The Effect of Vibrating Inner Cylinder on Natural Convective Heat Transfer in Concentric and Eccentric Horizontal Cylindrical Annuli

Baydaa K. Khudhair *, **Adel M. Saleh** (ID), **Ali L. Ekaid** (ID)

Mechanical Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: baydaakhalil7@gmail.com

HIGHLIGHTS

- Heat transfer rate from vibrated heated inner cylinder increased with increased vibration intensity.
- After a critical value of vibrational inner cylinder heat transfer decreased.
- The decrease in temperature difference is higher for the negative eccentric position than for the centric and positive positions.

ARTICLE INFO

ABSTRACT

In this study, natural heat convection caused by centric and vertically eccentric long horizontal cylinders under the influence of vibration is experimentally investigated. The internal wall of the annulus is heated and kept at a constant heat flux, while the outside wall is cooled and maintained at a constant temperature. The vibration frequency impacts the annular convection heat transfer process and the effects of the Rayleigh number, heat flow, and eccentricity. This work employed a moderate, laminar-ranging Rayleigh number from (5×10^4 to 6.48×10^6), while the eccentricity range is varied from (-0.667, 0, and+0.667). The investigation is carried out at five different frequencies (0, 2, 5, 10, 15, and 20 Hz); therefore, it was decided to compare the case under the same circumstances in both the absence and presence of vibration. The present results' verification worked exceptionally well in concordance with previous studies. When heat fluxes are considered, the study demonstrates that the temperature difference along the gap (radial difference) between the two cylinders significantly decreases for negative as opposed to positive eccentricities for each Rayleigh number. For different eccentricities, it was discovered that the temperature difference decreased as the Rayleigh number increased. Along with these reductions, the temperature difference was promoted as the vibration frequency increased, which is significant at (20 Hz) within the range considered for controlling parameters. It was also observed that the decrease in temperature difference is higher for the negative eccentric position than for the centric and positive positions. At vertical positive eccentricity at a low Rayleigh number, the gain in vibrational average Nusselt number caused by applying vibration had a minimum value of 22.50601475%, While at the higher value of the Rayleigh number, the maximum increase in negative vertical eccentricity was 86.66933125%. However, the gain in the average Nusselt number depends on the position of the heated inner cylinder, the Rayleigh number, and the vibrational frequency.

1. Introduction

Heat transferring in concentric and eccentric vertical and horizontal annuli is applied in numerous industries, including paper production, rotary machines, bearings, gas or exploratory oil drills, boring rings, and heat exchangers. Other applications include solar collecting recipients, cooling underground electrical wires, and insulating and protecting buried pipelines from flooding for district heating and cooling [1].

Numerous types of research have been conducted recently on various methods of improving heat transferring, which is at the forefront of energy transfer and storage. Convection heat transferring has been enhanced by developing several ways to lower thermic resistance within heat-exchanged units, including and excluding surface area increases. The two basic kinds of enhancement approaches are operational procedures and passive ones. Active techniques need the input of some external power to the system, but passive methods do not. Instead, they use surface alterations or the insertion of swirl equipment to disrupt the flowing pattern, interrupt the thermic boundary layer, and promote considerable heat transference [2].

Consequently, because of the rapid advancement of technologies in various industrial and technical uses, including rocket engines, nuclear reactor cooling, space programs, and so forth, a thorough understanding of heat transferring generated by

vibration mechanisms appears to be essential. There is a ton of material accessible that explores the impact of vibrations on natural convection through experimental means. Experimental research on the natural and induced convections of a vibrational heat sphere was conducted by Baxi and Ramachandran [3]. Their findings demonstrated that since the vibrating Reynolds number becomes much less than 200, the Nusselt number increment may be insignificant. However, as it exceeds 200, the increase in heat transferring can reach seven times that of truly natural convection with no vibrating.

Forbes et al. [4] looked into the impact of mechanic vibrating upon natural convective heat transmission inside a container with a rectangular cross-section. The Researchers applied vibration pressures using an electrical vibrator. They discovered considerable influences on the heat-transferring properties, incredibly close to the vertical fluid immersed inside the enclosure's resonant natural frequencies. A maximum improvement in heat transmission of nearly 50% was attained.

The natural convection in a cavity that was simultaneously caused by gravity and vertical vibrating was examined by Shung and Jiann [5]. Based on the frequency magnitude, researchers showed that the thermic convection might be separated into five areas under these circumstances. They added that at large Rayleigh numbers, such as (= 10^6) or higher, buoyancy-produced thermic convection predominates, and vibrational movement is reduced, which does not affect the heat transfer rate. Fu and Shieh's experiment was designed to carefully examine how vibration affects transient heat convection in a two-dimensional square cavity [6]. Researchers argued that the transitory phase-out from the static to the stable flow condition is slowed down by raising the vibrating frequency.

Al-Ubaydi [7] used an aluminum cylinder that was heated at a consistent heat flux by running an electric charge through it with a (Ni-Cr) resisting to study the impact of vibrating upon the heat transferring via free convection. The resistance was set through the cylinder's interior space at various slopes ranging from 0° to 45°. It was discovered that when vibration increased, heat transferring factors also rose; however, as heat flow increased, characteristics of vibrational heat transferring decreased.

Helpful research on the impact of forced vibrating on the heat transferring factor of free convection out from the surface of a circular finned cylinder with various incidence angles was provided by Shakir [8]. It was discovered that, within a specific range, shaking the cylinder with still air boosts heat transmission. The factor of heat transferring of the heated cylinder that vibrates vertically reduces with increasing tilt angle and reaches its maximum value once the cylinder stands horizontally or nearly horizontally inclined.

Alawadhi [9] investigated the influence of transversely oscillating frequency for the inner cylinder enclosed by an annulus enclosure on the flow fields and thermal behavior at several Rayleigh numbers ranging ($10^4 \leq Ra \leq 10^5$) using air as the working fluid. It was concluded that the oscillating frequency of the inner cylinder greatly enhances the average heat transfer rate at the inner cylinder.

Experimentation research on the impact of vertical vibration on the factor of heat transferring by natural convection out of a flat aluminum surface was conducted by Abdalhamid [10]. Power levels extending from 250 to 1500 W/m2 were used to warm the bottom flat plate surface using constant heat flux as a fixed boundary condition. Tests were conducted to determine the impact of inclination angle (0, 30, 45, 60, and 90 degrees) on the thermal transferring factor. Additionally, several frequencies (2–16 Hz) and vibrating amplitude rantings were used (1.63 – 7.16 mm). The findings demonstrated that at tilt angles of (0°, 30°, 45°, and 60°), the vibrational amplitude plays a significant role in boosting the factor of heat transferring; the most substantial improvement has been seen at 13.3% within the downward direction. With increased excitation, the heat transferring factor in the vertical scenario of the plate reduces by a total of 7.65%.

Tawfik al. [11] Conducted an experimental study on the effect of vibration on mixed convection heat transfer at the entrance region of a concentric vertical annulus with a rotating inner cylinder and outer stationary heated cylinder with a radius ratio of 0.365. The findings demonstrate that the local Nusselt number increases as forced frequency increases.

A review study on the enhancement of the thermal performance of heat-exchanging equipment for energy transportation at low cost was presented by Dawood et al. [12]. The effects of several parameters, including Reynolds number, Rayleigh number, aspect ratio, geometrical parameters, and heat flux, were also thoroughly examined in a thorough review of earlier studies on focused, natural, and mixed convection. Furthermore, detailed studies were presented for annulus preparation, parameters, mechanisms, characteristics, and heat transfer enhancement. The experimental and numerical results included the practice and heat transfer characteristics of forced, natural, and mixed convection. The mechanics involved in heat transport phenomena are still poorly understood; nevertheless, the increased heat transfer capabilities continue to pique the attention of researchers. More research is needed to establish the principles in this subject because it is still a novel theory, and using annuli in industries is still an unfeasible approach. The investigations on annuli are missing; nevertheless, much study has been undertaken on this topic.

Practical research on the impact of vibration upon heat transferring by natural convection out of a metal plate having a sinusoidal end wall produced via a cable-cutting device was conducted by Zena and Hadi [13]. The plate's parameters are assumed to be 350 mm in length, 150 mm in breadth, and 10 mm in thickness. The amplitude-to-wavelength ratio is set at 0.3. A steady heat flux is applied to the bottom surface using an electrical heater with a 250–1500 W/m2 power range. The vertical direction is projected with forced vibrating at frequencies between 5 and 25 Hz at different peak-to-peak vibrating amplitudes [3, 4, and 5 mm]. Throughout the investigation, several Rayleigh numbers ranging (from 1.5×10^8 to 4×10^8) and vibrating Reynolds numbers (tend to range from 2×10^3 to 10×10^3 10103) with varying Prandtl numeric values were utilized (0.707 – 0.710). The horizontal, vertical, and top surfaces facing down were investigated in the three flat surface directions. According to the experimentation findings, the vibrational effect increases the rate of heat transmission, and the percent increase relies upon the Rayleigh value, the location of the heated surface, and the Reynolds number.

Hosseinian et al. [14] conducted an experimental investigation to determine how to improve heat transfer in a flexible PVDF (Polyvinylidene fluoride) dual pipe heat exchanger utilizing an MWCNT-water Nanofluid (multiwalled carbon nanofluid) to be the working fluid. The test rig was checked for various weight fractions, and electrical vibrators were used to apply forced vibrating toward the heat exchangers outside wall. The findings indicated that vibrating usage speeds heat transfer while slowing

nanoparticle deposits. Heat transferring is improved by a rise in various factors, including Nano - fluid temperature, vibrating level, and flowing rates of mass. The heat transfer factor increased at the maximum rate at the most significant degree of vibration (9 m/m^2) and the minor mass fraction (0.04%).

Using air as the working fluid, Murad et al. [15] empirically investigated the impact of forced vibrating upon the free convection heat transferring within a rectangle enclosure with a viewing angle of 0.5. For various frequency rates, a mechanic vibrator was employed to produce a transversal vibrating (0.87 –1.6). The experimentation was run under a continuous heat flux using thermic input power ranging from 20 W to 45 W and vibration Rayleigh numbers from 0.12 ×$10^7$and 2.7×10^7. The experiments revealed that forced vibrating impacts heat transfer characteristics and significant heat transferring was accomplished at consistent heat flowing and frequencies close to the scheme's natural frequency. Additionally, it is demonstrated that when using the correct heat flux and frequency rate, the highest amounts of heat-transferring characteristics may be produced with minimal power usage.

