Int. J. Chem. Sci.: 14(4), 2016, 2763-2774
ISSN 0972-768X
www.sadgurupublications.com

BUOYANCY INDUCED NATURAL CONVECTIVE HEAT TRANSFER ALONG A VERTICAL CYLINDER UNDER CONSTANT HEAT FLUX

RAVI BABU SAJJA[a*] and G. SAMBASIVA RAO[b]

[a]Department of Power Engineering, GMR Institute of Technology, RAJAM (A.P.) INDIA
[b]Sir C. R. R College of Engineering, ELURU (A.P.) INDIA

ABSTRACT

Buoyancy induced natural convective heat transfer along vertical cylinder immersed in Newtonian fluids such as water, water and ethylene glycol mixture with 75: 25 ratio under constant heat flux condition is investigated experimentally and presented. Thermal stratification was observed in the ambient fluid after steady state conditions achieved as the fluid temperature goes on increasing along the axial direction outside the boundary layer. Temperature variation of the cylinder along axial direction, temperature variations of fluid in both axial and radial direction are shown graphically. It is observed that the temperatures of the cylinder and the fluid increases along axial direction and the fluid temperature decreases in radial direction also, it is understood that thermal stratification is achieved. Experiments were conducted for different heat inputs (30W, 40W, 45W and 50W) and a correlation between the non dimensional numbers Nusselt number (Nu) and Rayleigh number (Ra) for uniform or constant heat flux condition is suggested as $Nu = 0.287 (Ra)^{0.287}$.

Key words: Natural convection, Constant heat flux, Thermal stratification, Newtonian fluids.

INTRODUCTION

Many research investigations both theoretical as well as experimental on the cooling of the electronic equipment in buoyancy induced free convection have been reported in the literature. The solution of a free convection problem involving less complex geometry starts with Polhansan's solution of the vertical plate, where the conditions on the plate and on the flow field are treated as limited in the interaction or even independent. Heat transfer has been a key and challenging area for designers of electronic equipment. The reliability and

*Author for correspondence; E-mail: ravibabu.s123@gmail.com; ravibabu.s@gmrit.org

life of electronic equipment mainly depends on its operating temperature and its life can be enhanced significantly by using it at lower temperatures.

Fujii and Uehra[1] compared the natural convection heat transfer between vertical cylinder and a vertical plate, which are situated in air. For any prandtl number, they presented a correlation equation for non dimensional Nusselt number. Cohen and Herman[2] experimentally investigated the unsteady state free convection heat transfer in vertical enclosures with uniform heating for different aspect ratios. Sharma et al.[3,4] numerically analyzed turbulent free convection from a radiating fin situated in air by integral method of analysis with inclusion of thermal radiation to the surrounding medium and also studies were performed on natural convection from a radiating fin to thermally stratified medium of air. Lee et al.[5] did the numerical analysis for the buoyancy induced free convection along slender vertical cylinders with variable surface temperature for the various mediums with prandtl numbers of 0.1, 0.7, 7 and 100 and graphically presented the local Nusselt number, velocity and temperature profiles. For Nusselt number, a correlation was given. Sharma et al.[6] analyzed the thermal performance of a vertical fin in a non Newtonian fluid for which prandtl is very much higher than 1. Amara et al.[7] numerically investigated the natural convection heat transfer in vertical cylinder opened at both ends and filled with porous medium and given periodical lateral heat flux density as a heat input. They used the darcy flow model in which the local thermal equilibrium between solid and liquid phases has been assumed. Trevino et al.[8] analyzed the natural convective conjugate cooling mechanism in vertical fins and an estimate of thermal perturbation length was presented. Popiel and Wojtkowiak[9] conducted experiments on natural convection heat transfer from a square cylinder immersed in air using lumped heat analysis method. Naidu et al.[10] numerically solved the problem of free convection heat transfer along a vertical fin to a saturated porous medium and they used the conjugate conduction convection analysis is used to solve the problem. Jarall and Campo[11] conducted an experimental study of laminar free convection heat transfer from vertical cylinder in air under steady state conditions and proposed the correlations for dimensionless Nusselt number. Experimental studies were performed on laminar free convection heat transfer from isothermal vertical cylinder by Popiel et al.[12] Zahmatkesh[13] analyzed the effect of thin vertical fin on natural convection heat transfer in porous medium with thermal stratification effect. Bairi et al.[14] reviewed and presented the applications on natural convection heat transfer in particular on paralleogrammic diode cavity. Xu et al.[15] conducted experiments on thermal flow and thin film present on the side wall of a cavity using natural convective heat transfer. Various techniques for measuring thermal conductivity of liquids are shown in Fig. 1. In this present work, transient hot wire method is chosen for measuring the thermal conductivity.

