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Free Convection Heat Transfer in an Inclined Open Thermosyphon

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ABSTRACT

This paper describes an investigation of flow structure and heat transfer by free convection in an open ended inclined cylindrical thermosyphon with application to an evacuated tube solar collector. The flow structure was visualised by thymol blue dye. The temperature profiles were measured by a traversing thermocouple rake. For the case of uniform heating of the tube a significant stagnation region was observed in the bottom of the tube, the length of which decreased with the increase of the wall temperature. This stagnation region is likely to occur during periods of low solar irradiation in an evacuated tube solar collector and other applications of open thermosyphons which will decrease the effectiveness of the heat transfer process.

INTRODUCTION

The natural convection of fluids in the presence of gravitational or coriolis forces can be implemented as an effective mean for cooling (or heating) applications. A particular application of this process is the transfer of heat from the hot walls of a tube to a cold reservoir. This is referred to as a thermosyphon. The first scientifically documented application of such devices goes back to 1938 in which Holzwarth [1938] suggested a system for cooling of gas turbine blades. Ernest Schmidt in World War II proposed to use a thermosyphon for cooling turbine blades, and a turbine incorporating his idea was designed and built in Germany during the war. Since World War II the thermosyphon problem, with many engineering applications, has been the focus of many experimental and analytical studies. Such applications include but are not limited to cooling of turbine blades electrical machine rotors, transformers, nuclear reactors, cryogenic apparatus, internal .combustion engines, water tube boiler and solar collector tubes. A comprehensive review of the applications and pertinent research is given by Japikse [1972].

Thermosyphon systems in the form of a tube open to a reservoir at the top and closed at the bottom are referred to as open thermosyphons. The study reported in this paper describes an experimental investigation of heat transfer by natural convection in an inclined heated tube sealed at its lower end and connected to a large constant temperature reservoir at the upper end.

The first general study reported on open thermosyphon was done by E.R.G. Eckert and T. Jackson [1950] which was analytical in nature. The authors assumed that the flow was basically a boundary layer phenomenon and that it would be turbulent in most practical applications. They attempted to find the maximum tube aspect ratio that could be used without the boundary layer becoming thick enough to block the circulation in the tube.

The first experiments on an open thermosyphon were reported by Foyle [1951] who observed that eddy motion developed as the fluid passed between the tube and the reservoir. He also noted that the heat transfer was independent of the tube length beyond a certain critical value, though it increased quickly with increasing diameter.

Lighthill [1953] presented the first detailed analytical study of thermosyphons for laminar and turbulent flow. Leslie [1959] extended Lighthill's analysis to include the effect of small angles of inclination to the vertical. Detailed experimental studies of the problem have been carried out by Foster [1953] and Martin [1955]. The analytical study performed by Lighthill has served as the foundation for most thermosyphon analysis and it identifies the basic flow regimes in an open thermosyphon. Lighthill's analysis yielded three laminar regimes and three turbulent regimes. For large tube aspect ratio (a/ℓ) or large Rayleigh number, Lighthill showed that a boundary layer flow will apply since the boundary layer will occupy only a small portion of the tube. For smaller aspect ratios the boundary layers reach the centre line of the tube and the incoming and outgoing streams interfere and restrict the circulation, thus giving rise to a second regime. For high aspect ratios the interaction of wall effects produces a constant flow profile and a similarity solution is thus possible, giving a third flow regime.

Leslie [1959] published the only analytical treatment of an inclined thermosyphon. He used a laminar perturbation technique which is restricted to small inclination angles. His analysis showed that tilting increased the heat transfer for both the impeded similarity solution and for the boundary layer flow solution. This analysis does not reproduce the unstable effects that were shown by Martin to decrease the heat transfer for small inclinations. However qualitative agreement was observed with Martins measurements for larger angles.

For vertical thermosyphons Lighthill [1953] predicted that if the parameter $t_1 = Gr.Pr\ (a/\ell)$ is less than 350 a stagnant region forms at the closed and of the tube. For an inclined tube the parameter governing the nature of the flow is $t_1 \cos\theta$ where θ is the tube inclination to the vertical.

