The Effect of Colour on the Thermal Performance of Building Integrated Solar Collectors

T.N. Anderson[1, 2*], M. Duke[2] and J.K. Carson[2]

[1] *School of Engineering, Deakin University, Geelong VIC 3217, Australia*

[2]*Department of Engineering, University of Waikato, Hamilton 3240, New Zealand*

Abstract

The use of solar collectors with coloured absorbers for water heating is an area of particular interest when considering their integration with buildings. By matching the absorber colour with that of the roof or façade of the building, it is possible to achieve an architecturally and visually pleasing result. Despite the potential for the use of coloured absorbers very little work has been undertaken in the field.

In this study, the thermal performance of a series of coloured (ranging from white to black), building integrated solar collectors for water heating was examined both theoretically and experimentally. Subsequently, the annual solar fraction for typical water heating systems with coloured absorbers was calculated. The results showed that coloured solar collector absorbers can make noticeable contributions to heating loads. Furthermore, although their thermal efficiency is lower than highly developed selective coating absorbers, they offer the advantage of improved aesthetic integration with buildings.

[*] Corresponding Author: Tel.: +61 3 5227 3403; Fax: +61 3 5227 2028;
E-mail address: timothy.anderson@deakin.edu.au (T.N. Anderson)

Keywords: solar collectors, colour, performance

1. Introduction

When examining solar collectors one could be excused for believing that they, as Henry Ford famously stated about the Model T Ford, can have them “painted any colour … so long as it is black” [1]. Until relatively recently, the idea of not using either a black, or other selective surface, coating appears to have avoided attention in the literature. The irony of significant amounts of research money and time being invested into developing high performance selective and black surfaces is that it misses the fact that 85% of architects would prefer solar collectors in colours other than black, irrespective of the effect it may have on the system performance [2].

This factor becomes even more pronounced when considering building integrated solar collectors. As Anderson et al. [3] noted in their study of building integrated photovoltaic/thermal collectors; there is a need to consider how collectors integrate *into* buildings rather than *onto* buildings in order to optimise performance and their aesthetics.

Tripanagnostopoulos et al. [4] were perhaps the first researchers to seriously address the issue of coloured absorbers for solar collectors. In their study they examined the performance of unglazed and uninsulated, unglazed and insulated and glazed and insulated solar collectors that were black, blue and brown in colour. They showed that the efficiency of the collectors was actually quite similar despite their external appearance. Further they proposed the use of reflectors as a means of augmenting the performance of their collectors. In a follow-up study [5], it was found that although coloured absorbers required higher levels of auxiliary heating, in a large domestic water heating application, the thermal output was only 18% lower than collectors with a selective surface.

In another recent study Medved et al. [6] demonstrated the use of a brown unglazed solar collector for swimming pool heating. Although the influence of colour was not an objective of their study, they note that their collector could achieve efficiencies of approximately 74% if it was optimised.

As an alternative to using a coloured absorber, Schuler et al. [7-9] examined the use of coloured glazing as a means of changing the appearance of solar thermal collectors. In these studies thin film interference filters and multilayer optical stacks were presented as a means of achieving a coloured appearance from the glazing placed over the standard selective surface absorbers. The downside however, as the authors mention, is that there is still significant development needed to prove these glazings both in terms of manufacturability and operational life.

In light of the lack of data relating to the performance of coloured solar collectors the aim of this study was to examine how colour influenced the efficiency of solar thermal collectors designed for building integration.

2. Collector Design

Unlike many commercially available collectors, and those of Tripanagnostopoulos et al. [4], the collectors in this study were not constructed from finned copper tubes. Instead the collectors were fabricated using commercially available colour coated (Colorcote®) mild steel sheets. Colorcote® uses a hot dipped galvalume steel coil substrate treated with a corrosion resistant primer and a coloured finish coat which is a flexible polyester paint baked on to the steel substrate. These sheets were folded to form a trapezoidal roof profile and an integrated rectangular cross section tube as shown in Figure 1.

Although the fabrication of finned copper tube style collectors is well understood, the unconventional design of the collector, and the desire for it to be made from relatively low-cost pre-coated steel, presented a number of challenges. The main challenge was due to the fact that the material is galvanised and coated in paint. As such the material cannot be welded without removing both these coatings. To overcome this issue, it was decided to bond the folded roof profile sheet to the absorber sheet using a high temperature Silicone adhesive.

The roof sheet was folded using a brake press and holes were drilled to allow fluid into the underside of the rectangular tube. Nipples were soldered to the rear surface around these holes to allow a manifold to be attached, the ends were sealed and the top absorber sheet was bonded into place. Finally, a removable low-iron-glass cover was placed over the collector to prevent convection losses and mineral wool insulation was placed behind the roof sheet.

