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An Inexpensive Technique to Determine the Parameter in Free Convection Heat Transfer from Two Parallel Heated Vertical Plates

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ABSTRACT

Heat transfer using natural convection and fluid flow is an important phenomenon in daily life and engineering applications such as HVAC systems of building, harvesting energy using non-conventional energy sources, extraction of heat from electronic equipment and cooling technologies integrated in computer systems. The present study investigates about the two experiments: (1) Heat transfer taking place between two parallel-Vertical Plates by natural convection, in which two walls are adiabatic and other two ends are open to the ambient air and (2) The estimation of constant C in the expression of Nusselt Number from the data of temperature distribution obtained by performing experiments using a parallel Vertical-Plate by maintaining steady state conditions. Two parallel vertical plates made of Aluminium are allowed to cool in air, to ensure that Lumped capacitance formulation is valid. In the first case the Nusselt and Rayleigh numbers were calculated experimentally and compared with the value available from the correlation which is found to be in good agreement. In the second case, the value of C in the expression of Nusselt Number was calculated using Least Square Residual Method and validated this result by introducing this value into the correlation available. The experimental setup which is required has been designed and fabricated.

Key words: Natural Convection, Vertical Plate, Least Square Residual Method

INTRODUCTION

Natural convection heat transfer occurs in many engineering applications such as extracting heat generated during the working of electronic equipment, cooling of electric transformer , chimneys and furnaces, cooling the reactor core in nuclear power generation to dissipate the heat generated by nuclear fission, cooling of solar collectors and geophysical flows. In these equipment's, the source of heating, in general is either due to volumetric heat generation or due to surface heat fluxes. For instance, electronic equipment generates heat, which can be expressed in terms of volumetric heat generation. Volumetric heat generation in nuclear fuel rods is due to nuclear reaction. The performance of devices involved in thermal energy conversion depends on the energy exchange that takes place through various heat and fluid flow processes prevailing in these devices. Therefore, research on flow and heat transfer through plate's demands significant attention. The amount of heat energy transported by the working fluid in a plate is dependent on the geometry of the plate, nature of the flow, and the thermal boundary conditions of the plate.

Electronic equipment's and devices have become essential ingredients in our day-to-day life. Among them the most widely used of these is the electronic computer, ranging in size from the hand-held personal digital assistant to large scale mainframes or servers. In numerous occurrences a computer is imbedded or integrated inside some other electronic devices and is not by any means conspicuous. The use of computers is increased in prominent spheres such as financial, defense, science and technology, banking, health sectors etc. As automation is proliferating into vital infrastructures, a computer failure can bring about a catastrophic interruption of basic administrations and can even have life threatening outcomes. As a result, efforts to improve the reliability of electronic computers are as important as efforts to improve their speed and storage capacity.

Various techniques and designs for cooling, that were implemented using air, water, and direct immersion are in line to accommodate the increased heat flux trend in heat removal. They include conduction cooling, air cooling, micro channel heat sink cooling, micro heat pipes, pool boiling, Jet impingement, multi-phase flow etc. Although forced convection and boiling using a liquid medium offer the highest heat transfer rates, air cooling technique has been widely used for heat removal for a long period. The main advantages of cooling using air as fluid are ease of application, abundance and availability [7]. The simplest method of cooling is by circulating air, facilitating natural convection. Natural-convection method of cooling of electronic equipment continues to be the effective way in their thermal management; because it provides the advantage of low noise and high system reliability and require the least maintenance. The forced convection air-cooled systems, which are widely used, produces the acoustic disturbances in their operating environment and the reliability of the blower, which forms its main part present serious concerns as the air velocity has to be increased to increase the cooling rate. Thus, the interest in natural-convection air cooling is growing to take advantage of the absolute absence of noise and energy savings inherent in that cooling mode [7].

Buoyancy-induced heat transport phenomena inside the casings of electronic devices have been concentrated on broadly for a long time. To understand this concept, there are several additional effects associated with this process has to be analyzed, such as heat-conduction mechanisms in solids, location of power input into the system ,radiations, vents, three dimensional effects etc.[2]. More recently, a large number of researchers have incorporated some of these parameters in an attempt to gather reliable data, which are valuable for thermal analysis and design.

