EXPERIMENTAL EVALUATION OF NATURAL CONVECTIVE FLUID FLOW PHENOMENON IN COMPOUND PARABOLIC CONCENTRATING (CPC) SOLAR COLLECTOR CAVITIES

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Abstract

In a CPC solar collector with a selectively coated absorber, natural convection within the cavity is the dominant mode of heat loss from the hotter absorber to the cold aperture cover and reflector walls. It is felt that accurate knowledge of the values of critical Rayleigh number (Ra_c) signifying the onset of natural convective flow of cavity air can lead to the design of suitable convection breakers at specific locations within the cavity to substantially suppress this loss and thus enhance the performance of the CPC solar collectors. This paper reports the results of an experimental investigation into natural convective air flow within the direct flow type CPC solar collector cavity simultaneously tilted between longitudinal angles of $0 \leq \theta \leq 10^{\circ}$ and transverse angles of $0 \leq \phi \leq 40^{\circ}$. A general contention that the results and correlations obtained for natural convection in regular shaped (rectangular or cylindrical annuli) cavities are sufficient to describe that in the cavity of a CPC solar collector is being challenged here. It is concluded that the employment of the results obtained for regularly shaped enclosures to describe the natural convection phenomena in CPC solar collector cavities will be misleading.

1. Intorduction- Critical Rayleigh Number (*Ra_c*) for Natural Convection in Cavities

For a situation in which a large (typically with longitudinal aspect ratio $A_z > 5$ for air) horizontal (heated from bottom and cooled from top) layer of a fluid is heated from below and cooled from above (Rayleigh-Benard convection), it is well known that for a Rayleigh number, *Ra*, less than a critical value, Ra_c, there is no convective motion and the heat is transferred within the enclosure only by conduction. The Nusselt number, *Nu*, for this case is unity. For $Ra > Ra_c$, there is convective fluid flow which can have a very complex three-dimensional structure. In such a situation, convective flow initiation is associated with what is called the 'top-heavy-situation'[1]. Pellow and Southwell [2] and Chandershekhar [3] reported a critical Rayleigh number of $Ra_c = 1708$ for onset of convective motion between two large horizontal plates. Variation of the critical Rayleigh number with factors such as transverse aspect ratio, temperature difference (ΔT) of active walls and transverse tilt angle based on the correlations and data presented in the past studies is depicted in Fig. 1 and 2. There is a general agreement among previously reported studies that for a given transverse tilt angle the critical Rayleigh number is higher for a comparatively smaller transverse aspect ratio, A_x. For $A_x = 0.38$, adiabatic side walls with higher emissivity resulted into a higher critical Rayleigh number in horizontally held rectangular honeycomb cells [4]. In a horizontal cavity with adiabatic side walls having the same emissivity the