3. Measurement of Coloured Absorber Performance

When examining the performance of either glazed or unglazed coloured flat plate solar collectors, it is important to characterise their spectral absorption characteristics. From a theoretical perspective the thermal efficiency of a flat plate solar collector can be represented by a relationship between the collectors heat removal factor (F_r), the collector heat loss coefficient (U_L), the inlet (T_i) and ambient temperatures (T_a), solar radiation (G'') and the collector transmittance-absorptance product ($\tau\alpha$) as shown in Equation 1.

$$\eta = F_r(\tau\alpha) - F_r U_L \left(\frac{T_i - T_a}{G''} \right) \tag{1}$$

Of these parameters, the transmittance-absorptance product is the only one that is based solely on a physical property of the collector materials. The absorptance provides a measure of the proportion of the radiation captured by an absorber surface, in this case the coloured absorber, while the transmittance component measures the portion of the radiation transmitted by any glazing layer. Therefore, in order to understand the optical characteristics of the coloured collectors it was decided to determine their absorptance properties over the solar radiation spectrum.

To determine the absorption of the colour coated mild steel, the diffuse reflectance (ρ) of a white (Titania), red (Pioneer Red), green (Rivergum), grey (New Denim Blue) and black sample were measured at 20nm wavelength intervals between 300nm to 2500nm (the AM1.5 solar spectrum) using a spectrophotometer and a 6° integrating sphere at Industrial Research Limited (Wellington, NZ). Based on the reflectance measurement results shown in Figure 2, it is possible to determine the absorptance (α) component using Equation 2, as it can be assumed that coloured steel is an opaque surface with zero transmittance [10].

$$\alpha = 1 - \rho \tag{2}$$

By integrating the absorptance derived from the measurements of the reflectance over the range of AM1.5 wavelengths it was found that the black painted steel had relatively constant reflectance characteristics; however the other coloured samples, as expected, were more sensitive to wavelength. In particular the white sample absorbed less than 35% of the AM1.5 radiation. Interestingly, the red sample absorbed a larger portion of the shorter wavelengths (<1100nm) than the longer wavelength radiation, where it reflected a similar portion of the radiation to the white sample. This was to be expected, as the sample appears red because it will absorb all wavelengths other than those that correspond to the red portion of the visible spectrum.

To determine the transmittance-absorptance product of a glazed coloured collector it was necessary to substitute the measured spectral absorption characteristics and the low iron glass transmittance characteristics of Dietz [11] into Equation 3.

$$\tau\alpha = \frac{\int_{\lambda_1}^{\lambda_2} \tau_\lambda \alpha_\lambda I_{\lambda,i} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda,i} d\lambda} \tag{3}$$

By integrating these values over the AM1.5 spectrum the transmittance-absorptance product for glazed solar collectors of the various colours was found. Based on this method, the transmittance-absorptance values determined for glazed collectors of each colour are shown in Table 1.

3. Theoretical Coloured Collector Performance

Having determined the transmittance-absorptance product for the various coloured glazed collectors it is possible to determine their theoretical performance using a one-dimensional steady state thermal model based on the Hottel-Whillier-Bliss equations presented by Duffie and Beckman [10].

Under these conditions the useful heat gain can be calculated using Equation 4.

$$Q = AF_R\left[(\tau\alpha).G''-U_L(T_i-T_a)\right] \tag{4}$$

Where the useful heat gain (Q) is given by a relationship between the collector area (A), the heat removal efficiency factor (F_R), the transmittance-absorptance product of the coloured collector ($\tau\alpha$), the solar radiation (G''), the collector heat loss coefficient (U_L) and the temperature difference between the collector inlet temperature (T_i) and the ambient temperature (T_a).

The heat removal efficiency factor (F_R) can be derived from Equation 5, which accounts for the mass flow rate in the collector (m) and the specific heat of the collector fluid (C_p).

$$F_R = \frac{mC_P}{AU_L}\left[1-e^{-\frac{AU_LF'}{mC_P}}\right] \tag{5}$$

To determine the heat removal efficiency factor it is necessary to calculate a value for the corrected fin efficiency (*F'*). This is done by first calculating the fin efficiency (*F*) using Equation 6. This determines the efficiency of the finned area between adjacent tubes and takes into account the influence of the tube pitch (*W*) and the tube width (*d*). The coefficient (*M*) accounts for the thermal conductivity of the absorber and is derived from Equation 7.

$$F = \frac{\tanh\left(M\frac{W-d}{2}\right)}{\left(M\frac{W-d}{2}\right)} \tag{6}$$

$$M = \sqrt{\frac{U_L}{k_{abs}L_{abs}}} \tag{7}$$

Therefore, the corrected fin efficiency (*F'*) can be calculated using Equation 8, noting that there is no bond resistance term as would be found in the analysis of a finned tube analysis, and where the overall heat loss coefficient (U_L) of the collector is the summation of the collector's edge, bottom and top losses. It is taken that the bottom loss coefficient is given by the inverse of the insulations R-value (i.e. K_b/L_b) and Equation 9 gives the edge losses, where *p* is the collector perimeter and *t* is the absorber thickness.

