ICE Energy

Development of a Cassette-Panel Transpired Solar Collector

Richard Hall
MEng, AIEMA
SBEC Research Associate
Welsh School of Architecture
Cardiff University, UK

Christopher Kendrick
MSc
Senior Lecturer
Oxford Institute for Sustainable Development
Oxford Brookes University, UK

R. Mark Lawson
Ph.D, BSc. (Eng), M.ICE, M.Strct, MASCE, CEng ACGI
SCI Professor of Construction Systems
Division of Civil, Chemical and Environmental Engineering
University of Surrey, UK

Date of last revision: 5th March 2013

Submitting Author: Richard Hall
Hallr8@Cardiff.ac.uk
+44 (0) 7903866548

Number of words:	4,073
Number of Tables:	1
Number of Figures:	13

ICE Energy Keywords: Energy – Heat, Energy in buildings – HVAC, Renewable Energy – Solar power – Thermal

ICE Journal Keywords: Renewable Energy, Sustainability

Nomenclature

Symbol	Description	Units
$\boldsymbol{\alpha}$	Absorptivity	-
$\boldsymbol{\rho}$	Density	kg/m^3
$\dot{\boldsymbol{Q}}_{to-from}$	Energy	W
e_{HX}	Heat Exchange Effectiveness	-
Ψ	Heat Exchange Effectiveness Coefficient	-
H	Height	m
υ	Kinematic Viscosity	m^2/s
$\dot{\boldsymbol{m}}$	Mass Flow Rate	kg/s
Pr	Prandtl Number	-
C_p	Specific Heat of Air	J/kg.K
$\boldsymbol{\sigma_{SB}}$	Stephan-Boltzmann Constant	W/m^2.K^4
A	Surface Area	m^2
T	Temperature	K
G_T	Total Solar Radiation	W/m^2
$\boldsymbol{V}$	Velocity	m/s
F	View Factor	-
$\boldsymbol{U}_\infty$	Wind Speed	m/s

Subscripts	Description
abs	Absorber
conv	Convection
rad	Radiation
SFV	Suction Face Velocity

Abstract

Transpired Solar Collectors (TSC) are an elegantly simple façade-integrated solar air heating technology that is widely used to pre-heat the ventilation air supply of industrial buildings. TSCs have historically been manufactured from long profiled pre-finished steel cladding sheets that whilst suitable for industrial buildings, are not always architecturally suitable for office and multi-storey residential buildings. To enable architects to aesthetically integrate solar ventilation air pre-heating into offices and multi-storey residential buildings, a novel flat Cassette-Panel TSC (CP-TSC) solar air heating system has been developed and trialled in-situ. Two prototype CP-TSC systems were installed onto an unoccupied 1960s multi-storey residential building at Oxford Brookes University and operated for 95 days during the winter of 2010/2011. The results show that under typical operating conditions, the CP-TSCs heated the ventilation air stream by 10 to 15 °C on clear sky winter days and that this air temperature rise can be predicted by a relatively simple energy balance model. Overall, the undertaking of the Oxford Brookes CP-TSC Field Trial has proven that it is possible to integrate an effective and aesthetically pleasing solar air heater into the façade of office and multi-storey residential buildings.

1.0 Introduction

The UK Government is committed to reducing Greenhouse Gas (GHG) emissions by 80 % of 1990 levels by 2050 (OPSI, 2008; RCEP, 2000). Buildings account for around 36 % of the UK's GHG emissions and the Committee on Climate Change (CCC), the independent body set-up to advise the UK Government on meeting their emissions reduction target, "expect the building sector to be zero carbon" by 2050 (CCC 2010, p.237). One way of reducing the operational GHG emissions of a building is by pre-heating the building's ventilation air supply using solar radiation.

Transpired Solar Collectors (TSCs) are a well-known, highly efficient, form of solar air heater (Rhee & Edwards,1983; Christensen et al., 1990; Kutscher, 1996) and are typically used in the pre-heating of a building's ventilation air supply. TSCs heat the ventilation air supply by drawing the fresh outside air through small perforations in a solar heated metal sheet installed on the south-facing elevation of a building (Hall et al., 2011). By pre-heating the building's ventilation air supply, the load on the building's main heating system can be significantly reduced, resulting in lower heating bills and lower operation GHG emissions (Pearson & Anderson, 2007; Battle McCarthy, 2007).

TSCs have historically been used on large industrial buildings and the TSC collector (the part which collects and transfers the solar energy to the ventilation air supply) is generally manufactured from long profiled pre-finished steel cladding sheets. For industrial buildings, the profiled TSC collector has been shown to be one of the most aesthetic types of solar thermal system for this type of building (Probst & Roecker, 2007). Whilst the profiled TSC collector can be coherently integrated into a non-industrial building, such as shown in Figure 1, where the position and profile of the collector is coherent with main wooden façade, it may not always be possible to achieve this level of architectural integration for office and high-rise residential buildings with the profiled TSC collector.

Figure 1 Envelope-mounted profiled TSC installed at the BRE Innovation Park, Watford

To enable architects to achieve a high level of aesthetic integration when a profiled TSC collector is not suitable, a novel flat TSC collector has been developed. This TSC combines cassette cladding panels often found on prestige office and high rise residential building with TSC solar air heating technology. To test the performance of the new Cassette-Panel Transpired Solar Collector (CP-TSC), two prototypes were manufactured and installed on the south-facing elevation of an unoccupied residential tower block on the Oxford Brookes University campus and trialled in-situ for 95 days during the winter of 2010/2011.

