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STUDY OF FLOW CHARACTERISTICS IN THERMOSYPHON SOLAR SYSTEM

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SUMMARY An experimental and theoretical study was conducted to gain insight into the mechanism of reverse flow development in the riser of a thermosyphon circuit. Using a Laser Doppler anemometer to measure flow rates it was found that the reverse flow phenomena depends on the heat input and flow restriction in the circuit. A numerical simulation of a similar flow between two parallel heated plates was also performed. Theoretical results were obtained for the range of Rayleigh number from 100 to 300,000; Reynolds number from 5 to 100; aspect ratios of the heated section from 1 to 10. A numerical study was also conducted for a cavity inclined at 40 and 60 degrees to the vertical. It was shown that reverse flow is most likely to occur in a thermosyphon system operating at low Reynolds number and with a relatively long heat transfer section.

1. INTRODUCTION

Solar collectors are one of the simplest and most widely used devices utilising fluid motion resulting from buoyancy forces. Natural convection in solar collectors has attracted considerable interest and is well documented. However, aspects of this phenomena such as development of flow irregularities and distortions in velocity and temperature profiles, have received little attention. Ranatunga (1978) pointed out the need for detailed knowledge of the velocity and temperature profiles in order to improve the buoyancy and frictional resistance analysis of the thermosyphon loop. Ranatunga (1978) suggested that the velocity profile in the heated section of the solar collector may develop a peak near the wall and a dip in the centre. The lack of information on thermosyphon velocity is partially due to the problem of measuring relatively small flow rates without introducing probes into the circuit. The present study has been carried out to gain some insight into the flow structure in the thermosyphon solar system under different heat input and flow restriction conditions. The flow structure was examined by injecting a filament of dye into the circuit below the heat transfer section. A Laser Doppler anemometer system interfaced with an Apple II microcomputer was used to measure velocities upstream and downstream from the heated section in a double glass wall thermosyphon circuit (Fig. 1). Theoretical investigations were also conducted for flow through a cavity formed by two parallel heated plates with fully developed laminar entry flow. Numerical solutions were obtained using Peaceman-Rachford alternating direction implicit scheme. Theoretical results were also obtained for the flow through a cavity inclined at 40° and 60° angles from the vertical.

2. EXPERIMENTAL RESULTS

In order to observe the flow patterns for different heat input conditions, a dye solution of potassium permanganate, was introduced into the flow. The dye was introduced into the flow 720mm below the elevation at which heating began. A distinctive laminar stream of dye developed in the unheated length of the circuit but immediately upon entering the heated section, the dye moved towards the wall, indicating a blockage of the central region of flow in the heated section. When the dye was turned off, the main volume of dye was washed away by the flow and a stable core of dye remained in the centre of the flow. This core of dye remained visible up to one hour after the dye entered

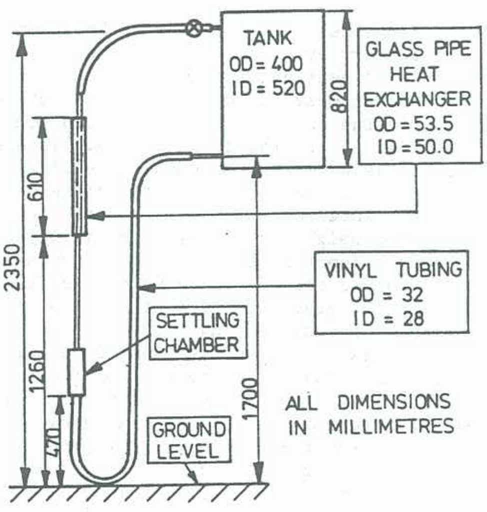


Fig. 1 Experimental installation with all principal dimensions

the system. At the exit from the heated section, the central core was unstable and dye was drawn into the core at this point. There was also a very slow contortion in the nose area. A sketch of the flow pattern for Rayleigh number of 1.56×10^6 is shown in Fig. 2.

