Experimental Study of Natural Convection Heat Transfer on A Vertical Cylinder with Varying Heat Flux

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Abstract

The most commonly used heat transfer in cooling and heating systems is convective heat transfer. Natural convection heat transfer is typically employed in cooling systems with immersion cooling such as in data centers and transformers. In addition to cooling systems, natural convection is also utilized in heating systems as seen in nuclear reactors. More specifically, natural convection around heated cylinders has widespread applications. The flow of natural convection around vertical heated cylinders is a critical concern in various applications, including vertical tubes within HVAC systems, the heating of electronic components, and the storage of nuclear rods in waste facilities. In this study, a test apparatus in the form of a box measuring 300x200x150 mm with a 650-watt heater installed in the center was used. The heater is jacketed with an outer diameter of 38mm and a length of 195mm. Thermocouple type K are installed on the heater jacket wall and fluid. Convective heat transfer is transiently calculated with constant heat flux. The research results show that in the first phase, there is a significant increase in heat flux of 512.82 W/m^2, 769.23 W/m^2, and 1025.4 W/m^2, respectively, at rates of 0.34, 0.46, and 0.61 ℃/minute. In phase 4, the temperature increase is relatively small, with rates of 0.01, 0.02, and 0.03 ℃/minute, respectively. Heat transfer coefficients (h), Nusselt numbers (Nu), and Rayleigh numbers (Ra) increase with increasing heat flux.

Kata kunci: experimental; constant flux; natural convection; heat transfer; vertical cylinder

Abstrak

Perpindahan kalor yang paling banyak digunakan dalam sistem pendinginan maupun pemanasan adalah perpindahan kalor secara konveksi. Perpindahan kalor konveksi alami biasanya digunakan pada sistem pendinginan dengan jenis pendinginan direndam seperti pada sistem pendinginan pada data center dan transformator. Selain pada sistem pendinginan, konveksi alami juga digunakan pada sistem pemanasan seperti yang terjadi pada reaktor nuklir. Secara lebih spesifik konveksi alami dari silinder pemanas memiliki aplikasi yang sangat luas. Aliran konveksi alami di sekitar silinder panas vertikal merupakan masalah penting yang berkaitan dengan tabung vertikal pada sistem Heating, Ventilation, and Air Conditioning (HVAC), pemanasan resistif komponen elektronik, landasan peluncuran pesawat ulang-alik, dan batang nuklir yang disimpan di tempat penyimpanan limbah. Dalam penelitian ini alat uji berbentuk kotak dengan ukuran 300x200x150mm dengan pemanas 650watt dipasang di tengah. Pemanas dipasang jaket dengan diameter luar 38mm dengan panjang 195mm. Temperatur dinding jaket pemanas dan fluida dipasang termokopel tipe k masing-masing sebanyak tiga buah. Perpindahan kalor konveksi dihitung secara transien dengan heat flux konstan. Hasil penelitian menunjukan bahwa pada fasa pertama memiliki kenaikan yang cukup signifikan pada heat fluk 512,82 W/m^2; 769,23 W/m^2; dan 1025,4 W/m^2 masing-masing sebesar 0,34; 0,46; dan 0,61 ℃/Menit. Pada fasa 4 kenaikan temperatur cukup kecil yaitu masing-masing sebesar 0,01; 0,02; dan 0,03 ℃/Menit. Koefisien perpindahan panas (h), Bilangan Nusselt (Nu), dan Bilangan Rayleigh (Ra) meningkat seiring dengan meningkatnya fluks panas.

Kata kunci: eksperimental; fluks konstan; konveksi alami; perpindahan kalor; silinder vertikal

1. Introduction

Heat transfer is the process of thermal energy transfer from a higher temperature to a lower temperature (1-4). The concept of heat transfer comprises conduction, convection, and radiation (5). Conduction heat transfer is the process of thermal energy transfer without the movement of particles within the material. This type of heat transfer commonly occurs in solid materials. Convection heat transfer involves both solid objects and fluids. This type of heat transfer is accompanied by the movement of particles within the fluid. Radiation heat transfer is the transfer of heat between materials without an intervening medium. This type of transfer can occur even in a vacuum.