Martin [1959] presented the first experimental study of inclined open thermosyphon behaviour for both laminar and turbulent conditions. For $700 \geq Pr \geq 20$ he observed that Nusselt number initially decreased with increasing inclination up to six degrees from vertical. For larger angles Nu increased and reached the value for a vertical tube when the inclination reached 45°. The initial drop in heat transfer was attributed to a disorderly flow pattern and the consequent mixing of the hot and cold fluid streams. For larger angles the secondary pressure gradients, normal to the tube axis, yielded a more stable flow structure in which the hot stream is displaced towards the top edge.

The particular application that prompted this study is the problem of heat extraction in dewer type evacuated tubular solar collectors, Window [1983] and Zhiqiang [1984]. Evacuated tube solar collectors consist of a 30 to 50mm diameter, 1.5 to 2.5m long glass tube with heat removal by natural convection of water in and out of the single ended tube to a large diameter header tube. This problem also applies to applications such as flow in turbine blades, nuclear reactors and transformer cooling. In these flows, fluid adjacent to the heated tube wall due to bouyancy rises to the upper side of the inclined tube and discharges from the open end, while cool fluid is drawn into the bottom side of the open end of the tube. Inclination of the tube sets up a pressure gradient normal to the tube axis, which assists the circulation of fluid from the bottom to top sides of the tube. Inclination of the tube might be expected to improve the heat transfer relative to vertical tubes.

In stage one of this study, covering uniform wall temperature difference between the walls of the tube and the inlet fluid a stagnant region is observed at the bottom of the tube. The length of the stagnant region decreases as the temperature difference increases. This stagnant region shortens the effective heat transfer length of a single ended dewer flask type evacuated tube solar collector thus reducing the efficiency during periods of low incident solar irradiation.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus shown in Figure 1 was designed to simulate the geometry of an evacuated tubular solar collector.

The thermosyphon flow was established in a glass cylinder 1300mm long and 21.3mm in internal diameter. A concentric annular heat exchanger 1200mm long and 60mm in diameter was used to model an approximately constant wall temperature boundary condition by circulating water from a regulated constant temperature heated bath. The thermosyphon tube was connected by an unheated section of tube 10mm long to an insulated reservoir 500 x 500mm (Figure 1). The thermosyphon tube was sealed at its lower end and the top connected to the large constant temperature reservoir at its upper end. A five element thermocouple rake was traversed along the tube to measure the temperature distribution. The wall temperature was controlled by circulating constant temperature water through the annular heat exchanger. Flow visualisation was carried out by injecting thymol blue dye through a three outlet thin stainless steel T-bar tube into the thermosyphon flow. The annular flow exchanger was made of plexiglass in order to make flow visualisation possible and future laser doppler velocity measurements. The inclination of the tube can be varied from 30° to 60° to the vertical.

Flow Visualisation

Flow visualisation was used to study the flow structure for tube inclinations of 30, 45 and 60 degrees. For each inclination the flow was investigated for temperature differences between the water jacket and the water in the reservoir from a minimum of 2K until temperature fluctuations in the tube were observed.

Before each experiment the reservoir was thoroughly mixed to eliminate thermal stratification and then allowed to settle ensuring no currents in the tank. A period of two hours was allowed for the settling motion in the tank before the heating was started. The heating was maintained for two hours to ensure that steady state conditions were obtained before dye was injected into the flow through a fine tube passing up through the bottom end of the thermosyphon tube.

Temperature Measurements

A thermocouple rake as shown in Figure 2 was traversed through the inner glass cylinder to measure the fluid temperature distribution. The rake consisted of five copper constantan thermocouples fed through a 2mm stainless steel T-bar tube. The thermocouple junctions were sealed against water leakage using araldite cement. One of the thermocouples was mounted on the centre of the head of the rake which spanned the thermosyphon tube diameter. The other four thermocouples were mounted 5 and 10mm on either side of the centre line of the tube. The rake was moved axially along the tube by feeding it through a sealed gland in the bottom end of the thermosyphon tube.

RESULTS

The first stage of the project reported in this paper is concerned with the overall flow structure and the stability of the flow. This information is needed to gain a better understanding of the problem in order to develop a numerical method for the prediction of flow structure and heat transfer.