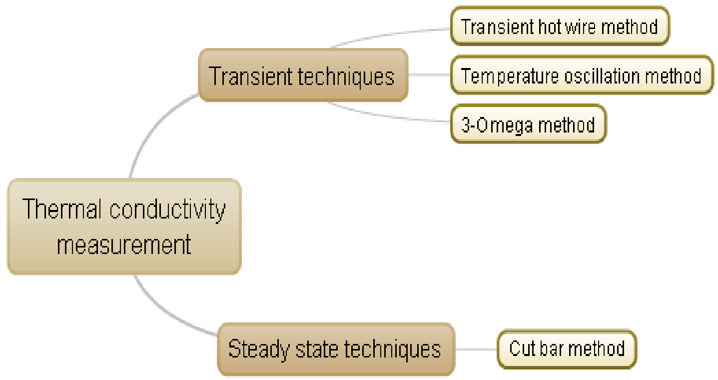

Fig. 1: Thermal conductivity measurement techniques

EXPERIMENTAL

The experimental setup consists of an aluminum square prismatic container which contains the testing liquid, Brass tube of 1.27 cm diameter and 25 cm length, a cartridge type tubular heater, Outer shell with cooling water in and out arrangement, Chrome-Al type thermocouples of teflon coated to resist the temperature effects, instrumentation panel with dimmerstat or variac to vary the heat input, Voltmeter, Ammeter, and digital temperature indicator. All the thermocouples were calibrated with constant temperature bath at various temperatures and obtained the error less than 1^oC. In order to reduce the loss of heat and to conduct full amount of heat from heater to the brass tube, magnesium oxide (MgO), which is having high thermal conductivity, is filled in the gap between the heater and brass tube. Test liquid is filled till the vertical brass tube is completely immersed in it. Before starting the experiments, all the rotating equipment like fans, which causes pressure difference were switched off. Desired power supply was given to the heater by adjusting the variac so that the vertical cylinder is heated at uniform heat flux.

At a particular heat flux, the bulk fluid temperature at a point, which is beyond the boundary layer region was made constant by adjusting the water flow rate in the outer shell.

The regulation of cooling water flow rate is done in such a way that the increase in enthalpy of cooling water compensates the heat input, which was giving to the cylinder. In that case, whatever the heat is supplied to the cylinder will be carried away by the cooling water; thereby, steady state condition is prevailed. Once steady state conditions are taken place, the readings of vertical cylinder surface temperatures at various positions and bulk fluid temperatures were noted. The pictorial view of the experimental setup is shown in Fig. 2(a) and the schematic diagram is shown in Fig. 2(b).

