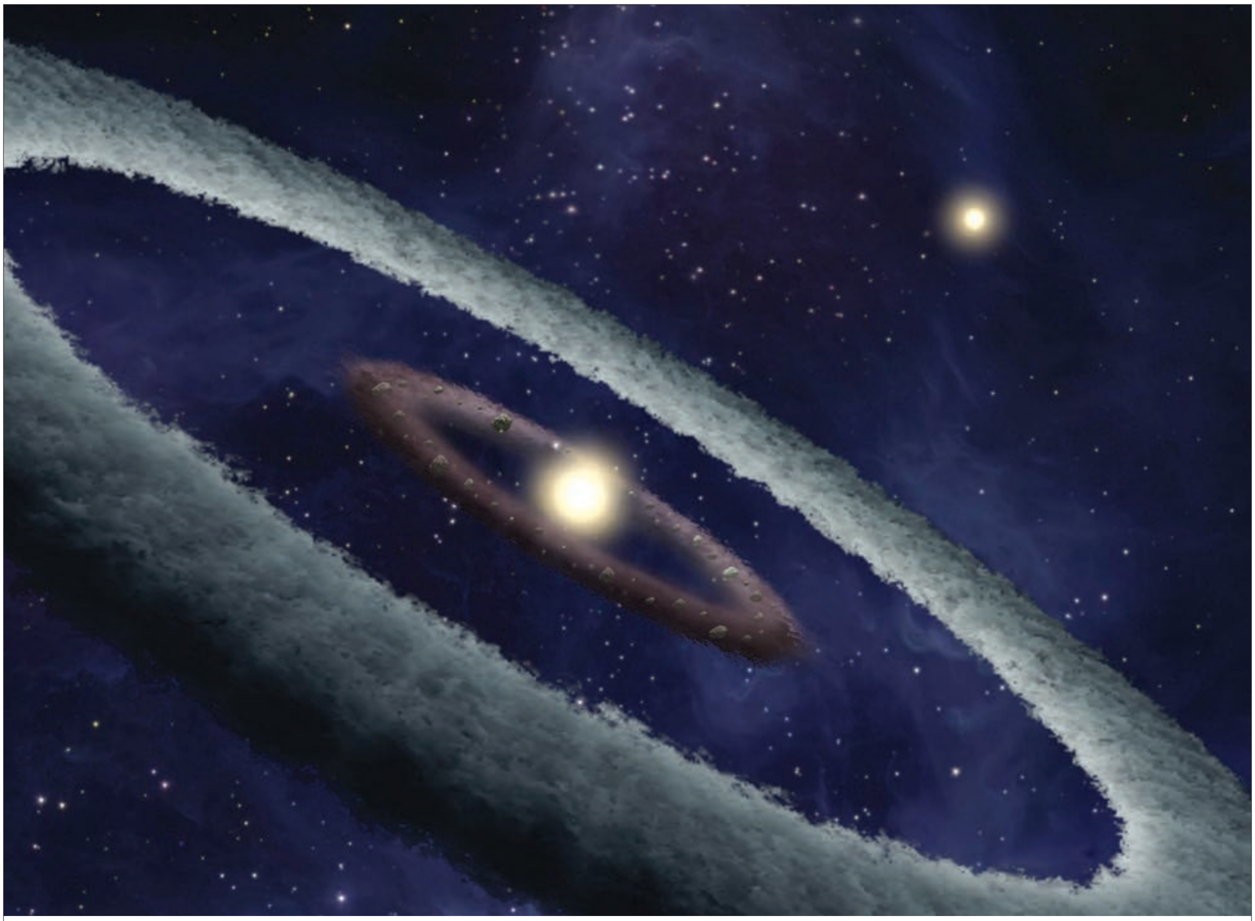

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Analysis of Thermal Losses in the Flat-Plate Collector of a Thermosyphon Solar Water Heater*

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Abstract: The performance of any solar water heater is largely affected by the losses experienced within the system. This research reports the effect of wind speed, number of glazing cover, ambient temperature, gap spacing between absorber plate and the glazing cover, tilt angle and the emissivity of the absorber plate on the overall heat-loss coefficient of a flat-plate collector. The results reflect the contribution and significance of each of these parameters to the collector overall heat-loss coefficient.