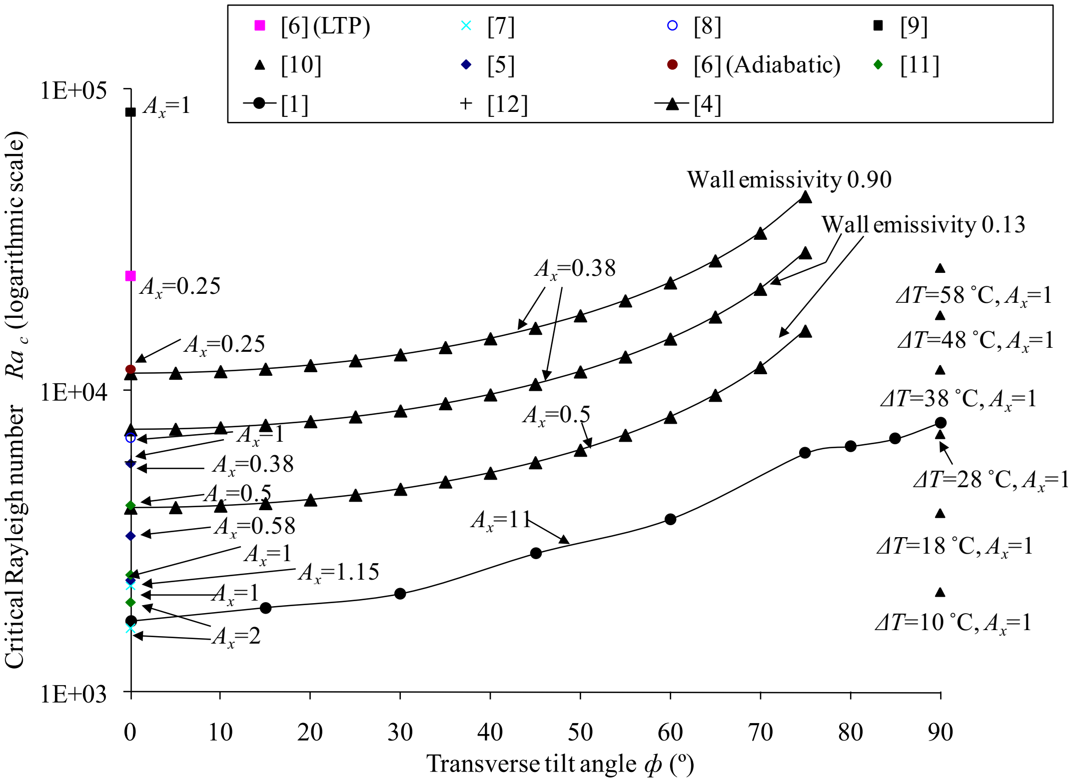

Fig. 1. Ra_c at different transverse tilt angles due to previously reported work.

critical Rayleigh number increases with a decrease in A_x [4, 5]. However, the values of Ra_c in the case of CPC collector cavities significantly differ from those for rectangular cavities with same transverse aspect ratios and thermal boundary conditions. For horizontal rectangular and CPC cavities with same transverse aspect ratio, $A_x = 1$, reported critical Rayleigh number ranges over $Ra_c = 2250$-6969. In rectangular cavities with transverse aspect ratio, $A_x = 1$ and $\Delta T = {\sim}10$ °C values of Ra_c varied from 6969 to 2250 with the former reported for a cubical cavity with side walls having a linear temperature profile (LTP) [8] and the later for a long cavity with longitudinal aspect ratio of $A_z = 36$ and adiabatic side walls [7]. The later value of $Ra_c = 2250$ and that for a rectangular cavity with transverse aspect ratio of $A_x = 1$, longitudinal aspect ratio of $A_z = 6.5$ and LTP in side walls [11] are within 10% of the the critical Rayleigh number ($Ra_c = 2342$) for a two-dimensional CPC cavity with transverse aspect ratio of $A_x = 1$ and adiabatic side walls [5]. This agreement between the CPC and rectangular cavities in the reported critical Rayleigh number values is limited only to $A_x = 1$ as a value of $Ra_c = 5745$ for a CPC cavity with $A_x = 0.38$ [5] differs starkly from $Ra_c = 7460$ for a rectangular honeycomb cavity with transverse aspect ratio of $A_x = 0.38$ with insulated boundary conditions [4]. Similarly reported value of the critical Rayleigh number of $Ra_c = 3292$ for the same CPC with $A_x = 0.58$ differ greatly from $Ra_c = 4165$ for a rectangular cavity with $A_x = 0.50$ and LTP in side walls [11]. Thus such similarities can be regarded as mere coincidental. Hart [14] reported that a conducting wall increases the value of critical Rayleigh number required to start convective motion. Abdel-Khalik et al. [14] found that convection is suppressed till a higher value of the critical Rayleigh number in CPCs with higher concentration ratios implying smaller aspect ratios. Abdel-Khalik et al. [5] presented a correlation for the critical Rayleigh number given in [14]. For horizontal rectangular enclosures Ra_c decreased from $Ra_c = 24000$ to $Ra_c = 11800$ as the side wall thermal conditions changed from LTP to

