Performance of a Building Integrated Collector for Solar Heating and Radiant Cooling

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ABSTRACT

Due to their limited temperature range, unglazed solar collectors have long been relegated to providing low cost heating in applications such as swimming pool heating systems. This limited temperature range is due to heat loss: firstly by convection to the surrounding air and secondly by radiant heat transfer to the cold sky. During the day an unglazed collector can be operated as a standard solar absorber to heat water in a storage tank. However, it is possible to take advantage of radiant cooling of unglazed solar collectors by operating them at night. Under night conditions when there is no solar radiation and the sky temperature is low, the collector can radiate heat to the sky and cool a cold storage tank to provide cooling in the building the following day.

This study theoretically and experimentally examines the performance of a building integrated collector for heating and cooling and explores the contribution it can make to heating and cooling loads in typical New Zealand and Australian buildings.

***Keywords* : building integrated, unglazed solar collector, radiant cooling**

INTRODUCTION

The integration of solar devices into roofs has a number of advantages over conventional ‘bolt on’ systems; in particular the installation of both the roof and solar panel occur at the same time meaning reduced labour and reduced material cost as well as potentially superior aesthetics.

The use of water cooled solar collectors as building elements has, until recently, been largely ignored. Many systems essentially integrate panels *onto* a building rather than *into* the building. A case in point being Kang et al. (2006) who discussed the performance of a roof integrated solar collector which utilised an array of “standalone” solar water heaters as a roof. This system although integrated *onto* the building was not integrated *into* the building. Probst and Roecker (2007) found this method of integrating solar collectors to be “acceptable” to architects. However they emphasise that in the future, building integrated solar collectors “should be conceived as part of a construction system” and although somewhat self-evident their findings appear to have been overlooked by the research community.

Medved et al. (2003) however examined a large area unglazed solar thermal system that could be truly integrated into a building. In their system they utilised a standard metal roofing system as a solar collector for a swimming pool heating system. They found that they were able to achieve payback periods of less than 2 years, a reduction of 75% in the time taken to pay for a glazed solar collector system.

In New Zealand and Australia long run metal roofing is widely used for domestic, commercial and industrial applications (Fig. 1). Moreover, its low cost, high durability, aesthetics and relatively good thermal conductivity make the material well suited to use as the basis for a large area solar heating system. However for many of the warmer areas of Australia, demand for cooling can be more significant than for heating (Watt et al, 2003), meaning that the use of large area solar collectors solely for heating water is of little value in standalone houses. As such, there has been significant attention given to the development of solar cooling systems particularly those using absorption and adsorption cycles (Kim and Ferreira, 2008, Chidambaram et al, 2011). The down side of such systems however, is that they require large amounts of high grade heat, which results in the need for large (and expensive) collector areas.

Now previously, the authors have shown that long run metal roofing can be used for heating over a wide temperature range, from low temperature pool heating (Anderson et al, 2010) through to domestic water heating (Anderson, 2009). However, it has been noted that these collectors have relatively high overall heat loss coefficients, part of which can be attributed to the high emissivity of the polyester paint surface (Colorcote®).

This high emissivity is undesirable for heating systems due to the increased radiant heat loss; however it could be beneficial if heat is to be "dumped" from the collectors to provide cooling. Systems such as this are often referred to as radiant cooling systems or night/sky radiators (Bagiorgas and Mihalakakou, 2008, Dimoudi and Androutsopoulos, 2006) and rely on heat being lost from a panel by radiant heat transfer to the "sky". Hence, under night conditions, when there is no solar radiation and the sky temperature is low, the collector can radiate heat to the sky and cool a storage tank to provide cooling in the building the following day.

BUILDING INTEGRATED COLLECTOR DESCRIPTION

The system developed in this study is designed to be directly integrated into a troughed sheet metal roof. During the manufacturing process in addition to the normal troughed shape, channels are added to the trough for the thermal cooling medium to travel through. An absorber sheet, analogous to the fin of a finned tube absorber, is bonded into the trough. The channels formed in the trough are thus enclosed by this sheet; forming a riser tube having an inlet and outlet at opposite ends of the trough to which heat can be transferred. Fluid is pumped through a manifold (header tube), through these "riser" tubes and out through a manifold (header tube) before being fed to a heat exchanger that removes the heat from the fluid.