Furthermore, several new studies are being conducted to investigate buoyancy-driven flow in annular space under various conditions, such as Laidoudi et al. [16]. They studied numerically the natural convection of Newtonian fluids between two cylinders with various forms with a radii ratio of 2.5. The inner cylinder is supposed to be hot and the outer cylinder is assumed to be cold. The influence of Rayleigh number, Prandtle number, and inclination angle of the inner cylinder were all studied. The observation from the results is that the flow is more stable for the horizontal position of the inner cylinder. The heat transfer rate increased as Rayleigh number increased, and the effect of Prandtle number on the rate of heat transfer was diminished when Pr> 7.01.

Laidoudi [17] performed a numerical study of natural convection within horizontal cylinders of different cross-sectional forms. The inner cylinder was formed by the orthogonality of two elliptical cylinders whereas the outer cavity was ordinarily kept circular. The simulations are well done in a steady state with a laminar regime. The studied fluid was Newtonian which is modeled by the Oswald model. The studied parameters were: the Prandtl number, power-law index, and Rayleigh number. The results of the computations proved that the shear-thinning fluids increase the evacuation of thermal energy whereas, the shear-thinking fluids reduced the rate of evacuated energy. Laidoudi [18] presented results of the roles of physical and geometrical parameters on the natural convection in an annular space of the square cylinders. The influence of Rayleigh number, Prandtle number, and the geometrical modification is based on converting the walls' inner square cylinder from straight form to concave form. The results were mainly shown that the concave walls of the inner cylinder reduce the rate of heat transfer which can be useful to use this form in insulating applications instead of straight walls. Laidoudi [19] numerically studied the effect of governing factors of natural convection on the fluid motion and heat transfer rate of four heated circular cylinders placed inside a circular cavity of a cold surface. The cylinders are arranged across each other. The investigation examined the effects of prandtle number 7.1≤Pr ≤1000, and Rayleigh number $10^3 \le Ra \le 10^5$. It is found that the heat transfer rate of cylinders is highly dependent on their position inside the enclosure. Laidoudi and Ameur [20] examined heat transfer performance in a brass body of a concentric vertical cylinder and the effect of induced vibration upon the free convection heat transfer. The cylinder was heated under constant heat flux (q``=35, 45, 55, and 75 W/m^2), the vertical vibrational frequencies range (f=90, 110, 140, and 180 Hz). The results indicated that the heat transfer rate was improved and increased, and the thermal boundary layer increased from the bottom to the top surface under vibration. In addition, the Rayleigh number negatively affected the heat transfer rate, whereas the Reynolds number positively impacted the heat transfer rate during the vibration.

The observation from the literature showed that, for countless Rayleigh numbers, Prandtle numbers, and a variety of boundaries on the internal and external cylinders, numerous theoretical as well as empirical studies had been concentrated on transferring natural heat from an annulus bound by two horizontally vertically eccentric cylinders to flowing within fixed or rotary cylinders [21-24], these investigations were conducted to understand the effects of the eccentric internal cylinder's orientation. Each of these investigations overlooked the possibility that equipment utilized in application areas can work within dynamic conditions brought on by movement and oscillating, implying that every thermal device will experience some level of vibration during regular usage. Meanwhile, the mechanical vertical vibration effects have been successfully used to control heat and mass transfer, such as in heat exchangers, cooling the surfaces in nuclear reactors in power applications stirrers, mineral separators, nuclear reactors, and crystal growth. Therefore, a good understanding of the fundamental theory of thermal vibrational convection behind those applications and phenomena is necessary. So, this is the motivation, the "innovation," and the main contribution of this paper.

Also, the influence of the vibrating upon heat transfer by natural convection for many different geometries at various heat flux, surface heating conditions, and ranges of frequencies was not considered. The outcomes of these investigations vary from extensive enhancements to none or even decreases in heat transfer- rate. No experimental work was found under mechanical vibration in a vertical eccentricity closed-ended horizontal annulus. For that reason, the current work aims to experimentally study the influence of eccentricity, Rayleigh number, heat flux, and the impact of vibration on the heat transferring by natural convection from the vibrating heated internal cylinder, the concentric and vertically eccentric two horizontal cylinders. The annulus of the external wall is cooled and maintained at a consistent temperature, where the annulus contains air at atmospheric pressure, and it is spontaneously heated via its internal cylinder that has maintained at constant heat flux q.

2. Experimental Work

2.1 Experimental apparatus

Figure 1 displays a diagrammatic representation of the experimental apparatus. It consists primarily of a cylindrical annulus, where the centric and positive and negative vertical eccentricities can change the internal cylinder's position within the outer

cylinder. The outer and interior cylinders were molded into a 20-centimeter tube with an inside diameter of (Di=4cm) and (Do=10.4cm) using solid copper bar material. This made the radius ratio (Rr=2.6), and $\frac{L}{Di} = \frac{Ro-Ri}{Di} = 0.8$, as L represents the annulus gap, both cylinders were machined into a tube 20 cm long. The inner cylinder was suspended inside the outer cylinder with a moveable instrument to achieve concentric and different eccentric positions. The stationary outer cylinder is cooled by the two copper strips with a 1.3 cm outer diameter placed helically around the external surface of the outer cylinder to form a dual helix. This allowed water to flow in the opposite direction in nearby passageways. Additionally, the strips soldered onto the external cylinder act as fins to improve the heat transfer factor to the cooling water. The strips were connected with the feed line of the water reservoir in EACs (evaporating air-cooling system). The cooling water was driven in a closed circuit by a waterproof circulation pump (water pump) through the flexible hose. Four thermocouples in the mid-plane, 90° apart, were used to measure the temperatures on the cylinder surfaces. The internal cylinder gets electrically heated, which gives constant heat flux uniformly by the cartridge heater, which is put inside the inner cylinder. Teflon rods with the same diameter as the inner cylinder walls are used to insulate the heater's ends to stop heat loss from the heater's faces. The voltage supply to the heater is regulated by an electrical transformer (TDGC CHINA SHANGHAI) to adjust the input heat flux as required. Two holders aligned the inner cylinder with the outer cylinder and bolted the inner cylinder and its parts to a frame. The two cylinders are bolted to the iron structure, then fixed on the wooden plate. In a similar location to the outer cooling cylinder, four thermocouples were placed within (1mm) of the interior surface. Schematic diagram electrical power measuring instruments circuit of the test rig is shown in the block diagram in Figure 2.

The vibration exciter (shaker) type (4808B&K) instruments utilized for vibration testing are linked and placed in the center of the external cylinder. The internal cylinder is then excited by placing holders on its right and left sides (test model). In this setup, the vibration exciter is controlled by a function generator (type FG2712-2003), which is programmed to produce a sinusoidal waveform at the desired frequency. A power amplifier (kind 2712, B&K) was used to drive the exciter, and the vibration meter type (BVB-8207SD) was used to measure the excitation signal. The test section's (sample's) reaction is detected with an accelerometer and fastened using a ring cap screw in the vibrational exciter's center (shaker).

Table 1: Location of NTC

Quantity of NTC	Radius (cm)	θ Angle in degree	Z axial distance (cm)
4	R=Ri=2	θ=0°,90°,180°,270°	Z=10
1	R=2.5	θ=90°	Z=20
1	R=3	θ=90°	Z=0
5	R=3.6	θ=45°,60°,90°,120°,135°	Z=12
5	R=4	θ=45°,60°,90°,120°,135°	Z=8
6	R=4	θ=0°,30°,60°,90°,120°,180°	Z=16
6	R=4.4	θ=0°,30°,60°,90°,120°,180°	Z=4
4	R=Ro=5.2	θ=0°,90°,180°,270°	Z=10

The temperature is measured using a thermistor with the factor of negative temperature (NTC). The resistance for NTC thermistors reduces as the temperature rises because they have a negative temperature factor. They are generally utilized as current-limiting and resistive temperature sensors. The element of temperature sensitiveness is approximately ten times larger than the one of resisting temperature detectors (a solicitor) (RTD) and roughly five times more than the one of silicon temperature sensors. 32 NTC thermistors are positioned to measure the temperature on the internal and external cylinder walls within the annulus at various axial and circumferential positions, as indicated in Figures 3 and 4, with Table 1. One half (left half) of the annulus was tapped to embedded NTC), presuming that symmetry will cause the wall temperature distributing on the opposed end to be similar, while the (right half) was used to move and change the inner cylinder position. The estimated error for calibrating the NTC thermistors is 0.18℃. The NTC junctions were embedded into holes and drilled on the back surface of cylinders; 7 holes are made of (2mm) diameter of the crest and concave along the outer cylinder wall. After that, the NTC, which can withstand high temperatures, gets inserted, and a high-temperature treatment of epoxy steel glue secures the measurement junctions entirely in the hole. After removing any extra glue, fine-grinding paper is used to polish the outside cylinder surfaces properly. The heater terminals and every NTC thermistor wire have been removed from the test area. The output signal out of an NTC thermistor is sent to an electronic card with capacitors, which transforms the resisting value into voltage. The movement is then transmitted to a data-gathering device, which records and displays it for the control program using Lab VIEW software before being attached to a personal computer.