The most commonly used heat transfer in cooling and heating systems is convective heat transfer. Convective heat transfer consists of two types: natural and forced. Natural convective heat transfer occurs when no other forces influence it. Forced convective heat transfer is influenced by external forces that move the fluid. Forced convective heat transfer is usually used in heat exchangers. Natural convective heat transfer is typically used in immersion cooling systems, such as those in data center cooling systems (6) and transformers. Besides cooling systems, natural convection is also utilized in heating systems. such as in nuclear reactors (7).

Research on natural convection using vertical hot cylinders has been conducted in various ways for nearly 100 years (8). Research using heated cylinders remains relevant today due to its wide range of applications. Natural convection flow around vertical hot cylinders is an important issue related to vertical tubes in HVAC systems, heating of electronic components, and nuclear rods stored in waste storage (9). Convective heat transfer is influenced by the properties of the fluid used. Currently. research on the fluids used for cooling systems is still evolving (10-14). There are experimental setups for natural convection heat transfer in the form of cylinders (15) as well as boxes (10-14) with heaters installed inside them. This study was conducted using a box-shaped experimental setup for natural convective heat transfer with a vertical cylinder heater installed in the center.

2. Materials and Methods

The fluid used in this study is water with its characteristics presented in Table 1 (5).

Table 1. Properties of Water

Temp. **°C**	**Spesific Heat (c_p)** ***kJ/kg.°C***	**Density *(ρ)*** ***kg/m³***	**Dinamic Viskosity*(μ)*** ***kg/m.s***	**Thermal Conductivity*(k)*** ***W/m.°C***	**Prandlt Number** ***(Pr)***	$\frac{g\beta\rho^2 c_p}{\mu k}$ ***1/m³.°C***
0	4.225	999.8	1.79×10^{-3}	0.566	13.25	
4.44	4.208	999.8	1.55	0.575	11.35	1.91×10^9
10	4.195	999.2	1.31	0.585	9.40	6.34×10^9
15.56	4.186	998.6	1.12	0.595	7.88	1.08×10^{10}
21.11	4.179	997.4	9.8×10^{-4}	0.604	6.78	1.46×10^{10}
26.67	4.179	995.8	8.6	0.614	5.85	1.91×10^{10}
32.22	4.174	994.9	7.65	0.623	5.12	2.48×10^{10}
37.78	4.174	993.0	6.82	0.630	4.53	3.3×10^{10}
43.33	4.174	990.6	6.16	0.637	4.04	4.19×10^{10}
48.89	4.174	988.8	5.62	0.644	3.64	4.89×10^{10}
54.44	4.179	985.7	5.13	0.649	3.30	5.66×10^{10}
60	4.179	983.3	4.71	0.654	3.01	6.48×10^{10}
65.55	4.183	980.3	4.3	0.659	2.73	7.62×10^{10}
71.11	4.186	977.3	4.01	0.665	2.53	8.84×10^{10}
76.67	4.191	973.7	3.72	0.668	2.33	9.85×10^{10}
82.22	4.195	970.2	3.47	0.673	2.16	1.09×10^{11}
87.78	4.199	966.7	3.27	0.675	2.03	
93.33	4.204	963.2	3.06	0.678	1.90	
104.4	4.216	955.1	2.67	0.684	1.66	
115.6	4.229	946.7	2.44	0.685	1.51	
126.7	4.250	937.2	2.19	0.685	1.36	
137.8	4.271	928.1	1.98	0.685	1.24	
148.9	4.296	918.0	1.86	0.684	1.17	
176.7	4.371	890.4	1.57	0.677	1.02	
204.4	4.467	859.4	1.36	0.665	1.00	
232.2	4.585	825.7	1.20	0.646	0.85	
260	4.731	785.2	1.07	0.616	0.83	
287.7	5.024	735.5	9.51×10^{-5}			
315.6	5.703	678.7	8.68			

The experimental apparatus for natural convection heat transfer is constructed using stainless steel SUS 304 material with a thickness of 2mm. The apparatus is box-shaped with dimensions of 300x200x150 mm, and a 650-watt heater is installed in the center. The heater is jacketed with an outer diameter of 38mm and a length of 195mm. Three type K thermocouples are installed on the jacket wall of the heater and in the fluid, respectively. Convective heat transfer is calculated transiently with constant heat flux. The wall temperature of the heater (Tw) and the fluid temperature (Tb) are recorded every two seconds for three hours using a data logger. The experimental scheme is illustrated in Figure 1.