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L(d+(W-d)F}\right]+\frac{1}{\pi d h_{fluid}}} \tag{8}$$

$$U_{edge} = \frac{K_{edge}pt}{L_{edge}A_{collector}} \tag{9}$$

The top loss coefficient is a function of both radiation and wind losses, and can be calculated using Klein's empirical equation (Equation 10) [10].

$$U_{top} = \left\{ \frac{N}{\frac{c}{T_{pm}}\left(\frac{T_{pm}-T_a}{N-f}\right)^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma\left(T_{pm}+T_a\right)\left(T_{pm}^2+T_a^2\right)}{\left(\varepsilon_p + 0.00591Nh_w\right)^{-1} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \quad (10)$$

Where:

$c = (520 - 0.000051\beta^2)$ $\quad$ $f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$

$e = 0.430(1 - \frac{100}{T_{pm}})$ $\quad$ $T_{pm} = T_{in} + \frac{Q / A_{collector}}{F_R U_L}\left(1 - F_R\right)$

and β is the collector mounting, σ is the Stefan-Boltzmann constant, N is the number of covers or glazing layers, ε_g is the emittance of the glazing, ε_p is the emittance of the plate and h_w is the convection heat transfer due to the wind.

From these equations it is then possible to calculate the useful heat gain from the solar collector. By taking the ratio of the useful heat gain to the total radiation falling on the collector area (*Q/AG"*) we can subsequently determine the theoretical efficiency as given in Equation 1.

Therefore, by substituting the design parameters listed in Table 2 into the equations listed above, in combination with the measured transmittance-absorptance products for glazed collectors (Table 1), it is possible to determine the theoretical thermal efficiency for the coloured collectors.

Subsequently the predicted thermal efficiency for each of the coloured collectors can be seen in Figure 3. As would be expected, the black collector has the highest predicted efficiency while the white collector has the lowest.

4. Experimental Method and Analysis

Although Figure 3 illustrates the potential performance of glazed colour collectors, good practice necessitates validating the model experimentally. As such two glazed prototype collectors were constructed for testing: one green and one grey. Although there are a number of potential methods for determining the thermal efficiency of solar water heaters, for this study a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1 [12] was used, as shown in Figure 4.

In order to test the prototype collectors, an unimpeded north facing test location was found on the University of Waikato library roof. The global solar radiation incident on the collectors' surface was measured using a calibrated WMO First Class pyranometer mounted inline with the collector at an angle equal to the local latitude (37 degrees).

Calibrated T-type thermocouples (±0.3K) were used to measure the inlet and outlet temperatures to the collector, and the ambient air temperature. A cup anemometer mounted adjacent to the test stand was used to monitor the wind speed. The flow rate through the collector was set at a constant rate and monitored throughout the testing periods by measuring the time taken for a known mass of water to pass through the collector.

Additionally, an instantaneous electric water heater with temperature control was mounted on the inlet side of the collector to provide a controllable inlet water temperature. The outlet from the collector was returned to a 700-litre water tank where it was well mixed to ensure that the heater did not encounter large instantaneous temperature variations.

A prerequisite to accurately determining the performance of the collector is to conduct a number of outdoor tests under a range of ambient conditions and allow it to reach steady state for each condition. Subsequently, when analysing the collectors, the instantaneous collector efficiency can be reached directly from the experimental results by taking the ratio of heat transfer in the collector to the product of the collector area and the global solar irradiance.

5. Experimental Results and Model Validation

From the experimental data collected during the testing it was possible to derive the efficiency equation of the both coloured collectors using a linear least squares regression analysis. The experimental data yields two equations that describe the grey and green collector efficiencies respectively, as shown in Equations 11 and 12.

$$\eta = 0.65 - 10.4 \frac{T_i - T_a}{G''} \qquad (11)$$

$$\eta = 0.63 - 14.6 \frac{T_i - T_a}{G''} \qquad (12)$$

Although this is a common way of presenting the efficiency of collectors, it can be better understood from an inspection of Figures 5 and 6, where the theoretically predicted efficiencies of the glazed coloured collectors are also shown.

In Figure 6, it can be seen that there is a larger discrepancy between the experimental and theoretical result for the green collector. This was due to unusually high wind speeds during the tests, combined with minor leaks around the glazing, leading to higher convective heat losses in the experiment than predicted by the model. However for both collectors, the theoretical prediction corresponds fairly well with the experimental data. Based on the experimental validation, it is possible to optimise the collector using the measured values of the transmittance-absorptance product and the one-dimensional thermal model presented.