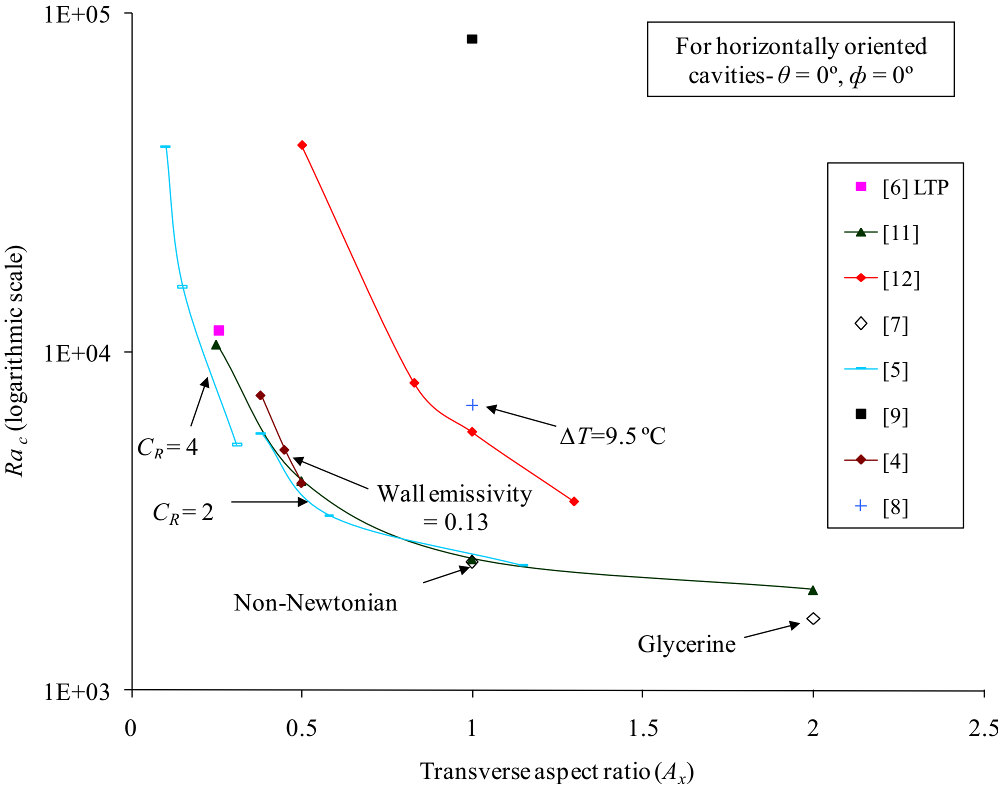

Fig. 2. Values of Ra_c at different transverse aspect ratios due to various previously reported studies.

adiabatic [6]. Cane et al. [15] concluded that in a tilted rectangular cavity base flow along the upslope direction and radiative heat transfer between cavity walls has a definite effect on the critical Rayleigh number. As the side wall emissivity increased from 0.13 to 0.90 the critical Rayleigh number decreased by 1.53 times over a transverse tilt angle range of $0 \leq \phi \leq 75^{\circ}$ [4]. Variation of critical Rayleigh number with changing temperature difference, ΔT, reported in [10] is limited to vertically oriented rectangular cavities. This defies the tendency of past researchers [5] to apply the results from rectangular enclosures into CPC cavities. The critical Rayleigh number for a rectangular cavity was found to be independent of the longitudinal tilt over the range $0 \leq \theta \leq 15^{\circ}$ and $25 \leq \theta \leq 90^{\circ}$ [16]. It definitely shows a very complex dependence on longitudinal aspect ratio, cavity shape, tilt angle, side wall boundary conditions, side wall emissivities, temperature difference and the fact whether Bousssinesq approximation is adopted or not. This complex dependence of the critical Rayleigh number on these factors limit the use of previously reported values in only those situations for which they were first reported and their use for other situations will lead to a significant error in the final results, although these might be used as initial guide. There are very few studies that have reported the variation of critical Rayleigh number with transverse tilt angles whilst its variation with longitudinal tilt remains totally neglected. The curve due to [12] shown in Fig. 2 is for a horizontal rectangular cavity with side walls having thermal conditions midway between LTP and adiabatic with the scope of correlation for the critical Rayleigh number limited to transverse aspect ratio of $A_x \leq 1$. For horizontal rectangular cavities with transverse aspect ratio of $A_x = 1$ with the same side wall boundary conditions, values of $Ra_c = 5800$ (for $A_z = 1$) [12] and $Ra_c = 84000$ (for $A_z = 5$) [9] differed significantly indicating a strong dependence of the critical Rayleigh number on longitudinal aspect ratio, A_z. The critical Rayleigh number increased threefold when the boundary conditions on the side walls varied from perfectly insulating to perfectly conducting for a square plan form of cavity [6]. There is no experimental or numerical data to validate the values of critical Rayleigh number predicted for horizontal CPC cavities in [5], however theirs still remains the sole correlation for Ra_c for CPC collector cavities.