Elenbass [3] conducted experimental investigations in laminar natural convection heat transfer using smooth parallel plate vertical channel and reported a detailed study on the thermal characteristics of cooling by natural convection. Wirtz [8] have considered geometry, with constant heat sources placed over the entire length of the wall. Since the geometry could not simulate discrete placement of chips, the method of placing a number of discrete heat sources over a wall. Bodia and Osterle [1] conducted numerical analysis on free convection heat transfer for development of boundary layer between parallel isothermal vertical plates and recorded results for velocity, temperature and pressure variation throughout the flow field .The numerical method used is Hybrid Finite Difference Method.

Krishnan and Balaji [4] conducted a synergistic approach to parameter estimation in multimode heat transfer. This paper reports the efficacy of the Least Square Residual Method in parameter estimation when more than one mode of heat transfer is encountered. Oztop et al [5] carried out numerical investigation of natural convection heat transfer and fluid flow of two heated partitions which was placed within a square enclosure. The left wall and top wall provided Isothermal condition, while the bottom and the right side wall were adiabatic in nature. The two heated partitions were placed at the bottom of the square enclosure at different aspect ratio and the studies were focused on the effect of heights and position of heated partitions. The results were monitored at different Rayleigh number in the range of 10^4 to 10^6.The energy and flow equations were solved with TDMA, using finite difference equation, based on the finite control volume approach with non- staggered grid arrangement and SIMPLEM algorithm.

Oztop et al [6] investigated the characteristics of natural convection heat transfer in a square cavity, with a heated plate placed in vertical and horizontal manner. The governing equations were solved with TDMA using finite difference equation based on the finite control volume approach with non- staggered grid arrangement and SIMPLEM algorithm. Computation was done with Rayleigh number ranging from10^4 to 10^6 at different aspect ratios and position of heated plate. Air was used as a working fluid (Pr=0.71).The effect of the position and aspect ratio of heated (Vertical and horizontal) plate on heat transfer and flow in square cavity were analyzed. The result showed that Rayleigh number increases with increase in mean Nusselt number at both vertically and horizontally oriented positions. At higher Ra numbers, when the plate is placed horizontally, heat transfer was found decreased as about 80% less than that of the plate placed in vertical position. Atchonouglo et al [9] used the Finite Element Method for an inverse analysis to identify simultaneously the constant thermal conductivity and heat capacity.

Boukhattem et al [10] conducted numerical investigation of natural convection heat transfer in a two-dimensional closed room, containing air, in the presence of a thin horizontal heater plate. The horizontal walls are kept isothermal, while the vertical walls are adiabatic. The flow and energy equations in the room are solved using a finite differential equation based on the finite control volume approach with non-staggered grid arrangement and the SIMPLEC algorithm. A thin horizontal plate is placed inside the square room with an aspect ratio equal to 0.5.The horizontal plate has higher temperature compared to the isothermal wall. Computation of Rayleigh number in the range of 10^4 to 10^6 has been performed. The result showed that Rayleigh number increases with increase in heat transfer coefficient which is marked above the heater plate region and this effect is attributed to Chimney Effect.

More recent investigations for free convection in vertical channels are presented [11-12] for symmetric and asymmetric heating conditions, respectively. Again, heat transfer characteristics were provided on an average basis. Schlieren Optical Technique has been extensively used for the measurement of local heat transfer coefficients, where water was used as working fluid [13-14]. Finally numerical value is compared with experimental result and found to be reasonably in good agreement.

From literature survey it can be inferred that free convection in vertical channel geometry with discrete heat source has drawn considerable attention. This geometrical configuration has physical relevance with respect to electronic chip placement inside an electronic device. This research aims at developing new concepts to find out the thermo physical parameters such as emissivity, thermal conductivity, thermal diffusivity etc. Such an attempt is made in this paper where, the unknown constant 'C' in the expression of Nusselt-number is determined from the known values of temperature from different experiments. The goal of the study is to compare the value of constant C in the Nusselt number in parallel Vertical plate with available correlation (Krishnan et al, 2004) using the Least Square Residual Method.

EXPERIMENTAL METHODOLOGY

Experimental apparatus has been specially designed, fabricated and set-up to carry out investigations on different types of electronic devices. The layout of test- setup consist of an apparatus, Data Acquisition System, Computer, T-Type Thermocouple and AC power supply whose schematic diagram is as shown in Fig.1.