2.0 Cassette-Panel Transpired Solar Collector Concept

The CP-TSC pre-heats the ventilation air supply by actively (using a fan) drawing relatively cold outside air through small holes in an array of perforated solar heated cassette-panels (see Figure 2). As the air is drawn through the solar heated cassette-panels, it is heated by convection, travels up the plenum and through the outlet opening. To ensure exterior air only enters the plenum through the holes in the solar heated metal sheets, the edges around the plenum are sealed. The solar heated air can then be either directly fed into the building, or further heated to achieve the desired temperature using a more conventional heating source, such as a gas burner. When there is no requirement for pre-heating of the ventilation air supply, the CP-TSC will be bypassed so that the CP-TSC system does not result in the over-heating of the building.

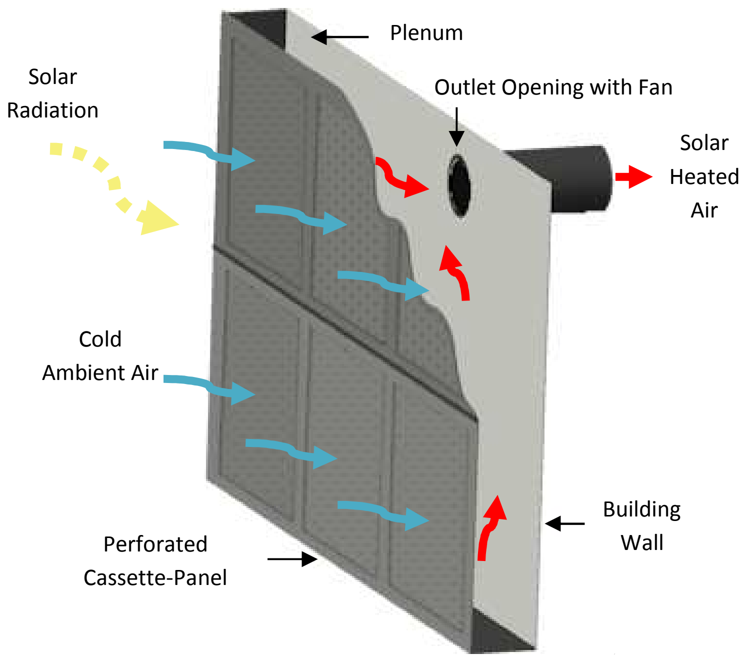

Figure 2 Conceptual illustration of a CP-TSC solar air heating system

3.0 Oxford Brookes Cassette-Panel Transpired Solar Collector Field Trial

To assess the practical feasibility of the CP-TSC concept and to develop a thermal model capable of predicting the long term performance of the system, two prototype CP-TSCs were trailed in-situ on an unoccupied 1960s multi-storey residential building at Oxford Brookes University campus as part of the EU ‘Renovation of Building Using Steel Technologies’ (ROBUST) project. Figure 3 shows the original façade and Figure 4 shows the renovated façade with the CP-TSCs situated between the windows.

The building was located at latitude: 51.75 °, longitude: -1.13 °and the orientation of south-facing elevation was +10 ° West. The original façade of the building was made up of precast concrete panels with 75 mm external leaf textured aggregate concrete facia, 25 mm Expanded Polystyrene Insulation (EPS) and 150 mm solid concrete internal wall. The over-cladding system, including the perforated cassettes, was manufactured and installed by CA Refurbishment Projects. Four perforated panels were installed between the windows, and to create a coherent over-cladding system, unperforated ‘dummy’ cassettes were installed around the perforated panels.

Each perforated panel was 2730 mm wide and 870 mm high, and were manufactured out of 1.2 mm thick colour coated steel in Merlin Grey. For rigidity, each cassette has an edge return of 30 mm and two stiffening ribs (top hat sections) bonded to the rear face at 1 m spacing. Within each perforated panel, there were three perforated sections spanning the stiffening ribs, totalling 2.13 m^2.

All of the cassettes were supported by cold-formed steel rails (200 mm wide x 2 mm thick ‘top hat’ sections) placed along the vertical edges of the panels. The rails were connected through the inner leaf of the precast concrete wall by 120 mm long chemical anchors using 8 mm diameter stainless steel rods. The distance between the outer face of the over-clad panels and the external façade of the original building was 140 mm. Flashings and closure pieces were installed at the periphery of the over-clad area, around the windows and on the corners. The existing windows were not replaced.

Figure 3 Building façade before the renovation of the lower two storeys

Figure 4 Building façade after the renovation of the lower two storeys (the perforated cassette-panels are the four panels directly between the windows, all other panels are not perforated and installed to create a aesthetically coherent over-cladding system)

4.0 Installation Types and Monitoring

To simulate a range of installation conditions, two CP-TSC systems were trialled. On the lower storey (Floor 1), 80 mm of closed-cell polyurethane insulation board was attached to the existing façade with the aim of simulating an installation onto a modern building with a high performance building fabric. On the upper storey (Floor 2), no additional insulation was installed with the aim of simulating an installation onto an existing building where the thermal performance of the building fabric is fairly low.