The NTC thermistors were arranged in this manner to use the temperature reading of the air confined inside the annular. Temperature sensors were used to depict how the air in enclosed annuli reacted to vibrations, and they were also used to calculate the Nusselt number, which showed how vibrations affected the rate of natural heat transfer.
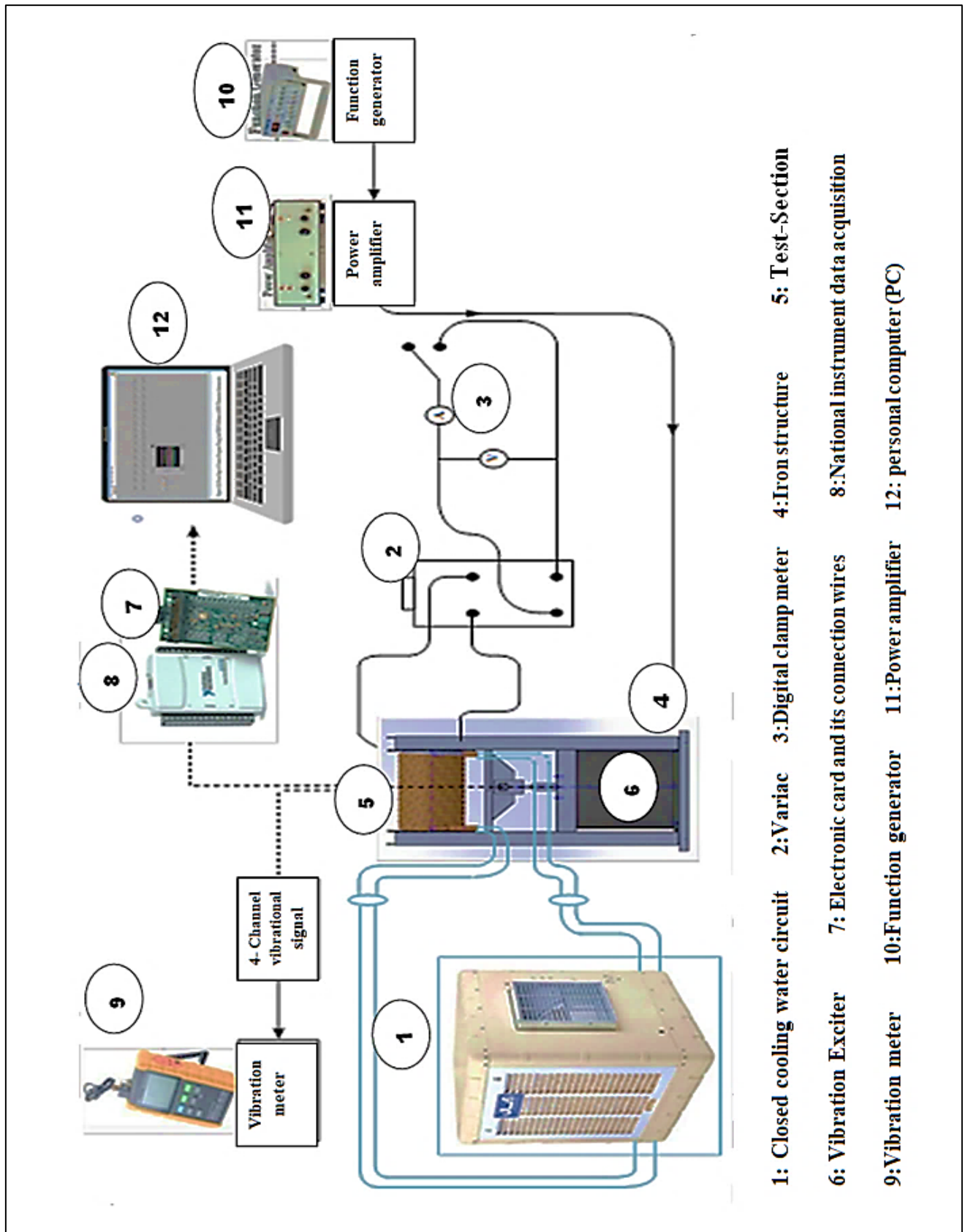
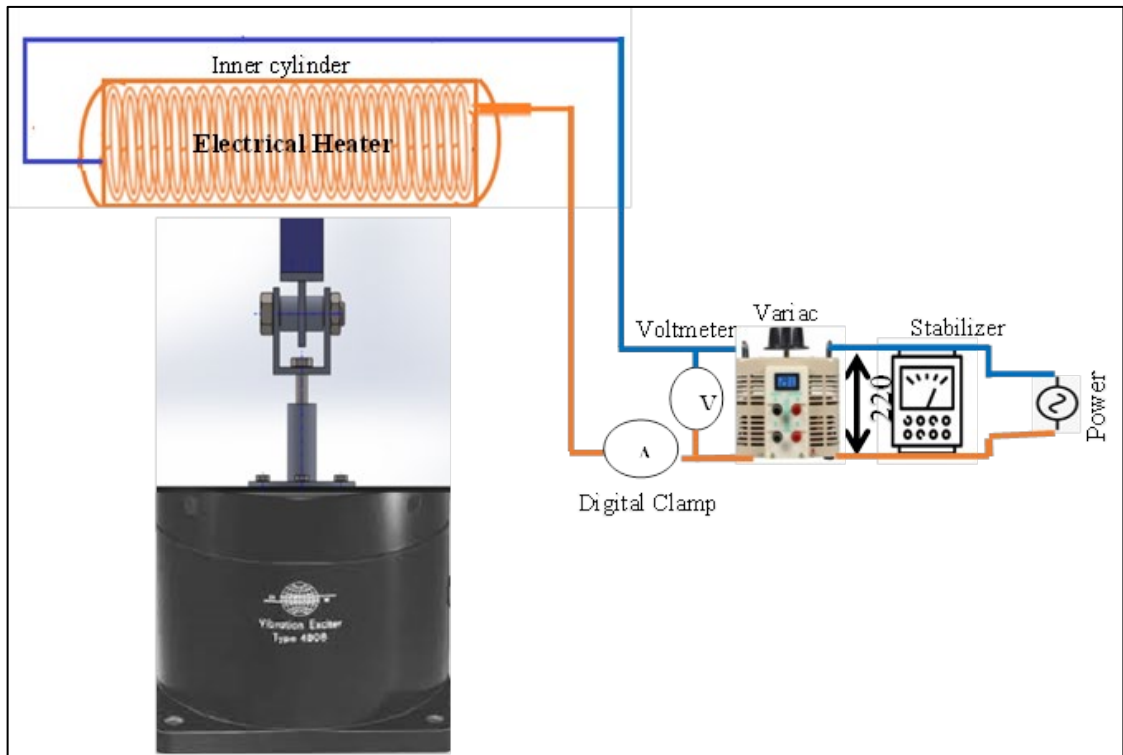**Figure 1:** Schematic diagram of the experimental setup

Figure 2: Schematic Diagram of the Electrical Power Measuring Instrument Circuit of the Test Rig
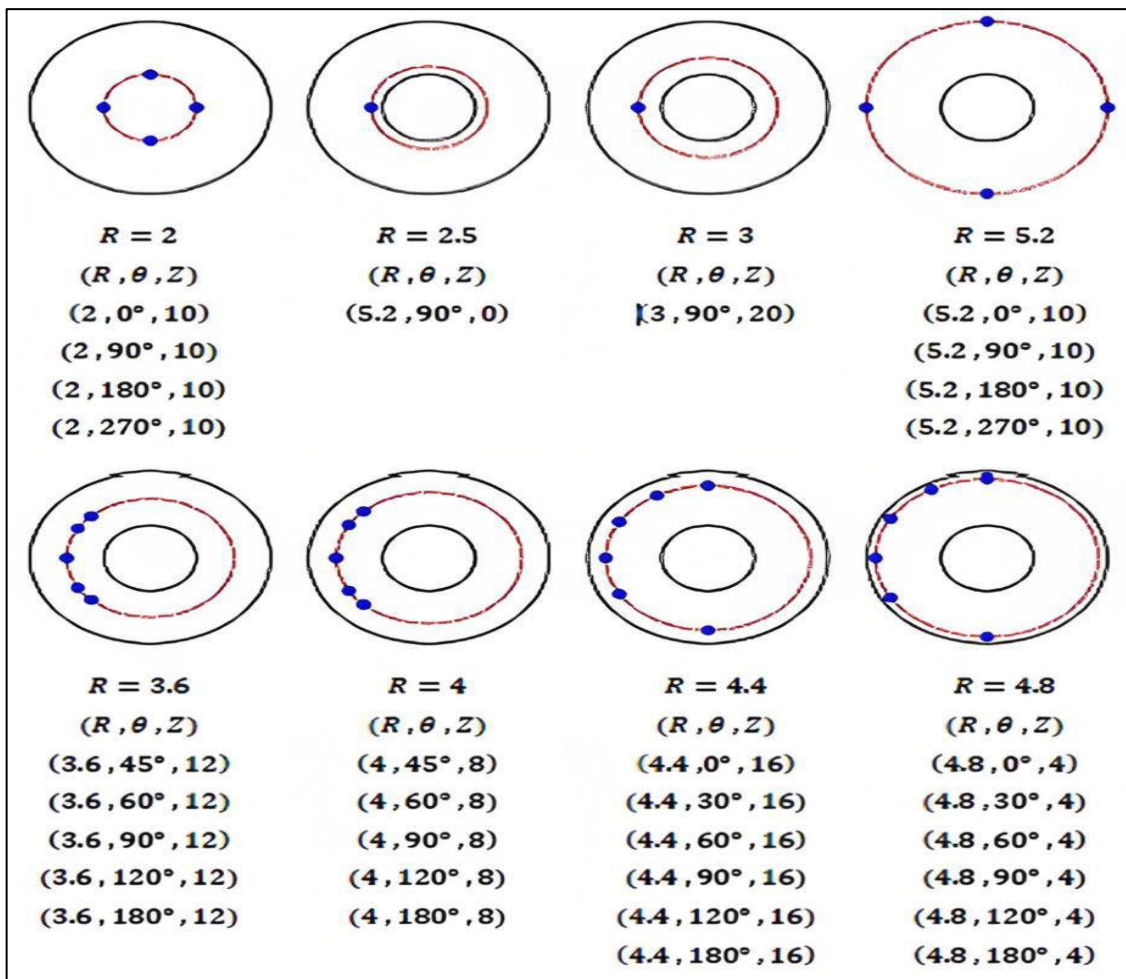

$R = 2$	$R = 2.5$	$R = 3$	$R = 5.2$
(R,θ,Z)	(R,θ,Z)	(R,θ,Z)	(R,θ,Z)
$(2,0°,10)$	$(5.2,90°,0)$	$(3,90°,20)$	$(5.2,0°,10)$
$(2,90°,10)$			$(5.2,90°,10)$
$(2,180°,10)$			$(5.2,180°,10)$
$(2,270°,10)$			$(5.2,270°,10)$

$R = 3.6$	$R = 4$	$R = 4.4$	$R = 4.8$
(R,θ,Z)	(R,θ,Z)	(R,θ,Z)	(R,θ,Z)
$(3.6,45°,12)$	$(4,45°,8)$	$(4.4,0°,16)$	$(4.8,0°,4)$
$(3.6,60°,12)$	$(4,60°,8)$	$(4.4,30°,16)$	$(4.8,30°,4)$
$(3.6,90°,12)$	$(4,90°,8)$	$(4.4,60°,16)$	$(4.8,60°,4)$
$(3.6,120°,12)$	$(4,120°,8)$	$(4.4,90°,16)$	$(4.8,90°,4)$
$(3.6,180°,12)$	$(4,180°,8)$	$(4.4,120°,16)$	$(4.8,120°,4)$
		$(4.4,180°,16)$	$(4.8,180°,4)$