The unique design of the collector presented a number of challenges due to the fact that the material was galvanised and dip coated in black paint, so could not be easily welded without removing both coatings. Therefore the roof profile was folded using a CNC folder (rather than rolled) and holes were drilled to allow fluid into the underside of the coolant channel where a manifold was attached. The top absorber sheets were glued to the roof section, and the channels sealed, with a high temperature silicone adhesive sealant thereby forming a standalone watertight collector with a roof profile, as shown in Figure 1.

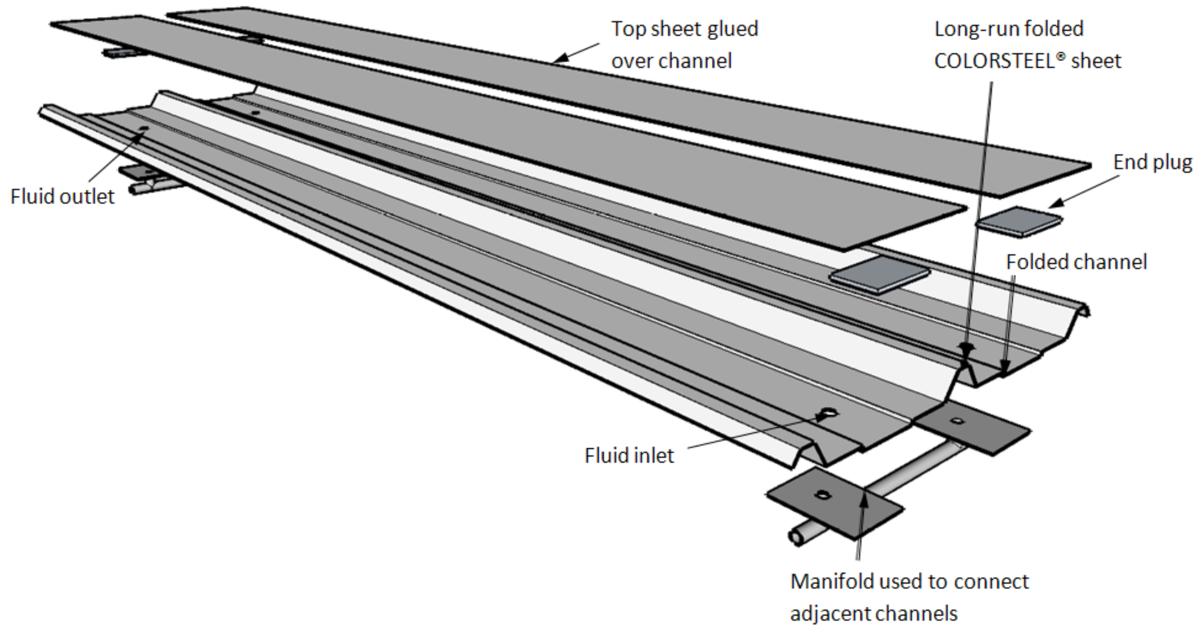

Figure 1: Building integrated collector

THEORETICAL ASSESSMENT OF THE COLLECTOR

To determine the theoretical performance of the building integrated solar collector a one-dimensional steady state thermal model for an unglazed solar collector was utilised (Duffie and Beckman, 2006).

Under these conditions the useful heat gain can be calculated using Equation 1.

$$Q = AF_R\left[G''(\tau\alpha) - U_L(T_{in} - T_a)\right] \quad (1)$$

Where the useful heat gain (Q) can be represented as a function of the collector area (A), the heat removal efficiency factor (F_R), the transmittance-absorptance product of the collector ($\tau\alpha$), the solar radiation (G''), the collector heat loss coefficient (U_L) and the temperature difference between the collector inlet temperature (T_{in}) and the ambient temperature (T_a).

The absorptance provides a measure of the proportion of the incoming solar radiation captured by the absorber surface, in this case grey Colorcote® steel with an absorptance of 0.875. The transmittance component measures the portion of the radiation transmitted by any glazing layer and in this case for an unglazed collector it was assumed to be equal to unity.

