.

Following equations (3 and 5), the average control volume amounts are assumed to be equal to the free flow quantities.

Combination of eq. (1) and eq. (5) and substitution in eq. (2):

$$\dot{S}_{gen} = \iint q''\left(\frac{1}{T_\infty} - \frac{1}{T_s}\right) dA \qquad (6)$$

Assume the $|T_s - T_\infty|$ is smaller than absolute T_s or T_∞, Eq. (6) can be expanding in Taylor series and by neglected the terms of second and higher orders[55) 56)]:

$$\dot{S}_{gen} = \frac{1}{T_\infty^2} \iint q''_{conv}(T_s - T_\infty) dA \qquad (7)$$

The temperature related to heat fluxes may be gives as:

$$T_s - T_\infty = \frac{q''_{conv}}{\alpha_{conv}} \qquad (8)$$

Substitute in eq. (7):

$$\dot{S}_{gen} = \frac{q^{2''}_{conv}}{T_\infty^2} \int \frac{dA}{\alpha_{conv}} \qquad (9)$$

Where the outside area = $\pi \cdot D_o \cdot l$

$$\dot{S}_{gen}\Big/l = \frac{q''^2_{conv}}{T_\infty^2}\int_0^\pi \frac{D_o * d\theta}{\alpha_{conv}}$$

$$\dot{S}_{gen}\Big/l = \frac{q''^2_{conv} * D_o}{T_\infty^2}\int_0^\pi \frac{d\theta}{\alpha_{conv}}$$

The general form for the solution of the natural convection is[56]:

$$Nu = m * Ra_D^n$$

$$\frac{\alpha_{conv} * D_o}{k_a} = m * Ra_D^n$$

$$\alpha_{conv} = \frac{m * Ra_D^n * k_a}{D_o} \qquad (10)$$

Substitute in equation (9)

$$\dot{S}_{gen}\Big/l = \frac{q''^2_{conv} * D_o}{T_\infty^2}\int_0^\pi \frac{D_o\, d\theta}{m * Ra_D^n * k_a}$$

$$\dot{S}_{gen}\Big/l = \frac{q''^2_{conv} * * D_o^2 * \pi}{m * T_\infty^2 * k_a * Ra_D^n}$$

where $q_{conv}{}''^2 = \frac{q'^2}{\pi^2 * D_o^2}$

$$\dot{S}_{gen}\Big/l = \frac{q'^2_{conv}}{m * T_\infty^2 * \pi * k_a * Ra_D^n} \qquad (11)$$

The term in right hand for eq. (7) represent the entropy generation due to the heat and done because of the convection and radiation, therefore add term to eq. (7) in order to represent the radiation;

$$\dot{S}_{gen} = q''_{rad}\left(\frac{1}{T_\infty} - \frac{1}{T_s}\right) \qquad (12)$$

$$\dot{S}_{gen} = \frac{1}{T_\infty^2}\iint q''_{rad}(T_s - T_\infty)dA$$

Also, $T_s - T_\infty = \frac{q''_{rad}}{\alpha_{rad}}$

$$\dot{S}_{gen} = \frac{q''^2_{rad}}{T_\infty^2}\int \frac{dA}{\alpha_{rad}}$$

$$\dot{S}_{gen}\Big/l = \frac{q''^2_{rad} D_o}{T_\infty^2}\int_0^\pi \frac{d\theta}{\alpha_{rad}}$$

where $\alpha_{rad} = \frac{\varepsilon * \sigma * (T_s^4 - T_\infty^4)}{(T_s - T_\infty)}$ [54], the equation become:

$$\frac{\dot{S}_{gen}}{l} = \frac{q''^2_{rad}}{T_\infty^2}\,\frac{\pi\, D_o\,(T_s - T_\infty)}{\varepsilon\sigma(T_s^4 - T_\infty^4)} \quad \text{where} \quad q''^2 = \frac{q'^2}{\pi^2 * D_o^2}$$

$$\frac{\dot{S}_{gen}}{l} = \frac{q'^2_{rad} * (T_s - T_\infty)}{\pi * D_o * T_\infty^2 * \varepsilon * \sigma * (T_s^4 - T_\infty^4)}$$