Key words: Thermal losses, flat-plate collector, collector overall-heat loss coefficient, solar water heater

INTRODUCTION

Solar water heating is a technology that is simple to adopt for both urban and rural applications. It basically consists of the flat-plate collector, the flow pipe network and the water storage tank. The storage tank is placed at a height 30-60 cm relative to the top of the collector to prevent the reverse circulation during off-sunshine hours (Garg, 1987). As the sun heats the collector, the hot water inside rises by natural convection and the colder storage tank water leaving from its bottom flow into the collector by gravity. Thus the circulation loop is automatically established whenever there is sufficient insolation and circulation automatically stops during insufficient insolation when the upward buoyancy force is unable to overcome the fluid friction losses inside the pipes.

A natural circulation solar water heater is a passive energy system which operates on the principles of conduction, convection and radiation without assistance of a mechanical device (Hunt, 1982). This makes them generally more reliable, less expensive, easier to maintain and possibly longer lasting than active systems. Hence, the option of utilizing natural circulation solar water heater for rural application is particularly attractive given the level of deforestation in these areas and the absence of national grip for alternative power supply.

Flat-plate collector is one of the most important components of a solar water heater. Flat-plate collectors are the simplest and most commonly used collectors for converting the sun's radiation into useful heat. They are designed for applications requiring energy delivery at moderate temperature (less than 100°C) as in water and space heating (Duffie and Beckman, 1974). They have the advantages of using both beam and diffuse solar radiation, not requiring orientation towards the sun and requiring little maintenance. A conventional flat-plate collector is made up of a flat absorbing plate, normally metallic upon which solar radiation falls and is absorbed, changing to heat energy. The absorb plate is usnally black in colour for optimum collection and its area is the same as the area intercepting the radiation. Attached to the collector absorb plate are tubes, channels or passages which circulate the heat transfer fluid. A transparent or translucent cover of glass or plastics is attached on the absorber plate maiuly to reduce the upward convection and radiation heat losses from the collector. Translucent low

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iron glass is a common glazing material for flat-plate collectors because low iron glass transmits a high percentage of the total available solar energy (www.mearsecroft.co.uk). Insulation is provided at the back and sides of the absorber plate to minimize heat losses by conduction. Flat-plate collectors are usually mounted in a stationary position with an orientation optimized for a particular location.

The output useful energy from a flat-plate collector depends on the thermal and optical losses occurring within the system. Thus, the performance of the collector in particular and the entire solar water heater can be optimized if the losses are reduced minimally. Several works (Yeh *et al*., 2003; Mumah, 1995; Morrison and Ranatunga, 1980; Eiseumann *et al*., 2004; Agbo and Unachukwu, 2006) have been done in the area of design, performance evaluation and optimization of the collector units of thermosyphon solar water heaters. Evaluation of the collector losses had been carried out by most of these authors using the Klein model of the loss coefficient. Pillar and Agarwal (1981) had reported on the optical and thermal losses of the flat-plate collector as a function of the number of glazing cover, plate emittance, wind velocity and the ambient temperature using the Klein model. This research however, utilizes the Malhotra *et al*. (1981) model for the collector overall heat-loss coefficient to investigate the effect of wind speed, number of glazing cover, ambient temperature, gap spacing between collector plate and the glazing cover, collector tilt angle and the plate emissivity on energy losses in the collector. This model is simpler than the Klein's and can also be used to study the effect of collector tilt angle which is not reflected in the Klein's model. The choice of a theoretical model for scientific evaluations is cost-effective and tremendously reduces the empiricism associated with system's designing and performance evaluation.