2. Experimental Procedure

An experimental investigation into the natural convection heat transfer phenomena that occur in the cavities of full height ($C_R \leq 2$), three-quarter height and half height CPC solar collectors (height of CPCs, $H = 0.130\text{-}0.259$ m) with flat plate absorbers under normal radiation incidence has been undertaken. One full height CPC and CPCs truncated to three-quarter and half height were designed, constructed and studied using a purpose built solar simulator. The developed experimental test apparatus in addition to the CPCs and solar simulator consisted an angular orientation table and the water supply system. The CPC solar collectors had longitudinal and transverse aspect ratios of $3.85 \leq A_z \leq 7.70$ and $0.385 \leq A_x \leq 0.77$. The experiments were carried out for tilt angles in longitudinal and transverse directions of $0 \leq \theta \leq 10°$ and $0 \leq \phi \leq 40°$ respectively, Fig. 3. Tilt angles were measured to an accuracy of ± 0.15º. The radiation intensity at the CPC aperture cover from the purpose built solar simulator was 350 ± 23 W/m^2. The water supply system supplied water at a constant flow rate (within ± 1%) of 0.011 kg/s per m^2 of aperture area and maintained water temperature to within ±0.5 ºC of set point temperatures of 11, 20, 30, 40, 50 and 60 ºC. The rationale for selecting this experimental parametric range has been described in [17]. The temperature at various locations on the components of the solar collectors and within their air cavities was measured with copper-constantan type thermocouples and recorded with a Keithley 2750 data acquisition system. Further details of the experimental set up can be found in [17].

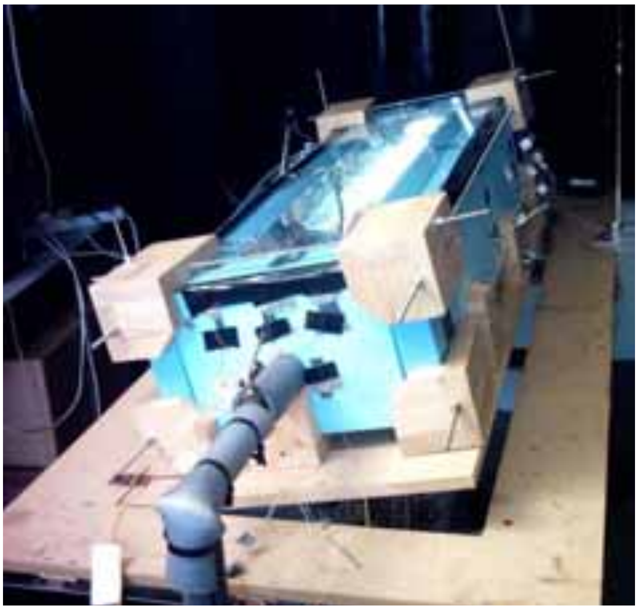

Fig. 3. A transversely tilted CPC solar collector mounted on the tilt table.