Flow Structures

For tube inclinations between 30 and 60 degrees there were two regions: (I) an active region where there is recirculation of fluid between tank and the tube and (II) a stagnant region in the bottom of the tube in which there is very little circulation, see Figure 4. The stagnation region was identified by dye injection and was found to be very stable maintaining a fixed section of the tube for the duration of the experiments (up to eight hours). The stability of the stagnation region of the flow was investigated by physically disturbing the junction between the stagnation and recirculating regions using the thermocouple rake. The stagnation region was also disturbed thermally by increasing the wall temperature until the flow became turbulent and the stagnation region broke-up; the temperature was then reduced to the initial value and re-establishment of the stagnation region was observed. The variation of the length of stagnant region as a function of $Gr.Pr.\frac{\ell}{a}.\cos\theta$ is shown in Figure 3 where Gr is based on the tube diameter and the temperature difference between the reservoir and the water jacket.

The modified critical parameter $t_1 \cos\theta$ which predicts the existence of a stagnant region at the closed end of the tube revealed a temperature difference of less than 2.8, 3.4 and 4.8°c for inclinations of 30, 45 and 60° respectively. These values of Lighthill's modified criteria were found to underestimate the conditions at which a stagnation region developed in the tube geometry used in this study. This may be due to Lighthills assumption that $Pr = \infty$ which resulted in inertia terms being neglected in the governing equations.

The flow structure in the circulating region of the thermosyphon was studied by injecting dye in the flow region between the tube inlet and the top of the stagnation region. The cold flow from the reservoir enters through the bottom two thirds of the cross-section and the hot flow leaves through top one third of the orifice cross-sectional area in the form of a crescent (Figures 4 and 5). From the movement of the dye it appeared that the outgoing flow was faster in the case of steeper angles. The first streak line from the cold stream peeling off and joining the outgoing flow was noticed at a distance of 20 diameters from the orifice for the case of 60° and at 30 diameter length for 30°. For tube inclination of 30° the incoming stream travels a greater distance down the tube than for 60°, before the interchange with the warm stream begins.

Entry Effects

In order to determine the effect of the tube entry geometry on the flow the centre line of the inlet orifice was covered by a horizontal 5mm wide tape. It was observed that the length of the stagnant region decreased by 75% compared to the unrestricted entry. Further when the tape was replaced by a 5mm diameter cylindrical rod, the length of the stagnant region was unaffected. When the obstructions were placed vertically across the opening the length of the stagnant region increased by 50% and 30% for the tape and cylindrical rod respectively. When the tube was heated only on the top half no stagnant region was observed.

Temperature Measurements

Figures 6, 7 and 8 show non-dimensional temperature profiles measured on a vertical plane passing through the axis of the tube. The dimensionless temperature is defined as (T local -T reservoir) divided by (T jacket -T reservoir). T_0 and T_4 are the non-dimensional temperatures near the top and bottom walls of the tube respectively. T_2 is the non-dimensional temperature along the axis of the tube. T_1 and T_3 are non-dimensional temperatures half way between T_0, T_2 and T_2, T_4 respectively. It can be seen that for low temperature difference between the reservoir and the jacket, (ΔT), T_4 crosses T_3 towards the end of the recirculating zone. This is due to the very weak recirculation near the stagnant region hence heat transfer by conduction is more significant than convection in this region. This can also be seen by the temperature profile. It is also observed that the temperatures near the upperwall of the tube decreases towards the tube entrance. This is due to mixing between hot fluid from the bottom region of the tube with colder fluid that has convected up the curved walls from the cold inlet fluid moving along the lower wall. As a result of uniform heating of the cold fluid stream on the bottom of the tube the fluid temperature in this region increases all the way down to the stagnant end.