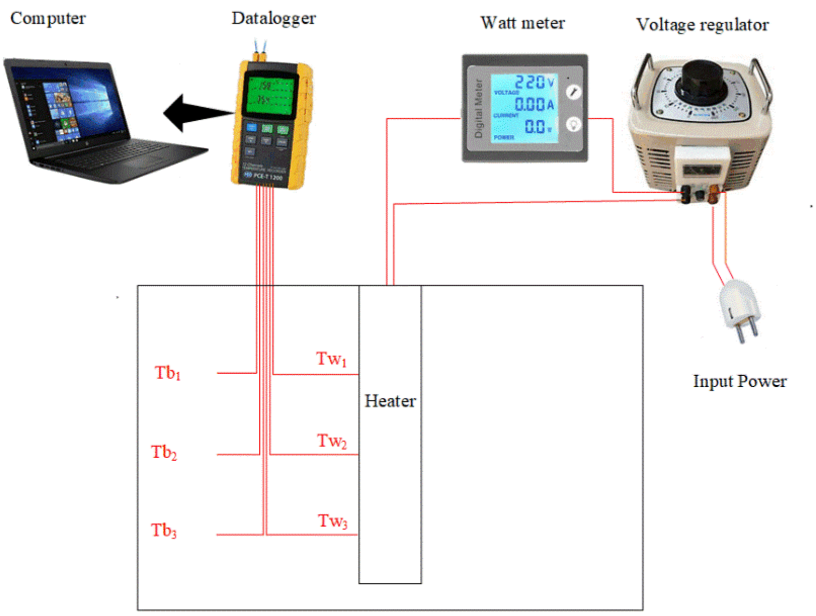

Figure 1. Experimental scheme

The heat flux on the heater wall is kept constant using a voltage regulator. Heat flux calculation is performed using equation (1) (12, 16, 17).

$$q" = \frac{I.V}{A} \tag{1}$$

I is the electrical current value, V is the voltage applied to the device, and A is the cross-sectional area of the heater wall. The convective heat transfer coefficient at constant heat flux is calculated using equation (2) (12, 16, 17).

$$h = \frac{q"}{(T_w - T_b)} \tag{2}$$

Tw and Tb represent the temperature of the heater wall and the bulk temperature of the fluid, respectively, taken using type K thermocouples installed on the heater jacket and in the fluid surrounding the heater. During natural convection heat transfer, the process is driven solely by density variations resulting from temperature differences between fluid layers. As heated, the density of lower fluid layers decreases, causing upward fluid movement. The extent of this movement depends on fluid type, temperature differences, and volume. Buoyancy is the force driving fluid motion. The Grashof number (Gr), a dimensionless parameter in natural convection, represents the ratio of buoyancy to viscous forces and is calculated using equation (3).(12, 16, 17).

$$Gr = \frac{g\rho^2 Cp(T_w - T_b)L^3}{v^2} \tag{3}$$

g is the acceleration due to gravity (9.81 m/s²), β is the coefficient of volume expansion of the fluid, L is the length of the heater jacket, and ν is the kinematic viscosity defined in equation (4).

$$v = \frac{\mu}{\rho} \tag{4}$$

In equation (5), μ represents dynamic viscosity, while ρ stands for density. In free convection heat transfer, the Nusselt number (Nu) is contingent upon both the Grashof (Gr) and Prandtl (Pr) numbers. The values of Nu and Pr are delineated in equations (5) and (6).