3. Results

Based on the experimental data collected during the current experimental study equation {1} with a correlation coefficient of 0.92 is proposed to characterise the natural convection situations involving the water inlet temperature of 11 ºC in the CPC solar collector cavities of varying heights. This correlation has been found to predict the experimentally derived Nusselt number values to within ± 10 %.

$$Nu = 1.961 HT_{in}^{0.091} (0.186 \cos\theta + 0.003 \cos\phi)^{4.42} A_x^{-0.473} A_z^{2.04} (\ln(Ra))^{2.631} \qquad \{1\}$$

This correlation has been derived from experimental data for CPC solar collectors over the parametric range described earlier. Values of critical Rayleigh number determined by assuming the value of Nusselt number as unity [18] in equation {1} for all three CPC collector configurations over the parametric range covered in the present study agree to these general trends as shown in Table 1 and figures 4 and 5.

Table 1. Experimentally determined critical Rayleigh numbers, Ra_c, for the CPC collectors

Transverse tilt angle ϕ (º)	Half height CPC		Three-quarter height CPC		Full height CPC	
	A_x	Ra_c	A_x	Ra_c	A_x	Ra_c
0	0.77	10480	0.51	17366	0.38	24835
10	0.77	10541	0.51	17407	0.38	24893
20	0.77	10727	0.51	17528	0.38	25066
30	0.77	11044	0.51	17728	0.38	25352
40	0.77	11505	0.51	18004	0.38	25746

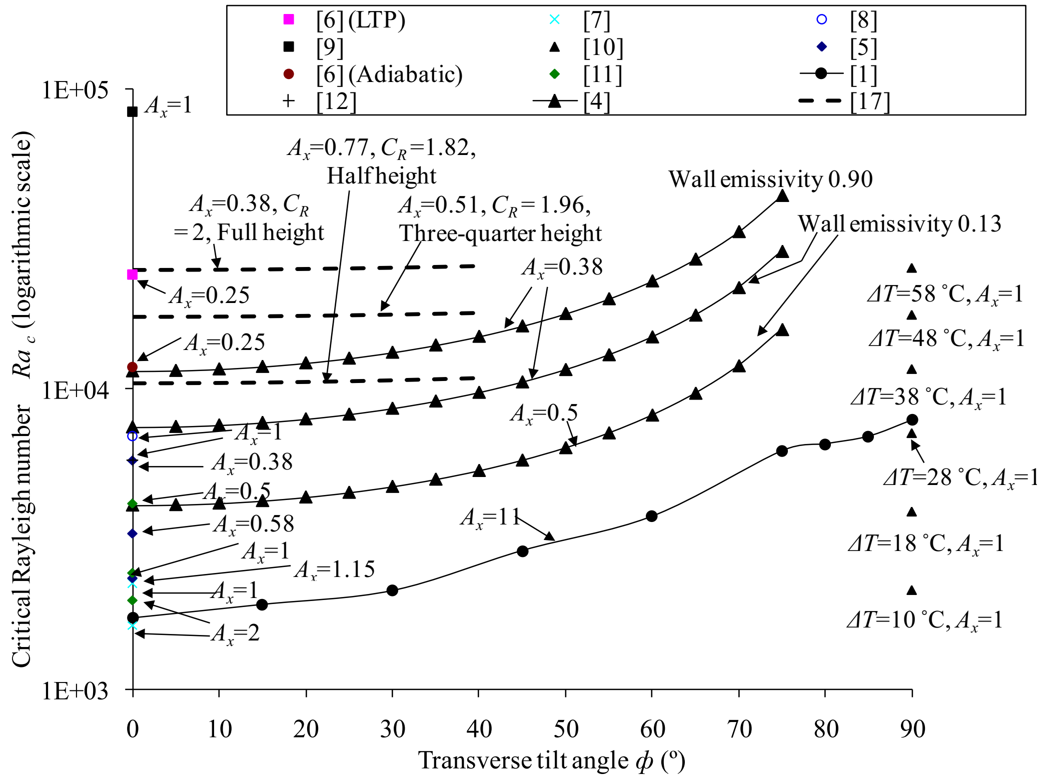

Fig. 4. Variation of critical Rayleigh number, Ra_c, with transverse tilt angle, ϕ, as determined by previous research and calculated using {1} at varying transverse aspect ratio, A_x, in present work