REFERENCES

1. Eckert, E.R.G and Jackson T.W (1950): Analysis of Turbulent Free-Convection Boundary Layer on Flat Plate. Nat. Adv. Comm. Aeronaut. NACA TC 2207
2. Foster, C.V (1953): Heat Transfer by Free convection to Fluids contained in Vertical Tubes. Ph.D Thesis Univ. of Delaware, Newark, Delaware
3. Foyle, R.T (1951): Proc. Inst. Mech. Eng. A.S.M.E. (Lond) Conf. Proc. 382.
4. Japikse, D (1972): Advances in Thermosyphon Technology. Advances in Heat Transfer. Volume 9 pp (1-111).
5. Leslie, F.M (1959): Free convection in the tilted open thermosyphon. Journal of Fluid Mechanics Volume pp (115-127).
6. Lighthill, M.J (1953): Quarterly Journal of Applied Mathematics Volume 6, Part 4.
7. Martin, B.W (1955): Free convection in an open thermosyphon. Proclaimation of Royal Society Series A 230 pp (502-530).
8. Martin, B.W (1959): Free convection heat transfer in the inclined open thermosyphon. Proclaimation of Institution of Mechanical Engineers (London) Volume 173 (32) pp (761-775).
9. Window, B and Harding G.L (1983): Bouyancy effects and the manifolding of single ended absorber tubes. Solar Energy Volume 31 pp (153-157).
10. Zhiqiang, Y, Harding, G.L and Window, B (1984): Water in glass manifolds for heat extraction from evacuated solar collector tubes. Solar Energy Volume 32 pp (223-230).

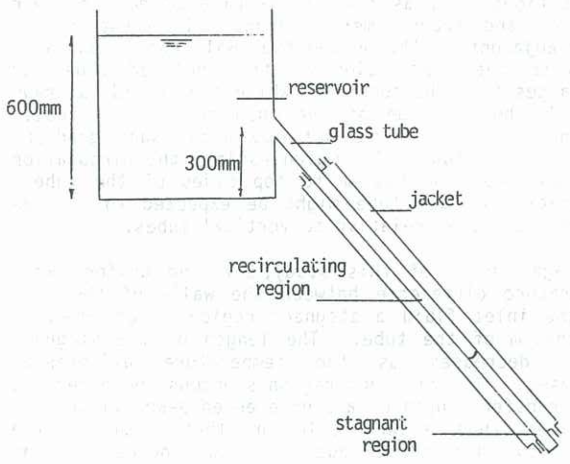


Fig 1: General Arrangement of the experimental Apparatus.

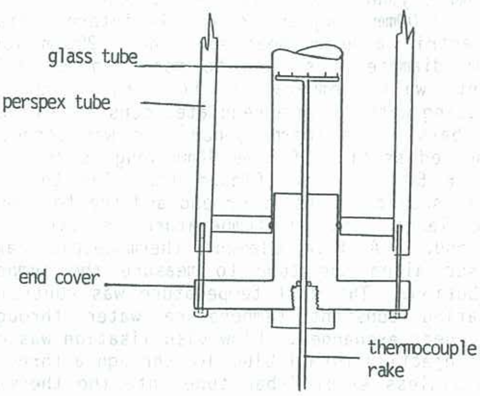


Fig 2: Sectional view of the couple rake inside the tube's end.

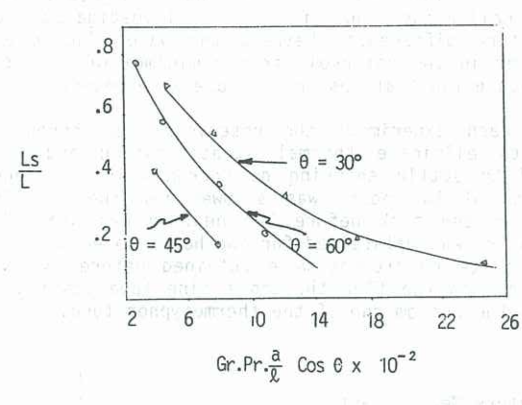


Fig 3: Graph of dimensional stagnant region at various inclinations.