The apparatus consists of a heat source placed inside a large rectangular box, which is open at top and bottom to simulate natural convection condition. Rectangular box has a dimension of 500 x 500x 1000 mm. The three sides of the rectangular box are made up of plywood and are supported by slotted L-Angle. The fourth side is made up of acrylic sheet to have visibility. The central heat source plate, by itself, is an assembly of two Aluminium plates of dimensions 250 x 50 x 3 mm with a flat heater formed by winding a Nichrome wire over a Mica sheet sandwiched between twoplain mica sheets. Fig.2 shows a photograph of the flat heater used to heat the central plate.

The surface of the central plates, those are exposed to the ambient air are given a suitable surface treatment like polishing by buffing. On the other side of the aluminium plate, i.e. on the side not exposed to the ambient air, two blind holes of 1.5 mm diameter and 1.5 mm deep are drilled at the points of temperature measurement, into which thermocouples are fixed. The bead of the thermocouples is attached to the slot in the aluminium plate by using thermobond. Thermobond is inorganic low expansion cold setting cement. Thermobond is ideal adhesive cement for applications which require high resistance to electricity, chemicals and thermal shocks. It is suitable for a service temperature of 1250^{0}C. Fig. 3 shows the plates that form the central plate, along with the thermocouples fixed at their respective position and taken out along the grooves for large and small heat source respectively.

Fig .1 Photographic View of the Experimental setup

Fig.2 Flat heater

Fig.3 Central plate ready to be assembled

Fig.4 Central plate heater

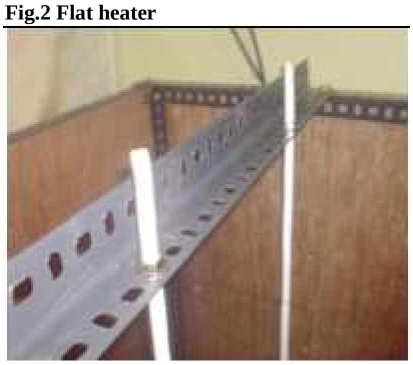

Fig.5 Hexagonal Nut arrangement for height adjustment

In these experiments temperatures were measured using T-type thermocouple which can withstand up to 400^{0}C. Thermocouples thus fixed were laid into grooves, milled on the same side as that of the blind holes and taken out of the plate. As it could be seen there are 8 holes on each of the plate which house the screws that are used in fastening the plate together after the heater is sandwiched in between the plates. The whole assembly was highly polished on its outer surface to obtain an emissivity of 0.05. The final plate heater assembly is shown in Fig.4. At the two corners of the final heater assembly, two metal strips are attached, one on each side of the plate heater assembly.

The plate heater assembly is thus hung vertically using Teflon rods through thin metal strips. Teflon wire used has 10mm diameter and 5m length. The Teflon rods and the metal strips serve the purpose of minimizing the conduction losses. The Teflon rods in turn are fastened to slot L-Angle as shown in Fig.5.The Teflon rods pass through holes in the slotted L-Angle, above which there is a hexagonal nut, which facilitate the adjustment of the position of the central plate. The lead wire from all the thermocouples is connected to a Data acquisition system. Data acquisition system consists of a temperature scanner having 40 channels; accuracy±3^{o}C.The heater assembly is heated by using a regulated DC power supply, 0-600V, and 0-1.5A.

UNCERTAINTY ANALYSIS

All the measurement devices used in the present study are calibrated with standard instruments. The uncertainties involved in the measurement of temperature, voltage and current are given in Table 1.

Table -1Uncertainities in the Measured Quantities

Quantity	Uncertainity(%)	Units
Temperature	± 3	^{0}C

Table -2 Uncertainities in the Derived Quantities

Quantity	Uncertainty (%)
Nusslet Number	±5

The uncertainties in the derived quantities are obtained using the relation $$\Delta y = \sqrt{\sum \left(\frac{\partial y}{\partial x_i} \Delta x_i \right)^2} \quad (1)$$

Where X_i is the measured quantity and Y the derived quantity and Δx and $\Delta\, y$ are the uncertainties in the measured and derived quantities respectively. Based on Eq. (1), the uncertainties in the derived quantities are determined and these are reported in Table 2.