The heat removal factor (F_R) can be derived from Equation 2, which accounts for the mass flow rate in the collector ($\dot{m}$) and the specific heat of the collector fluid (C_p).

$$F_R = \frac{\dot{m}C_P}{AU_L}\left[1 - e^{-\frac{AU_L F'}{mC_P}}\right] \quad (2)$$

To determine the heat removal 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 3. 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). Furthermore, the coefficient (M) accounts for the thermal conductivity of the absorber and is derived from Equation 4.

$$F = \frac{\tanh\left(M\frac{W-d}{2}\right)}{\left(M\frac{W-d}{2}\right)} \tag{3}$$

$$M = \sqrt{\frac{U_L}{K_{abs}L_{abs}}} \tag{4}$$

Therefore, the collector efficiency factor (*F'*) can be calculated using Equation 5, 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. The bottom loss coefficient is given by the inverse of the insulations R-value (i.e. K_b/L_b) and the edge losses are represented by Equation 6, where *p* is the collector perimeter and *t* is the absorber thickness.

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L(d+(W-d)F}\right] + \frac{1}{\pi d h_{fluid}}} \tag{5}$$

$$U_{edge} = \frac{K_{edge}pt}{L_{edge}A_{collector}} \tag{6}$$

Now, for unglazed collectors, as used in this study, the top loss coefficient is a function of radiation, natural convection and forced convection (wind). Hence it is necessary to calculate the top loss coefficient (U_{top}) by taking the summation of the individual contributions. Therefore, the heat loss due to radiation can be expressed as a radiation heat transfer coefficient in terms of the sky temperature (T_s), the mean collector plate temperature (T_{pm}) and the plate emissivity (ε_p) as shown in Equation 7.

$$h_r = \sigma\varepsilon_p(T_{pm}^2 + T_s^2)(T_{pm} + T_s) \tag{7}$$

where the sky temperature is represented by the modified Swinbank equation as a function of the ambient temperature as shown in Equation 8 (Fuentes, 1987) and the mean collector plate temperature is determined from Equation 9.

$$T_s = 0.037536T_a^{1.5} + 0.32T_a \tag{8}$$

$$T_{pm} = T_{in} + \frac{Q/A_{collector}}{F_R U_L}\left(1 - F_R\right) \tag{9}$$

The forced convection heat transfer coefficient (h_w) can be calculated using a correlation in terms of wind velocity (v), as shown in Equation 10 (Watmuff et al, 1977), while the natural convection loss (h_{nat}) can be represented by a function of the temperature difference between the mean collector plate temperature (T_{pm}) and the ambient temperature (T_a) as shown in Equation 11 (Eicker, 2003).

$$h_w = 2.8 + 3.0v \tag{10}$$

$$h_{nat} = 1.78(T_{pm} - T_a)^{1/3} \tag{11}$$

By combining both forced and natural convection heat transfer it is possible to determine an overall convection heat transfer coefficient (h_c) as shown in Equation 12 (Eicker, 2003). Taking the sum of both the convection and radiation losses, it is possible to determine the overall top loss heat transfer coefficient (U_{top}) for the unglazed collector and subsequently the overall heat loss coefficient (U_L).

$$h_c = \sqrt[3]{h_w^3 + h_{nat}^3} \tag{12}$$

However, in the absence of solar radiation the collector acts as a radiator and the heat transferred from the absorber (S) is given in terms of a linearised form of the Stefan-Boltzman law, as shown in Equation 14 (Erell and Etzion, 2000).

$$S = 4\varepsilon_p \sigma T_a^3 (T_{pm} - T_S) \tag{14}$$

where the heat loss is a function of the sky temperature (T_s), the mean collector plate temperature (T_{pm}), the plate emissivity (ε_p) and the ambient temperature (T_a).

By utilising this knowledge it is then possible to calculate the useful heat gain or loss from the absorber, and, the efficiency of the collector under solar radiation.

EXPERIMENTAL TESTING AND MODEL VALIDATION

In the previous section the theoretical performance of the building integrated system was discussed and a number of parameters influencing its efficiency were identified. However, in order for the outcomes of the design methodology to be satisfactorily proven, it was necessary to validate the model against experimental data to ensure the validity of the model. To achieve this validation, the efficiency a single unglazed collector was measured using a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1 (1999). In Figure 2 the experimental results (under still conditions) are compared with the modelled results and it can be seen that the theoretical results predict the experimental performance within 10%. The variation between these may be due to an over prediction of heat loss due to the assumption of a lower sky temperature (Equation 8) than was occurring, possibly due to the presence of clouds or nearby heat sources.

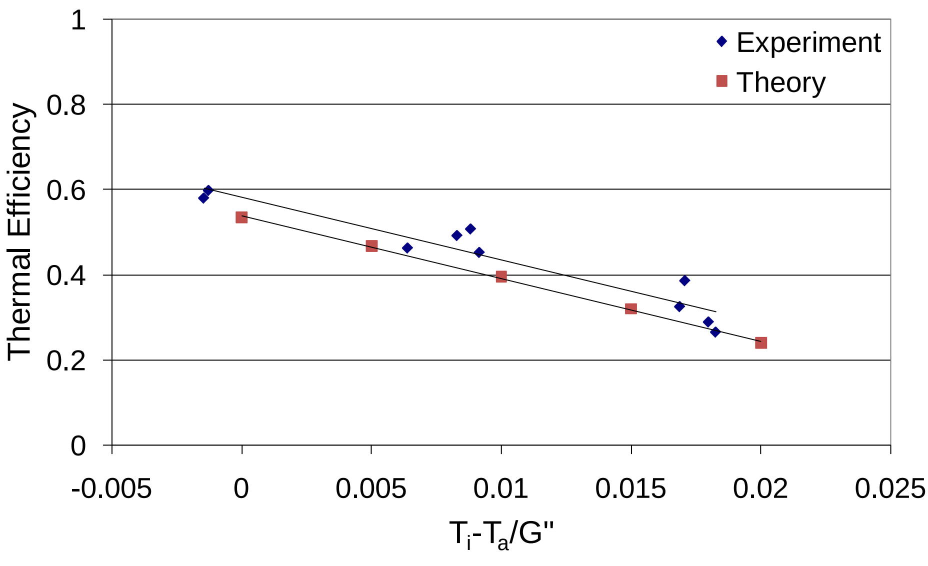

Figure 2: Thermal efficiency of unglazed solar collector

Having demonstrated the ability of the model to predict the performance of an unglazed collector, it was decided to test the collector on a larger scale both in heating and cooling modes, as shown in Figure 3.

T-type thermocouples were used to measure the temperature of the fluid entering and exiting the panels (grey absorbers labeled Row 2 in Figure 3), and also measure the temperature of the roof panels themselves. A pyranometer mounted in plane with the collector surface monitored the global solar radiation and a flow meter at the inlet to the collector was used to determine the flow rate in the collector. Wind speed near the collector was assumed to be negligible, as the test site was heavily sheltered from the prevailing winds. Additionally the rear surface of the collector panel was insulated with mineral fibre insulation held in place with plywood. The other pertinent design parameters for the collector are summarised in Table 1.

Figure 3: Building Integrated Collector test system

Table 1: Design parameters for building integrated collector

Parameter	Symbol	Value	Unit
Emittance of plate	ε_p	0.95	
Number of tubes	n	12	
System flow rate	m	340	l/h
Collector Length	L	2	m
Collector Breadth	b	3.15	m
Collector Area	A	6.3	m^2
Thermal Trans/Abs	$\tau\alpha$	0.875	
Absorber thickness	t	0.5	mm
Tube Hydraulic Diameter	d_h	8.5	mm
Tube Spacing	W	0.22	m
Ratio of Tube width to spacing	d/W	0.09	
Insulation Conductivity	k	0.045	W/mK
Back Insulation Thickness	L_b	0.1	m
Absorber Conductivity	k_{abs}	50	W/mK
Mounting Angle	β	10	degrees

The collectors were coupled to a storage cylinder which was heated during the day using energy collected by the absorber, then cooled at night by radiation. In Figure 4 it can be seen that during the morning, the tank temperature increases due to the increasing solar radiation. However, in the afternoon, the decreasing levels of solar radiation lead to more heat being rejected by the collector to the atmosphere than is gathered, and so a decrease in the temperature.