Figure 3: Schematic representation of the NTC thermistors and their fixing on the inner and outer cylinders

(A)   **(B)**   **(C)**
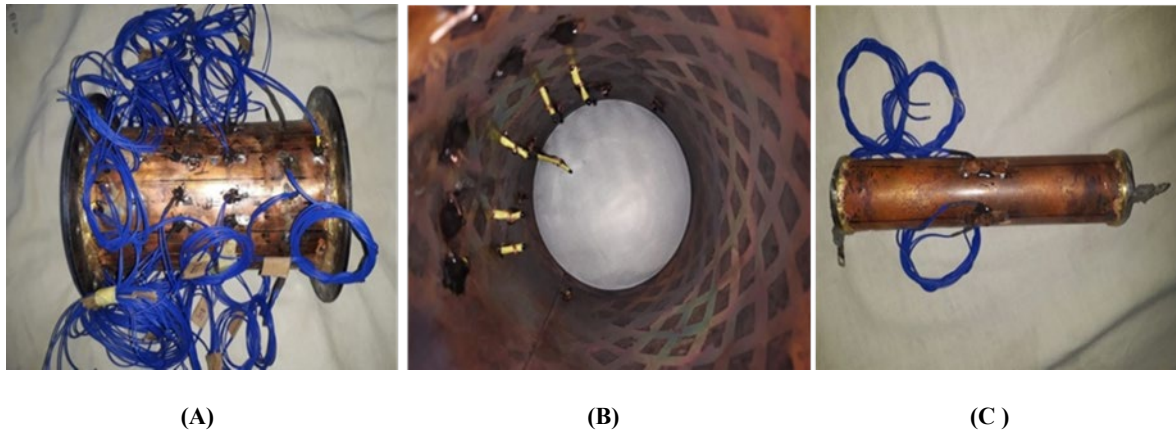
Figure 4: A, B and C representation of the NTC thermistors and their fixing location on inner and outer cylinders

2.2 Experimental Procedure

The following steps were taken to conduct the experimentations:

1) The motor EACs (evaporating air-cooling system) and the electrical heater are turned on.
2) After waiting more than four hours for the maximum needed voltage to attain a steady state, the device moved to the next voltage, at minimum, the lower one (to decrease the timing required for achieving the steady state).
3) Firstly, the experiments were conducted for natural convection after reaching the steady state without vibration to study the effect of Rayleigh numbers at each eccentricity.
4) The heated inner cylinder was vibrated by turning on the vibration system after it reached a steady state. The function generator was set to produce sinusoidal waves at the required frequency.
5) Modifying the exciter frequency of the model (test section) after 30 minutes of shedding each frequency to record its effect on heat transfer rate, then waiting about 15 minutes before varying the frequency.
6) The measuring parameters collected for each test run are:
   a) The inner cylinder position(eccentricity)
   b) The heater current voltage in Ampere and volts, respectively.
   c) Every minute,°C readings from an NTC thermistor were recorded and sent via a signal to a data acquisition system to be registered and shown to a control program using LabVIEW software and then displayed on a personal computer P.C. in an Excel worksheet.
   d) The amplitude and frequency at each run.

Repeating the process using different values for eccentricity parameters, heat flux, Rayleigh number, and frequency (f=0, 2, 5, 10, 15,20Hz).

The schematic diagram of the experimental procedure is indicated in Figure.5.

2.3 Experimental Analysis Procedure

As the internal heated cylinder vibrates and different heat fluxes are delivered to the inner cylinder at every eccentricity while the external cylinder is cooled and maintained at to, the heat transferring procedure in an annulus was examined using simplified methods. The total input power supplied to the inner cylinder can be calculated by:

$$P = V \times I \tag{1}$$

The internal cylinder's convection and radiation transport heat are:

$$Qcr = P - Qcond \tag{2}$$

Wherein, Qcond is the heat by conduction, as determined by the equation given below:

And it experimentally equals 5% [25].

$$Q_{conduction} = \frac{\Delta Toi}{ln\frac{roi}{rii}/2\pi kl} \tag{3}$$

A representation of the convection-radiating heat flux is:

$$q_{cr} = \frac{Qcr}{Ai} \tag{4}$$

where: Ai is the surface area of the internal cylinder, which (Ai = πDil) The radiation heat flux from the following equation as in [26]

$$Q_{Radiation} = \frac{\sigma * Ai((\overline{T_{hs}}+273)^4 - (\overline{T_{os}}+273)^4)}{\frac{1}{\varepsilon 1} + \frac{1-\varepsilon 2}{\varepsilon 2}(\frac{Di}{Do})} \tag{5}$$

where $\overline{T_{hs}}, \overline{T_{os}}$, is the inner and outer surface mean temperature.

σ = Stefan Boltzmann constant = 5.67×10^{-8} W/m². °C,

ε 1, ε 2: Emissivity of inner and outer surfaces, respectively, ε = 0.04

The computed and predicted heat loss via radiation and conduction is ($2\% \leq \frac{q_{c-conv}}{q_t} \leq 5\%$) [25].

$$Q_{convection} = P - Q_{conduction} - Q_{Radiation} \tag{6}$$

$$q``_{conv} = \frac{Q_{convection}}{Ai} \tag{7}$$

The internal heated cylinder's average temperature increase is calculated using

$$\Delta T_{ave} = \overline{T_{sl}} - \overline{T_b} \tag{8}$$

$\overline{T_{sl}}$: represents the average surface temperature of the internal cylinder, which can be calculated as of

$$\overline{T_{sl}} = \frac{1}{\pi di} \int_0^{\pi di} T_{si} dr = \frac{\sum_{i=1}^N T_{si}}{N} \tag{9}$$

where N=4 T_{si}: is the local surface temperature of the heated inner cylinder measured.

$$\overline{T_b} = \frac{1}{L} \int_0^L T_b dr = \frac{\sum_{i=1}^N T_b}{N} \tag{10}$$

T_b: is the bulk mean (air) temperature assessed at the outlet inside the annuli, as the procedure outlined in [27].

All thermodynamics air properties of β, ϑ, α, ρ, K, and μ, were evaluated at the average mean film temperature $\overline{T_f}$.

$$\overline{T_f} = \frac{\overline{T_{sl}} + \overline{T_b}}{2} \tag{11}$$

Based on the film temperature and for a constant heat flow through convection q", dimensionless variables are derived as shown below:

Grashof and Rayleigh's numbers are calculated from the following equation at a continuous heat flux [22]

$$Gr = \frac{\rho^2 g_o \beta q'' L^4}{K_f \mu^2} = \frac{g_o \beta q'' L^4}{K_f \vartheta^2} \tag{12}$$

$$Ra = \frac{\rho^2 g_o \beta q'' L^4}{K_f \mu^2} Pr = \frac{g_o \beta q'' L^4}{K_f \vartheta^2}. Pr \tag{13}$$

The vibrational Rayleigh number represents the rate between the buoyancy force to the viscous force, where the acceleration results from the vibrations

$$Ra_{vib} = \frac{1}{2}\left[\frac{\rho^2 (b\Omega)\beta q'' L^2}{K_f \mu^2}\right]^2 Pr = \frac{1}{2}\left[\frac{(b\Omega)\beta q'' L^2}{K_f \vartheta^2}\right]^2 \tag{14}$$

The average factor of heat transferring and the average Nusselt number could be calculated using the equation below [26]:

$$\bar{h} = \frac{q``}{\Delta T_{ave}} \tag{15}$$

Average Nusselt number [26]

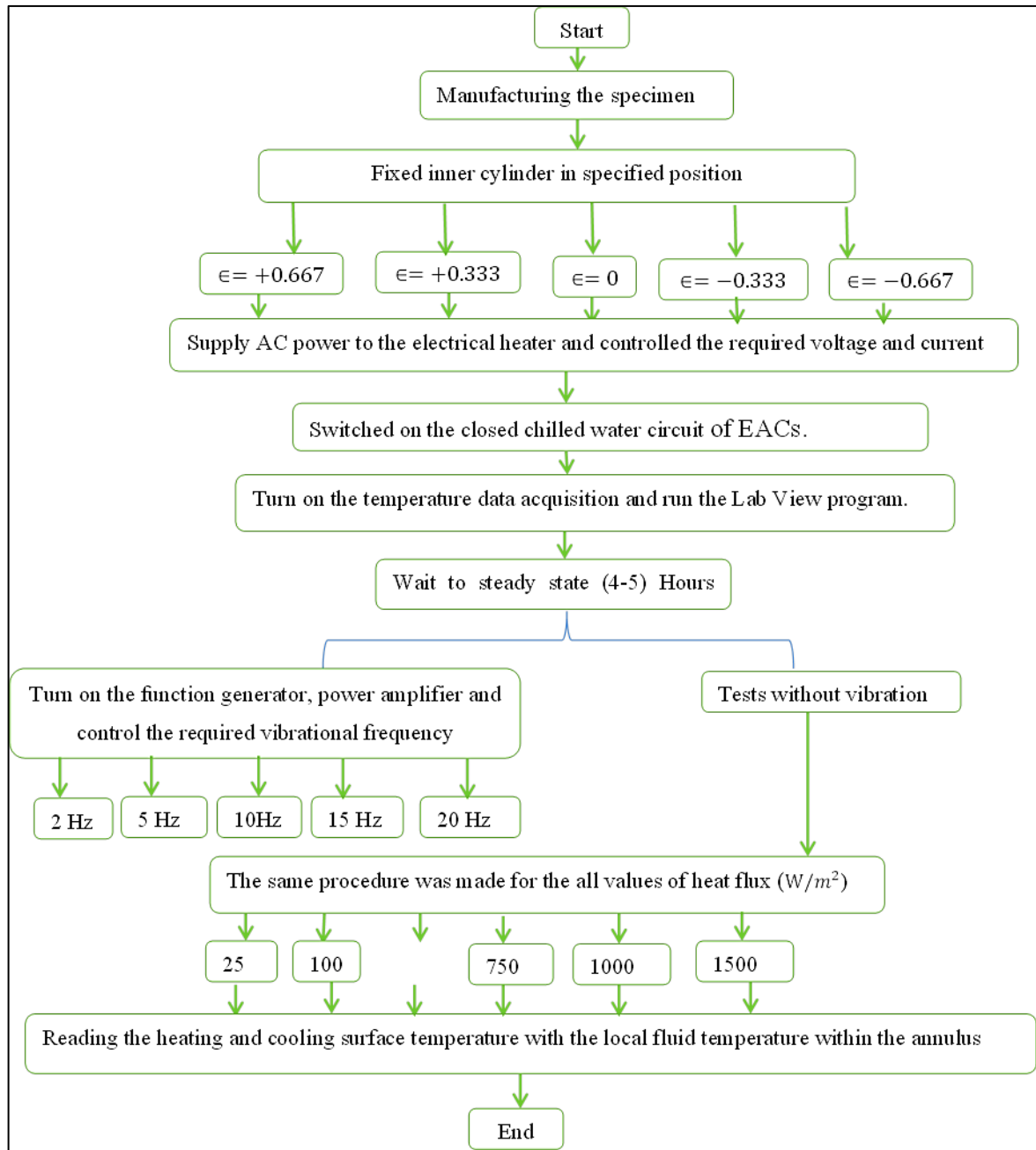$$\overline{Nu} = \frac{\bar{h} L}{k} \tag{16}$$

