Thermal behaviour of heated stationary inner cylinder of a concentric vertical annulus formed with rotating outer cylinder

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Abstract. Experimental studies have been conducted to investigate the convective heat transfer from the inner stationary heated cylinder of a vertical concentric annulus with outer cylinder rotating, corresponding to rotation speeds from 500rpm to 1000rpm. The centrifugal force arising due to the outer cylinder rotation and the buoyant force developed due to the heat generated from the stationary inner cylinder has been characterized by using a non-dimensional number denoted as Rotation parameter (ζ = \( \frac{\text{Re} \omega^2}{Gr} \)). The influence of Rotation parameter on the convective thermal behaviour of the heated stationary inner cylinder has been explained.

1. Introduction

Convection in annuli has been a problem of interest for many researchers because of the geometrical resemblance in many engineering systems viz, power generators, motors, cooling systems for electronic devices, solar collectors etc. [1, 2]. The annular configuration these systems can either be horizontal or vertical with heated or unheated, rotating/ stationary wall/walls. Among these configurations thermal behaviour of fluid in vertical concentric annuli with heated inner stationary cylinder and outer rotating cylinder has been a subject of interest due to its applications in vertical axis generators, motors, vertical rotating heat exchangers etc. Nagendra et al. [3] experimentally and numerically investigated the flow and heat transfer in vertical annular space formed between two concentric vertical cylinders. They suggested three different correlations for three different categories of annuli, (viz, short, medium and long) \( (Ra \frac{D_o}{L}) > 10^4, 0.05 \leq (Ra \frac{D_o}{L}) \leq 10^4, (Ra \frac{D_o}{L}) \leq 0.05 \).

Hessami, et al. [4] numerically studied the heat transfer and the resulting laminar flow patterns in enclosed concentric vertical annulus with air as the working fluid. In their work they look into the impact of, geometry, flow and thermal variables on temperature and velocity distributions. Flow patterns and heat transfer profiles were found for \( 1.2 \leq \text{Radius ratio} \leq 8.0, 10 \leq \text{Re} \leq 300 \) and \( 10^3 \leq \text{Ra} \leq 10^5 \), and they noticed that the flow and thermal profiles did not show a noticeable influence in Nusselt number values for different radius ratios, but when aspect ratio is changed with fixed Ra and Re, produced significant changes in Nusselt number.

Busse and Hood [5] experimentally and theoretically analyzed the mean zonal flow generated by the centrifugal forces driven thermal fields in a rotating annulus with heated outer wall and cooled inner wall. They conducted the study convex, concave and conical end surfaces. The researchers got
only a semi-quantitative agreement between theoretical predictions and experimental observations. For solving the boundary layer equations Sarhan et al. [6] suggested a finite-difference scheme, after coupling momentum and energy equations of laminar free convection flow in concentric vertical annuli with both the ends open, of radius ratio 0.5 with a fluid of Prandtl Number 0.7 and rotating inner wall. Their main aim of the study was to understand and find the development of the boundary layer displacement thickness in tangential direction for buoyancy effects created flows developing tangentially and the analysis of development of laminar natural convection in vertical concentric annuli with open ends, having either rotating or stationary inner walls. Experimental investigations were conducted by Yong N. Lee and Minkowycz [7] to study the heat transport enhancement characteristics of an annulus formed between two vertical concentric cylinders, with one of it rotating, in the range of Reynolds numbers of axial flow (Re) from 50 to $10^3$ and Taylor number ranging from 1000 to $2 \times 10^7$. They conducted experiments with smooth and grooved inner cylinders and found that the grooves present on the inner rotating cylinder considerably increase the Nusselt number, over the plane cylinder. They also found that large gap ratios are favourable for higher heat transfer. Rothe and Pfizter [8] studied both numerically and experimentally, the flows of turbulent nature and thermal transport in an annular space formed between two concentric rotating cylindrical tubes. They carried out computational studies for the case of outer heated cylinder and inner adiabatic cylinder using Reynolds stress turbulence model, and also by reversing the thermal conditions on the walls. They also reported the effectiveness of mixing length turbulence model and Reynolds stress turbulence model for the aforesaid two cases respectively, and reported that the experimental and numerical results compare well, so the effects of rotation on heat transfer can be predicted correctly with the help of these complex turbulence models. Their results reveals that the increase in Nusselt number with increasing speed of rotation of the inner tube is not dependent on radius ratio and thermal boundary conditions. In addition, they also reported that if the outer cylinder counter-rotates, improvements in thermal transport occur in narrow gap annuli. The thermal behaviour of a sole rotating outer cylinder is mainly affected by its radius ratio. An increase in Nusselt number with speed can be seen in a narrow gap annulus, while the opposite is true in wide gap annulus.

The literature survey reveals that most of the earlier work has been done with inner wall of the annuli rotating and outer wall stationary. However, the literature pertaining to outer wall rotating and inner wall heated and stationary are scarce. This type of geometry finds application in vertical axis generators, electric motors etc. and therefore it is of utmost importance to analyze the influence of the outer cylinder rotation on the thermal performance of the inner heated cylinder. Keeping this in view the objective of the present investigation is to understand the thermal performance of the heated inner cylinder, when the outer cylinder is rotating with high rotation parameters (high rotation speeds).