Velocity measurements were taken at different axial positions in the flow. Measurements were limited to regions with velocity greater than 0.71mm/sec due to the low frequency limit of the laser signal processor. All experimental points were checked by repeating measurements over one hour intervals. Some experimental results are presented in Figures 3, 4 and 5. (where $\bar{T}_{TANK}$ is mean tank temperature and $T_{H.F.}$ is temperature of the heating fluid). For more details see Litvak (1982). The experimental study revealed that in the heated section of a thermosyphon circuit, there are two distinct zones of flow: the first is set up immediately adjacent to the wall forming a hot fast upward flowing cylindrical lamina along the heated boundaries; the second is established at the centre of the pipe in the form of a colder recirculating core. The upper section of the recirculating

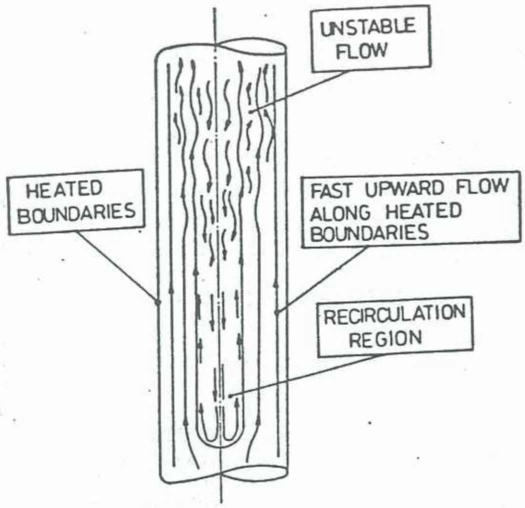


Fig. 2 Flow pattern observed during the flow visualization experiment.

region is unstable. The hot fast layer absorbs heat from the boundary by conduction and the buoyancy caused by local heating produces relatively fast convection layer near the wall. The rate of heat convection in the axial direction is much greater than the conduction in the radial direction. This mechanism essentially maintains a temperature differential between the two zones. Owing to the presence of viscous shear interaction, the motion of the hot layer drags up neighbouring colder fluid layers. Above the heat input section the shear force reduces and the entrained cold fluid commences to fall under the influence of gravity. At certain points along the downward path, the descending particles get caught in the shear interaction layer, as described earlier and thereby complete the cyclic pattern of flow. As can be seen from Fig. 5 the velocity is maximum close to the wall and drops to zero at approximately 1/5 of the pipe diameter from the wall. The strength of the recirculation flow for Ra = 2.41×10^6 can be appreciated by comparison of the total volume flow rate at the beginning of the heated section ($1115 mm^3/sec$) whilst the total upwards volume flow rate outside the recirculation bubble was $1302 mm^3/sec$. Hence the reverse flow rate is 16.8% of the volume flow rate into the heated section. For Ra = 2.98×10^6 reverse flow rate is 1.5% of the volume flow rate into the heated section.

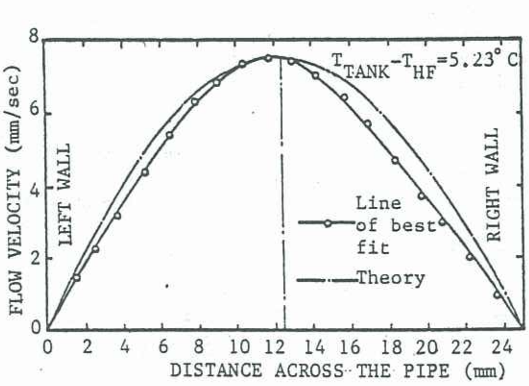


Fig. 3 Measurements taken at 15.2 pipe diameters below the elevation at which heating started

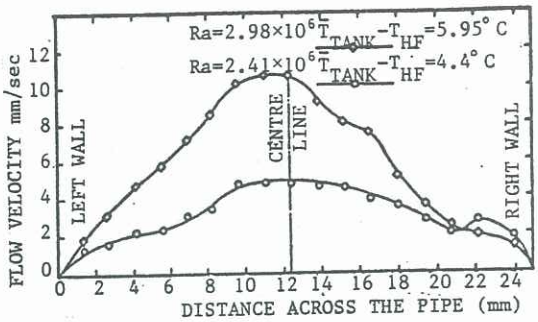


Fig. 4 Measurements taken at 1.6 pipe diameters below the elevation at which heating started.