Figure 5: Schematic representation of the experimental procedure

3. Uncertainty Analysis

The uncertainty within the assessed parameters is calculated using the technique proposed by reference [28-31]. The computation for the uncertainty in the assessed parameters of (heat transferring ratio q``, average heat transferring factor, average Nusselt value, Rayleigh number, and vibrational Rayleigh number) used the uncertainty in the independent information, including geometric dimension, surface temperatures of the heated internal cylinder, fluid temperatures tapped in annular, voltages, currents, and vibrational frequency and amplitude of the vibrational heated inner cylinder. The problem solution for this random fluctuation in the measured values lies in repeating the measurements many times, and such uncertainty depends upon the technique proposed by [28].

The uncertainty in the values of the estimated parameters for a given heat flux $q``=25W/m^2$, as shown in Table 2, reveals that the maximum uncertainty in the estimated parameters is less than 12.68%

Table 2: Uncertainty of the various measured and estimated parameters

Measured								Estimated		
Di, Do (mm)	L (mm)	T (°C)	V (V)	I (Amp)	f (Hz)	**q``%** (**Wm²**)	**h̄%** ($\frac{W}{m^2}\cdot°C$)	**N̄u%**	**(Ra%)**	**(Ra_{vib})%**
0.01	0.01	0.001	0.05	0.01	0.08	4.27	7.546	12.658	3.509	12.680

4. Results and Discussion

Eccentricity plays a significant role in the flow and heat transfer behavior in the horizontal annulus with a vibrating heated inner cylinder and stationary outer cylinder. The eccentric case is much more complicated than its concentric counterpart because the flow fields are strongly influenced by the geometry of the annulus and its orientation. The temperature variation along the gap between two cylinders, the gain in average Nusselt number due to vibration, and the effect of the vibration intensities have been plotted for different eccentric positions. The vibrational vector was parallel to the gravity vector with the range of the Rayleigh number (Ra = $5 \times 10^4, 8.76 \times 10^4, 3.8 \times 10^5, 8.08 \times 10^5, 2.8 \times 10^6,$ and 6.48×10^6), heat flux(q`` = $25, 100, 500, 750, 1000,$ and $1500 \, W/m^2$), and the excitation frequency of the heated inner (f = 2,5,10,15, and 20Hz).

The eccentricity ranging $\left(\in= \frac{e}{L} = -0.667, -0.333, 0, +0.333 \& + 0.667\right)$ the two cylinders must be above the internal cylinder's center and below the external cylinder's center to be positive and negative, respectively. Comparing the two cases in the absence and presence of vibration of the heated internal cylinder will provide considerable insight into the physical function of vibrating and its influence on the fluid within the annulus.

The results for the concentric annulus are shown in Figure 6 when a test run was conducted for Ra = 5×10^4, and the radius ratio R = $\frac{Ro}{Ri}$ = 2.6, and $\frac{L}{Di} = \frac{Ro-Ri}{Di} = 0.8$. Figure (6) compares the local thermic conductivity to the experimental data from [21] and displays the results. The maximum local discrepancy at the top of the outer cylinder is less than 5 percent, as stated in the previous section.
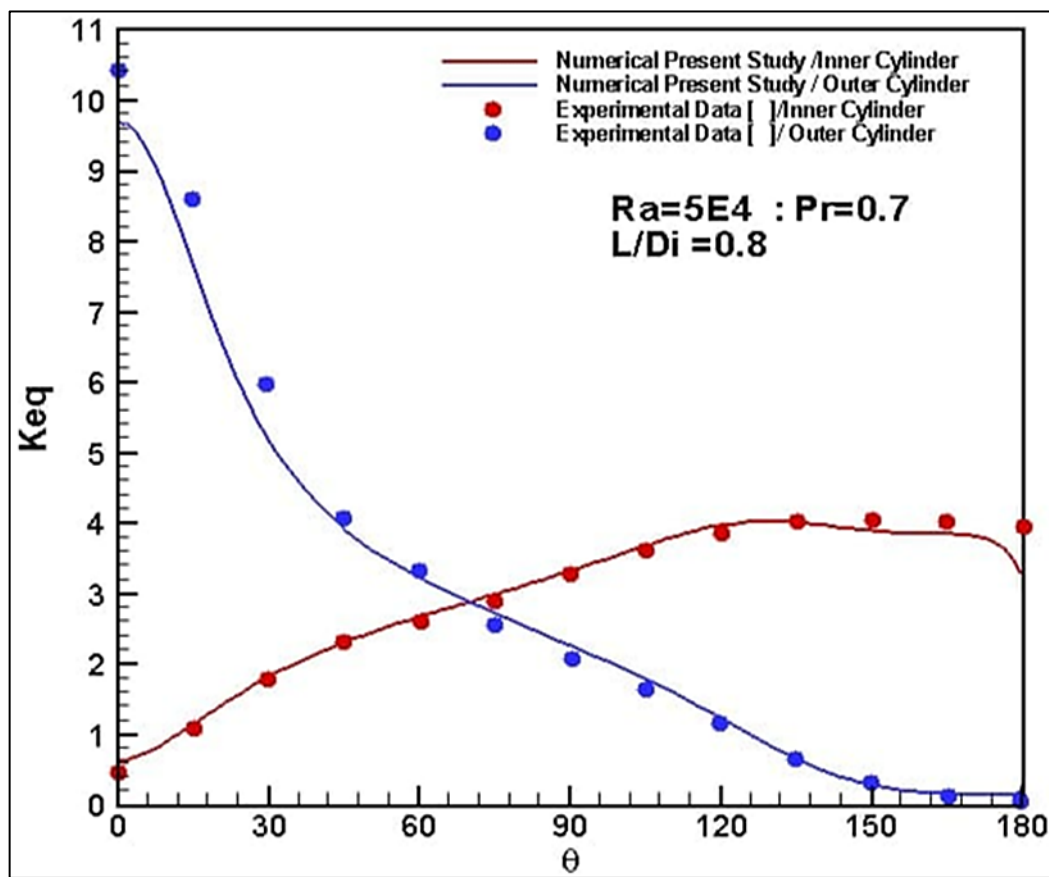

Figure 6: Validation of Concentric local heat transfer coefficients at $Ra = 4 \times 10^5, Pr = 0.7, \in= 0, \frac{L}{Di} = 0.8$, from [21]

4.1 Effect of Eccentricity

The dimensionless temperature distribution represents the results. The eccentric case is much more complicated than its concentric counterpart because the flow field is strongly influenced by the geometry of the annulus and its orientation. Figure (7) shows the variation of the dimensionless radial temperature from the external surface of the internal cylinder to the inner surface of the outer cylinder for heat flux $q`` = 500 \, W/m^2$ at all applied vibrational frequencies, this variation was compared with the stationary case when the vibrational frequency is zero and for two vertical eccentricities $\left(\in= \frac{e}{L} = +0.667, \text{and} -\right.$ $0.667\right)$, the centric position ($\in= \frac{e}{L} = 0$) is plotted for the selected runs. Since the temperature distribution at ($\in= \frac{e}{L} = +0.333$) is almost similar to those ($\in= \frac{e}{L} = +0.667$), and at $\left(\in= \frac{e}{L} = -0.333\right)$ is almost similar to those ($\in= \frac{e}{L} = - 0.667$), these results are not presented here for brevity. But if there is any difference between them, it will be mentioned. Generally, such figures reveal that the radial temperature variation decreased as the frequency increased from (5 to 20 Hz) for constant heat flux and at

each eccentric position. This can be explained by how the boundary layer next to the heated internal cylinder's external surface is affected by the vibration of the inner cylinder. This decrease in boundary layer thickness enhances the heat-transferring process between the mentioned surface and the annulus's bulk air temperature. However, the chosen influence is essentially based on the eccentricity of the inner cylinder and the response of the vibrating heated internal cylinder. The reduction in temperature difference at negative columnar position($\epsilon = \frac{e}{L} = -0.667$), is less than the centric position($\epsilon = \frac{e}{L} = 0$), which is, in turn, lesser than the favorable columnar position ($\epsilon = \frac{e}{L} = +0.667$) at each applied frequency.
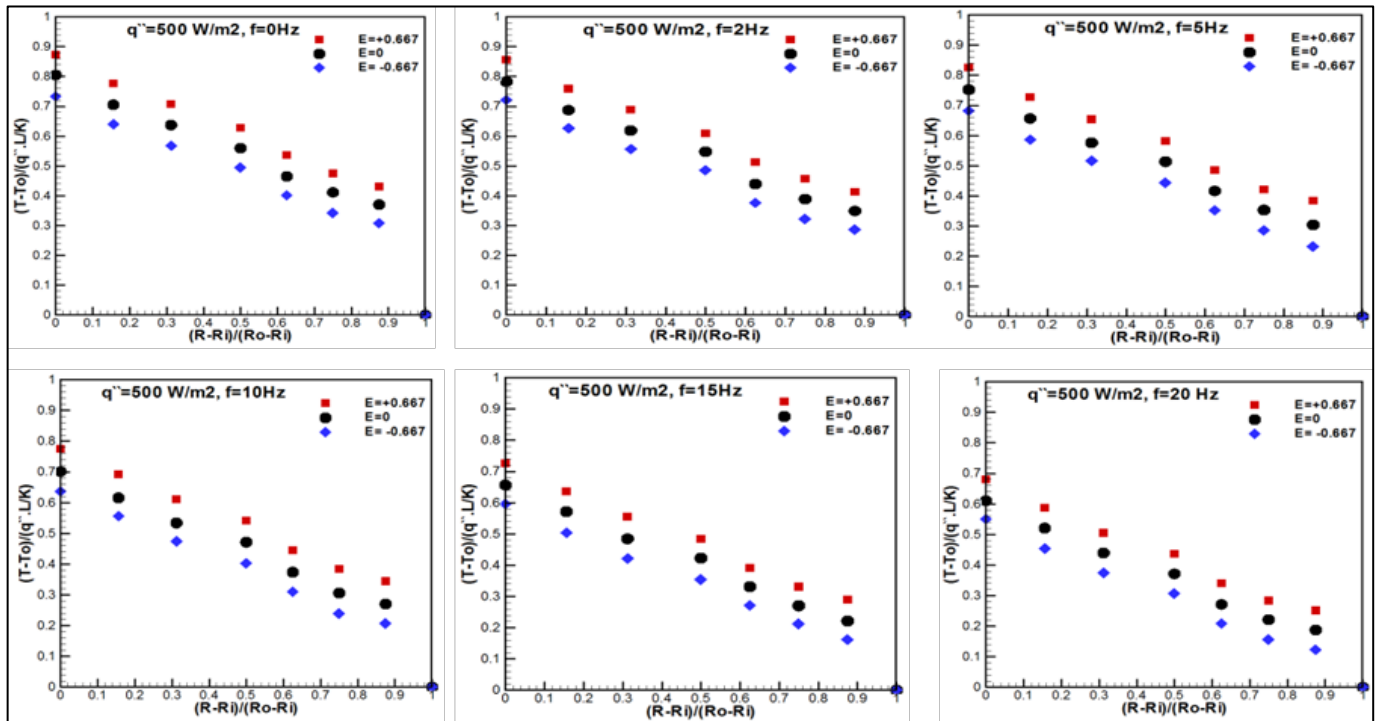
Figure 7: Variation of dimensionless radial temperature distribution along the annulus gap for heat flux$q`` = 500\,\text{W/m}^2$ of the centric $\epsilon = 0$, and eccentricity$\epsilon = \mp 0.667$; at each applied frequency

4.2 Effect of Heat Flux

Figures (8 and 9) explain the influence of changing the heat flux upon the variation of the dimensionless radial temperature from the external surface of the internal cylinder to the inner surface of the outer cylinder related to frequency (f=5 and 20Hz) and for two vertical eccentricities $\left(\epsilon = \frac{e}{L} = +0.667, \text{and} -0.667\right)$ with the centric position($\epsilon = \frac{e}{L} = 0$). It is clear that an increase in heat flow results in a decrease in temperature difference. Generally, the reduction in the temperature difference is relatively increased along the length of the annulus gap between two cylinders as the agitation frequencies increase at each location of the internal cylinder, and there is a significant increase within the reduction temperature difference at q`` = 1500W/m^2 whenever the frequencies increase at each eccentric position of the inner cylinder.

4.3 Effect of Vibrational Frequency

Figures (10, 11, and12) illustrate the vibrational dimensionless radial temperature difference when applying all frequencies (f=0, 2, 5, 10, 15, and 20) Hz and for heat flux (q`` = 100,500, and 1500 $\frac{W}{m^2}$), and for two vertical eccentricities $\left(\epsilon = \frac{e}{L} = +0.667, \text{and} -0.667\right)$ with the centric position($\epsilon = \frac{e}{L} = 0$). It could be seen that the vibrating temperature difference reduces along with increasing the applied frequency. Yet, the quantity of such reduction of the radial temperature difference depends on the value of applied frequencies and the location of the inner cylinder's heating eccentricity. This can be attributed to the area of the heating surface, which affects the thickness of the thermic boundary layer, which is thinner in opposing columnar positions compared to centric locations, which are more delicate than positive columnar locations. However, the decrease in temperature difference can be more significant at higher excitation vibrational frequencies (f=15 and 20Hz) than at lower excitation vibrational frequencies (f=2, 5, and 10). This result implies that the heat transfer mechanism improves and that frequency has a beneficial influence on it.
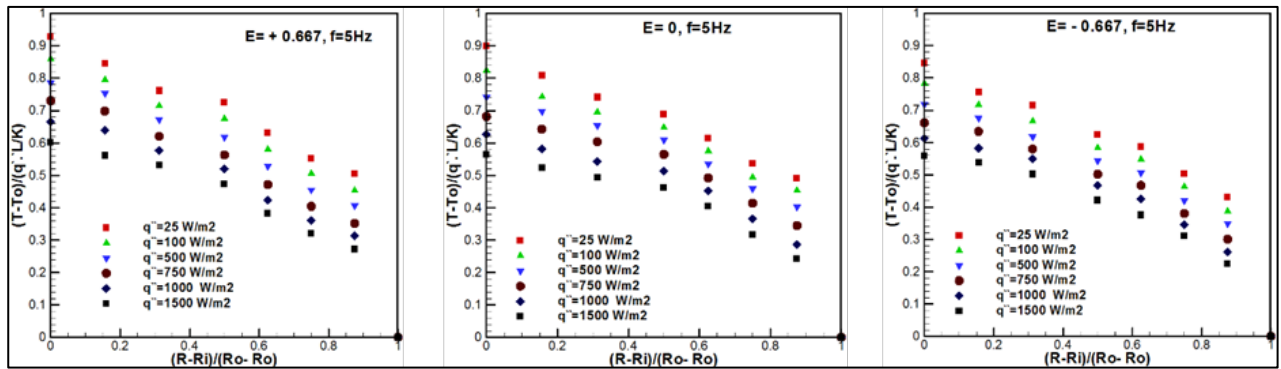
Figure 8: Variation of dimensionless radial temperature distribution along the annulus gap of all heat fluxes for three different eccentricities at a vibrational frequency of f=5 Hz.
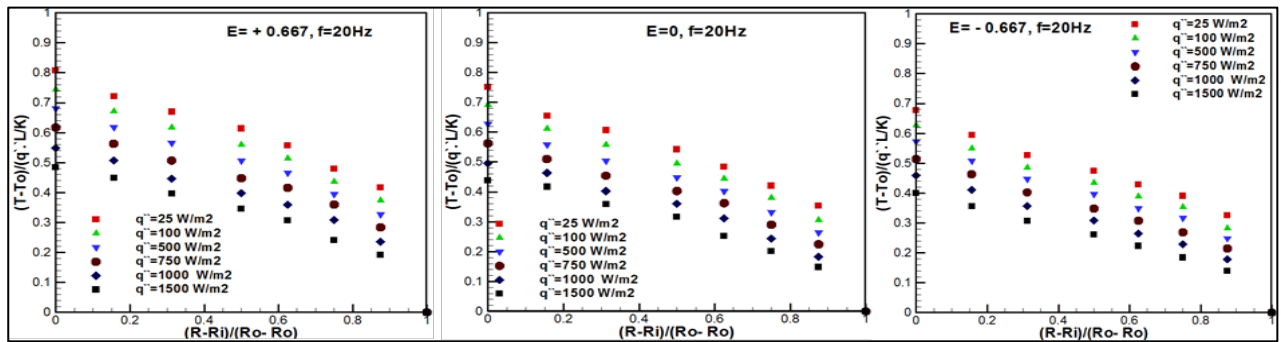

Figure 9: Variation of dimensionless radial temperature distribution along the annulus gap of all heat fluxes for three different eccentricities at the vibrational frequency of f=20 Hz
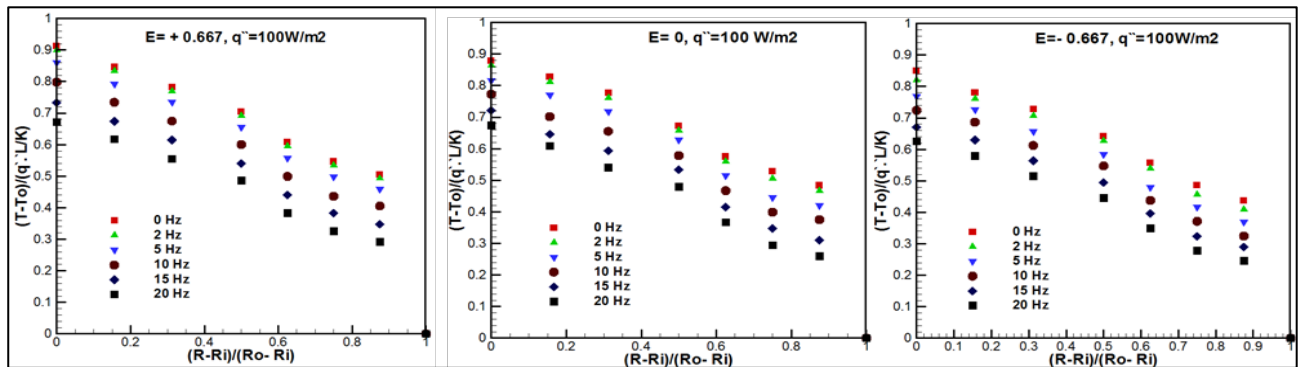