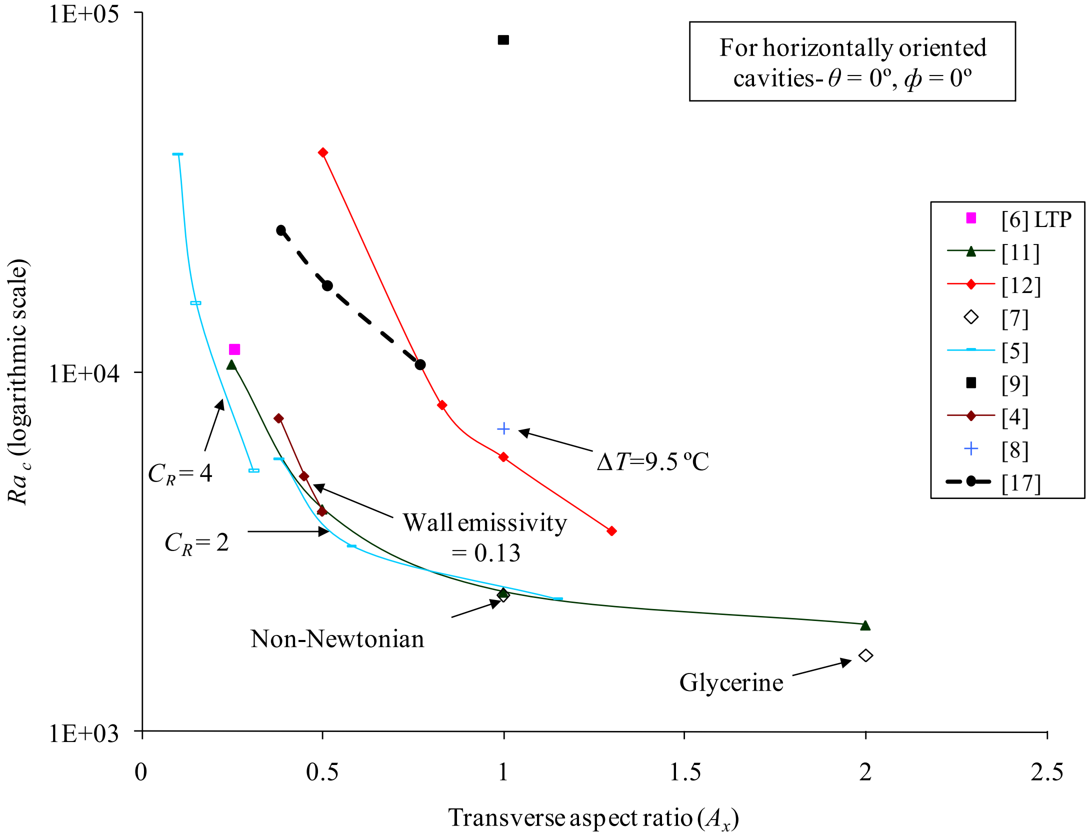

Fig. 5. Variation of critical Rayleigh number, Ra_c, for varying transverse aspect ratio, A_x, for horizontally oriented ($\theta = \phi = 0°$) rectangular and CPC cavities

4. Discusion of Results

In the present experimental study, the temperature profiles actually prevailing in the hot absorber plate and the cold collector cover were not isothermal with the temperature found to vary along both, longitudinal and transverse axes. The absorber plate temperature was observed to increase almost-linearly between the inlet and the exit sections during the present experiments. The side and the end walls of the CPC solar collectors made from 0.5 mm thick aluminium (MIRO-Silver) sheet were highly reflecting and conducting but well insulated with a minimum of 100 mm thick Styrofoam on the outside. For all CPC solar collectors studied over the parametric range considered, the temperature gradient in the reflector side walls (rate of change of temperature with collector height) was found to be positive in the exit-side half portion (length of walls between the central area and the exit cross-section) of the CPC collector, increasing as you approach the absorber, and negative, decreasing as you approach the absorber, in the inlet-side half portion (length of walls between the inlet cross-section and the central area). The average temperature difference in the reflector walls, shown as ΔT_{ref} in Fig. 6, was measured to be 4 °C on the inlet-side half length of the collectors and 2-3 °C on the exit-side half. The temperature gradient in the reflector walls in the exit-side half was not conducive to promoting natural convective motion in the air. The cavity air was thus subjected to two driving temperature gradients, the first in the central area of the cavity, shown as (T_h - T_c) in Fig. 6 away from the walls and the second, ΔT_{ref}, near the reflector walls. The first of these two gradients, characterised by a negative temperature gradient, favoured the onset of