6. Annual Performance of Coloured Collectors

Having demonstrated and validated the design model of the coloured solar collectors, it was decided to examine the fraction of a typical domestic water-heating load that could be provided by the various theoretical coloured collectors. Therefore, an F-chart was constructed for the operation of the collectors in Auckland, New Zealand, based on weather data taken from NIWA [13]. Although not as “in-depth” as a full annual transient analysis, such as could be performed by a program such as TRNSYS, the F-chart has been shown to provide good prediction of annual solar fractions [10].

For the calculation of the radiation it was assumed that the collector was oriented facing north and that the collector was inclined at an angle equal to latitude. Furthermore, the system was assumed to consist of $4m^2$ of coloured collectors, coupled to a 170-litre storage tank providing the monthly heating loads shown in Figure 7.

From the F-chart analysis it was found that, as expected, the black coloured collector had the highest annual solar fraction. However, it was also found that although the efficiency of the coloured collectors was lower, they were still able to provide a reasonable fraction of the heating load, as shown in Figure 8.

It is interesting to note that even the white collector is able to provide approximately 25% of the heating load. As such there appears to be significant scope to vary solar collector colour and maintain a degree of solar heating.

7. Conclusion and Discussion

Until recently research into the use of coloured solar collectors appeared to have been passed over in favour of improving black and selective surfaces. It has been shown that despite their lower efficiencies low-cost coloured mild steel collectors could potentially provide noticeable contributions to domestic water heating loads. It has also been shown that the performance of coloured solar collectors can be accurately modelled using a combination of experimental and numerical techniques.

Finally, given the recent drive towards building integration of solar collectors [2] it would appear that the use of coloured solar collectors will start to be an area that receives more attention than it has to date.

8. References

[1] Knowles, E. (Ed.), The Oxford Dictionary of Quotations, 2005, Oxford University Press, Oxford

[2] Weiss, W, Stadler, I., Façade integration – a new and promising opportunity for thermal solar collectors, Proceedings of the Industry Workshop of the IEA Solar Heating and Cooling Programme, Task 26, 2001, Delft

[3] Anderson, T.N., Duke, M., Morrison, G.L., Carson, J.K., Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector, Solar Energy, (2009), 83 (4), 445-455

[4] Tripanagnostopoulos, Y., Souliotis, M, Nousia, T., Solar collectors with colored absorbers, Solar Energy, (2000), 28(4), 343-356

[5] Kalogirou, S. Tripanagnostopoulos, Y., Souliotis, M, Performance of solar systems employing collectors with colored absorber, Energy and Buildings, (2005), 37, 824-835

[6] Medved, S., Arkar, C., Cerne, B., A large-panel unglazed roof-integrated liquid solar collector—energy and economic evaluation, Solar Energy, (2003), 75, 455–467

[7] Schuler, A., Roecker, C., Scartezzini, J.-L., Boudaden, J., Videnovic, I.R., Ho, R.S.-C., Oelhafen, P., On the feasibility of colored glazed thermal solar collectors based on thin film interference filters, Solar Energy Materials & Solar Cells, (2004), 84, 241-254

[8] Schuler, A., Boudaden, J., Oelhafen, P., De Chambrier, E., Roecker, C., Scartezzini, J.-L., Thin film multilayer design types for colored glazed thermal solar collectors, Solar Energy Materials & Solar Cells, (2005), 89, 219-231

[9] Schuler, A., Roecker, C., Boudaden, J., Oelhafen, P., Scartezzini, J.-L., Potential of quarterwave interference stacks for colored thermal solar collectors, Solar Energy, (2005), 79, 122-130

[10] Duffie, J.A., Beckman, W.A., Solar engineering of thermal processes, Wiley, New York, 2006

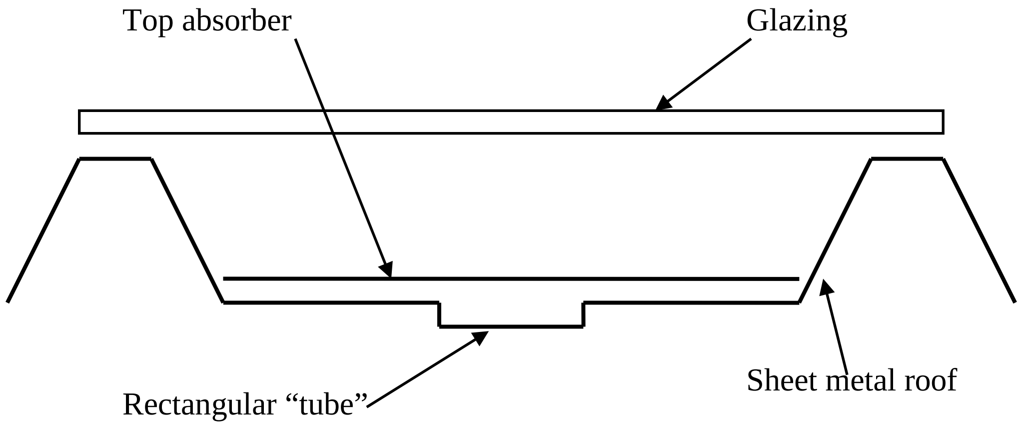
[11] Dietz, A.G.H., Diathermous materials and properties of surfaces, 1954, in Space Heating with Solar Energy, MIT Press, Cambridge, Massachusetts