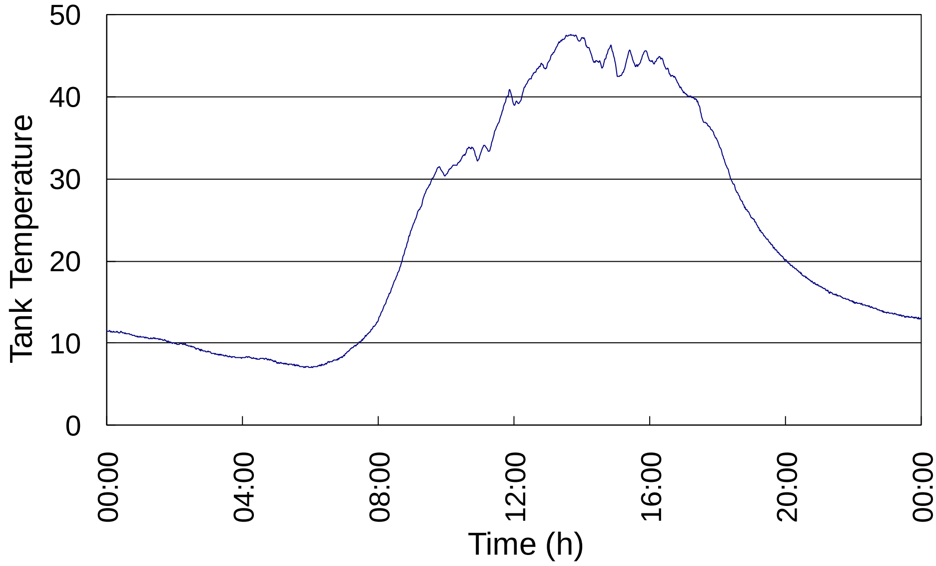

Figure 4: Tank water temperature

This can be better understood through examination of Figure 5, where it can be seen that in the absence of any radiation, there is a net heat loss from the collector of approximately 50 W/m^2.

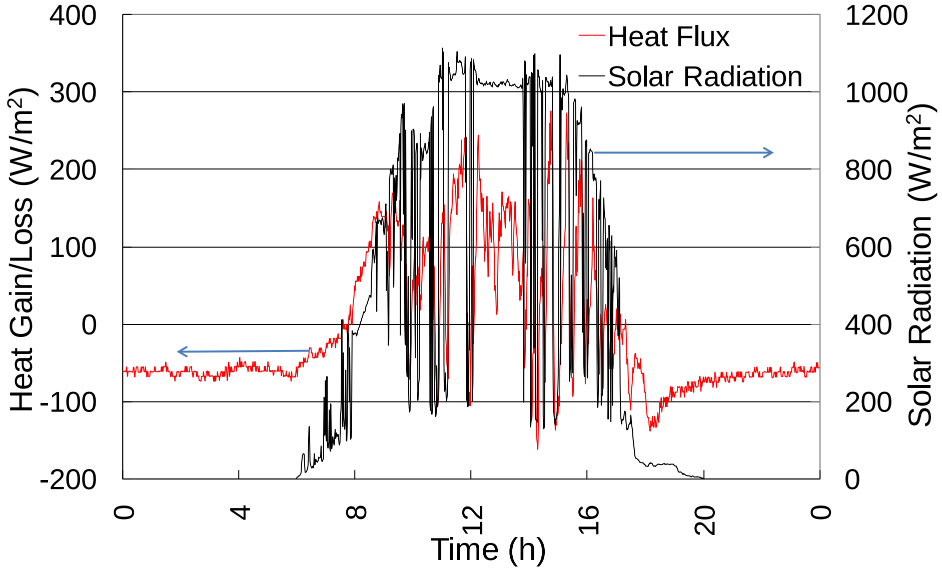

Figure 5: Heat transfer to and from the collector

In the absence of solar radiation this heat loss is principally due to the radiation heat transfer from the absorber to the cold sky as discussed in the theoretical analysis. This is best illustrated by determining the heat loss due to radiation, as discussed in Equation 14. In Figure 6, it can be seen that there is relatively good agreement between the prediction and the calculated values for the collector.