The summation of (convection and radiation) be:

$$\dot{S}_{gen}\Big/l = \frac{q'^2_{conv} * Ra_D^n}{m * T_\infty^2 * \pi * k_a} + \frac{q'^2_{rad} * (T_s - T_\infty)}{\pi * D_o * T_\infty^2 * \varepsilon * \sigma * (T_s^4 - T_\infty^4)} \qquad (13)$$

in order to find Ra number in this term to be like the first term which represent the convection, multiply (13) equation by the following term:

$$\frac{g * \frac{1}{T_m} * \rho^2 * D_o^3}{\mu^2} * \frac{Pr}{Pr} * \frac{\mu^2}{g * \frac{1}{T_m} * \rho^2 * D_o^3}$$

Equation (13) be:

$$\frac{\dot{S}_{gen}}{l} = \frac{q'^2_{conv} * Ra_D^{-n}}{m * T_\infty^2 * \pi * k_a} +$$

$$\frac{q'^2_{rad} * Ra * \mu^2}{T_\infty^2 * \pi * \varepsilon * \sigma * Pr * g * \frac{1}{T_m} * \rho^2 * D_o^4 * (T_s^4 - T_\infty^4)} \qquad (14)$$

Rearrangement equation (14), considering the variable parameter is Ra while others are constant, equation (14) become:

$$\frac{\dot{S}_{gen}}{l} = Ra_D^{-n} \cdot \mathcal{A} + Ra_D \cdot \mathcal{B} \qquad (15)$$

By differencing Equation (15) and equating the results to zero:

$$\frac{d\frac{\dot{S}_{gen}}{l}}{dRa_D} = 0 = -n * Ra_{D,opt}^{-n-1} * \mathcal{A} + Ra_{D,opt} \cdot \mathcal{B}$$

$$n * Ra_{D,opt}^{-n-1} * \mathcal{A} = \mathcal{B}$$

$n * Ra_{D,opt}^{-n} = \frac{\mathcal{B}}{\mathcal{A}}$ and the

$$Duty\ factor = \frac{\mathcal{A}}{\mathcal{B}} \qquad (16)$$

the duty factor is important to find the Ra,opt that is used to create the ratio Ra/Ra,opt with Ns on figure 3 to determine the case in range of the natural or radiation.

And the new form of eq. (15) be:

$$\frac{\dot{S}_{gen,opt}}{l} = Ra_{D,opt}^{-n} \cdot \mathcal{A} + Ra_{D,opt} \cdot \mathcal{B} \qquad (17)$$

The fraction of the result equation is the first term 4/5 due to the effect of the natural convection of the total heat transfers, while the radiation takes the fraction 1/5 of the total heat transfers according to the experimental work and its results and Pareto theory. this percentage is not constant, it is change according to the effect of each part, the natural convection and the radiation.

Dividing equation (15) by equation (17) the result gives the entropy generation number (Ns).

$$N_s = \frac{4}{5}\left(\frac{Ra_D}{Ra_{D,opt}}\right)^{-n} + \frac{1}{5}\left(\frac{Ra_D}{Ra_{D,opt}}\right) \qquad (18)$$

Using the correlation for constant heat flux by Kim[16]:

$Nu = 0.57 \,.\, Ra^{0.2}$ for $10^{2} < Ra < 10^{7}$ (19)

The above equation is suitable to this study experimental test, the form of eq. (18) be:

$$N_s = \frac{4}{5}\left(\frac{Ra_D}{Ra_{D,opt}}\right)^{-0.2} + \frac{1}{5}\left(\frac{Ra_D}{Ra_{D,opt}}\right) \quad (20)$$

The ratio of the radiation heat effect to natural convection is irreversibility distribution ratio $\emptyset$ in this case can be represent by:

$$\emptyset = Ra_{D,opt} \cdot \mathcal{B}/Ra_{D,opt}^{-n} \cdot \mathcal{A} \quad (21)$$

The optimum value for the entropy generation is at the ratio $\frac{Ra_D}{Ra_{D,opt}}$=1 and entropy generation number must be Ns=1.

Be is another irreversibility distribution ratio which defined by [36) 37) 38)]; Bejan number is:

$$Be = \frac{1}{1+\emptyset} \quad (22)$$

3. Experimental work

The test was carried out using three heated cylinders, which consist of a cast iron tube with a diameter of 6.56, 7.86, and 11.1 mm. There is also a resistance heater inside the tube. These diameters for the heaters are the available sizes in local markets. However, larger sizes are not available. A Regavolt variable transformer was used to supply power to the heaters. The power output is 0-6 amperes and 0-220 volts. The input power was the source of single-phase power. The cylinder heater was fixed from the ends by wood pieces with a height of 30 cm from the base table. This was done in order to eliminate the effect of the base on the flow of air by the bouncy forces of natural convection. Three temperature sensors were used to evaluate the cylinder surface at three different angles (bottom, top, at 90° from the bottom) and one to assess the environmental temperature. A digital thermometer FLUKE CNX HVAC was connected to the thermocouples (K-type). In figure 2, we can see a measuring device, as well as the volt and ampere. DS devices and services company model AE1&RD1 was used to measure surface emissivity. The tests were done in a large room environment.