$$Nu = \frac{h.L}{k} \tag{5}$$

$$Pr = \frac{Cp.\mu}{k} \tag{6}$$

$$Ra = Pr.Gr \tag{7}$$

The Rayleigh number (Ra) is a crucial parameter in the context of natural convection. Natural convection occurs when temperature differences cause fluid mass movement without the aid of external equipment such as pumps or fans. When the Rayleigh number (Ra) is sufficiently large, natural convection becomes dominant in heat transfer. If Ra is smaller than a critical value that depends on the geometry and boundary conditions, natural convection may not be significant compared to conduction. Therefore, in the analysis of natural convection, measuring and calculating the Rayleigh number is key to understanding and predicting flow patterns and heat transfer in a particular system. The Rayleigh number (Ra) can be expressed as the product of the Grashof number (Gr) and the Prandtl number (Pr), and thus can be defined in equation (7).

3. Result and Discussion

3.1. Temperature measurement

The temperature measurements are the main parameters used for the analysis of convective heat transfer coefficients in natural convection. Measurements were taken for 3600 seconds and recorded every 2 seconds. The measurements were conducted at constant heat flux values of 512.82, 769.23, and 1025.4 W/m^2 and were sustained for 3600 seconds. From Figure 2, it can be observed that the temperature increases over time. This indicates that the system has not yet reached a steady state. The main purpose of temperature data collection is to determine the temperature difference between Tw and Tb, denoted as ΔT. In Figure 3, the increase in ΔT over one hour is divided into four phases, each lasting 15 minutes. Figure 3a shows that the value of ΔT continues to increase over time. This indicates that heat transfer is ongoing and has not reached a steady state. The magnitude of temperature increase per minute in each phase is shown in Figure 3b. In the first phase, there is a significant increase in temperature for heat flux values of 512.82 W/m^2, 769.23 W/m^2, and 1025.4 W/m^2, with rates of 0.34, 0.46, and 0.61 °C/minute, respectively. In phase 4, the temperature increase is relatively small, with rates of 0.01, 0.02, and 0.03 °C/minute, respectively. This indicates that as heating time increases, the system approaches a steady state.