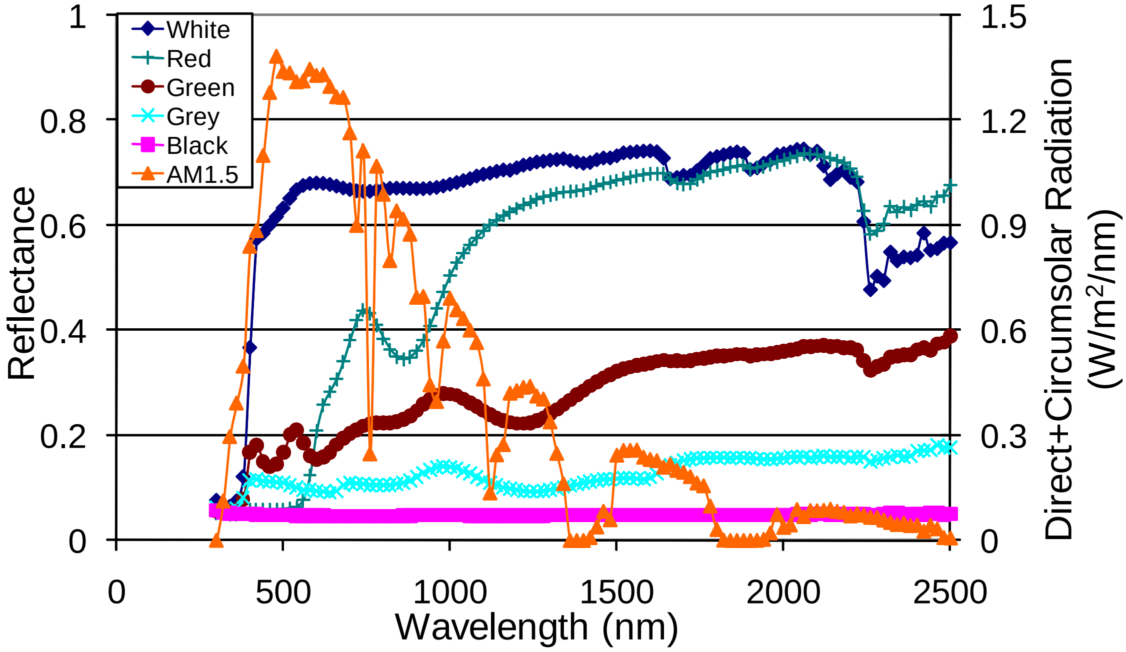
[12] AS/NZS 2535.1, Test methods for solar collectors Part 1: Thermal performance of glazed liquid heating collectors including pressure drop, Standards Australia, Homebush, 1999

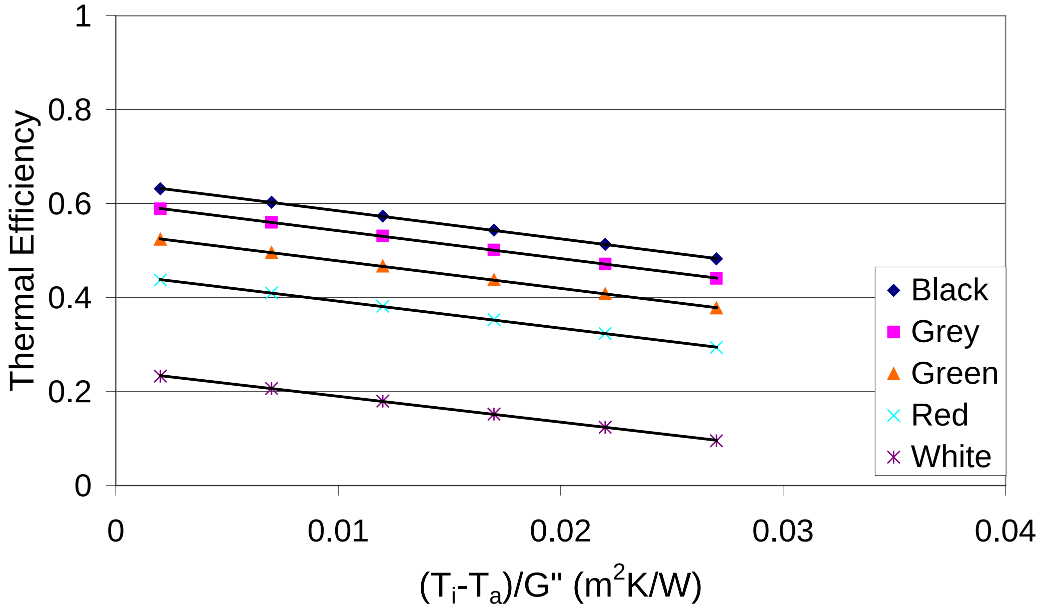
[13] NIWA, Climate Summaries, www.niwascience.co.nz [cited 20/8/07]

Table 1: Transmittance-absorptance product of glazed coloured collectors

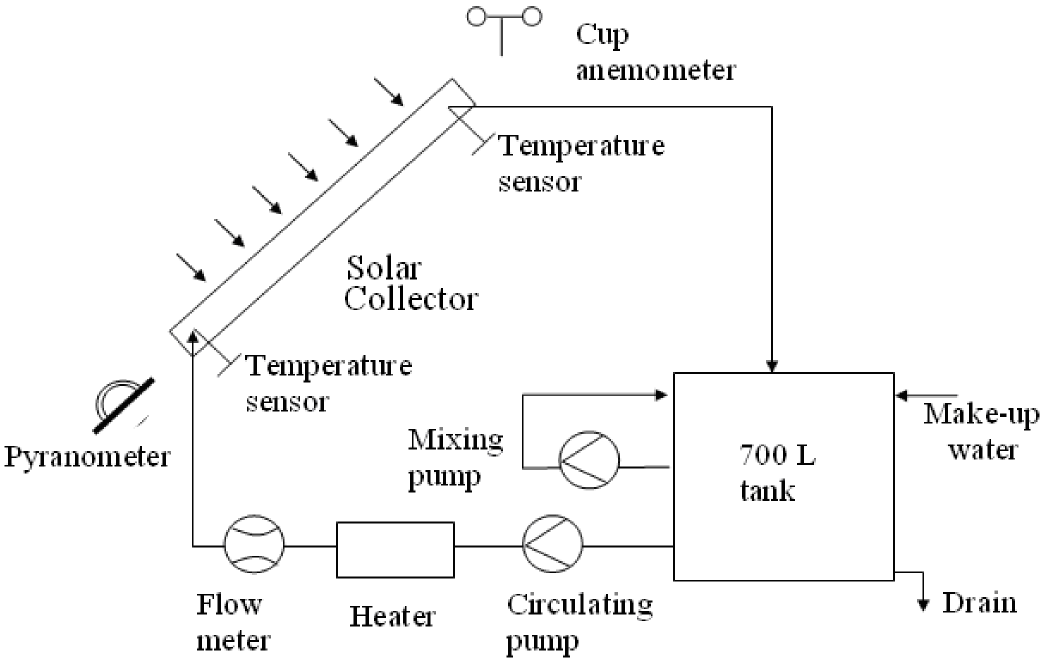
Table 2: Design parameters for coloured solar collectors

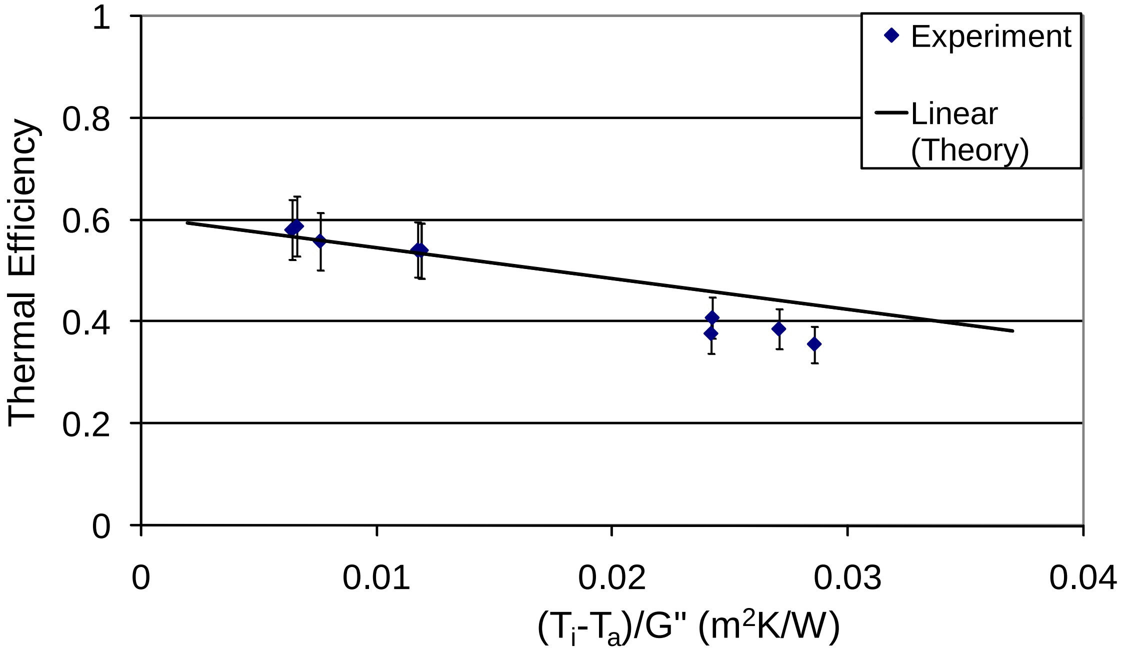

Top absorber
Glazing
Rectangular “tube”
Sheet metal roof


White
Red
Green
Grey
Black
AM1.5
Reflectance
Direct+Circumsolar Radiation
(W/m2/nm)
Wavelength (nm)
0
0.2
0.4
0.6
0.8
1
0
0.3
0.6
0.9
1.2
1.5
0
500
1000
1500
2000
2500

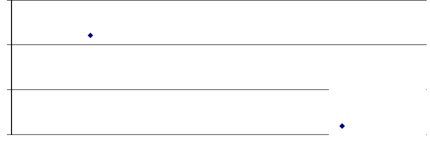


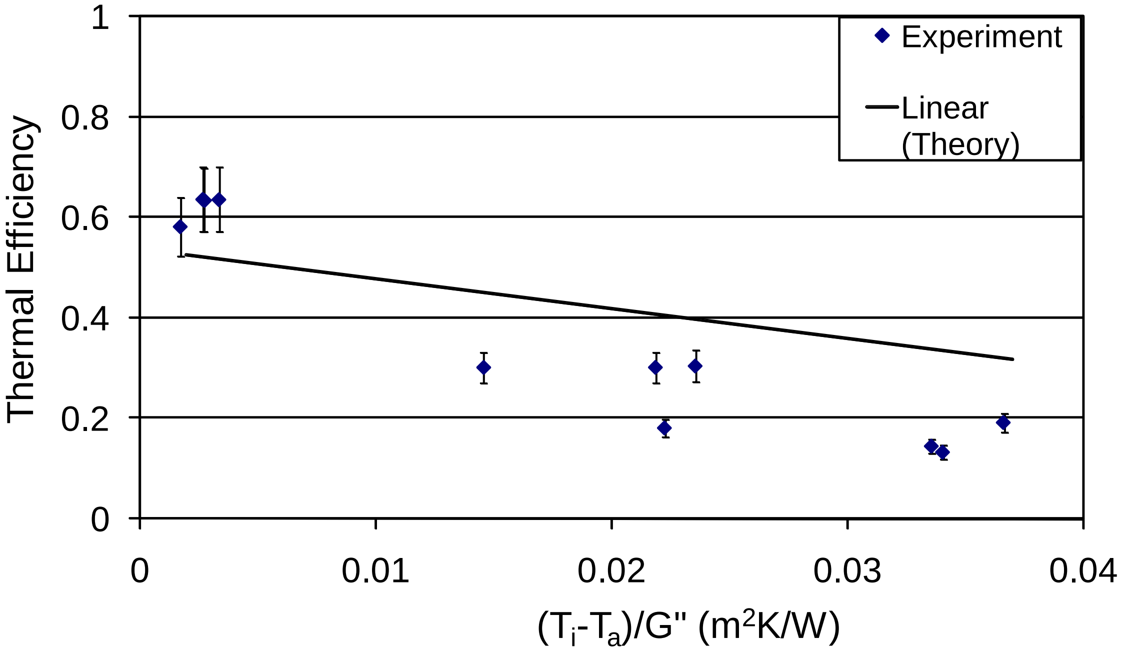
Thermal Efficiency
(Ti-Ta)/G" (m2K/W)
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
Black
Grey
Green
Red
White

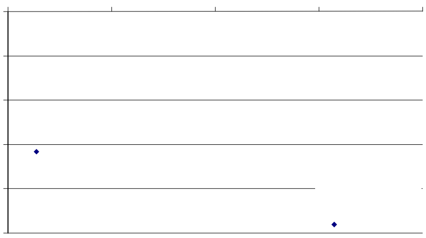

Cup
anemometer
Temperature
sensor
Solar
Collector
Temperature
sensor
Pyranometer
Mixing
pump
700 L
tank
Make-up
water
Flow
meter
Heater
Circulating
pump
Drain