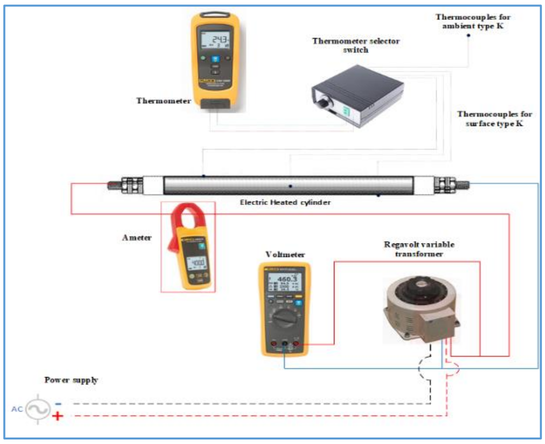

Fig. 2: the experimental rig for testing the cylinder electric heaters

The uncertainty for the measuring parameters as shown in Table 1.

Table 1 the uncertainty of measuring parameters

parameters	I Ampere	Volt	$T_{s\ avg}$ °C	T_∞ °C	ε
Accuracy	±0.1 of full scale	±2 of full scale	±1.5 °C	±1.5 °C	±0.01

4. Results and discussion

Figure (3) shows the entropy generation number via the ratio of Ra/Ra, opt of the natural convection and radiation-heated cylinder. The lowest entropy generation occurs at Ns=1 and Ra/Ra, opt=1. The optimum point for entropy generation is where the natural convection effect is 4/5 and the radiation impact is 1/5.

When Ra/Ra, opt < 1 the natural convection heat transfer is dominated for entropy generation. Ns increased above the optimum point by a few points and reached Ns=3 when the ratio of Ra/Ra, opt was 0.001Radiation heat transfer is the effective parameter for entropy generation when Ra/Ra, opt >1.1. The Ns increased sharply to Ns=200 at Ra/Ra, opt be 1000.

The experimental data for the three heated cylinders are near the optimum point. The data of the large diameter cylinder will be in the natural convection area, while the data of the small diameter cylinder will be in the radiation area. According to our research objective, the larger diameter heated horizontal cylinder results in better heat transfer on the air side of the wire-on-tube heat exchanger owing to lower entropy generation, while the smaller diameter horizontal cylinder results in a more efficient heater design.

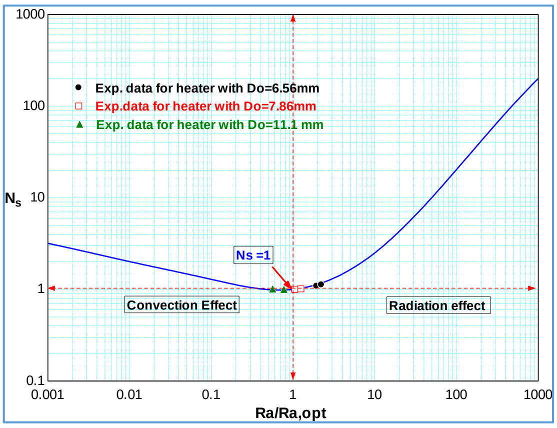

Fig. 3: the ratio of Ra/Ra, opt and entropy generation number.

In order to obtain Ra/Ra, opt for Figure (3). Finding Ra, opt is vital to completing the analysis. Equation 17 from the analysis defines the duty factor and can be applied to find Ra, as shown in Figure (4).

The duty factor is the result of dividing the natural convective heat transfer coefficient in the first term of equation 16 by the radiant heat transfer coefficient in the second term.

Results of this study indicate a positive relationship between the duty factor and Ra, opt of the heated cylinder. The results show that the duty factor increases as the Ra, opt of the heated cylinder increases. This study's experimental data was collected in areas where Ra, opt values were less than 10^4.

This is a variant of Figures (1) and (2), representing forced convection flow around heat cylinders. It did not give a duty factor value at low values of forced convection flow than normally occurs during natural convection.

