17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

Flow Distribution in Large Area Building Integrated Solar Collectors

T.N. Anderson[1], M. Duke[2], J.K. Carson[2] and B. Smith[3]

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

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

[3] WaikatoLink Limited, University of Waikato, Hamilton, 3240, New Zealand

Abstract

There is a growing trend towards the integration of solar collectors into buildings such that they form a structural element of the building fabric, for example the roof. This integration presents a number of challenges particularly when there must be a compromise not only between engineering objectives but also the architectural. Such compromises are common on roofs where features such as hips and valleys can lead to irregular profiles.

These irregular profiles in building integrated solar collectors challenge the existing design methods. Trying to utilise the maximum area, and hence harness the most solar radiation available, on a roof with an irregular shape may involve sub arrays of non-uniform size, or result in a series of riser tubes of varying lengths. Now typically, the thermal design (theoretical) efficiency of solar collectors is calculated based on the assumption of uniform flow through each individual riser tube. However, when developing large building integrated solar collectors this assumption cannot always be achieved in practice.

This paper examines the development of two large building integrated solar collectors and experimentally examines the effect of non-uniform flow within them. In doing this it shows how non-uniform flow can affect the installed collector efficiency relative to the design efficiency.

Introduction

Uniformity of flow is commonly assumed in the design of many fluid and heat transfer systems, be it steam flowing in boiler tubes or air flow through a car radiator. In reality however, this assumption is not always, or cannot be, achieved due to the compromises that must be made when designing devices for practical real world situations.

The realities of non uniform flow have been observed and documented in a number of applications such as electronics cooling systems, fuel cells and cross flow heat exchangers. In general these systems are characterised by a desire to distribute flow over large surface areas to improve heat transfer. In such systems it is common for the flow to be distributed through manifold systems that distribute and combine the flow paths which can be modelled using methods such as the Hardy-Cross method, through solving the continuity equations for mass, momentum and energy or by implementing algebraic approximations [1-3].

One area in which flow distribution has been quite extensively studied is in the design of solar collectors [4-6]. A common configuration of the solar collector is seen in "flat-plate" style collectors where two horizontal manifolds, or headers, are joined by a series of vertical finned- tube risers through which heat is absorbed and transferred (Figure 1), typically in a Z flow arrangement.

In general, an Australian or New Zealand detached house requires only a moderate amount of water heating. As such it is relatively common for solar water heating systems to be made up of two parallel flat plate collectors of approximately 4m^2 coupled to a storage tank. However, rapidly changing demographics and increasing energy prices will inevitably lead to an increase in medium and high density residences as well as a greater desire to make greater use of solar thermal heating. Such trends are already apparent in Europe where solar thermal energy has been used for district heating and also in the form of large individual solar combisystems for heating detached houses [7].

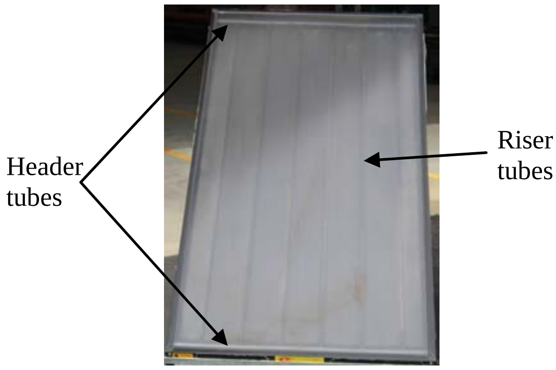

Figure 1: Flat plate style solar water heater, showing header and riser layout

In order to meet this growing demand, one method is to develop large area building integrated solar collectors that are made to maximise the portion of the façade that can actively collect solar thermal energy. This is particularly important in medium and high density housing applications, as there will typically be a reduced useable surface area per occupant.

The challenge of these systems however, is meeting both the aesthetic and geometric constraints of real buildings in addition to maximising the energy absorbed. As such, these compromises in geometry can lead to compromises to the flow in the absorber. This study documents such a situation encountered during the development of two large area building integrated solar water heating systems at the University of Waikato.

Collector System Descriptions

Unlike many commercially available collectors 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. These sheets were folded to form a trapezoidal roof profile and an integrated rectangular cross section tube as shown in Figure 2.

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 sheets were folded using a brake press and holes were drilled to allow fluid into the underside of the rectangular tube. Nipples were bonded 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.

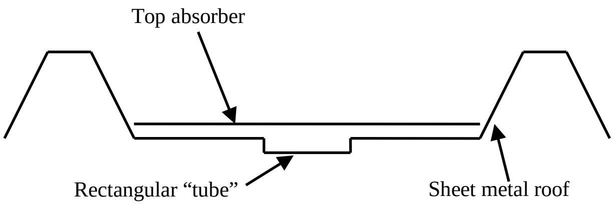

Figure 2: Partial cross section of the building integrated solar collector

The first system consisted of a “simulated” roof of 30m^2 installed at the University of Waikato Aquatic Centre for research and demonstration purposes. The collector was divided into three sections of different coloured roofing steel – black (top), grey (middle), and green (bottom). This enabled researchers to test the relative performance of different coloured panels as shown in Figure 3.

Figure 3: “Simulated” low slope roof, building integrated solar collector

A circulating pump draws the water from the tank (seen beneath the roof in Figure 3) and passes it through the collector panels. As the water flows through the channels integrated into the metal roofing, it absorbs heat provided by the sun. The water exits the panels at a higher temperature, and is returned to the tank. Thermocouples are used to measure the temperature of the fluid entering and exiting the panels, and also measure the temperature of the roof panels themselves. A pyranometer measures the intensity of the solar radiation and a flow meter at the inlet to the collector measures the flow through the array.

The second system was developed to provide heat to the diving pool at the University of Waikato and also demonstrate on a large scale the potential of the collectors. In addition it sought to prove that the collectors were capable of performing in a real life situation, as well as providing a sun shade for bathers. The roof consists of 120 panels in six rows, with the panels not uniformly distributed amongst these rows due to the shape of the roof (Figure 4). The system provided an active surface area of 108 m^2 (Figure 5), which was used to heat the 400m^3 diving pool.

Once the water was heated in the collector it was fed into a heat exchanger. This water was cooled by the water from the pool, which in turn was heated, and returned to the pool. Flow meters were used to measure the flow rate of water through the collectors. This water was circulated around the system using two pumps. Thermocouples were used to measure temperatures at various locations in the system, and the solar radiation was measured using a pyranometer.

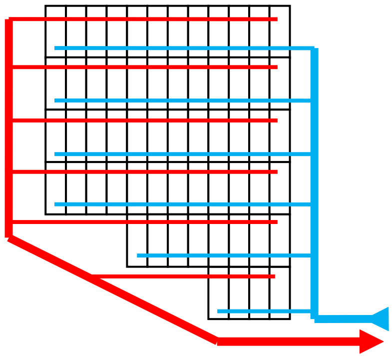

Figure 4: Solar collector piping layout for half of solar heating system

Figure 5: Building integrated solar collector for heating diving pool

Theoretical Performance of Building Integrated Solar Collectors

The theoretical performance of a building integrated solar collector can determined using a one- dimensional steady state thermal model based on the Hottel-Whillier-Bliss equations [8].

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

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

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 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 heat removal efficiency 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).

$$F_R = \frac{\dot{m}C_P}{AU_{loss}}\left[1-e^{-\frac{AU_{loss}F'}{mC_P}}\right] \tag{2}$$

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 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.

Therefore, the corrected fin efficiency (*F'*) can be calculated using Equation 5, noting that there is not a 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 6 gives the edge losses, where *p* is the collector perimeter and *t* is the absorber thickness.

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

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

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

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

For unglazed collectors as used in this study, the top loss coefficient is a function of both radiation and wind. As such it is necessary to calculate the top loss coefficient (U_{top}) by taking the summation of the individual contributions of radiation, natural and forced convection. Under such conditions, 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 a function of the ambient temperature as shown in Equation 8 [9].

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

Furthermore, the losses due to natural and forced convection must also be taken into account. The forced convection heat transfer coefficient (h_w) can be calculated using a correlation in terms of wind velocity (*v*), as shown in Equation 9 [10], 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 10 [11].

$$h_w = 2.8 + 3.0v \tag{9}$$

$$h_{nat} = 1.78(T_{pm} - T_a)^{1/3} \tag{10}$$

Using this method it is possible to determine an overall convection heat transfer coefficient (h_c) by combining both forced and natural convection heat transfer as shown in Equation 11 [11]. Subsequently by taking the summation of the convection and radiation losses, it is possible to determine the overall top loss heat transfer coefficient (U_{top}) for the unglazed collector.

$$h_c = \sqrt[3]{h_w^3 + h_{nat}^3} \tag{11}$$

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.

In Figure 6, it can be seen that the model is able to provide an accurate prediction of the efficiency of an individual grey unglazed collector panel under steady state test conditions.

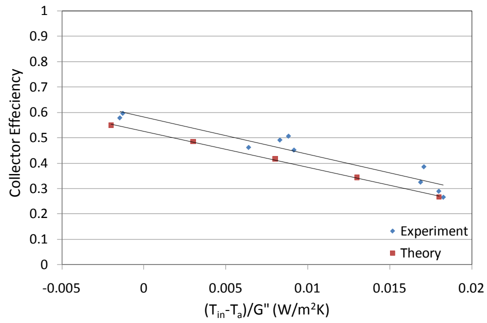

Figure 6: Experimental and theoretical performance of an individual collector, demonstrating validation of model

Flowrate Effects on the Performance of Building Integrated Solar Collectors

One of the underlying assumptions in the development of the model for determining the theoretical performance of the collector is that there is a uniform mass flowrate in each "tube" of the collector, or each collector in an array. However, if we consider an individual collector, with the same design parameters as those installed in the experimental rigs, in which the flowrate is varied, we see that there is a marked difference in the maximum efficiency of the collector (Figure 7).

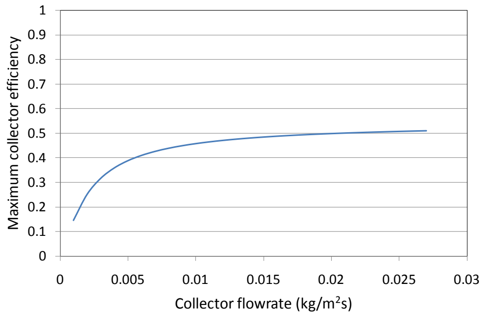

Figure 7: Effect of flowrate on maximum collector efficiency

As such, if we consider the case of two identical collectors operating with the same flowrate, inlet temperature and thermal efficiency, then the mean temperature of both collectors should be identical.

However, during commissioning and initial operation of both systems, it was noticed that there was a significant variation in the temperature across the collector array. This was particularly pronounced in the operation of the large dive pool heating system. In Figures 8-10 it can be seen that there is an increase in the temperature of the tubes in the centre of each row. Furthermore, as the height of the row increases (row 1 being the lowest), there is also an change in the temperature not only across the row, but also relative to the preceding rows.

The implication of this is that the flow is not being uniformly distributed throughout the system. In turn this implies that although some sections of the array are performing with the collector design efficiency there are significant areas of the array that are not performing as designed.

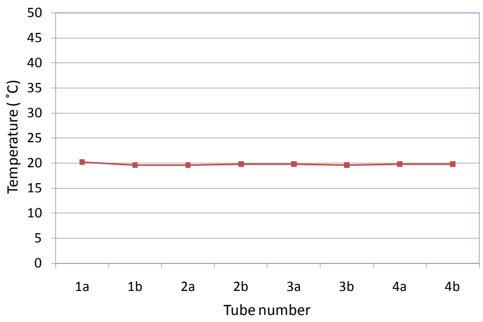

Figure 8: Temperature profile for tubes in row 1 of the pool array

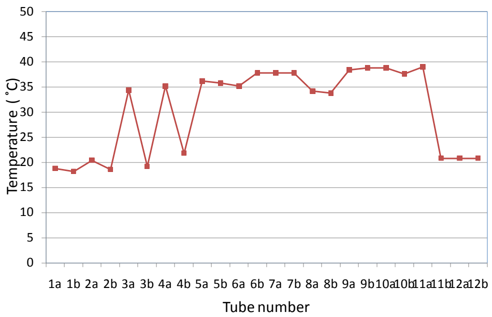

Figure 9: Temperature profile for tubes in row 3 of the pool array

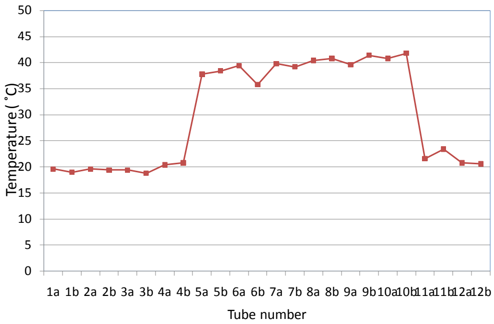

Figure 10: Temperature profile for tubes in row 5 of the pool array

Similarly, it was noted that on the smaller $30m^2$ system that there were large areas which had little or no flow leading to hot spots and the effect of this was low overall system efficiency.

In order to help overcome the flow distribution problems, the pipe layout was altered and the number of panels in parallel was reduced from eight to four as shown in Figure 11. This solution was proposed by Dunkle and Davey [12], who found that it resulted in a more uniform temperature distribution in their large solar collector array. It was found that this resolved the problem somewhat but not completely; this may be due to flow also not being distributed equally to the individual rows as suggested by Figures 8-10. Finally, it has been suggested that there may be further opportunities to minimise the non-uniformities by increasing the ratio of the manifold diameter to that of the riser tubes [5] and this is an area of ongoing development.

Conclusions and Discussion

The trend towards the integration of solar collectors into buildings presents a number of challenges particularly when there must be a compromise not only between engineering objectives but also the architectural. In this study it was shown the assumption of uniform flow distribution when developing large building integrated solar collectors may not always be achieved in practice. This in turn can lead to reduced efficiency as observed in this study. To overcome this it was found that reducing the number of parallel tubes can help achieve more uniform flow. However, great care must be taken when mixing non equal sized rows, as this can also lead to non-uniform flow.

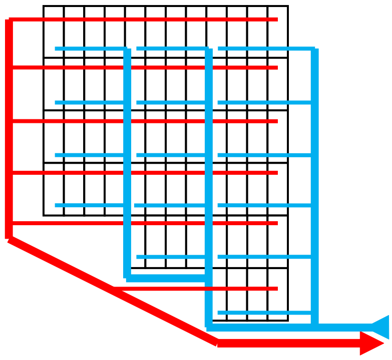

Figure 11: Modified piping layout of half of the pool solar collector array

References

[1] Huddleston, D.H., Alarcon, V.J. & Chen, W., Water distribution network analysis using Excel, *J. Hydr. Engrg.*, **130 (10)**, 2005, 1033-1035

[2] Majumdar, A.K., Mathematical modelling of flows in dividing and combining flow manifold, *App. Math. Modelling*, **4 (6)**, 1980, 424-432

[3] Riggs, J.B., Development of an algebraic design equation for dividing, combining, parallel, and reverse flow manifolds, *Ind. Eng. Chem. Res.*, **26 (1)**, 1987, 129–133

[4] Jones, G. F. & Lior, N., Flow distribution in manifolded solar collectors with negligible buoyancy effects, *Solar Energy*, **52 (3)**, 1994, 289-300

[5] Chiou, J.P., The effect of nonuniform fluid flow distribution on the thermal performance of solar collector, *Solar Energy*, **29 (6)**, 1982, 487-502

[6] Weitbrecht, V., Lehmann, D. & Richter, A., Flow distribution in solar collectors with laminar flow conditions, *Solar Energy*, **73 (6)**, 2002, 433-441

[7] Weiss,W.W., *Solar heating systems for houses: a design handbook for solar combisystems*, 2003, James & James, London

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

[9] Fuentes, M.K., 1987, “A simplified thermal model for flat-plate photovoltaic arrays”, Sandia National Laboratories Report, SAND85-0330-UC-63, Albuquerque

[10] Watmuff, J.H., Charters, W.W.S., and Proctor, D., Solar and wind induced external coefficients for solar collectors, *Comples* **2**, 1977, 56

[11] Eicker, U., *Solar technologies for buildings*, John Wiley and Sons, Chichester, 2003

[12] Dunkle, R.V. & Davey, E.T., Flow distribution in solar absorber banks, *1970 ISES Conference*, Melbourne