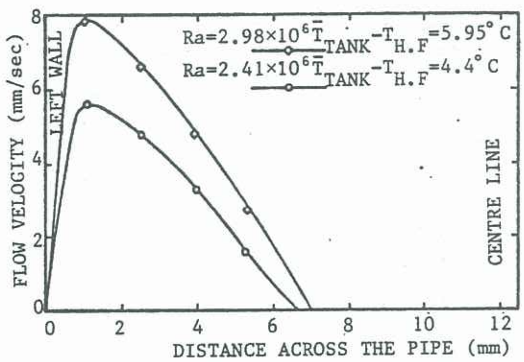


Fig. 5 Measurements taken at 9.4 pipe diameters above the elevation at which the heating started.

3. NUMERICAL STUDY

Dyer (1968), (1975) predicted distortions in temperature and velocity profiles under different heat input, geometrical and flow conditions for laminar flow through heated ducts. In a later study he observed reverse flow developing in a natural-convective flow through a vertical duct with entry restrictions (1978). Scheele, Rosen and Hauratley (1960) also predicted distortions in velocity profiles in laminar flow through a vertical pipe. However, numerical models presented by these authors would handle only uni-directional laminar flow. Ranatunga (6) also indicated the possibility of a drop in centre line velocity in circular vertical pipe due to non-uniform temperature distribution over the cross-section of the riser in a solar collector. Irregularities in velocity and temperature fields have also been observed by Ohanessian and Charters (1978) in other natural convection devices such as the Trombe-Mechel wall. Experiments conducted in the present study also revealed reverse flow in a thermosyphon circuit under different heat input and flow restrictions conditions. However, the experiment was conducted only for a single vertical circular pipe due to the cost and time restrictions associated with a production of a number of pipes. Therefore, in

order to study the development of thermal and velocity fields in thermosyphon flow for different heat input and geometrical conditions, the problem was simulated numerically by solving the finite difference equivalents of the governing flow equations on a digital computer. As a first step in the numerical study, a simple model of flow between parallel plates was investigated. The inlet boundary conditions were set as fully developed laminar to simulate the conditions observed during the experimental investigation. Numerical simulation of flow between two parallel heated plates was carried out for the range of Rayleigh number from 100 to 300,000; Reynolds number from 5 to 100; Aspect Ratios of the solution region from 5 to 20; Aspect Ratios of the heated part of the system from 1 to 10. The Prandtl number was kept equal to 5 as all solutions were obtained for water as the working fluid. Numerical solutions were also obtained for an inclined cavity.
Recirculation flow was predicted numerically for two cases: first for $Ra = 0.1 \times 10^6$, $Ra = 5$, $Pr=5$, $AO_s=5$, $AO_h = 1$ (see Fig. 6) second for $Ra = 0.3 \times 10^6$, $Re = 50$, $Pr = 5$, $AO_s = 20$ and $AO_h = 10$ (see Fig. 7). (The numbers from 0.0 to -1.0 represent contour levels for stream function). For more details on the numerical solution obtained see Litvak (1982).

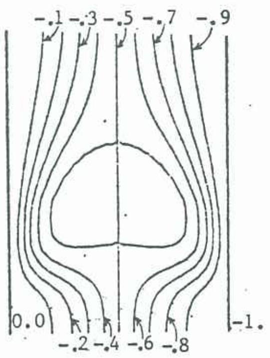


Fig. 6 Plot of stream function field for $Ra = 0.1 \times 10^6$ $Re = 5$, $Pr = 5$, $AO_s = 5$, $AO_h = 1$

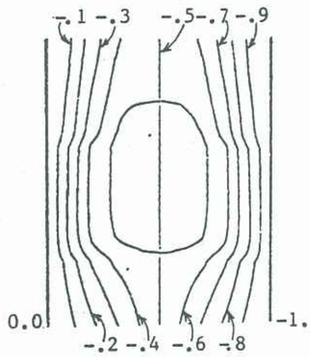


Fig. 7 Plot of stream function field for $Ra = 0.3 \times 10^6$ $Re = 50$, $Pr = 5$, $AO_s = 20$, $AO_h = 10$