For each of the cassette-panel systems, a 150 mm diameter outlet opening was drilled through the existing concrete façade, allowing the solar heated air to be drawn into the building. At the end of the duct was a 150 mm diameter in-line centrifugal fan, which was controlled by a voltage control dial. The fans could be modulated between 0.06 m^3/s and 0.127 m^3/s, which is equivalent to an air flow velocity of around 0.015 m/s and 0.030 m/s through the perforated surface area.

Figures 5 and 6 show the location and labels of the monitoring sensors installed within the complete over-cladding system[1]. The façade sensor data was logged by a computer located in the former bedrooms. The environmental conditions were monitored on site by the weather station located on the podium, monitoring the local air temperature, relative humidity, rainfall, wind speed, wind direction and solar radiation levels on the horizontal. Long-wave radiation data from the University of Reading[2] was used to calculate the sky temperature (Harrison, 2011). Since the surface of the perforated cassettes were vertical, a custom FORTRAN-Excel solar radiation separation-transposition function was developed based on the methodology described in Muneer (2004) and verified against TRNSYS (Solar Energy Laboratory, 2007; Hall, 2013).

---

[1] this paper only investigates the performance of the CP-TSC element of the over-cladding system, see http://steel-renovation.org/ for further information on performance of the complete over-cladding system

[2] these observations were obtained by the automatic measurement system of the Department of Meteorology at University of Reading which is at 51.44 ° Latitude, 0.94 ° Longitude and 66 m above sea level

Figure 5 Location of sensors and insulation

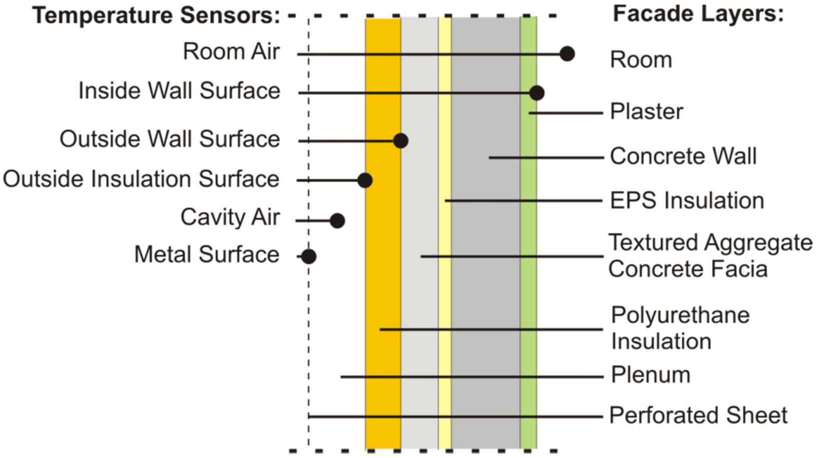

Figure 6 Location of sensors within the façade construction

5.0 Measured Performance

The two CP-TSC systems were run and monitored continuously over 95 days to assess their thermal performance in both the flow (active state – 88 days) and no flow (bypass state – 7 days) conditions during the winter of 2010/2011. The bypass state investigation was undertaken to assess the metal surface temperature, which is important in controlling the operation of a TSC.

5.1 Active State

Figure 7 plots the air temperature rise[3] against solar radiation intensity for the two systems when they were operating at a Suction-Face-Velocity (SFV)[4] of 0.026 m/s and 0.025 m/s for Floor 1 and Floor 2 respectively. The graph shows that for a typical clear winter's day, the CP-TSCs were able to increase the temperature of the ventilation air stream by around 10 to 15 °C.