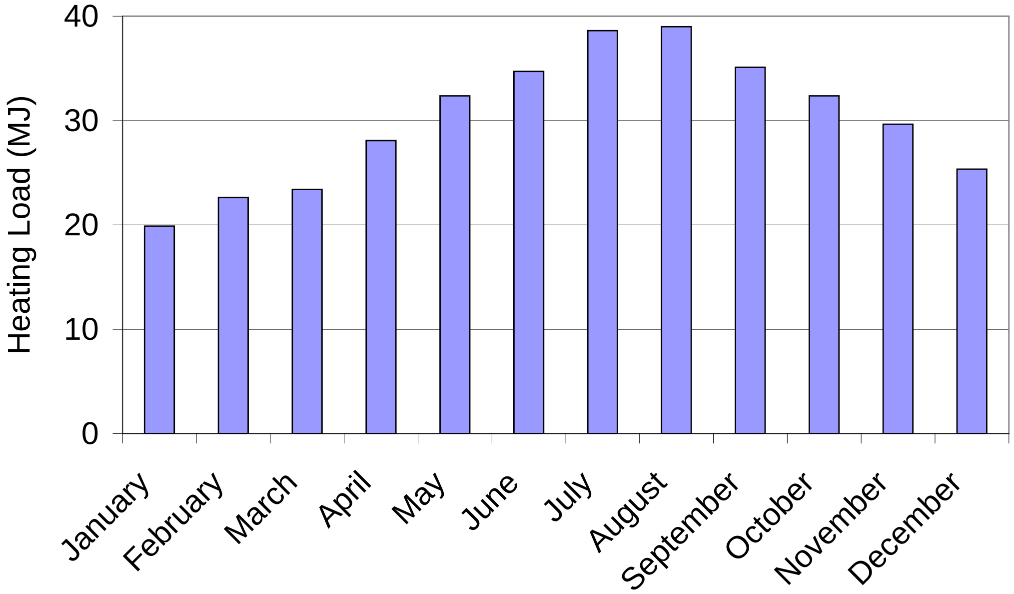


1
0.8
0.6
0.4
0.2
0
Thermal Efficiency
0
0.01
0.02
0.03
0.04
(Ti-Ta)/G" (m2K/W)
Experiment
Linear (Theory)

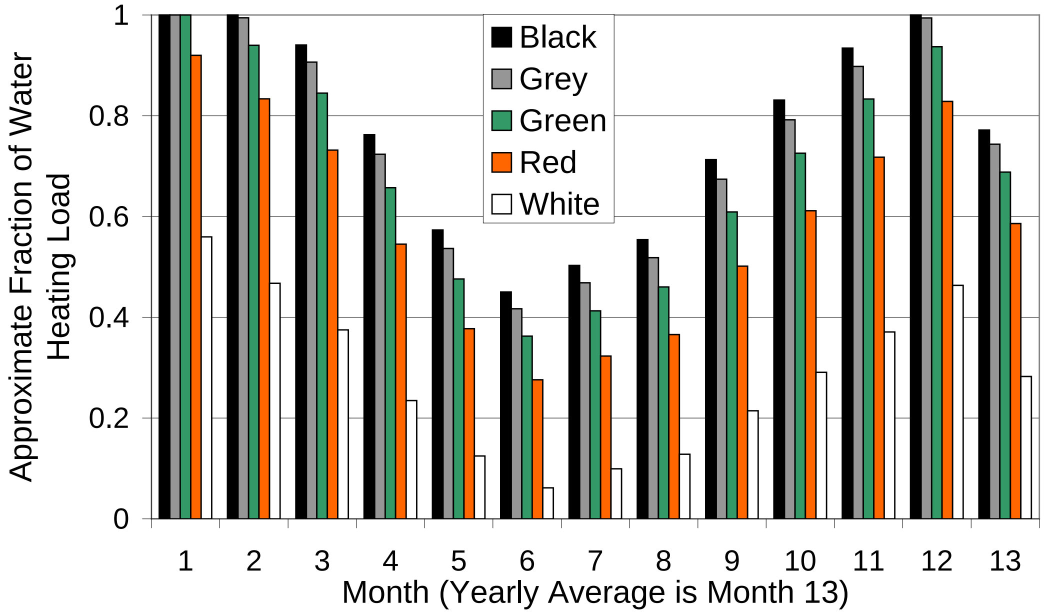



Experiment
Linear (Theory)
Thermal Efficiency
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
(Ti-Ta)/G" (m2K/W)





Heating Load (MJ)
40
30
20
10
0
January
February
March
April
May
June
July
August
September
October
November
December



1
0.8
0.6
0.4
0.2
0
Approximate Fraction of Water Heating Load
Black
Grey
Green
Red
White
1
2
3
4
5
6
7
8
9
10
11
12
13
Month (Yearly Average is Month 13)

Colour	**Transmittance-absorptance product**
Black	0.87
Grey	0.81
Green	0.72
Red	0.60
White	0.32

Parameter	Symbol	Value	Unit
Number of covers	N	1	
Emittance of plate	ε_p	0.95	
Emittance of cover	ε_c	0.88	
Number of tubes	n	2	
Collector Length	L	1.96	m
Collector Breadth	b	0.5	m
Collector Area	A	0.98	m^2
Absorber thickness	t	0.5	mm
Tube Hydraulic Diameter	d_h	9	mm
Tube Spacing	W	0.2	m
Tube Width	d	50	mm
Insulation Conductivity	k	0.045	W/mK
Back Insulation Thickness	L_b	0.1	m
Edge Insulation Thickness	L_{edge}	0.025	m
Absorber Conductivity	k_{abs}	50	W/mK
Mounting Angle	β	37	degrees