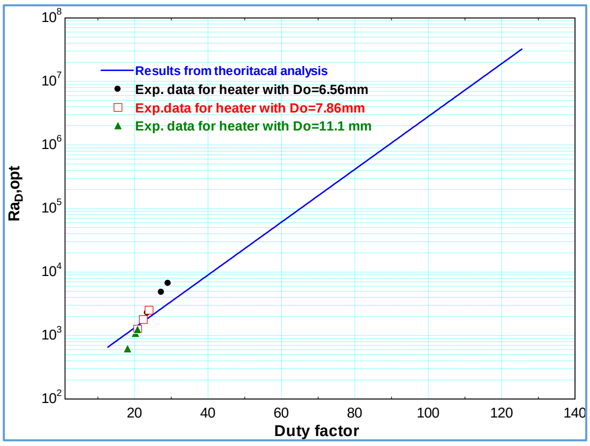

Fig. 4: The duty factor and Ra, opt for the experimental data.

The irreversibility distribution ratio (Ø) is identified in [36,37,38] as the ratio of entropy generation by friction to entropy generation by forced convection. This definition is not suitable for the case of natural convection and radiation. Therefore, the revised definition is the ratio of entropy generation by radiation to entropy generation by natural convection as shown in Figure (5).

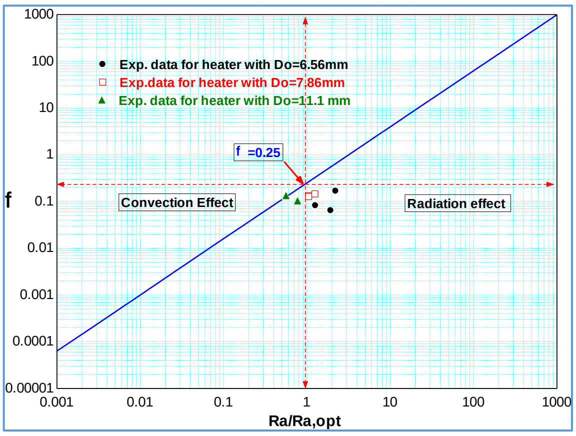

Fig. 5: the irreversibility distribution ratio Ø and Ra/Ra,opt.

According to the figure, the irreversibility distribution ratio Ø and Ra/Ra, opt are positively related. At Ra/Ra, opt=1, the optimal entropy generation value, the value of Ø=2.5 produces a low entropy generation number Ns=1.

As determined by the irreversibility distribution ratio Ø, the effect of radiation decreases and the effect of natural convection increases when Ra/Ra, opt Ø= 1. However, when Ra/Ra, opt > 1, the effect is inverse. In the experiments, the small diameter heated cylinder was located in the radiation effect range, while the large diameter heated cylinder was located in the convection effect range.

According to references [36,37,38], the Bejan Number and the alternative distribution parameter (Be). The relationship between the generation of entropy from forced convection heat transfer and the sum of the generation of entropy from convection heat and the pressure drop. In this study, the appropriate definition is the ratio of entropy generation by natural convection heat transfer to total entropy generation by natural convection and radiation.

Figure (6) represents the relationship between Bejan Number (Be) and the Ratio of Ra/Ra,opt of the natural convection and radiation of a heated cylinder.

The irreversibility of natural convection heat transfer dominates when Be=1, while at Be=0 the opposite effect of radiation dominates.

When Be = 0.8, entropy generation by radiation and natural convection will both be at a maximum point (Ns=1, Ra/Ra, opt=1) with lower entropy generation for the thermal system.

As shown in Figure (6), the data consist of a large diameter heated cylinder located in the natural convection effect area, while the small diameter heated cylinder was located in the radiation effect area.

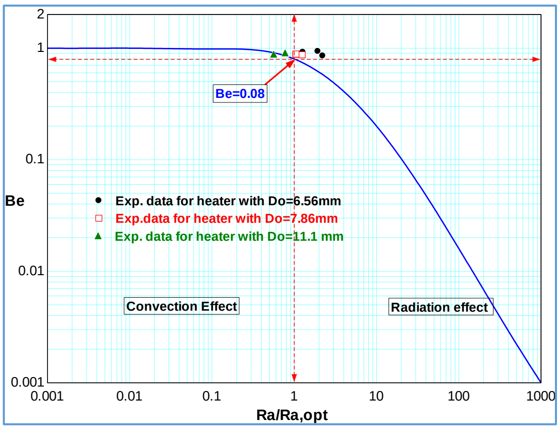

Fig. 6: The ratio of Ra/Ra, opt and Bejan Number.