Research Method

The approach adopted in this study is a numerical method based on the Malhotra et al model of the overall heat-loss coefficient of a flat plate collector. The design and the operational parameters of the system used are that of the NCERD thermosyphon solar water heater (Agbo and Unachukwu, 2006) developed and installed at Nsukka (Latitude 6.8°N longitude 7.29°E).

Thermal Losses in a Flat-Plate Collector

Heat losses from any solar water heating system take the three modes of heat transfer: radiation, convection and conduction. The conduction heat losses occur from sides and the back of the collector plate. The convection heat losses take place from the absorber plate to the glazing cover and can be reduced by evacuating the space between the absorber plate and the glazing cover and by optimizing the gap between them. The radiation losses occur from the absorber plate due to the plate temperature. Figure 1 below shows the heat loss pattern in a typical flat-plate collector.

The heat losses from the transparent cover to the ambient air are due to radiative and convective exchanges which are affected by the wind velocity, ground, surrounding condition and by long wave

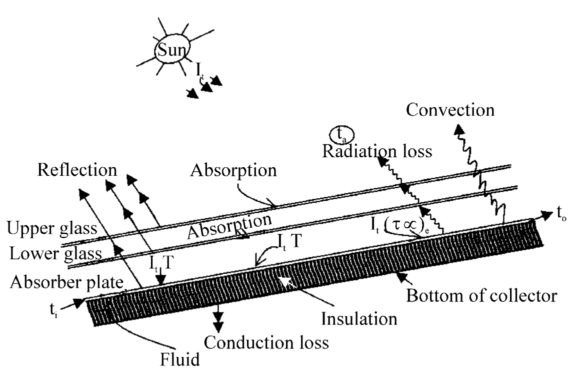

Fig. 1: Energy balance of a Flat-plate collector (Adapted from Garg, 1987)

radiation from the sky. They can be considerably reduced by selective black coatings which have high solar absorptivity and low long wave emmissivity (Garg, 1987). These coatings prepare surfaces such that their absorption characteristics remain high for wavelength below 2 μm and their emission characteristics low for wavelengths above 2 μm. The overall effect is the reduction of the global emissivity coefficient, ε_g which relates the absorber plate emissivity, ε_a and the transparent cover emissivity, ε_t as follows:

$$\varepsilon_g = \frac{1}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_t} - 1} \tag{1}$$

Collector overall -heat loss coefficient, U_l: The collector overall heat loss coefficient is the sum of the top, edge and bottom loss coefficients.

$$U_L = U_T + U_B + U_E \tag{2}$$

For a well-designed collector having a very small collector perimeter to area ratio, the edge losses are almost negligible (Garg, 1987). The bottom loss coefficient, U_B derives from the thermal conductivity, K_S and the thickness, L_s of the bottom insulator as:

$$U_B = \frac{K_s}{L_s} \tag{3}$$

Thus,

$$U_L = U_T + U_B \tag{4}$$

Following the basic procedure of Hottel and Woertz, Klein developed an empirical equation for the top loss coefficient, U_T as (Yeh *et al*., 2003):

$$U_T = \left[\frac{N}{\frac{Ca_{ir}}{T_p}\left[\frac{T_p - T_a}{N+f}\right]^e} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{\left[(\varepsilon_p + 0.00591Nh_w)^{-1} + \frac{\left[2N + f - 1 + 0.133\varepsilon_p\right]}{\varepsilon_g} - N \right]} \tag{5}$$

where $f = (1 + 0.089h_w - 0.1166h_w\ \varepsilon_p)\ (1 + 0.07866N)$, $C_{air} = 520\ (1 - 0.00005\beta^2)$,

$$e = 0.43\ (1 - \frac{100}{T_p}),$$

β is the collector tilt and σ is the Stephan Boltzmann constant.