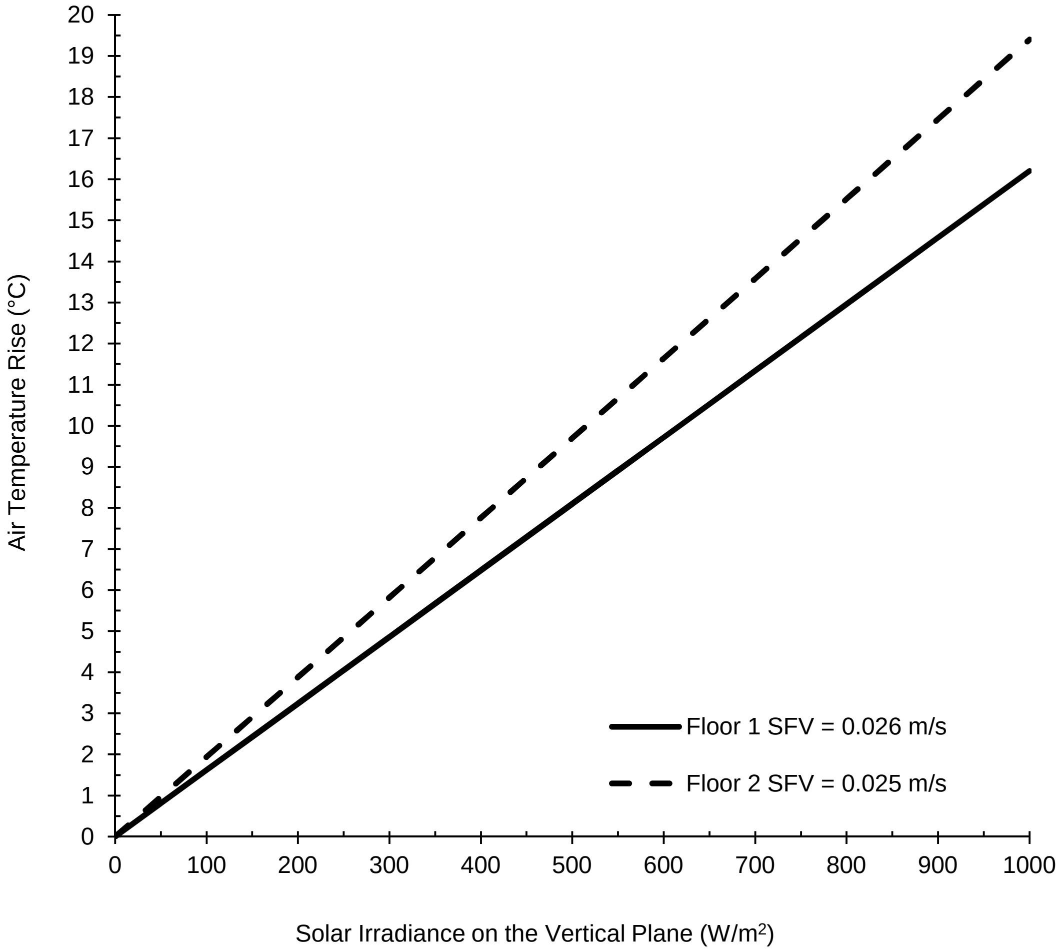

Figure 7 Floor 1 and Floor 2 CP-TSC air temperature rise for a typical flow rate

---

[3] Air temperature rise is defined here as the difference between the outside air temperature and the outlet air temperature

[4] SFV is the total system flow rate divided by the surface area of the perforated section of the cassette-panel, 0.025 m/s is a typical SFV for a TSC

Figure 7 also shows that the Floor 2 system (uninsulated) was able to generate a slightly higher air temperature rise than the Floor 1 system for a given solar radiation intensity. This was caused by a slight flow non-uniformity through the perforations in the Floor 1 system which was likely to be a result of the lower than typical cavity depth (60 mm compared with at least 100 mm for a typical TSC) (Dymond & Kutscher, 1997; Hall, 2013).

The impact of the thermal storage capacity of the concrete wall on the night-time output air temperature of Floor 2 can be seen in Figure 8, which shows a surface temperature cross section during five instances on the 12th March 2011. On Floor 1, with the layer of insulation, the concrete wall temperature stayed at around 10 °C ± 1°C during the day and night. On Floor 2 however, during the day, the concrete wall heated up by around 5 °C and at night, this heat was then transferred back to the air. Depending upon the application, this small heat capacitance effect could have a neutral, positive or negative impact on the performance of the CP-TSC.