RESULTS AND DISCUSSION

Investigation of Natural Convection over a Vertical Isolated Plate

The problem of free convection in a vertical plate was studied experimentally. These results are compared with the standard correlation for vertical channels in laminar region developed by Churchill and Chu as shown in Eq. (2).

$$Nu = 0.68 + \frac{0.67 Ra^{0.25}}{\left[1 + \left[\frac{0.492}{\Pr}\right]^{\frac{9}{16}}\right]^{\frac{4}{9}}} \quad (2)$$

Percentage of error can be calculated by the relation

$$\%\,Error = \frac{Nu_{\exp erimental} - Nu_{correlation}}{Nu_{\exp erimental}} \times 100 \quad (3)$$

The Rayleigh number is varied from 10^5 to 10^8 by changing the heat input and the Nusselt number obtained from experiment is compared in Table 1 with those obtained from correlation. A maximum percentage variation of 18.69 at a Rayleigh number of 10^5 is found.

Figure 6 shows the Comparison of Nusslet number in an isolated vertical plate. When input power of heater increases convective heat transfer coefficient by experiment increases. When input power increases, it will increase the temperature of the horizontal plate, which increases the heat transfer coefficient and there by increases the Nusselt number. When power input increases, the convective heat transfer coefficient by correlation shows a downward trend. This is because of two reason (1)the horizontal dimension of the heat source is small the viscous forces try to predominate over the buoyant forces, causing a Rayleigh number decreases and therefore decrease in Nusselt number (2) the temperature increases beyond a particular value.

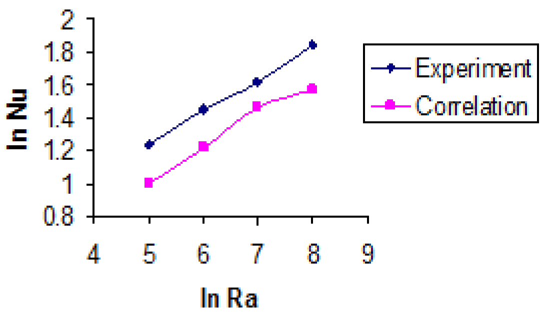

Fig.6 Comparison of Nusselt number in an isolated vertical plate

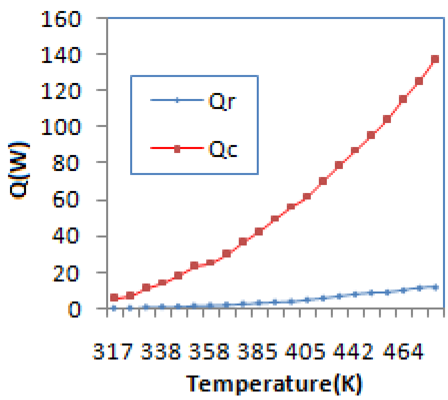

Fig.7 Variation of power with surface temperature

Fig.7 shows the radiation heat transfer and convective heat transfer is depending strongly on surface temperature of the plate. The energy emitted depends on (1) the temperature of the body and (2) nature of radiating surface of the body. Both Convective and Radiative heat transfer increases non linearly with increase in plate temperature. At low temperature, radiation may be significant. So we expect that radiation heat transfer is directly proportional to temperature (i.e, Q α T^n for free convection, where 1.2<n<1.33 and Q α T^4 for radiation).

Least Square Residual Method

The Standard correlation for Parallel Vertical plate losing heat by free convection is

$$Nu=CRa^n$$

The constant C in the above relation was determined by least square residual method.

Fig.8 shows the Variation of Plate temperature with Time. Time increases with increase in plate temperature due to the lattice vibration of molecules between plate and heater. It is interesting to note that the value of C in the Nusslet Number is dependent on base temperature and time.

Assumptions

- There is no heat loss from/to the stainless steel plate.
- The temperature of the enclosure remains constant throughout.
- The properties of the SS plate do not change with temperature
- The foil is spatially isothermal (lumped capacitance formulation)

For the above assumptions, the heating of the SS Plate can be mathematically represented as

$$E_{stored}=E_{lost}+E_{gen}$$

$$mc_p\frac{dT}{dt}=-hA(T-T_a) \tag{4}$$

Eq.(4), the left hand side represent the rate of change of enthalpy and the right hand side represents the heat transfer by convection. For substituting Nusselt number for h, becomes