The convective heat-transfer coefficient h_w, for air flowing over the outside surface of the glass cover depends primarily on the wind velocity, v and can be determined from (Duffie and Beckman, 1974):

$$h_w = 5.7 + 3.8v \tag{6}$$

A more recent analysis carried out by (Malhotra *et al*., 1981) gives the overall loss coefficient in terms of gap spacing, L and reflects the effect of the collect tilt angle in a much simpler way.

$$U_L = \left[\frac{N}{\left\{\frac{204.429}{T_p}\right\} \frac{\left\{L^3 \cos\beta [T_p - T_a\right\}^{0.252}}{N+f} / L} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma(T_p^2 + T_a^2)(T_p + T_a)}{\left[\left\{\varepsilon_p + 0.0425N(1-\varepsilon_p)\right\}\right]^{-1} + \frac{2N+f-1}{\varepsilon_g} - N} \tag{7}$$

where

$$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1+0.091N) \tag{8}$$

RESULTS AND DISCUSSION

Figure 2-7 show the effect of the number of glazing cover, N, wind velocity, V, tilt angle, β, air gap spacing between collector plate and the glazing cover, emissivity of the absorber plate and the ambient temperature, respectively on the overall heat-loss coefficient of the flat plate collector of a natural circulation solar water heater.

Following from Fig. 2, the number of glazing cover significantly contributes to the thermal losses within the collector. Double glazing reduces the overall heat-loss coefficient by 44%, hence resulting in improved overall system performance. This result agrees with an earlier work (Agbo and Unachukwu, 2006) based on the Klein model of the collector top-loss coefficient. The glazing cover reduces the radiation heat losses from the hot absorber plate since glass being transparent to the solar radiation is a good absorber of thermal energy since it is nearly opaque to the long wave thermal radiation from the absorber to the surroundings.

Figure 3 indicates that the wind velocity can contribute to losses in the collector though not as significant as the number of glazing cover. The loss coefficient increases as the wind velocity also increases and this is attributed to the increased convective and radiative losses from the glazing cover to the surrounding.