The equations of Mc Adams[15] and Morgan[22] are represented in the table along with the experimental data of the heated cylinders in this study. The average deviation between the experimental data and references[15,16] is approximately 20%, and 5% with reference[22].

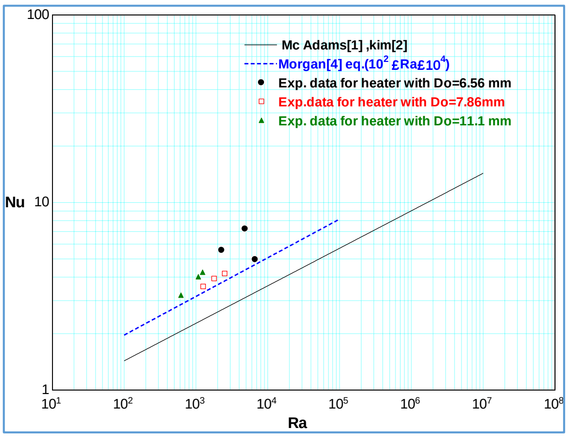

Fig. 7: Ra & Nu for natural convection with three references

5. Conclusion:

Entropy generation from a heated cylinder by natural convection and radiation has been investigated. The most significant conclusions that were obtained from this study are:

- The optimum thermal point is at Ns=1 and Ra/Ra, opt=1, where entropy generation reaches a minimum value.

When radiation dominates, the entropy generation rate is high, reaching Ns=200 when Ra/Ra, opt=1000. Furthermore, it was found that the entropy generation number is low when natural convection is the effective parameter, and Ns=3 when Ra/Ra, opt=0.001.

- The optimum value for the irreversibility distribution ratio Ø=0.25 at Ra/Ra, opt=1.

- It can be concluded that the optimum value for Be=0.8 is at Ra/Ra, opt=1.

As a result of this study, future studies will explore the mutual effect of convection and radiation on the generation of entropy in other forms of heat transfer surfaces. Developing the potential of heat transfer and reducing losses requires such studies.

Nomenclature

A	Area (m^2)
Be	Bejan number
Do	outer diameter (m)
Do, opt	Optimum outer diameter (m)
g	Gravity ($m.s^{-2}$)
G	Mass velocity ($Kg.s^{-1}\ m^{-2}$)
h	Enthalpy ($kJ.kg^{-1}$)
k	Thermal conductivity ($W.m^{-1}\ K^{-1}$)
L	Length (m)
$\dot{m}$	air flow rate ($kg\ sec^{-1}$)
P	Pressure ($N.m^{-2}$)
q'	Heat transfer per unit length ($W.m^{-1}$)
q"	Heat flux ($W.m^{-2}$)
Ra	Rayleigh number
$\dot{S}$	Entropy generation ($kJ\ kg^{-1}\ K^{-1}$)
T	Temperature (°C)
Ns	Entropy generation number
V	Volume (m^3)

Greek symbols

$\alpha_{conv.}$	Natural heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
α_{rad}	Radiation heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
ε	Emissivity
σ	Boltzmann constant $5.669*10^{-8}$ ($W.\ m^{-2}.\ K^{-4}$)
ρ	Density ($kg\ m^{-3}$)
Ø	irreversibility distribution ratio

Subscripts

a	Constant
n	Constant
s	surface
∞	Free stream
$\mathcal{A}$	Constant
$\mathcal{B}$	Constant

References:

1) H.M. Al-Maamary, H.A. Kazem and M.T. Chaichan, M.T., "Changing the energy profile of the GCC States: A review". *International Journal of Applied Engineering Research (IJAER)*, **11**(3) 1980-1988 (2016).
2) S. Agarwal, M. Tyagi, and R.K. Garg, "Circular economy reinforcement to diminish ghg emissions: A grey DEMATEL approach. *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **10** (01) 389-403 (2023).
3) A. Pal, K. Uddin, K. Thu, B.B. Saha, "Environmental assessment and characteristics of next generation refrigerants". *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **05** (02) 58-66 (2018).
4) H. Han, M. Hatta and H. Rahman, "Smart ventilation for energy conservation in buildings", *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **06** (01) 44-51 (2019).
5) M. Kalsia, A. Sharma, R. Kaushik, R., R.S. Dondapati, Evaporative cooling technologies: Conceptual review study. *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **10** (01) 421-429 (2023).
6) D. Singh, A. Singh, Role of building automation technology in creating a smart and sustainable built environment. *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **10** (01) 412-420（2023).
7) M.I. Alhamid, S. Bismo, I.T. Ramadhan, A. Yatim, "Study on the effectiveness of ozonation technique in preventing scale precipitation on closed system cooling towers", *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **06** (01) 65-70 (2019).
8) M.I. Alhamid, N. Nasruddin, E. Susanto, T.F. Vickary, M.A. Budiyanto, "Refrigeration cycle exergy-based analysis of hydrocarbon (R600a) refrigerant for optimization of household refrigerator", *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **06**, (01) 71-77 (2019).
9) U. Perera, N. Takata, T. Miyazaki, Y. Higashi, K. Thu, "The exergy investigation of a mechanical vapor compression chiller for cooling using R410a", *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **08** (01) 213-220 (2021).
10) N. Olleh, N.A. Husain, H.M. Kamar, N.B. Kamsah, M.I. Alhamid, "Outlets airflow velocity enhancement of an automotive HVAC duct", *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **08** (01) 163-169 (2021).
11) M.T. Kibria, M. Islam, B.B. Saha, T. Nakagawa, S. Mizuno, "Assessment of environmental impact for air-conditioning systems in Japan using HFC based refrigerants", *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **06** (03) 246-253 (2019).
12) Q.A. Jawad, A.M. Mahdy, A.H. Khuder, M.T. Chaichan, "Improve the performance of a solar air heater by adding aluminum chip, paraffin wax, and nano-SiC", *Case Studies in Thermal Engineering*, **19**, 100622 (2020).
13) H.A. Kazem, A.H. Al-Waeli, M.T. Chaichan, K.H. Al-Waeli, A.B. Al-Aasam, K. Sopian, "Evaluation and comparison of different flow configurations PVT systems in Oman: A numerical and experimental investigation", *Solar Energy*, **208**, 58-88 (2020).
14) A.H. Al-Waeli, H.A. Kazem, M.T. Chaichan, K. Sopian, "Photovoltaic/thermal (PV/T) systems: principles, design, and applications". Springer Nature, 2019.
15) W.H. McAdams, Heat Transmission, 3rd edit. McGraw- Hill, New York (1954).
16) C.B. Kim, T.J. Pontikes. and D.E. Woilersheim, "Free convection from a horizontal cylinder with isothermal and constant heat flux surface conditions", *J. Heat. Transfer. ASME* **97**(1), pp.129-130 (1975).
17) R.M. Fand, E.W. Morris, and M. Lum, "Natural convection heat transfer from horizontal cylinders to air, water and silicone oils for Rayleigh numbers between 3 × 102 and 2 × 107," *Int. J. Heat Mass Transf.* **20**(11), pp. 1173–1184 (1977).
18) K. Kitamura, F. Kamiiwa, and T. Misumi, "Fluid flow and heat transfer of natural convection around large horizontal cylinder," *Int. J. Heat Mass Transf.* **42**(22) 4093–4106 (1999).
19) I. M. O. Gorman, D. B. Murray, G. Byrne, and T. Persoons, "Natural convection from isothermal horizontal cylinders," *ASME Int. Mech. Eng. Congr. Expo. Proc.* **9**(PART C) 1891–1897 (2010).
20) J.T. Cieslinski, S. Smolen and D. Sawicka, "Free convection heat transfer from horizontal cylinders," *Energies* **14** 559 (2021). https://doi.org/10.3390/en 14030559
21) S.W. Churchill and H.S. Chu, "correlating equations for laminar turbulent free convection from horizontal and turbulent free convection from a horizontal cylinder", *Int. J. Heat and mass transfer* **18**(9) 1049–1053 (1975).
22) V.T. Morgan, "The overall convective heat transfer from smooth circular cylinders," *Adv. Heat Transf.* **11** 199–264 (1975).
23) V.T. Morgan, "Heat transfer by natural convection from a horizontal isothermal circular cylinder in air," *Heat Transf. Eng.* **18**(1) 25–33 (1997).
24) J.H. Merkin, I. Pop, "A note on the free convection boundary layer on a horizontal circular cylinder with constant heat flux," *Wärme- und Stoffübertragung* **22**(1–2) 79–81 (1988).
25) R. Chouikh, A. Guizani, M. Maâlej, and A. Belghith, "Numerical study of the laminar natural convection