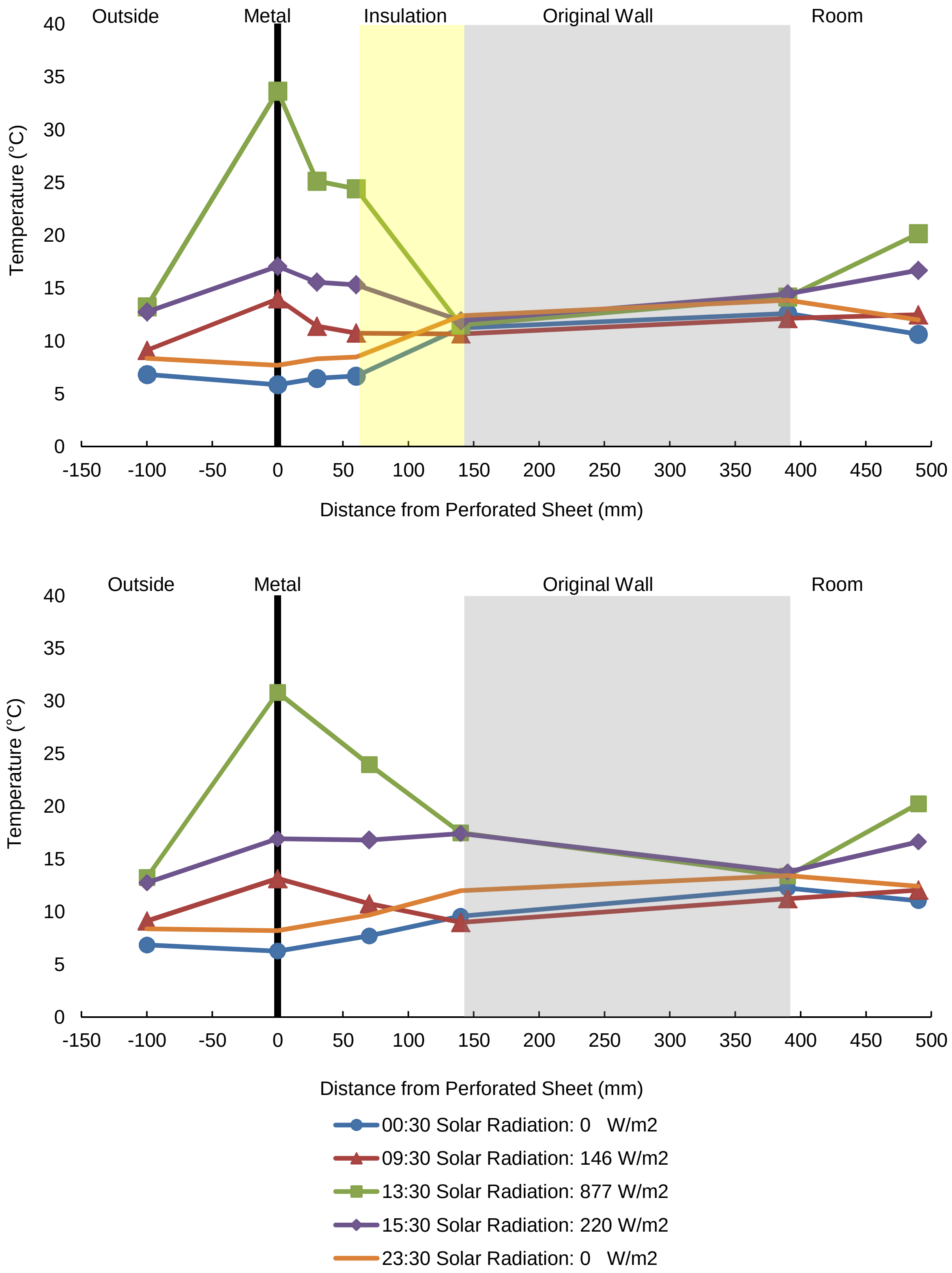

Figure 8 Temperature profiles through the wall on the 12th March 2011 for Floor 1 (Above) and Floor 2 (Below)

5.2 Bypass State

The systems were monitored with no air flow for a week between the 16th and 22nd February 2011. Figure 9 shows the metal surface temperature of the Floor 1 CP-TSC panels over the first three days of this period, when the solar radiation peaked around 400 W/m^2 to 600 W/m^2. The Figure shows that at night when there were no clouds, shown as a lower than ambient effective sky temperature, the metal surface radiated heat to the sky, resulting in a lower than ambient metal surface temperature. Although the reduction in temperature was only around 2 or 3 °C, this could create the potential for active night cooling of the ventilation air stream.