Figure 10: Variation of dimensionless radial temperature distribution along the annulus of all applied frequencies for heat flux $q`` = 100\,W/m^2$ for the centric $\epsilon=0$, and eccentricity$\epsilon= \mp0.667$
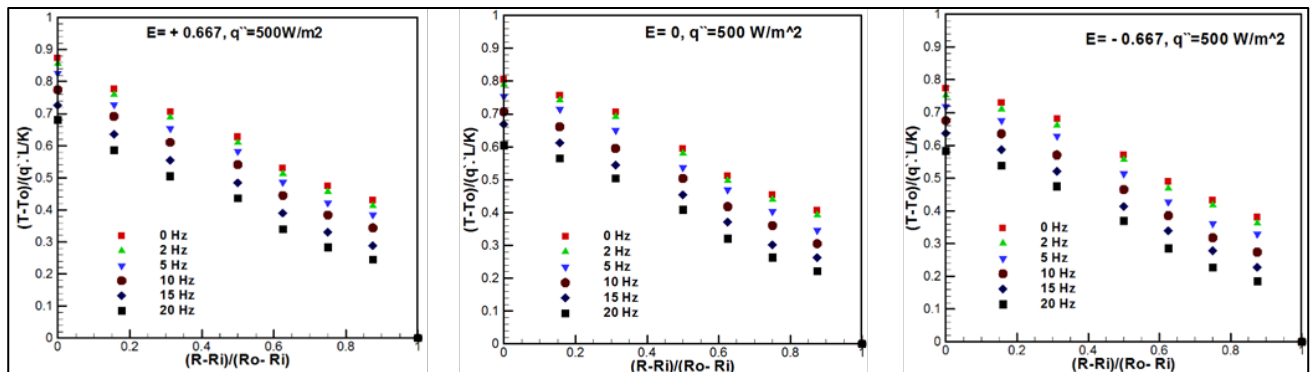

Figure 11: Variation of dimensionless radial temperature distribution along the annulus of all applied frequencies for heat flux $q`` = 500\,W/m^2$ for the centric $\epsilon=0$, and eccentricity$\epsilon= \mp0.667$
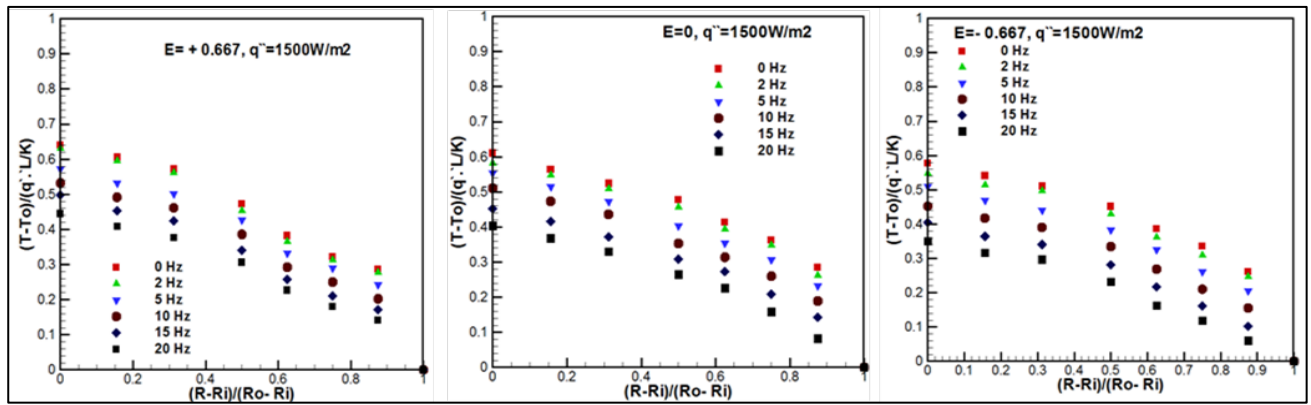
Figure 12: Variation of dimensionless radial temperature distribution along the annulus of all applied frequencies for heat flux q`` = 1500 W/m² for the centric ∈=0, and eccentricity∈= ∓0.667

4.4 The Gain in Average Nusselt Number ($\overline{Nu}$)

The gain in Nusselt number due to the mechanical vibration was estimated at the lower and higher value of the Rayleigh number $Ra = 5 \times 10^4$, and 6.48×10^6, at all vibrational frequencies used in this study(f = 0,2,5,10,15,20)Hz , and for eccentric sites of the inner cylinder($\in = \frac{e}{L} = -0.667, 0$, and $+0.667$) which are listed in Tables 3 and 4.

$$\text{Gain}(\overline{Nu}) = \frac{(\overline{Nu})v - (\overline{Nu})}{(\overline{Nu})} \times 100\% \tag{16}$$

Table 3: $Gain(\overline{Nu}) = \frac{(\overline{Nu})v-(\overline{Nu})}{(\overline{Nu})} \times 100\%$ [32] at $Ra = 5 \times 10^4$

f(Hz)	∈=-0.667	∈=0	∈=+0.667
0	0	0	0
2	3.789970928	1.275566794	0.066113316
5	4.409297636	2.708536405	0.634825513
10	12.94426972	11.08624164	7.940882556
15	20.69568236	16.19494147	13.80764335
20	34.29165989	29.96649678	22.50601475

Table 4: $Gain(\overline{Nu}) = \frac{(\overline{Nu})v-(\overline{Nu})}{(\overline{Nu})} \times 100\%$ [32] at $Ra = 6.48 \times 10^6$

f(Hz)	∈=-0.667	∈=0	∈=+0.667
0	**0**	**0**	**0**
2	13.21686988	9.740053321	7.624531889
5	30.95760255	23.34798395	19.36311496
10	36.67899771	25.86179462	24.29291765
15	59.103177	48.99750849	48.43345106
20	86.66933125	76.65264216	62.40585348

It is evident that the heat transfer rate increases proportionally as the vibrational frequency increases, but to different extents depending on the eccentricity of the heated inner cylinder.

The values of the heat gain in $\overline{Nu}$ at high Rayleigh number $Ra = 6.48 \times 10^6$ are greater than $Ra = 5 \times 10^4$. Also, it is noted that the heat transfer rate enhancement reaches the minimum value when $Ra = 5 \times 10^4$, and at $\in = \frac{e}{L} = +0.667$; however, the augmentation of the heat transfer rate reaches the maximum value at ($\in = \frac{e}{L} = -0.667$) for $Ra = 6.48 \times 10^6$. At the negative vertical position of the inner cylinder, the effect of vibration on the gain in Nusselt number increases with the increase in Rayleigh numbers, where the chaos and mixing process of the various layers in laminar flow are more potent than at the lower value of Rayleigh numbers. However, the mechanical vibration has a less positive effect on the heat transfer at the positive vertical eccentric of the heated inner cylinder.

4.5 The Effect of Vibration Intensity on Nuv

The vibration intensity is defined as the product of vibration amplitude by a frequency (b.f) with a unit of (m/s). Figure (13) illustrates the effect of the vibration intensity upon the average vibrational Nusselt number for all levels of applied heat fluxes at

$\left(\in= \dfrac{e}{L} = +0.667, \text{ and } -0.667\right)$ of eccentric locations of the internal cylinder. The average vibrational Nusselt number increases similarly, although its value varies depending on the frequency. According to the reference [21], when the vibrating frequency increased, which caused an increase in vibration density (intensity), there was a corresponding rise in the average vibrating Nusselt number. Thus, the maximum value of the average Nusselt number can be attained once the vibration intensity becomes equal to (0.092) m/s at the vibration amplitude (4.6 mm peak to peak) for all applied frequencies and for the three different inner cylinder positions.

In general, there is a proportional increase in $\overline{Nuv}$ along with increasing the vibrational intensity for all power levels in these experiments. The influence of vibration is limited at low power levels but significant at high.
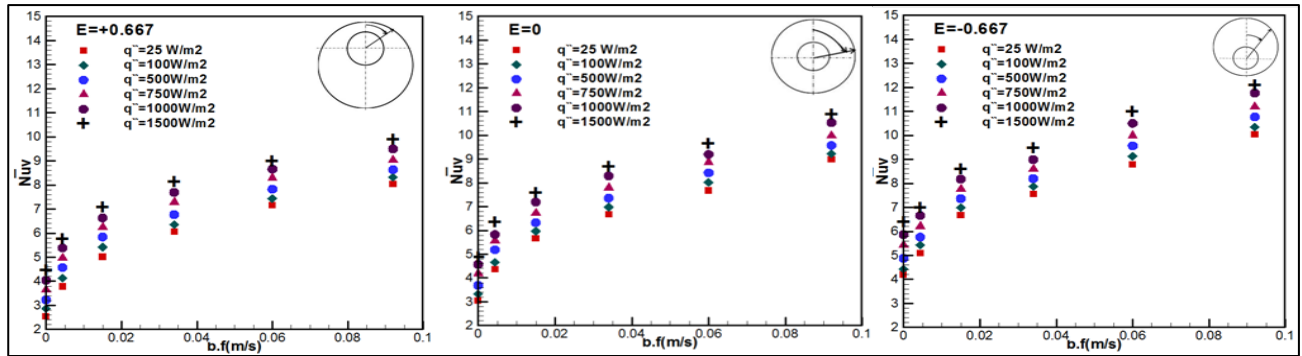

Figure 13: The effect of vibration intensity on average Nusselt number for all applied heat flux at the centric $\in=0$, and Eccentricity $\in= \mp 0.667$

5. Conclusion

This work investigated natural convection in centric and vertically eccentric horizontal cylindrical annular structures under the effect of vertical mechanical vibration that was parallel to gravity's direction. The internal cylinder is heated at a constant heat flux, whereas the external cylinder is cooled at a constant temperature. The radius ratio in this work is $(Ro/Ri) = 2.6$, while the rate of the gap width to the internal cylinder diameter is $(L/Di) = 0.8$, with five different eccentricities of the internal cylinder $\left(\in= \dfrac{e}{L} = -0.667, -0.333, 0, +0.333 \& + 0.667\right)$, and frequency $(f = 2, 5, 10, 15, and\ 20\ Hz)$ with the steady-state without vibration ($f = 0\ Hz$). It was found that the heat transfer was influenced by eccentricity, heat flux, Rayleigh number, and vibration intensity. The variation of the temperature difference along the gap (radius ratio) between two cylinders without the vibration of the heated inner cylinder has the same trend as the inner cylinder in the presence of vibration. The temperature difference between the two cylinders at the opposing positions significantly decreases compared to centric and positive positions. Therefore, the eccentricity for the same heat flux and the vibrational frequency affects the heat transferring rate. The effect of temperature difference is decreased with increasing the heat flux for the same eccentricity and vibrational frequency. The reduction in temperature difference increased as the excitation frequency increased for the same abnormality, heat flux, and vibration frequency. The vibration intensity was also observed to influence the vibrational average Nusselt number. In our experimental conditions, the vibrational moderate Nusselt number increases as the vibration intensity increase at each Rayleigh number and for each eccentric position of the heated inner cylinder.