flow around an array of two horizontal isothermal cylinders," *Int. Commun. Heat Mass Transf* **26**(3) 329–338 (1999).
26) M. Miana, C. Cortés, J.L. Pelegay, J.R. Valdés, and T. Pütz, "Characteristic scales in natural convection around an isothermal horizontal cylinder for Pr < 1 fluids," *Int. J. Therm. Sci.* **65** 39–61 (2013).
27) G. Sebastian, S.R. Shine, "Natural convection from horizontal heated cylinder with and without horizontal confinement," *Int. J. Heat Mass Transf.* **82** 325–334 (2015).
28) S. Sedighi and M.S. Aghighi, "Simultaneous free convection and heat generation on a horizontal isothermal circular cylinder," *Mod. Appl. Sci.* **9**(12) p. 21 (2015).
29) G. Cesini, M. Paroncini, G. Cortella, and M. Manzan, "Natural convection from a horizontal cylinder in a rectangular cavity," *Int. J. Heat Mass Transf.* **42**(10) 1801–1811 (1999).
30) Ö.A. Zgür and I. Teke, "Experimental and numerical study of the natural convection from a heated horizontal cylinder," *Int. Commun. Heat Mass Transf.* **36**(7) pp. 731–738 (2009).
31) M. Ashjaee, S. Yazdani, S. Bigham, and T. Yousefi, "Experimental and numerical investigation on free convection from a horizontal cylinder located above an adiabatic surface," *Heat Transf. Eng.* **33**(3) pp. 213–224 (2012).
32) E.E. Habib, "Numerical study of natural convection from a horizontal cylinder with different cross sections," *J. Mech. Eng. Res. Dev*. **43**(5) 246–259 (2020).
33) S.E. Razavi, F. Barar, and V. Farhangmehr, "Characteristics-based finite-volume solution for natural convection around a horizontal cylinder," *J. Appl. Sci.* **8**(10) 1905–1911 (2008).
34) K.C. Lin, Y. Bhosale, and C. Y. Zhou Huang, "3D-CFD investigation into free convection flow above a heated horizontal cylinder: Comparisons with experimental data," *Appl. Therm. Eng.* **120** 277–288 (2017).
35) D. Poulikakos, J.M. Johnson, "Second law analysis of combined heat and mass transfer phenomena in external flow". *Energy* **14**(2) 67-73 (1989).
36) A. Bejan, "Entropy generation minimization". First edition, CRC Press LLC. (1996).
37) Bejan, A. Tsatsaronis, G. Moran, M. Thermal design & optimization, John Wiley & sons, Inc. 1996.
38) A. Bejan, "Advanced engineering thermodynamics". Third edition, John Wiley & sons, Inc. (2006).
39) L.A. Mahdi, Entropy generation minimization theoretical analysis for external flow around horizontal cylinder at low Reynold number", *Engineering and Technology Journal*, **36**(2) (2018). https://doi.org/10.30684/etj.36.2a.12
40) B.A.K. Abu-Hijleh and E.A. Nada, "Entropy generation due to natural convection from a horizontal isothermal cylinder in oil" *Int. Comm. Heat Mass Transfer* **25**(8) pp. 1135–1143 (1998).
41) B.A.K. Abu-Hijleh, M. Abu-Qudais, and E. Abu Nada, "Numerical prediction of entropy generation due to natural convection from a horizontal cylinder," *Energy* **24**(4) 327–333 (1999).
42) D. Bhowmick, P.R. Randive, S. Pati, H. Agrawal, A. Kumar, P. Kumar, "Natural convection heat transfer and entropy generation from a heated cylinder of different geometry in an enclosure with non-uniform temperature distribution on the walls," *J. Therm. Anal. Calorim.* **141**(2) 839–857 (2020).
43) R. Petela, Exergy of heat radiation. *Journal of Heat Transfer* **86**(2) 187–192 (1964).
44) V.S. Arpaci, "Radiative entropy production". *AlAA 23rd Aerospace Sciences Meeting 24*(11) 1859–1861 (1985).
45) P.K. Sarma and P.V. Sunita, "Interaction of thermal radiation with laminar natural convection from a horizontal cylinder in air", *Wärme - und Stoffübertragung* **26***(*2) 65–69 (1991).
46) M.M. Molla, S.C. Saha, M.A.I. Khan, M.A. Hossain, "Radiation effects on natural convection laminar flow from a horizontal circular cylinder". *Desalination and Water Treatment* **30**(1–3) 89–97 (2011).
47) N. Zainuddin, I. Hashim, M. Ismoen, R. Roslan, "The effect of radiation on free convection from a heated horizontal circular cylinder", *Appl. Mech. Mater.* **773** 378–386 (2015).
48) A. Sciacovelli, V. Verda, E. Sciubba, "Entropy generation analysis as a design tool - A review," *Renewable and Sustainable Energy Reviews* **43** 1167–1181, (2015). https://doi.org/10.1016/j.rser.2014.11.104
49) P. Biswal, T. Basak, "Entropy generation vs energy efficiency for natural convection-based energy flow in enclosures and various applications: A review". *Renewable and Sustainable Energy Reviews* 80 1412–1457 (2017). https://doi.org/10.1016/j.rser.2017.04.070
50) X. Chen, T. Zhao, M.Q. Zhang, Q. Chen, "Entropy and entransy in convective heat transfer optimization: A review and perspective". *International Journal of Heat and Mass Transfer* **137** 1191–1220 (2019). https://doi.org/10.1016/j.ijheatmasstransfer.2019.04.017
51) S._Morsli, A. Sabeur, M.El. Ganaoui, "Numerical simulation of entropy generation in hydrogen-air burner". *Fluid Dynamics and Materials Processing* **11**(4), 342–353 (2015). https://doi.org/10.3970/fdmp.2015.011.342
52) K. Said, A.Q. Sabeur, "Turbulent double-diffusive natural convection and entropy generation within an inclined square cavity". *Fluid Dynamics and Materials Processing* **18**(6) 1621–1629 (2022). https://doi.org/10.32604/fdmp.2022.022220