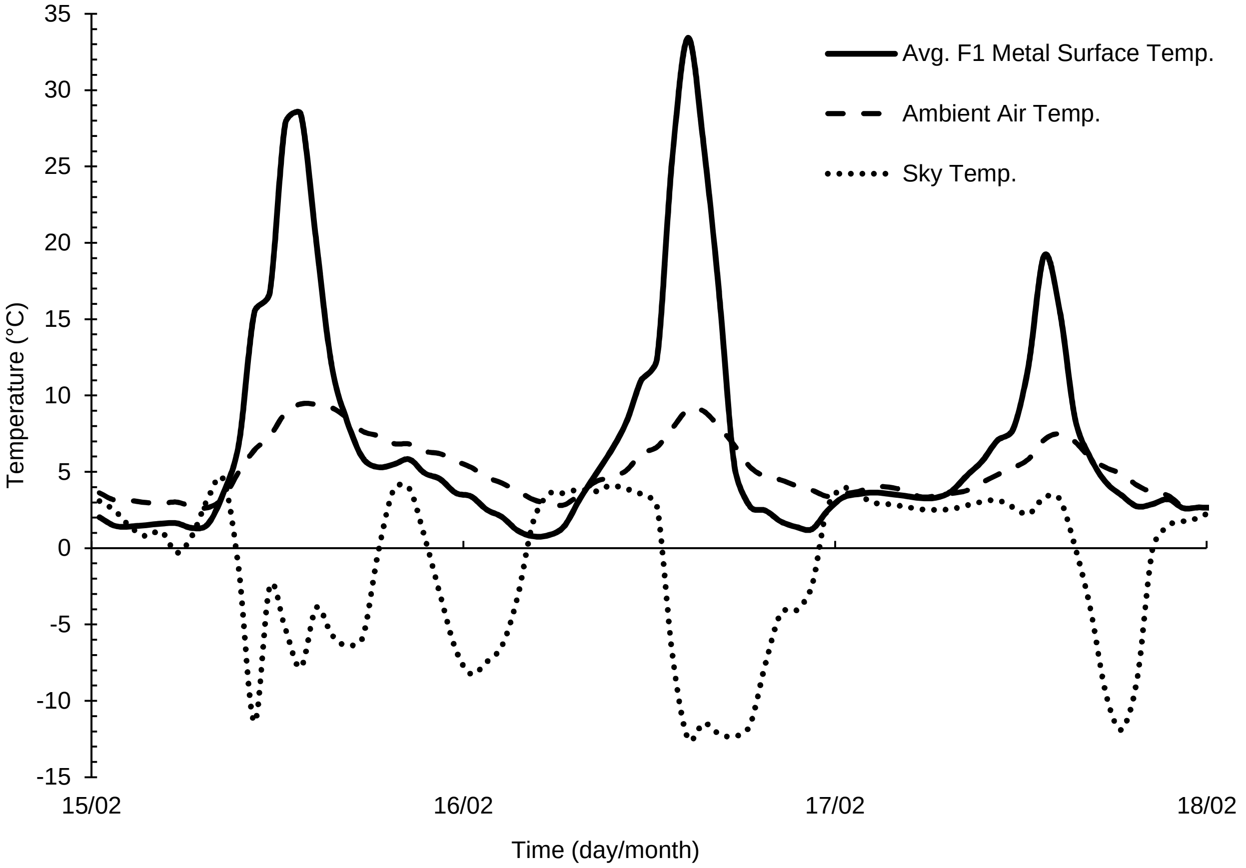

Figure 9 Metal surface temperatures for the Floor 1 CP-TSC when there is no flow

6.0 Modelling the Cassette-Panel Transpired Solar Collector

In order to model the performance of the CP-TSC in different locations or integrated with different building types, a CP-TSC thermal model which can be integrated into a whole building energy model is required. To achieve this, a new relatively simple, CP-TSC TRNSYS[5] component was developed. Figure 10 shows the inputs, parameters and outputs of the new CP-TSC TRNSYS component.

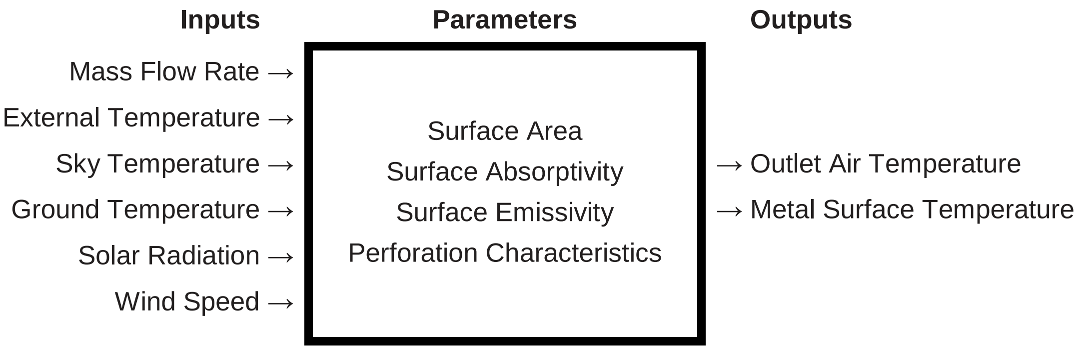

Figure 10 Input, parameters and outputs for the CP-TSC TRNSYS component

The CP-TSC component is based on the standard TSC steady-state energy balance approach, which is generally considered a suitable method for predicting the performance of solar air heaters (Kutscher, Christensen, & Barker , 1003; Duffie & Beckman 2006, pp.288-298). The model assumes that the air flow through the perforated sheet is uniform, there are no leakages, wind travels across the surface of the sheet, and that the back of the sheet is adiabatic (meaning there is no heat transfer occurring on this surface).

Figure 11 illustrates the is energy balance, where $\dot{Q}_{rad,sun-abs}$ is the energy in the solar radiation being absorbed by the sheet, $\dot{Q}_{rad,abs-ground}$ and $\dot{Q}_{rad,abs-sky}$ are the radiation losses to the environment, $\dot{Q}_{conv,abs-wind}$ is the wind heat loss and $\dot{Q}_{conv,abs-outlet}$ is the energy transferred to the air stream. A heat exchange effectiveness (ε_{HX}) modifier constant (Ψ) as suggested by Kozubal et al (2008).

The 95 days of monitoring data was fed into the TRNSYS component, optimised for the HEE modifier and the Root Mean Square Difference (RMSD) between the actual and modelled data was calculated. The results are shown in Table 1 and an illustrative selection of the output is shown in Figure 12. The results show that the CP-TSC TRNSYS component is able to predict the daytime outlet air temperature (Active Outlet) with a high degree of accuracy. At night however, the component generally predicts a lower outlet air temperature than was measured, most likely due to the dominance of non-solar heat gains and losses, which are not fully taken into account by the model. The model is good at predicting the metal surface temperature when there is no flow through the perforations (Bypass Metal), and is

---

[5] TRNSYS is a commercial simulation software program used to design complex thermal processes by connecting together simpler sub-system components models, and includes a wide range of components that can model the thermal performance of different parts of energy systems (TESS, 2011).

slightly better at predicting the performance of Floor 2, due to the inability of the model to account for non-uniformity of the airflow in Floor 1 CP-TSC.

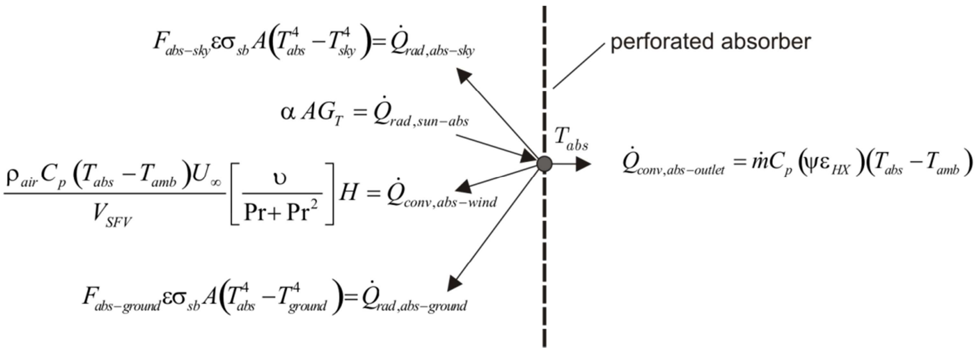

Figure 11 Energy balance of the perforated absorber, assuming the back is adiabatic