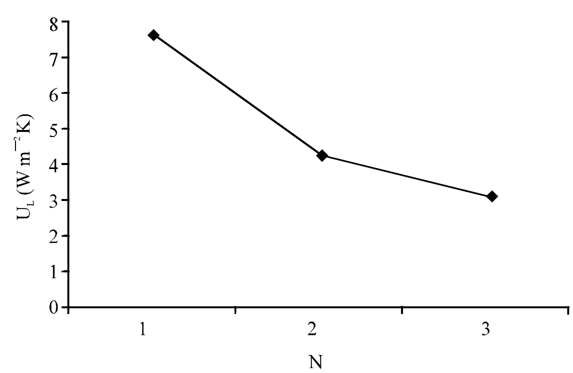

Fig. 2: A graph of U_L against N

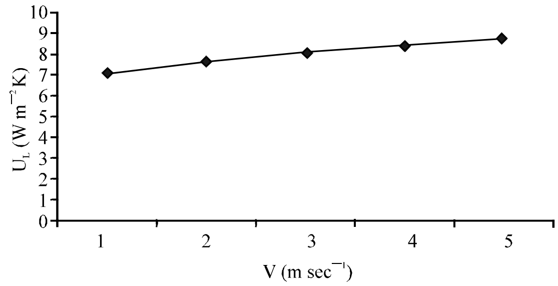

Fig. 3: A graph of U_L against V

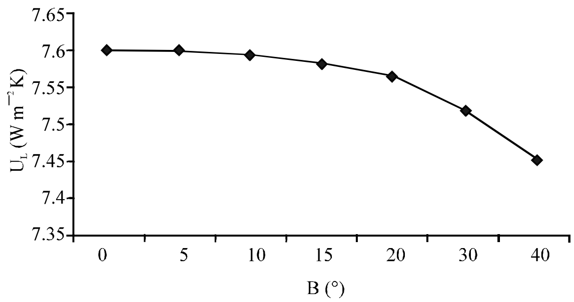

Fig. 4: A graph of U_L against B

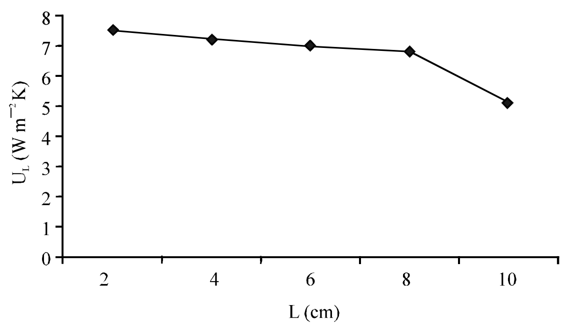

Fig. 5: A graph of U_L against L

The effect of the collector tilt angle is one of the major improvements of the Malhotra model. Figure 4 presents the tilt angle as it affects the collector overall heat-loss coefficient. It shows that the loss coefficient is insignificantly affected by variation in tilt angle for tilt angle values within the range: 0-40°. It has been reported (Duffie and Beckman, 1974) that flat plate collectors installed within regions close to the equator are not significantly affected by the collector tilt angle. However, the loss factor progressively drops with higher values of tilt angle and an optimum value is obtained based on the latitude of the location among other factors (Igbal, 1983).

The air gap spacing between the absorber plate and the glazing cover is a factor that contributes to the overall collector loss coefficient (Fig. 5). The loss coefficient decreases as the air gap spacing increases. Optimizing this gap reduces convective heat losses from the absorber plate to the glazing cover. A gap width that is $\geq$ 5 cm is suitable for optimum system performance (Agbo and Unachukwu, 2006).

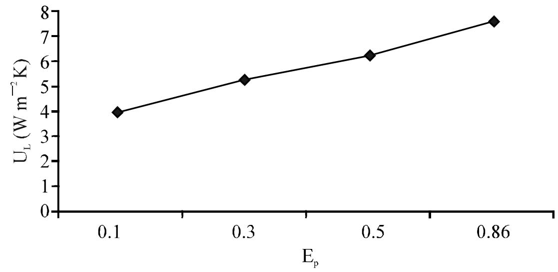

Fig. 6: A graph of U_L against E_p

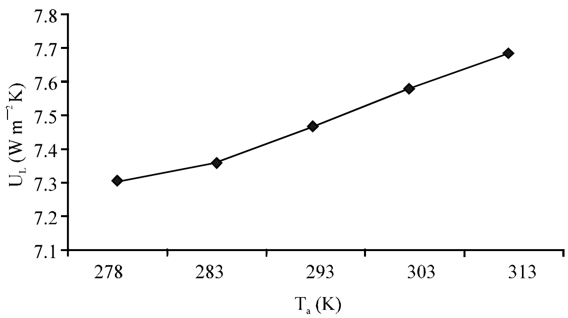

Fig. 7: A graph of U_L against T_a

The variation of the absorber plate emissivity significantly affects the overall heat-loss coefficient as shown in Fig. 6. Radiation heat loss contribution to this coefficient can be reduced by using absorber plate of low long wave emissivity. The result shows that the collector loss coefficient is reduced by 47% for an emissivity value changing from 0.86 to 0.10. The choice of absorber plate material for solar collector design derives not just from its conductivity but also from its emissivity. Selective coating with materials having high solar absorptivity and low long wave emissivity can also be used to reduce radiation losses from the absorber plate.

Figure 7 presents the pattern of correlation between the overall heat loss coefficient and the ambient temperature. The loss factor increases as the ambient temperature also increases. The result indicates that for a 10 K rise in the ambient temperature, the collector overall heat-loss coefficient increases by 0.1. This trend implies that the collector losses will be minimum in the early hours of the morning.

CONCLUSION

It has been shown that the overall losses occurring within the collector unit of the solar water heater is affected by parameters such as: number of glazing cover, wind speed, tilt angle, air gap spacing between absorber plate and the glazing cover, absorber plate emissivity and the ambient temperature at varying degrees. The degree of the effect of these parameters on the collector performance as has been shown is a strong gnide for designers and users of solar flat plate collector for optimization of the system design and its operation.

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