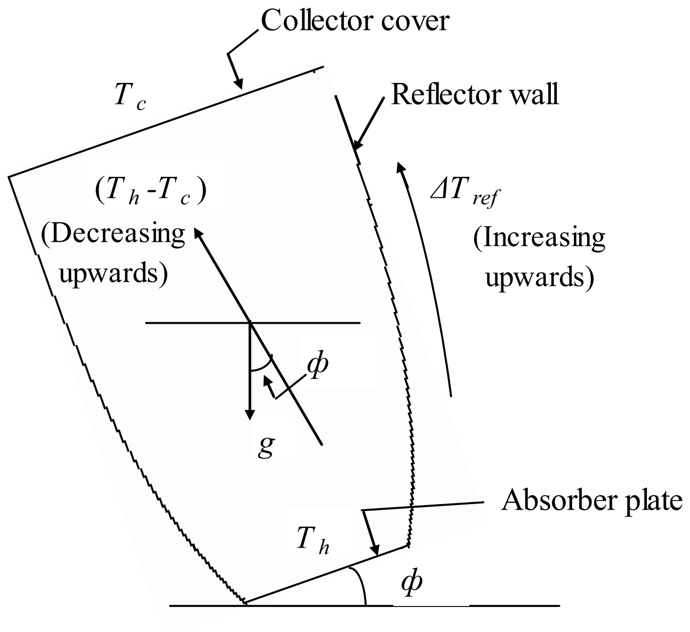

Fig. 6. Illustration of the temperature distribution causing opposing density gradients in the cavity air in the exit-side half.

convective motion the later opposed this motion. The interaction of these opposing density gradients delayed the initiation of convective motion in the cavity air till a higher value of Rayleigh number was achieved. The co-existence of these opposing density gradients in the cavity air gave rise to a complex distribution of buoyancy forces, which drove the natural convective motion in the air. Fig. 6 illustrates the opposing temperature gradients that co-exist in the exit-side half of the collector cavity when tilted transversely at an angle ϕ. In this figure, the gravitational force is indicated by g. The existence of highly conductive reflective side and end walls within the collector cavity resulted in an increase in the critical Rayleigh number, delaying the onset of natural convective flow in (the cavity air) to values higher than those which occur in cavities with adiabatic boundary conditions that have been employed in the previously reported studies. In addition, the prevailing near-linear temperature profiles along the absorber plate and the collector are expected to have played a similar role in the inclined cavities. This is shown in figures 4 & 5. The physical presence of end walls in the present investigation is also expected to have raised the critical Rayleigh numbers to higher values than those reported from earlier numerical studies that assumed two-dimensional natural convection. All of the studies referred to in figures 2-5 involved rectangular cross-section cavities except the one reported by Abdel-Khalik et al. [5], and hence different values of the critical Rayleigh number would be expected. The drawbacks of [5] were the assumption of two-dimensional natural convection in the cavity with isothermal top and bottom walls and adiabatic side walls.

4. Conclusions

Experimentally determined critical Rayleigh number values for CPC solar collectors have been presented. It has been found to increases with a decrease in the transverse aspect ratio for a given transverse tilt angle and to increase with increasing transverse tilt angle for a fixed transverse aspect ratio. The studied CPC solar collectors had thermal boundary conditions of almost linear temperature profiles in the absorber plate and aperture cover. The side walls were found to have internally conducting and externally well insulated conditions with different temperature profiles at the inlet-side half and the exit-side half. These thermal boundary conditions caused the critical Rayleigh number to have values higher than those predicted in past studies that assumed two-dimensional natural convection flow in CPC solar collector cavities. It is concluded that the employment of the results obtained for regularly shaped enclosures to describe the natural convection phenomena in CPC solar collector cavities will be misleading.

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