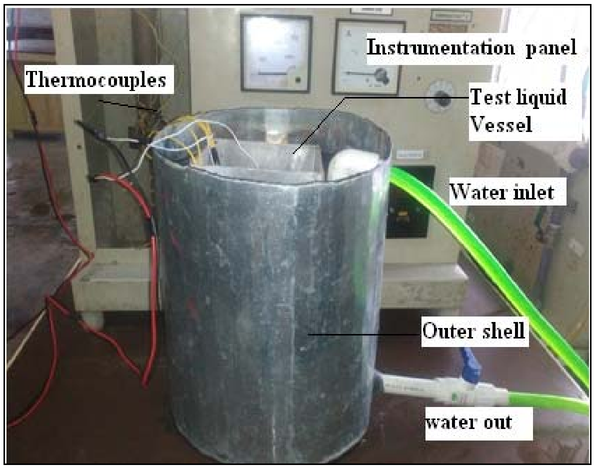

Fig. 2(a): Pictorial view of experimental setup

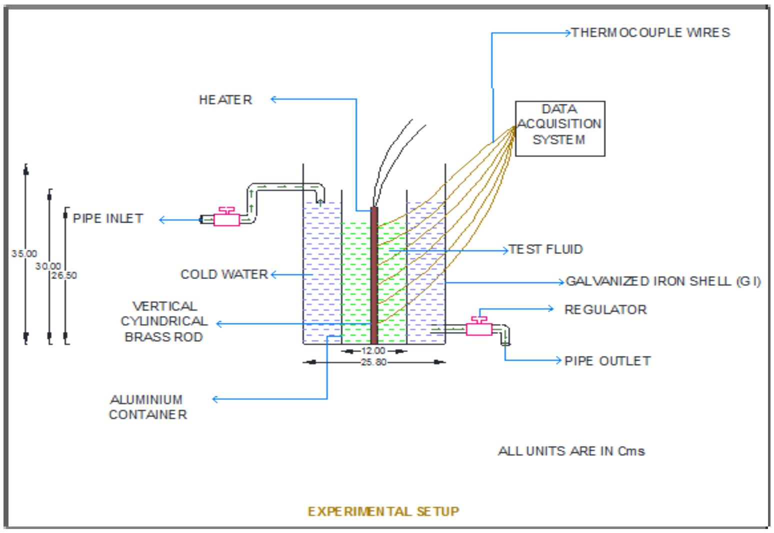

Fig. 2(b): Schematic diagram of experimental setup

RESULTS AND DISCUSSION

Experiments were performed for different heat inputs say 30W, 40W, 40.5W and 50W by regulating the voltage supply with the help of variac. The surface temperatures of the brass vertical cylinder in the axial direction for water and water + ethylene glycol (EG) as medium are depicted in Figs. 3, 4. It is observed that for any heat flux, the surface temperature of cylinder is increased in the axial direction due to high local heat transfer coefficients occur at the bottom portion of the cylinder.

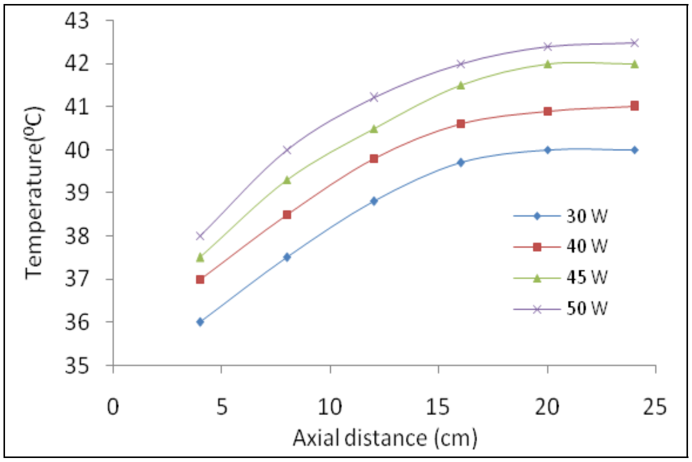

Fig. 3: Variation of surface temperature of vertical cylinder in axial direction for water

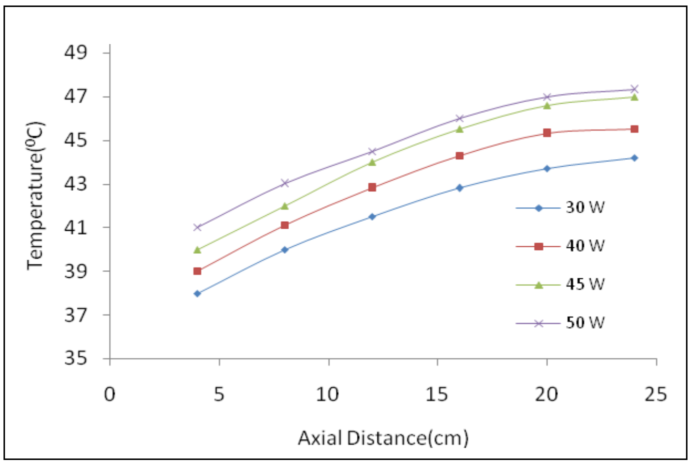

Fig. 4: Variation of surface temperature of vertical cylinder in axial direction for water + EG