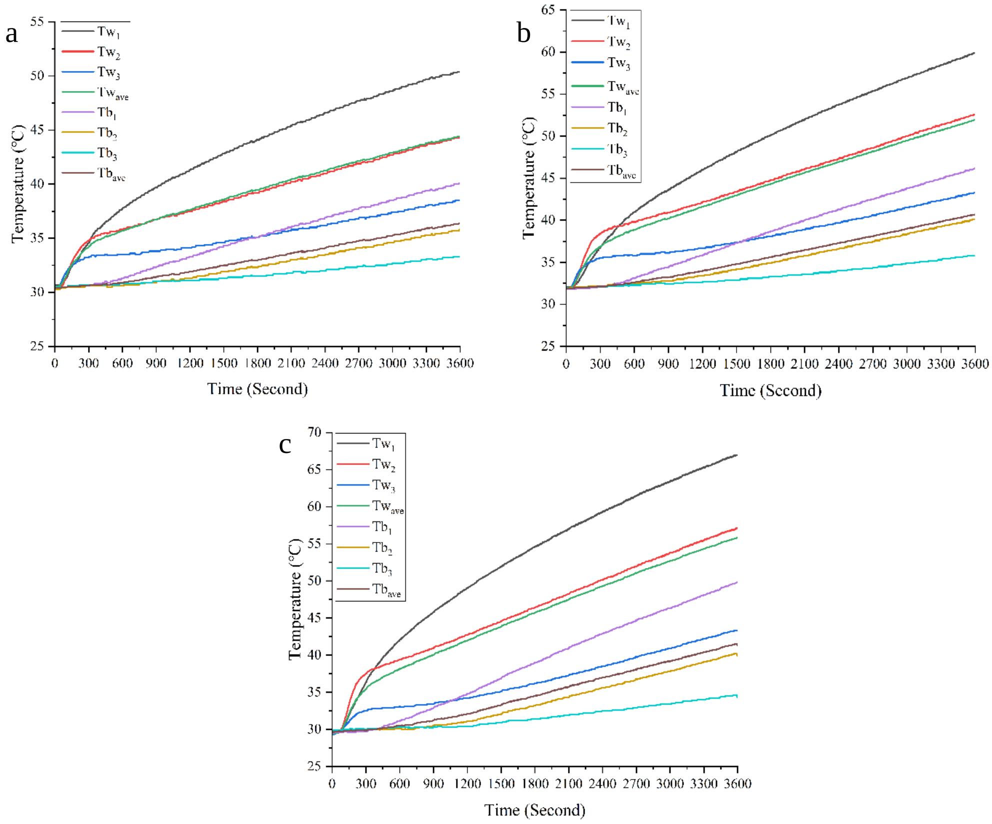

Figure 2. Temperature increase rates for each heat flux: a) 512.82 W/m^2, b) 769.23 W/m^2, c) 1025.4 W/m^2

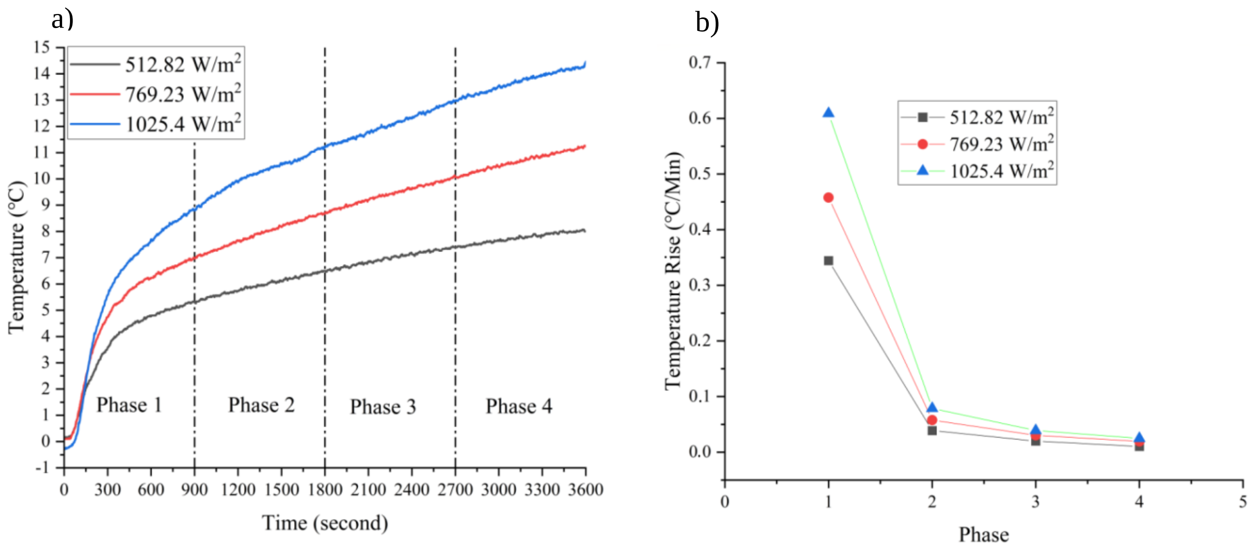

Figure 3. ΔT Value: a) Over Time, b) Temperature Increase

3.2. Characteristics of heat transfer

The natural heat transfer coefficient is affected by numerous factors, as evidenced by the components of equation 2. Among these factors, the temperature difference emerges as the primary influencer of natural convection heat transfer. Through equation 2, the convective heat transfer coefficient for each phase can be ascertained. Figure 4 illustrates that the coefficient of natural convective heat transfer escalates alongside increasing heat flux. With the rise in the heat transfer coefficient, there is a corresponding augmentation in natural heat transfer, underscoring the pivotal role of this parameter in facilitating heat transfer processes.

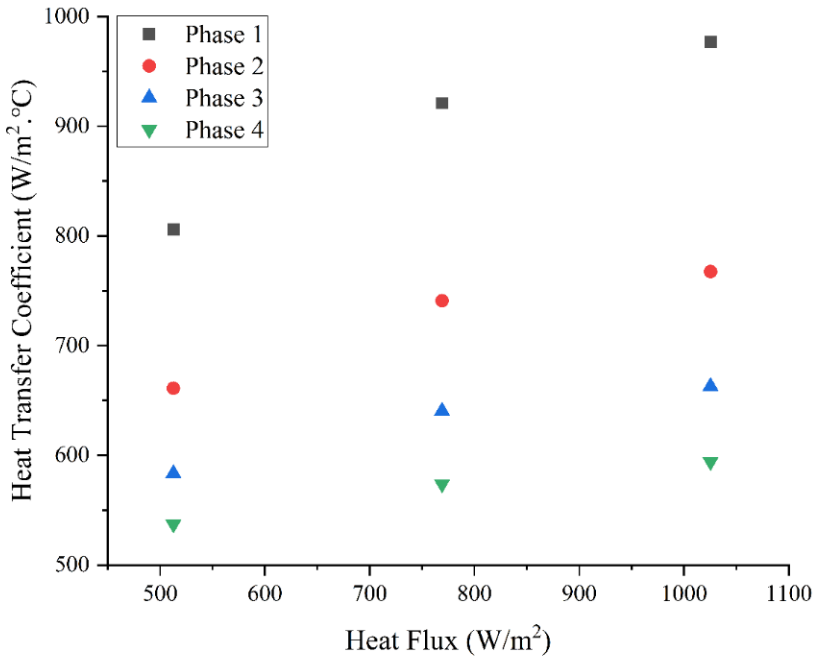

Figure 4. Convective heat transfer coefficient

In natural convection, the Nusselt number (Nu) plays a key role in describing heat transfer characteristics. Natural convection occurs due to density differences generated by temperature variations in the fluid, resulting in spontaneous fluid flow. The Nusselt number demonstrates a rise in correlation with escalating heat flux, as depicted in Figure 5. The Nu value also affects the fluid flow patterns around the heated or cooled surface, with higher Nu values resulting in more intense flow. With higher Nu values, heat transfer efficiency increases, allowing more heat to be transferred between the surface and the surrounding fluid. Additionally, surface geometry characteristics also affect the Nu value, where rough surfaces can increase fluid flow turbulence and ultimately increase the Nu value. Furthermore, high Nu values accelerate the formation of effective temperature gradients within the fluid, allowing for faster heat exchange between the surface and the fluid. Overall, understanding the influence of the Nusselt number in natural convection is not only important for heat transfer analysis but also for developing more efficient systems in engineering and industrial applications.

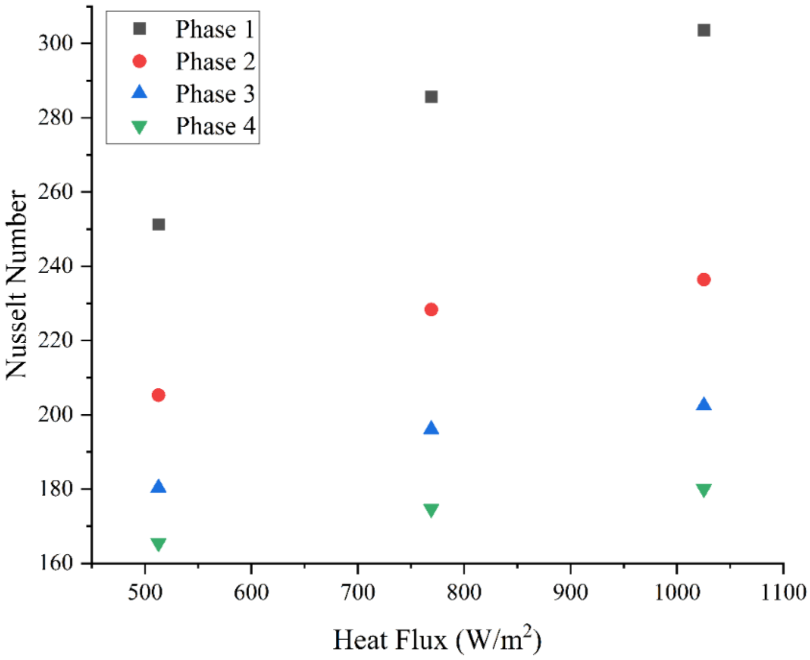

Figure 5. The value of the Nusselt number

In Figure 6, there is an increase in the value of the Rayleigh number (Ra) with increasing heat flux. In the context of natural convection, if there is a continuous increase in temperature difference or an increase in the strength of convective forces in the system, the Rayleigh number will increase. In the case of continuous heating of a fluid, the temperature difference between the hot fluid around the heat source and the cooler surrounding fluid can continue to increase over time. In this scenario, the longer the heating continues, the greater the temperature difference, which in turn increases the strength of convective forces in the system. An increase in Ra indicates an increase in the dominance of natural convection in heat transfer within the system, which may result in changes in flow patterns and temperature distribution.

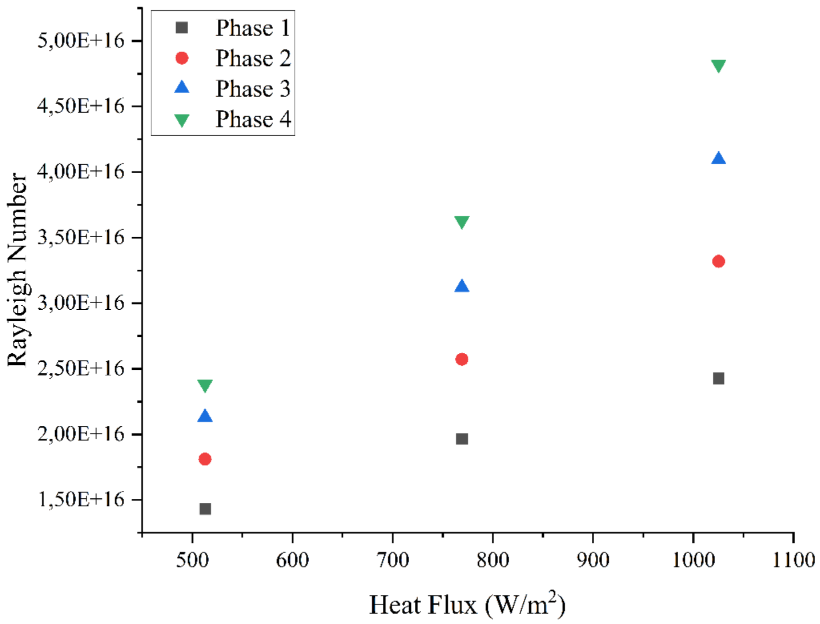

Figure 6. The value of the Rayleigh number

4. Conclusion

From the examination of the convective heat transfer coefficient (h), Nusselt number (Nu), and Rayleigh number (Ra), several significant insights into natural convection heat transfer characteristics can be gleaned. Firstly, the convective heat transfer coefficient (h) serves as a measure of the effectiveness of heat exchange between the surface and the surrounding fluid. An increase in h signifies an enhancement in heat transfer efficiency within the system. Secondly, the Nusselt number (Nu) represents the ratio of convective to conductive heat transfer in a given system, indicating the relative dominance of convection over conduction. An escalation in Nu reflects a heightened contribution of convection to heat transfer. Thirdly, the Rayleigh number (Ra), derived from the product of Grashof (Gr) and Prandtl (Pr) numbers, illustrates the ratio of gravitational to viscous forces relative to thermal conductivity, elucidating the prevalence of natural convection in heat transfer. Consequently, an elevation in Ra typically correlates with an augmentation in the convective heat transfer coefficient (h), denoting improved heat transfer efficiency in natural convection. However, it is crucial to consider the specific context of the observed system, including geometry, fluid properties, and operational conditions, when interpreting these values. A meticulous analysis of all these parameters is indispensable for a comprehensive understanding of the heat transfer characteristics in natural convection.

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