53) F. Zemani-Kaci, A. Sabeur-Bendhina, "Numerical study of natural convective heat transfer in an air filled square cavity heated from below and symmetrically cooled from the sides with a partition in the hot wall." *Fluid Dynamics and Materials Processing* **19**(2) 513–539 (2023). https://doi.org/10.32604/fdmp.2022.021974

54) J. M. Moran and H.N. Shapiro, "Fundamentals of Engineering Thermodynamics", 5th edition, John Wiley & sons, Inc. (2006).

55) J.P. Holman. Heat Transfer, Tenth Edition. McGraw-Hill (2008).

56) I. DeWitt, B. Lavine. Introduction to heat transfer. Fifth edition. John Wiley & sons, Inc. (2007).

Appendix A

Calculation for experimental tests data:

$$q_{total} = q_{conv} + q_{rad} \tag{A1}$$

$$q_{total} = I * V \tag{A2}$$

$$\alpha_{rad} = \frac{\varepsilon * \sigma * (T_s^4 - T_\infty^4)}{(T_s - T_\infty)}$$

$$q_{rad} = \alpha_{rad} * A * (T_s - T_\infty) \tag{A3}$$

$$q_{conv} = q_{total} - q_{rad}$$

$$q_{conv} = \alpha_{conv} * A * (T_s - T_\infty) \tag{A4}$$

And from equation (25) the experimental convection heat transfer coefficient can be found.

Table (A1) dimension of the tube heaters and the measurement parameters

Heater	D_o mm	L m	I Ampere	Volt	$T_{s\,avg}$ °C	T_∞ °C	ε
sample 1	11.1	1.002	0.5	20.13	41	22.2	0.35
			1	36.95	75	23.4	0.35
			1.2	44.5	117	22.5	0.35
Sample 2	7.86	0.99	0.5	23	55	22.5	0.35
			0.7	31.03	77	22.8	0.35
			1	51.85	133	22.2	0.35
Sample 3	6.56	1.005	0.4	20.87	48	22	0.4
			0.7	33.93	80	22.5	0.4
			0.8	40.62	95	22	0.4
Accuracy			±0.1 of full scale	±2 of full scale	±1.5 °C	±1.5 °C	±0.01

Table (A2) the heat transfer coefficient and the percentage effect of the natural convection and radiation.

heater	Power	α_{conv}	α_{rad}	q_{-conv}	q_{-rad}	Ratio= $q_{conv}/(q_{conv}+q_{rad})$	Ra
	W	W/m².°C	W/m².°C	W	W		
Sample 1	10.05	8.468	2.246	8.58	1.475	82.81	2289
	36.91	10.9	2.672	32.1	4.818	84.99	4880
	53.35	12.68	3.257	42.59	10.75	74.75	6780
Sample 2	11.49	10.58	2.412	9.572	1.916	79.98	1266
	21.7	12.03	2.691	18.13	3.566	80.34	1803
	51.8	14.38	3.506	42.3	9.497	77.55	2552
Sample 3	8.34	10.47	2.655	6.91	1.43	79.31	621.6
	23.73	12.77	3.117	20.02	3.712	81.45	1091
	32.46	13.56	3.345	27.41	5.057	81.55	1255
average						***80.3***	