2. Experimental setup

The photograph of the experimental set up is detailed in Figure 1. The experimental setup consists of a vertical annulus formed with a hollow copper tube with polished outer surface of diameter 51mm, and height 620mm and an acrylic the outer cylinder of inner diameter 83mm and height 620mm. The rotation speed of the outer cylinder is varied with a Variable Frequency Drive. A cartridge heater (Figure 2) inserted in the inner copper tube is used to heat it. The inner tube is heated at different heat fluxes by connecting the cartridge heater to a regulated DC power from a regulated DC power supply. To prevent the heat loss from the bottom face of the inner copper tube, a Teflon bush of outer diameter same as the inner diameter of the stationary copper cylinder is tightly inserted and, the same is fixed to the frame of the experimental set up, in such a way that it also acts as a support for the copper tube. The outer acrylic cylinder is mounted concentrically with the inner tube by means of two nylon bearings, at the bottom and top. The outer cylinder also carries a nylon pulley which is driven by an open belt drive passing through a pulley connected to the shaft a three-phase alternating current induction motor. To reduce the disturbances from the surroundings, an acrylic plenum with its bottom
open is placed at the inlet (bottom) of the annulus. To measure the outer surface temperature, sixteen calibrated T-type thermocouples (32 SWG), with eight thermocouples placed diametrically opposite and equidistant to each other, are fixed to different locations of the heated inner cylinder. All these thermocouples are fixed to their respective positions by using high thermal conducting cement, thermo bond (Fabrica India ltd). To measure the fluid temperature at outlet, two thermocouples placed at the outlet of the annulus are used. To measure the temperature of the fluid entering the inlet of the annulus two other T-type thermocouples are arranged in the plenum. All the thermocouples are connected to a data acquisition system (Keysight India Ltd). The entire assembly is mounted on an optical bench using rubber boots acting as vibration isolators.

Figure 1. Experimental setup

1. Rotating Outer Cylinder, 2. Heated Inner Cylinder, 3. Thermocouple wires, 4. Three Phase AC motor, 5. Variable Frequency drive, 6. Data Acquisition System, 7. DC Power Supply, 8. Adjustable clamp holding inner cylinder and heater, 9. Optical Bench, 10. Frame, 11. Laptop Computer, 12. Inner Cylinder Support, 13. Pulleys, 14. Belt, 15. Plenum, 16 Cartridge Heater, 17. Ceramic cap, 18. Heater electrical connectors.

Figure 2. Cartridge heater
3. Data Analysis
The average surface temperature rise of heated inner cylinder is calculated by equation (1)

$$\Delta T_{avg} = \frac{\sum_{j=1}^{N} T_j}{N} - T_f$$  \hspace{1cm} (1)

Where $N = 16$, $T_f = \frac{T_b + T_\infty}{2}$ and $T_b$ is the bulk fluid temperature.

The average heat transfer coefficient and average Nusselt number are defined as below.

Average heat transfer coefficient,

$$h_{avg} = \frac{\dot{Q}}{A \Delta T_{avg}}$$  \hspace{1cm} (2)

Average Nusselt number,

$$Nu_{avg} = \frac{h_{avg} d}{k_f}$$  \hspace{1cm} (3)

4. Experimental Uncertainty
The uncertainties in the measured and estimated parameters are calculated by the method suggested by Kline and McClintock [9] based on Equation (4), where $\sigma_R$ is the uncertainty in the estimation of the dependent parameter $R$ and $\sigma_X$ is the uncertainty associated with the independent parameter $X$.

$$\sigma_R = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial R}{\partial X_i} \right)^2 \sigma_{X_i}^2}$$  \hspace{1cm} (4)

The uncertainty analysis carried out at rotation parameter 1190, depicted in Table 1 clearly indicates that the estimated parameter uncertainty values are less than 3% which is well within the agreeable limits [10].

Table 1. Uncertainty of the various measured and estimated parameters

| Rotation parameter | Measured | Estimated |
|-------------------|----------|-----------|
|                   |          |           |
| $\zeta$           |          |           |
| 1190              | 0.01     | 0.01      |
| D                 | 1.0      | 1.0       |
| d                 | 0.20     | 0.10      |
| H                 | 0.10     | 0.01      |
| T                 | 1.0      | 2.2       |
| V                 | 0.16     | 2.1       |
| I                 | 2.3      | 2.2       |
| N                 | 1.9      | 1.9       |
| A                 | 0.87     | 0.87      |
| Q                 |          |           |
| A                 |          |           |
| Q                 |          |           |
| h_{avg}           |          |           |
| Nu_{avg}          |          |           |
| Re_{u}            |          |           |
| Gr                |          |           |
| $\zeta$           |          |           |

5. Results and Discussions
Experiments has been conducted for rotational parameter in the range $527 \leq \zeta \leq 2860$, keeping the heat flux as 80W/m² and the annular gap as 16mm. Figure 3 shows the variation in Nusselt number with respect to the Rotation parameter. It can be inferred from the figure that as the Rotation parameter is increased from 527 to 1190 there is a substantial improvement in heat transfer. This increase in heat transfer can be attributed to the formation of vortical structures resulting in increase in turbulent kinetic energy near the heated inner cylinder. Further increase in Rotation parameter resulted in only marginal improvement in heat transfer. This marginal improvement may be attributed to the flow recirculation in the horizontal plane of the annulus. This flow recirculation can reduce the thermal capacity of the bulk fluid resulting in the marginal improvement in heat transfer. To get qualitative and qualitative information of the flow and thermal field based on stream lines and isotherms is essential to substantiate the earlier statement. Due to the non-availability of flow visualization techniques, only the information gathered from the numerical simulations can substantiate the above statements. This may be considered as a future work.
Figure 3. Variation of Average Surface Nusselt Number with Rotation parameter

6. Conclusions

- Experimental investigations have been conducted to study the thermal behaviour of heated inner cylinder of a concentric vertical annulus with rotating outer cylinder.
- As the rotation parameter is increased from 527 to 1190, there shows a significant enhancement in heat transfer.
- As the rotation parameter changes from 1190 to 2860, shows only a marginal improvement in heat transfer.

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