4. DISCUSSION OF NUMERICAL RESULTS

4.1 Vertical Cavity

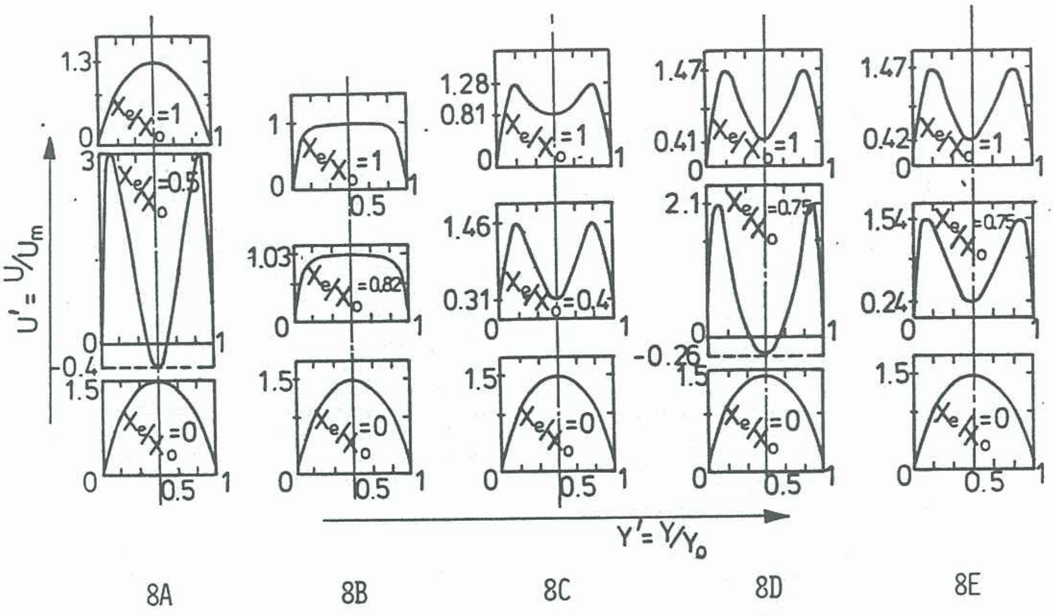
Non-dimensional velocity profiles for vertical cavity are presented in Figures 8A to 8E. Entry boundary conditions are fully developed laminar (see Fig. 8A). At the mid-section of the cavity ($x_e/X_o = 0.5$) (ratio of the distance from the cavity's entry to its height), the velocity reaches its maximum near the walls and undergoes a sign change in the central region to a minimum value of -0.4. The non-dimensional centre line velocity at the exit is 1.3. Increase in Reynolds number ($Re = 50$, $Ra = 0.1 \times 10^6$, see Fig. 8B) cause forced convection to prevail over natural convection. Close to the exit the velocity profile flattens and at the exit the centre line non-dimensional velocity is 1.0. Keeping all flow parameters the same as for the case shown in Fig. 8B, but increasing the aspect ratio of the system (AO_s) and aspect ratio of the heated section (AO_h - ratio of the length of the heated section to the interplate spacing) caused a dip in the centre line velocity and increase in velocity close to the boundaries at the elevation $x_e/X_o = 0.4$ (see Fig. 8C). At the central region of the exit, the velocity is still considerably lower than velocity near the walls (0.81 in the centre against 1.28 near the walls). Higher Rayleigh number ($Ra = 0.3 \times 10^6$, see Fig. 8D), i.e. higher heat transfer, causes the flow to accelerate along the walls. Owing to the presence of viscous interaction, this fast hot layer entrains neighbouring colder fluid layers. However, as soon as elements of the colder zone move out of the vicinity of the fast moving layer, the shear force reduces and these elements of fluid commence to fall. At certain points along the downward path, the descending particles get caught in the shear interaction layer, and thereby complete the cyclic pattern. As a result, the velocity in the centre is -0.26 at the elevation $x_e/X_o = 0.75$, whilst the velocity at $y' = 0.2$ from the walls is 2.1 (see Fig. 8D). Flow leaves the cavity with a dip in a centre line velocity ($u' = 0.41$) and maximum velocity at $y' = 0.2$ from the walls ($u' = 1.47$). Fig. 8E illustrates the effect of increasing Reynolds number up to 100, while keeping all other parameters the same as for the case shown in Fig. 8D. The minimum centre-line velocity ($u' = 0.24$) occurs at three quarters of the way along the heated section, whilst velocity near the wall reaches its maximum at this point ($u' = 1.54$). At the exit $u'_{centre} = 0.42$ against $u'_{wall} = 1.47$ (see Fig. 8E).