All the properties of the fluid are calculated at the film temperature, which is the average of the surface temperature of the cylinder and the bulk temperature of the fluid.

$$\text{Film temperature } T_f = \frac{T_w + T_\infty}{2} \qquad \ldots(1)$$

Local heat transfer coefficients at different positions are calculated at the points where thermocouples are located. The local heat transfer coefficient is calculated by using the following relation (2).

$$h_x = \frac{Q}{A(\Delta T_x)} \qquad \ldots(2)$$

The variation of local heat transfer coefficients in the axial direction is shown in Fig. 5, 6. It is observed that the local heat transfer is higher at the bottom and lower at the top of the cylinder. As the boundary layer thickness is very less in the bottom portion, the local heat transfer coefficient will be higher and as it goes on to top portion, the thickness of the boundary layer will be more; due to this, lesser heat transfer coefficients may be observed there. The variation of local Nusselt number along axial direction is depicted in Figs. 7, 8.

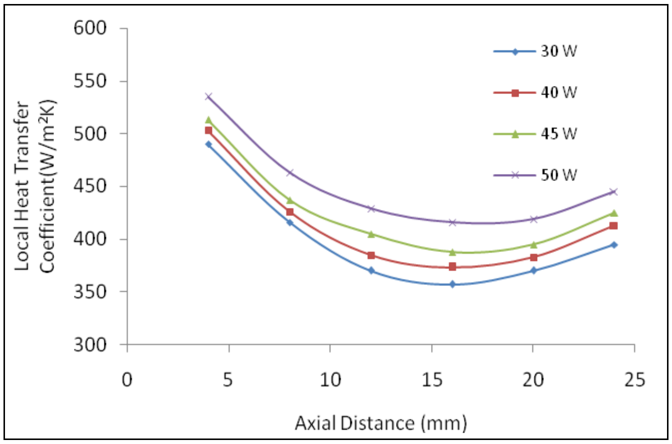

Fig. 5: Variation of local heat transfer coefficient with axial distance for water as medium

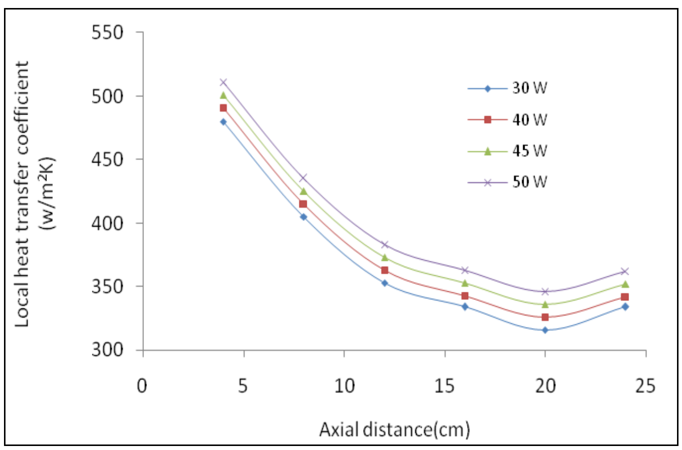

Fig. 6: Variation of local heat transfer coefficient with axial distance for water + EG as medium

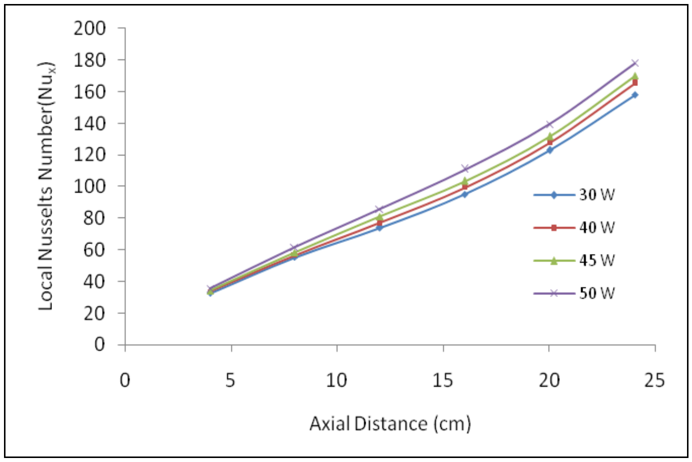

Fig. 7: Variation of local Nusselt number with axial distance for water as medium

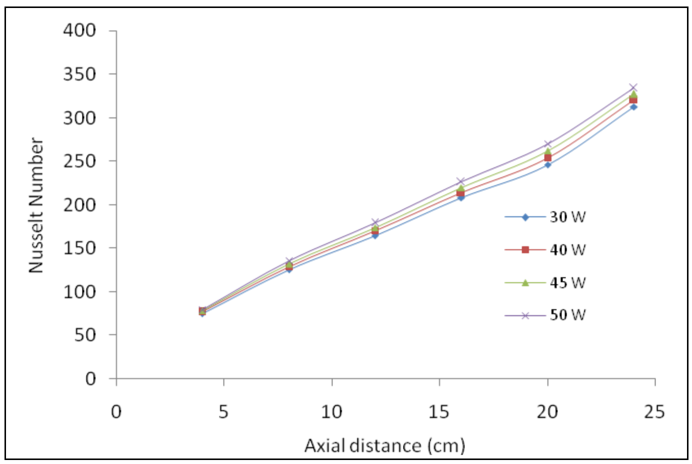

Fig. 8: Variation of local Nusselt number with axial distance for water + EG as medium

Local Nusselt number is calculated based on the following relation (3)

$$Nu_x = \frac{h_x x}{K} \quad \ldots(3)$$

It is observed that the local Nusselt number increases as the length increases and for all the heat inputs in case of water as medium. The similar trend is observed for the case of water + EG mixture. The thermal stratification is identified in the bulk fluid as the temperature of the fluid at a point, which is away from the boundary layer goes on increasing from bottom portion to the top portion. The variation of temperatures along radial direction when the mediums are water, water + EG, respectively is depicted in Figs. 9 and 10. It is observed that at the cylinder surface and the wall of the container, there is a steep change in the temperature because of the solid and fluid interface and also identified the lower temperatures of the fluid in radial directions in case of water + EG as medium compared to water because of the lower thermal conductivity of the ethylene glycol.

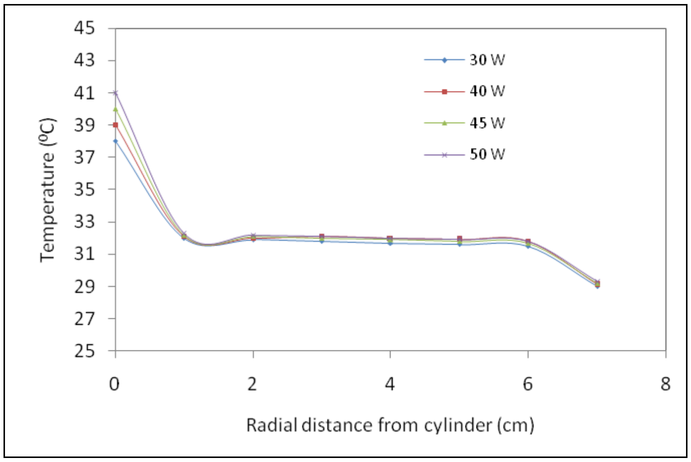

Fig. 9: Variation of temperatures in the radial direction 4 cm from bottom of cylinder (water)

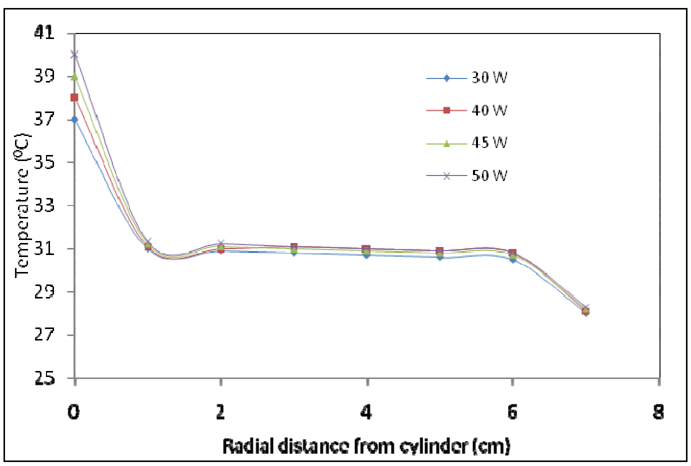

Fig. 10: Variation of temperatures in the radial direction 4 cm from bottom of cylinder (water + EG)

The Nusselt number is determined for various heat fluxes (both for water and water +EG) i.e. for different Rayleigh numbers and shown in Fig. 11. A correlation equation between dimensionless Nusselt number and Rayleigh number is presented as

$$Nu = 0.287\ (Ra)^{0.2} \qquad \ldots(4)$$

This correlation is validated by comparing the Mac Adams's equation (5)

$$Nu = 0.1\ (Ra)^{0.33} \qquad \ldots(5)$$

The eq. (4) is well fitted for water and water, ethylene glycol mixture and having good agreement with past literature (Mac Adam's equation) with ± 2% deviation.

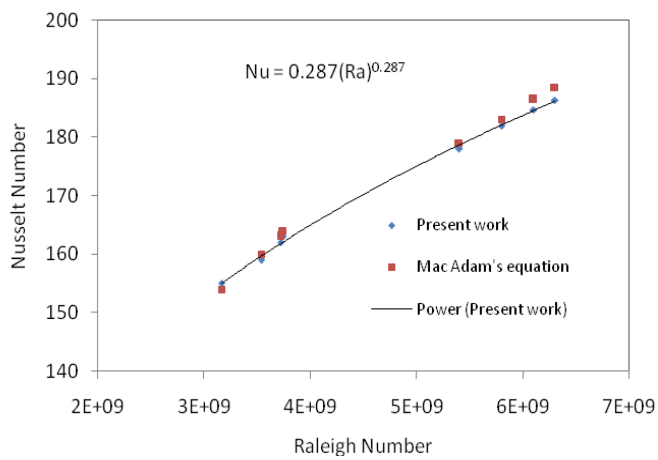

Fig. 11: Variation of Nusselt number with different Rayleigh numbers

CONCLUSION

The steady state free convection heat transfer of a vertical cylinder heated uniformly has been investigated in this study and presented for various heat fluxes. The variation of surface temperatures of the cylinder along the axial directions in case of water and water + EG as mediums is studied and presented.

(i) It is observed that in case of water + EG, the surface temperatures were recorded 8 to 10% higher than in case of water.

(ii) Local heat transfer coefficient and local Nusselt number are determined at different positions of the vertical cylinder and presented graphically.

(iii) A correlation is presented between non-dimensional Nusselt number and Rayleigh number as $Nu = 0.287\ (Ra)^{0.287}$.

ACKNOWLEDGEMENT

The authors are thankful to the management of GMR Institute of technology for the constant support and facilities provided for conducting of the experiments.