The difference between these may be a result of the sky temperature model, which was taken as a function of air temperature and is best suited to clear sky conditions. As such the presence of clouds and nearby heat sources could have lead to the variation observed.

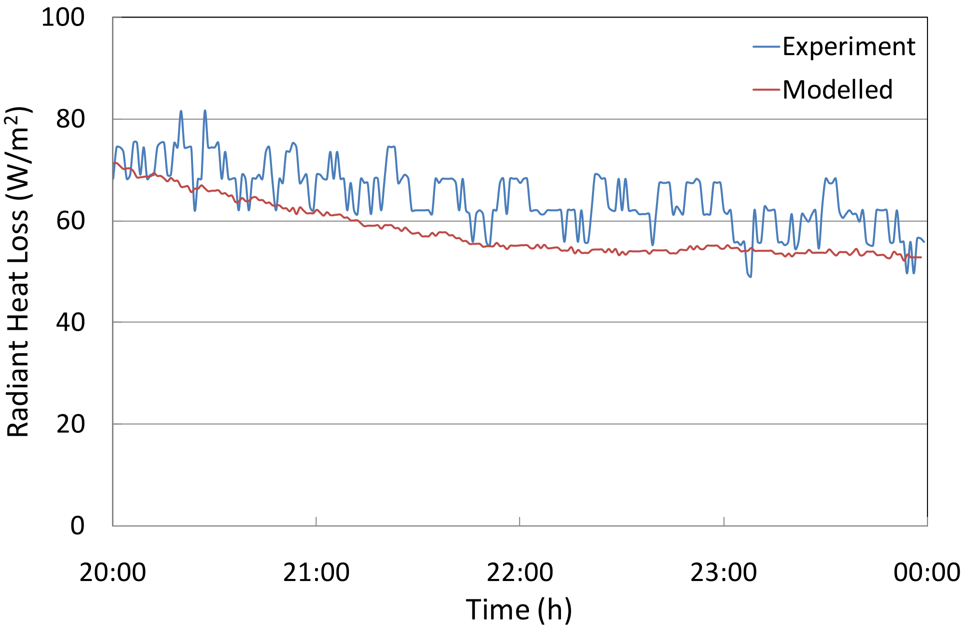

Figure 6: Cooling provided by radiant absorber

Now, from the proceeding description it can be seen that there is significant potential for unglazed building integrated collectors to act as both a solar collector and a radiant cooling system. During periods of high solar radiation in a sheltered location (low wind speeds) it was possible to heat water to an appropriately high level for domestic water use. Furthermore, it was found that when operated in the absence of solar radiation, the collector was able to achieve cooling in the order of 50W/m^2 with temperatures of approximately 10ºC being observed in the storage tank. This would be well suited for moderate cooling loads under summer conditions.

Given the flexibility of the system to be used as a roofing structure, there is significant potential to use large areas of the collector to operate in heating mode during daytime hours, with storage in a "hot" cylinder and subsequently at night with storage in a "cold" cylinder. Consider a simple case where the collector has an area of 60m^2 and is operated for 8 hours on a clear summer night, this could lead to 24kWh of energy being stored to perform cooling in the building the next day. Though simplistic, it serves to illustrate the point that radiant cooling systems represent a relatively untapped means of energy savings in the built environment.

DISCUSSION AND CONCLUSION

Unglazed solar collectors have long been relegated to applications such as swimming pool heating systems due to their low temperature range. This limited temperature range is due to heat loss: firstly by convection to the surrounding air and secondly by radiant heat transfer to the cold sky. However, if designed and sited correctly, an unglazed collector can be operated as a standard solar absorber to heat water in a storage tank. Now under night conditions when there is no solar radiation and the sky temperature is low, the collector can be used to radiate heat to the sky and cool a cold storage tank to provide cooling in the building the following day.

This study showed that there is scope to increase the use of such systems, by integrating them into low cost building materials thereby delivering (large area) low cost heating and cooling systems for buildings.

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