4.2 Inclined Cavity

Results were obtained for forty and sixty degree inclination angles for two cases where recirculation cell was predicted numerically for the vertical cavity: first for $Ra = 0.1 \times 10^6$, $Re = 5$, $Pr = 5$, $AO_s = 5$ and $AO_h = 1$. Second for $Ra = 0.3 \times 10^6$, $Re = 50$, $Pr = 5$, $AO_s = 20$ and $AO_h = 10$. Stream function distribution for inclined cavity for $Ra = 0.1 \times 10^6$ and $Re = 5$ shows a dramatic change in the flow structure in comparison with a vertical cavity. The recirculation cell is no longer present in the flow, but instead there is a back flow in the central region of the cavity. The back flow is caused by the strong free convective movement across the cell. As a result, flow moves from the lower to the upper boundary thus blocking the main flow. Thus, a cross-over area is generated between two boundaries resulting in the reverse flow in the centre. The influence of the cross-over zone on the main flow grows with inclination. The main difference between the solutions for $Ra = 0.3 \times 10^6$, $Re = 50$ and $Ra = 0.1 \times 10^6$, $Re = 5$ is that the forced convection prevails over the free convection. There is still a cross-over zone present where the fluid moves from the lower to the upper wall, but the reverse flow occurs further up the passage and is almost negligible.

5. CONCLUSIONS

Qualitative agreement was reached between results of the experimental and numerical studies of the flow structure in a vertical thermosyphon circuit. The experimental study conducted under operational conditions similar to solar collectors revealed that recirculation can be present in the heated part of a thermosyphon circuit. Flow visualisation revealed a recirculation core of fluid in the heat transfer section. The position of the recirculation core was found to depend on heat input and the frictional resistance of the total circuit. The more heat introduced into the flow, the higher was the position of the recirculation core with respect to the elevation at which the heating started. Velocity measurements revealed fully developed laminar velocity profile for flow 15.2 pipe diameters below the elevation at which heating started. However, just at



8A	8B	8C	8D	8E
$Ra=0.1 \times 10^6$,	$Ra=0.1 \times 10^6$,	$Ra=0.1 \times 10^6$,	$Ra=0.3 \times 10^6$,	$Ra=0.3 \times 10^6$,
Re=5, Pr=5,	Re=50, Pr=5,	Re=50, Pr=5,	Re=50, Pr=5,	Re=100,Pr=5,
$AO_s=5$, $AO_h=1$,	$AO_s=5$, $AO_h=1$,	$AO_s=20$,$AO_h=10$,	$AO_s=20$,$AO_h=10$,	$AO_s=20$,$AO_h=10$,
Mesh size = 55 by 21	Mesh size = 55 by 21	Mesh size = 111 by 11	Mesh size = 111 by 11	Mesh size = 111 by 11

FIG. 8 DIMENSIONLESS VELOCITY PROFILES FOR LAMINAR FLOW

the entry to this section the velocity profile was found to deviate from fully developed laminar due to the recirculation core in the heat transfer section. Measurements detected strong recirculation in the heated section for Ra = 2.41×10^6 and Re = 81. Under these conditions it was determined that at $x_h/X_h = 0.4$ (ratio of the distance from the beginning of the heated section to its overall length) the reverse volume flow rate is 16.8% of the volume flow rate into the heated section. Numerical simulation for flow through a cavity formed by two parallel heated plates was conducted by solving the finite difference equivalents of the governing flow and heat transfer equations on a digital computer. At the cavity's entry, flow was assumed to be fully developed and laminar, but at the exit, all parameters, viz temperature, vorticity stream function and velocity were computed using an extrapolating technique. The numerical study for vertical cavity indicated that recirculation is likely to occur for thermosyphon systems having large aspect ratio of the heated section, low Reynolds and high Rayleigh numbers. The numerical analysis also showed, that an increase in Reynolds number results in the displacement of the recirculation core up the fluid passage and thus reduces recirculation in the heat transfer section. Similar results were obtained during the flow visualisation experiment. The effect of the inclination on flow structure was investigated for two cases in which recirculation was predicted for the vertical case. It was found that recirculation is no longer present in the solution region for an inclined cavity. Instead, there is a cross-over area generated in the flow passage due to the motion of fluid from the lower to the upper boundaries. This cross-over zone blocked the flow path and produced a back flow in the upper boundary and central flow regions.

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