Nomenclature

T_f	Film temperature (^{0}C)
$T\infty$	Fluid temperature (^{0}C)
Tw	Wall temperature (^{0}C)
h	Heat transfer coefficient (W/m^{2}K)
K	Thermal conductivity (W/mK)
EG	Ethelyne glycol
L	Length of the cylinder (m)
g	Acceleration due to gravity (m/s^2)
β	Coefficient of thermal expansion (K^{-1})
υ	Kinematic viscosity (m^2/s)
Cp	Specific heat (J/Kg.K)
μ	Dynamic viscosity (Kg/ms)
Nu	Nusselt number $\left(\frac{hL}{K}\right)$
Gr	Grash of number $\left(\frac{g\beta\, L^3\Delta T}{\vartheta^2}\right)$
Ra	Rayleigh number $\left(\frac{g\beta\, L^3\Delta T}{\vartheta^2}\right)\left(\frac{\mu Cp}{K}\right)$

REFERENCES

1. T. Fujii and H. Uehra, Laminar Natural Convective Heat Transfer from the Outer Surface of a Vertical Cylinder, Int. J. Heat Mass Transfer, **13**, 605-615 (1970).

2. A. B. Cohen and A. Herman, Experimental Investigation of Transient Natural Convection Heat Transfer in Vertical Enclosure (Constant Heating), Letters in Heat and Mass Transfer, **4**, 111-118 (1977).

3. P. K. Sharma and T. Subrahmanyam, Turbulent Free Convection from a Radiating Vertical Surface Situated in Air-A Conjugate Problem, Int. Comm. Heat Mass Transfer, **16**, 883-894 (1989).

4. P. K. Sharma, T. Subrahmanyam and V. D. Rao, Natural Convection from a Radiating Fin to Thermally Stratified Medium of Air, The Canadian J. Engg., **68**, 38-44 (1990).

5. H. R. Lee, T. S. Chen and B. F. Armally, Natural Convection Along Slender Cylinders with Variable Surface Temperature, ASME J. Heat Transfer, **110**, 103-108 (1998).

6. P. K. Sharma, T. Subrahmanyam and V. D. Rao, Thermal Performance of a Vertical Fin in a Non Newtonian Ambient Medium, Appl. Sci. Res., **45**, 319-337 (1998).

7. T. Amara, K. Slimi and S. B. Nasrallah, Free Convection in a Vertical Cylindrical Enclosure, Int. J. Therm. Sci., **39**, 616-634 (2000).

8. C. Trevino, E. Luna, F. Mendez and F. J. Higuera, Natural Convective Conjugate Cooling Mechanism in Vertical Fins, J. Thermophysics Heat Transfer, **17(3)**, 396-401 (2003).

9. C. O. Popiel and J. Wojtkowiak, Experiments on Free Convective Heat Transfer from Side Walls of a Vertical Square Cylinder in Air, Experimental Thermal and Fluid Science, **29**, 1-8 (2004).

10. S. V. Naidu, V. D. Rao and P. K Sharma, Performance of a Circular Fin in a Cylindrical Porous Enclosure, Int. Comm. Heat Mass Transfer, **31(8)**, 1209-1218 (2004).

11. S. Jarall and A. Campo, Experimental Study of Natural Convection from Electrically Heated Vertical Cylinders Immersed in Air, Exp. Heat Transfer, **18**, 127-134 (2005).

12. C. O. Popiel, J. Wojtkowiak and K. Bober, Laminar Free Convective Heat Transfer from Isothermal Vertical Slender Cylinder, Exp. Thermal Fluid Sci., Elsevier, **32**, 607-613 (2007).

13. I. Zahmatkesh, Effect of a Thin Fin on Natural Convection Heat Transfer in a Thermally Stratified Porous Layer, Emirates J. Engg. Res., **19(2)**, 57-64 (2014).

14. A. Bairi, E. Zarco Pernia and J. M. Garcia de Maria, A Review on Natural Convection in Enclosures for Engineering Applications, The Particular Case of the Paralleogrammic Diode Cavity, Appl. Thermal Engg., **63**, 303-322 (2014).

15. F. Xu, J. C. Patterson and C. Lei, An Experimental Study of the Thermal Flow Around a Thin Fin on the Side Wall of a Differentially Heated Cavity, 16th Australian Fluid Mechanics Conference, Crown Plaza, Gold Coast, Australia, 2-7 December (2007).

Accepted : 03.11.2016