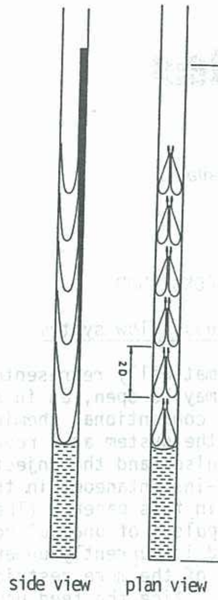


Fig 4

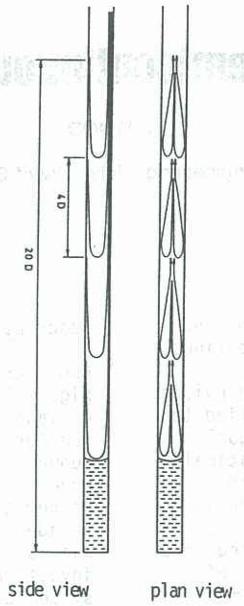


Fig 5

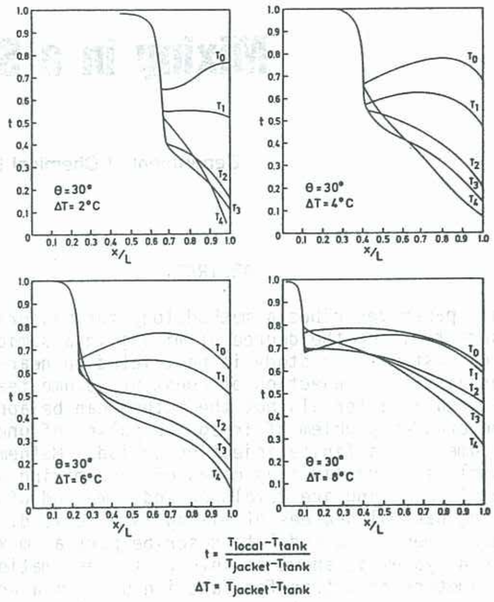
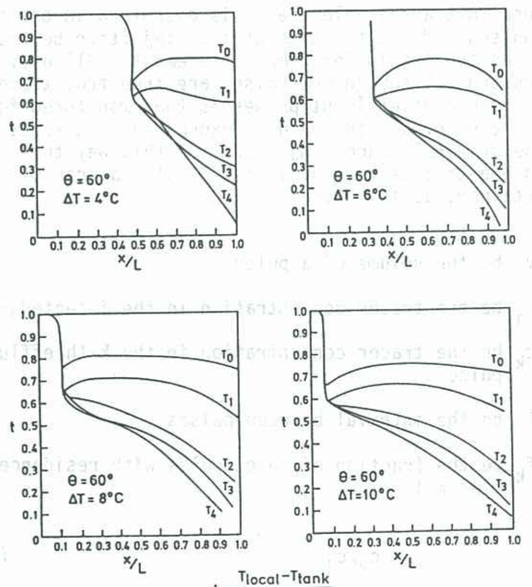


Fig 4: The flow pattern inside the tube for inclination of 60°.

Fig 5: The flow pattern inside the tube for inclination of 30°.

Fig 6: Variation of Fluid temperature along the tube inclination of 30°.



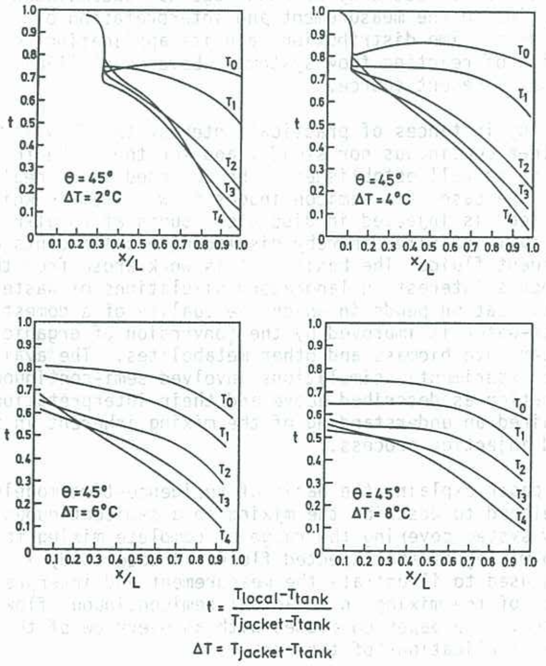


Fig 7: Variation of Fluid temperature along the tube for inclination of 60°.

Fig 8: Variation of Fluid temperature along the tube for inclination of 45°.