6. Recommendation

- Study the effect of vibration upon the forced or mixed convection heat transfer at the same vertical eccentric horizontal annulus condition experimentally.
- Study the effect of acoustic vibration on the heat transfer and experimentally compare with a vibrated heated inner cylinder at the same conditions.
- Changing the eccentricity of the heated inner cylinder to the horizontal or a radial positive and negative quirk and then applying the mechanical vibration experimentally.

$\beta(\frac{1}{°C})$	$K_f\left(\frac{W}{m.°C}\right)$	Pr	$\mu(\frac{Kg}{s})$	$\rho(\frac{Kg}{m^3})$	$\vartheta(\frac{m^2}{s})$
0.00313	0.02656	0.72541	1.89399×10^{-5}	1.10483	1.75918×10^{-5}

Nomenclatures

1. Ai: surface area of the heated vibrational inner cylinder
2. b: amplitude (mm)
3. CHF: constant heat flux
4. Di, Do: inner and outer cylinder diameter (m)
5. e: eccentricity (m)
6. $\in$:dimensionless eccentricity $=\dfrac{e}{L}$

7.   g: gravitational acceleration ($\frac{m}{s^2}$)
8.   A: current in Amper
9. K_f: thermal conductivity $\left(\frac{W}{m.°C}\right)$
10. k_{eq}: Local equivalent conductivity, hi Di $\ln(\frac{Do}{Di})/2K$ for inner cylinder , ho $Do \ln(\frac{Do}{Di})/2K$ for outer cylinder
11. $\overline{k}_{eq}$: Average equivalent conductivity $\overline{Nu}/Nucond$
12. l: axial length of the cylinder (m)
13.   L: the gap width= (Ro-Ri) in (m)
14.   N: the number of NTC thermistors
15.   Nu, $\overline{Nu}$: local and average Nusselt number
16.   *Pr: Prandtle number*($\frac{\vartheta}{\alpha}$)
17.   q``:heat flux ($\frac{W}{m^2}$)
18. Ra : Rayleigh number $(g\beta qL^4/K\vartheta^2)Pr$
19. Ra_{vib}: Vibrational Rayleigh number $(\frac{1}{2}[\rho^2(b\Omega)\beta q"L^2/K \mu^2]^2 Pr$)
20.   Ri, Ro: outer and the inner cylinder radius (m)
21.   Rr: radius ratio
22.   T: temperature (°C)
23.   V: voltage; volt

Greek Symbols

1.α thermal diffusivity ($\frac{m^2}{s}$)

2. ϑ kinematics viscosity($\frac{m^2}{s}$)

3. β thermal expansion coefficient($\frac{1}{°C}$)

4.Ω dimensional and dimensionless angular frequency

5. θ dimensionless temperature ($\frac{(T-T_C)K}{q"L}$) in the case of CHF

6. ρ density of the fluid $\frac{Kg}{m^3}$

Author contributions

All authors contributed equally to this work.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest

References

[1] R. Hosseini, A. Rezania, M. Alipur, and L. A. Rosendahl, Natural Convection Heat Transfer from a Long Heated Vertical Cylinder to an Adjacent Air Gap of Concentric and Eccentric Conditions, Heat Mass Transfer, 48 (2012) 55-60. https://doi.org/10.1007/s00231-011-0840-6

[2] H. Shokouhmand, S.M.A. Noori Rahim Abadi, and A. Jafari, The effect of the horizontal vibrations on natural heat transfer from an isothermal array of cylinders, Int. J. Mech. Mater. Des., 7 (2011) 313-326. https://doi.org/10.1007/s10999-011-9170-6

[3] C.B. Baxi, N.a.Ramachandra, Effect of Vibration on Heat Transfer from Spheres, Winter Annu. Meet. New York, N.Y.I, 68, 1968.

[4] R. E. Forbes, C. T. Carley, and C. J. Bell, Vibration effects on convective heat transfer in enclosures, ASME(1970), J. Heat Transfer, 92 (1970) 429-438. https://doi.org/10.1115/1.3449681

[5] F. Wu Shung and S. W. Jiann, A study of thermal convection in an enclosure induced simultaneously by gravity and vibration, Int. J. Heat Mass Transfer, 35 (1992) 1695-1710. https://doi.org/10.1016/0017-9310(92)90140-N

[6] W. S. Fu and W. J. Shieh, Transient thermal convection in an enclosure induced simultaneously by gravity and vibration, Int. J. Heat Mass Transfer, 36(1993) 437-452. https://doi.org/10.1016/0017-9310(93)80019-Q

[7] M. H. Al-Ubaydi, Study of Influence of Vertical Vibration on Heat Transfer Coefficient by Free Convection from Cylinders, M. Sc. Thesis, University of Technology, 2001.

[8] U.Shakir, Experimental study of the effect of vibrations on the free convection heat transfer coefficient from an annular finned cylinder, MSc Thesis, University of Technology, 2007.

[9] E.M. Alawadhi, Natural convection flow in a horizontal annulus with an oscillating inner cylinder using Lagrangian–Eulerian kinematics. Comput. Fluids, 37 (2008) 1253–1261. https://doi.org/10.1016/j.compfluid.2007.10.011

[10] A.R. Sarhan, Vertical Forced Vibration Effect on Natural Convective Performance Longitudinal Fin Heat Sinks, Tikrit J. Eng. Sci., 20 (2013) 60-69.

[11] M. A. Tawfik, A. Mohammed, H.Z. Zain, Effect of Vibration on the Heat Transfer Process in the Developing Region of Annulus with Rotating Inner Cylinder, Eng. Technol. J., 33 (2015) 590-611.

[12] H.K. Dawood, H.A. Mohammed, N. A. Che Sidik, K. M. Munisamy, M. A. Wahid, Forced, natural and mixed-convection heat transfer and fluid flow in annulus: A review, Int. Commun. Heat Mass Transfer, 62 (2015) 45-57. https://doi.org/10.1016/j.icheatmasstransfer.2015.01.006

[13] Z.K. Kadhim, H.O. Mery, Influence of Vibration on Free Convection Heat transfer from Sinusoidal Surface, Int. J. Comput. Appl. Technol., 136 (2016) 1-6. https://doi.org/10.5120/ijca2016908252

[14] A.Hosseinian, A.H.M. Isfahani, and E.Shirani, Experimental investigation of surface vibration effects on increasing the stability and heat transfer coefficient of MWCNTs-water nanofluid in a flexible double pipe heat exchanger, Exp. Therm Fluid Sci., 90 (2018) 275-285. https://doi.org/10.1016/j.expthermflusci.2017.09.018

[15] N. K. Murad, H.D. Lafta, S.E. Abdullah, the Effect of Transverse Vibration on the Natural Convection Heat Transfer in a Rectangular Enclosure, Int. J. Mech. Eng. Technol., 10 (2019) 266-277.

[16] H. Laidoudi, M. Helmaoui, M. Bouzit, and A. Ghenaim, Natural convection of Newtonian fluids between two concentric cylinders of a special cross-sectional form. Therm. Sci., 25 (2021) 3701-3714.https://doi.org/10.2298/TSCI200201190L

[17] H. Laidoudi, Enhancement of natural convection heat transfer in concentric annular space using inclined elliptical cylinder, J. Nav. Archit. Mar. Eng., 17 (2020) 89–99. http://dx.doi.org/10.3329/jname.v17i2.44991.

[18] H. Laidoudi, The role of concave walls of inner cylinder on natural convection in annular space, Acta Mech. Malaysia, 3 (2020) 24-28. http://doi.org/10.26480/amm.02.2020.24.28.

[19] H. Laidoudi, Natural convection from four circular cylinders in across arrangement within horizontal annular space, Acta Mech. Autom., 14 (2020), 98-102. https://doi.org/10.2478/ama-2020-0014.

[20] H. Laidoudi, H. Ameur, Investigation of the mixed convection of power-law fluids between two horizontal concentric cylinders: Effect of various operating conditions, Therm. Sci. Eng. Prog., 20 (2020)100731. https://doi.org/10.1016/j.tsep.2020.100731.

[21] M. M. Al-azzawi, A.R. abdullah, B.M. Majel, L. J. Habeeb, Experimental Investigation of the Effect of Forced Vibration on Natural Convection Heat Transfer in a Concentric Vertical Cylinder, J. Mech. Eng. Res. Dev., 44 (2021) 56-65.

[22] T.H. Kuehn and R.J.Goldstein, An experimental and theoretical study of natural convection in the annulus between horizontal concentric cylinders, J. Fluid Mech., 74 (1976) 695-719. https://doi.org/10.1017/S0022112076002012

[23] T.H. Kuehn and R.J.Goldstein, an Experimental Study of Natural Convection in Concentric and Eccentric Horizontal Cylindrical Annuli, ASME, J. Heat Transfer, 100 (1979) 635-640. https://doi.org/10.1115/1.3450869

[24] U.Projahn, H.Rieger, and H.Beer, Numerical Analysis of Lminar Natural Convection between Concentric and Eccentric Cylinders, Numer. Heat Transfer, 4 (1981) 131-146. https://doi.org/10.1080/01495728108961783

[25] D. Naylor, H. M. Badrand, J.D. Tarasuk, Experimental and Numerical Study of Natural Convection between Two Eccentric Tubes, Int. J. Heat Mass Transfer, 32 (1989) 171-181. https://doi.org/10.1016/0017-9310(89)90100-2

[26] F.A.W.Hamed, Experimental Study of Natural Convection Heat Transfer in Inclined Cylindrical Annulus, Sol. Wind Technol., 6 (1989) 573-579. https://doi.org/10.1016/0741-983X(89)90093-3

[27] Cengle, Y.A., Heat Transfer Practical Approach, International edition WCB/McGraw-Hill, 1998.

[28] Venkateshan SP, Mechanical measurements, 2nd ed. Ane Books Pvt.Ltd, India, 2015.

[29] Measurement Uncertainty, International Atomic Energy Agency, IAEATECDOC-1585, May 2008.

[30] S.J. Kline, F.A. McClintock, Describing uncertainties in single sample experiment, Mech. Eng., 175 (1953) 3-8.

[31] S.J. Kline, The purpose of uncertainty analysis, J. Fluids Eng., 107 (1985)153-160. https://doi.org/10.1115/1.3242449

[32] P.K. Nag, and A. Bhattacharya, Effect of Vibration on Natural Convection Heat Transfer From Vertical Fin Arrays, Lett. Heat Mass Transf., 99 (1982) 478-498. https://doi.org/10.1016/0094-4548(82)90020-0