Table 1 – RMSD between actual and TRNSYS CP-TSC component prediction

	Floor 1	Floor 2
HEE Modifier	0.81	1.05
Active Outlet RMSD	2.22	3.00
Bypass Metal RMSD	1.25	1.64

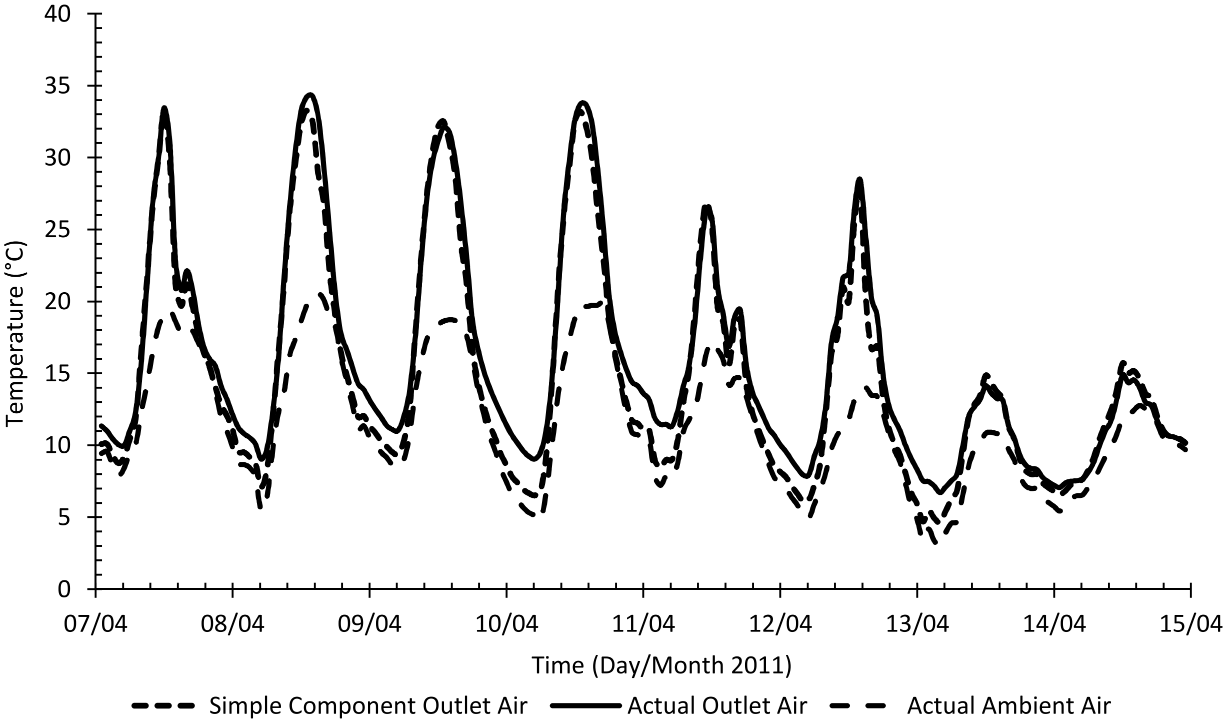

Figure 12 Comparison between the Floor 1 actual outlet air temperature and the predicted outlet air temperature using the TRNSYS CP-TSC component

7.0 Key Findings, Conclusions and Future Research

The Oxford Brookes Cassette Panel Transpired Solar Collector Field Trial has demonstrated that it is technically possible to manufacture, install and predict the performance of a CP-TSC. The key findings from the trial were that:

- CP-TSCs can increase the temperature of the ventilation air stream by 10 to 15 °C on typical clear sky winter days, and;
- a relatively simple steady-state energy balance is capable of accurately predicting the day-time CP-TSCs air temperature rise.

A new TRNSYS CP-TSC component based on this validated energy balance has been developed and can be used to assess the long-term performance of the solar air heating technology in various building types and locations.

CP-TSCs are a new form of TSC and can be used to aesthetically integrate solar air heating into offices and high rise residential buildings. Given that CP-TSCs are manufactured out of colorcoated steel, a wide range of colours are available and the dimensions of the cassettes can be designed to suit the aesthetic of the building. Also, as with profiled TSCs, the new CP-TSCs can be integrated with new and existing buildings.

Using the lessons learned from the Oxford Brookes CP-TSC Field Trial, the second generation CP-TSCs have been integrated with the Sustainable Building Envelopes Centre (SBEC) in North Wales. These CP-TSCs have been architecturally designed and use a special high-absorptivity coating. An investigation into the in-use performance of the CP-TSCs at SBEC is currently being undertaken.

Figure 13 Second generation lime green CP-TSC panels installed on the façade of the Sustainable Building Envelopes Centre in Shotton

Acknowledgments

The authors are grateful to the Engineering and Physical Sciences Research Council (EPSRC) for its support of the University of Surrey/Brunel University engineering doctorate programme in environmental technology, of which this study is part, and the Steel Construction Institute for continued support of this research. The installation and monitoring of the CP-TSC systems was part of the EU Research Fund for Coal and Steel Renovation of Buildings Using Steel Technologies (ROBUST) project. Thanks also go to TATA Steel and CA Group Ltd, for the manufacture and installation of the panels. We are also very grateful to Oxford Brookes University for the use of the building.