$$\rho v C_p\frac{dT}{dt}=\frac{-Nu.K}{L}.A(T-T_a)$$

$$\rho v C_p\frac{dT}{dt}=\frac{-CRa^{0.25}KA}{L}(T-T_{a)}$$

$$\frac{dT}{dt}=\frac{-CRa^{0.25}KA}{L\rho v C_P}\left(T-T_a\right)$$

Rayleigh Number $$Ra=\frac{g\beta\Delta TL^3}{\gamma\alpha}$$

$$\frac{dT}{T-T_a}=\frac{-CRa^{0.25}KA}{L\rho v C_p}dt$$

Initial Condition T=T_i at t=0

$$\int_{T_I}^{T}\frac{dT}{T-T_a}=\frac{-CRa^{0.25}KA}{L\rho v C_p}\int_0^t dt$$

$$\ln\left(\frac{T-T_a}{T-T_a}\right)_{T_i}^{T}=\frac{-CRa^{0.25}KAt}{LC_P\rho v}$$

$$\ln\left(\frac{T-T_a}{T-T_a}\right)-\ln\left(\frac{T_i-T_a}{T_i+T_a}\right)=\frac{-CRa^{.0.25}KAt}{LC_p\rho v}$$

$$\ln\left(\frac{T-T_a}{T+T_a}\right)+\frac{CRa^{0.25}KAt}{LC_P\rho v}=\ln\left(\frac{T_i-T_a}{T_i+T_a}\right) \tag{5}$$

One possibility of solving the inverse problem is to substitute various values of C in Eq. (5) and determine the temperature T_i at various time instants given in the problem. With these following can be calculated

$$\mathbf{S(C)} = \sum_{i=1}^{N}\left(T_{\exp,i}-T_{calc,i}\right)^2$$

Upon doing such an exercise for C ranging from 0.53-0.67 in the steps of 0.1.We obtain S(C) as shown in the table. From the table and the plot we can at the best, say that 0.53<C<0.67.The residual are plotted against the constant C and are shown in Fig.9.

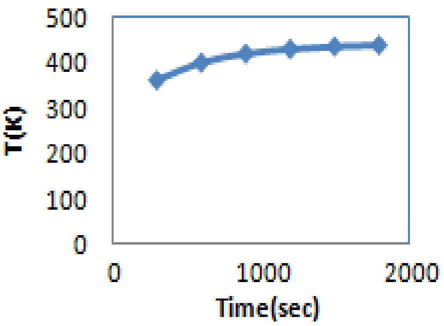

Fig.8 Plate temperature Vs Time

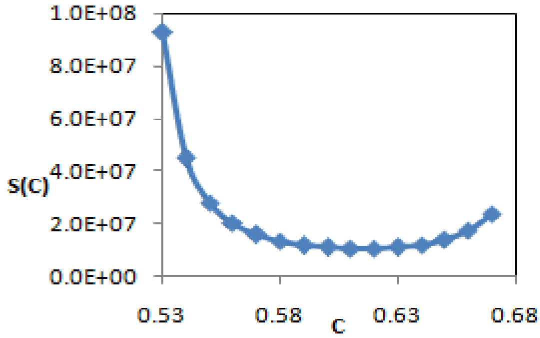

Fig.9 Residual Vs Constant C

By locally fitting a Lagragian interpolation polynomial for S(C), by employing three values of C where the residuals appear to be heading towards a minimum. These happens to be 0.54, 0.58and 0.63.

$$\mathbf{S=8316525916C^{2}-10107936032C+3078039891}$$

Take *dS/dC* and equate it to zero to make S Stationary

$$\frac{ds}{dC} = 16633051831C - 1010793032 = 0$$

$$\mathbf{C=0.608}$$

Therefore the best estimate of C with the level of computational intensity is 0.608

Table -3 Comparison of Optimization Result with Actual Result

Correlation	C
Actual Value(Krishnan et al, 2004)	0.593
Least square residual Optimization Method	0.608

CONCLUSION

Laminar heat transfer experiments were conducted with a spatially isothermal aluminum Vertical parallel plate losing heat to still air by convection. In this Paper, the Validation of Natural convection heat transfer in a vertical plate and Compare the value of C in the Nusslet Number expression with available correlation using Least Square Residual method have been conducted. In the first case, Nusslet Number and Rayleigh Number were determined experimentally and compared with the value available from correlation and found to be in good agreement. The value of C in the Nusslet Number Expression were calculated using Least square Residual optimization method and compared with the value with available correlation and found to be in reasonably good agreement air and Temperatures have been recorded. The result were found satisfactory and agree very well with Literature. In future the same experiment can be conducted after coating the surface of heat source with paint in order to emphasize radiation effect. Heat source can be supported side way in order to reduce flow disturbance. Experiment can also be conducted by tilting the entire geometry.

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