References

BARRETT, N. 2007. Steel Increases Record Market Share. New Steel Construction, April 2007.

CCC 2010. The Fourth Carbon Budget - Reducing emissions through the 2020s - 7 December 2010 Online: http://www.theccc.org.uk: Committee on Climate Change.

DEUTSCHE GESELLSCHAFT FÜR SONNENENERGIE 2005. Planning and installing solar thermal systems: a guide for installers, Berlin, James & James (Science Publishers) Ltd.

DUFFIE, J. A. & BECKMAN, W. A. 2006. Solar Engineering of Thermal Processes, New Jersey, John Wiley & Sons.

DYMOND, C. & KUTSCHER, C. 1997. Development of a flow distribution and design model for transpired solar collectors. Solar Energy, 60, 291-300.

ENERGYPLUS 2009. EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations. Online: http://apps1.eere.energy.gov/buildings/energyplus/documentation.cfm: US Department of Energy.

FRANK, E., BUDIG, C. & VAJEN, K. Experimental and Theoretical Investigation of Unglazed Transpired Air Collectors in a Multicomponent Solar Thermal System. Eurosun 2006, 29th June 2006 Glasgow.

GRIFFITH, B. 2006. A Model for Naturally ventilated Cavities on the Exteriors of Opaque Building Thermal Envelopes. Simbuild 2006 Conference. Cambridge, Massachusetts: NREL.

HALL, R., WANG, S. X., OGDEN, R. & ELGHALI, L. 2011. Transpired Solar Collectors for ventilation air heating. Proceedings of the Institution of Civil Engineers: Energy, 164.

HALL, R 2013 Investigation and Development of Transpired Solar Collectors, Engineering Doctorate in Environmental Technology, The Centre for Environmental Strategy, University of Surrey, August 2012

HARRISON, R. G. 2011. *RE: METFiDAS Data Set - Jan 2010 to July 2011.*

HOLLICK, J. 2000. Perforated unglazed collectors. In: MORCK, O. & HASTINGS, R. (eds.) Solar Air Systems: A Design Handbook. London: James & James (Science Publishers) Ltd.

IEA 2011. International Energy Outlook 2011. Online: http://www.eia.gov: U.S. Energy Information Administration.

IPCC 2007. IPCC Fourth Assessment Report. In: PACHAURI, R. K. & REISINGER, A. (eds.). Intergovernmental Panel on Climate Change.

IPCC 2011. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Online: http://www.ipcc.ch/: Intergovernmental Panel on Climate Change.

KOZUBAL, E., DERU, M., SLAYZAK, S., NORTON, P., BARKER, G. & MCCLENDON, J. 2008. Evaluating the Performance and Economics of Transpired Solar Collectors for Commercial Applications. 2008 ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, California.

KUTSCHER, C. F., CHRISTENSEN, C. B. & BARKER, G. M. 1993. Unglazed Transpired Solar Collectors: Heat Loss Theory. Journal of Solar Energy Engineering, 115, 182-188.

LAWSON, R. M., PEDRESCHI, R., FALKENFLETH, I. & POP-OLA, S. O. 1998. Over-cladding of Existing Buildings using Light Steel (SCI Publication P247). Ascot: The Steel Construction Institute.

LEON, M. A. & KUMAR, S. 2007. Mathematical modelling and thermal performance analysis of unglazed transpired solar collectors. Solar Energy, 81, 62-75.

MUNARI PROBST, M. & ROECKER, C. 2007. Towards an improved architectural quality of building integrated solar thermal systems (BIST). Solar Energy, 81, 1104-1116.

MUNEER, T. 2004. Solar Radiation and Daylight Models, London, Elsevier Butterworth-Heinemann.

OPSI 2008. Climate Change Act 2008 (c.27). Online: www.opsi.gov.uk: Office of Public Sector Information.

RCEP 2000. 22nd report: Energy - The Changing Climate (2000). Online: www.rcep.org.uk: The Royal Commission on Environmental Pollution.

STAMPS-III, A. E. 2000. Psychology and the Aesthetics of the Built Environment, London, Kluwer Academic Publishers.

SUMMERS, D. N. 1995. Thermal Simulation and Economic Assessment of Unglazed Transpired Collector Systems. Master of Science, University of Wisconsin-Madison.

TESS. 2011. TRNSYS - The Transient Energy System Simulation Tool [Online]. Online: www.trnsys.com.

PEARSON, C. & ANDERSON, N. (2007) SolarWall monitoring CA Roll Mill. BSRIA Limited

VAN DECKER, G. W. E., HOLLANDS, K. G. T. & BRUNGER, A. P. 2001. Heat-exchange relations for unglazed transpired solar collectors with circular holes on a square or triangular pitch. Solar Energy, 71, 33-45.

BATTLE MCCARTHY (2007) The SolarWall. Study Carried Out for CA Group [Online] www.cagroupltd.co.uk [Accessed 04 August 2012]

List of Tables and Figures

Tables:

Figures: