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Design Guidance on Transpired Solar Collectors in Renovation

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WP1: Design Guidance on

Transpired Solar Collectors for Heating in Renovation of Residential Buildings

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Symbol	•	**Description**	**Units**
n_i	•	instantaneous thermal efficiency	• -
h_{rad}	•	linearised radiation heat transfer coefficient	W/m^2.K
v	•	suction-face-velocity	m/s
C_P	•	specific heat of air	J/kg.K
ρ_{air}	•	density of air	kg/m^3
ε_{HX}	•	heat exchange effectiveness	-
T_{out}	•	outlet air temperature	K
T_{amb}	•	ambient air temperature	K
m	•	mass flow rate	kg/s
T_{col}	•	perforated absorber temperature	K
A	•	area of the perforated absorber	m^2
G_T	•	tilted solar irradiance	W/m^2

Introduction

In Europe, the operational energy use of buildings is around 40 % of total EU energy consumption. Approximately 50 % of the energy used in buildings due to the provision of heating, ventilation and air conditioning (HVAC) services.

One method of providing 'free' heating is through the use of solar thermal systems, which convert solar radiation into thermal energy. This design guidance describes a solar thermal system known as a Transpired Solar Collector (TSC) which uses a steel perforated absorber as the solar collecting component (Figure 1). TSCs can be used to pre-heat the ventilation air supply to buildings using solar radiation as its energy source.

This design guidance also applies the use of TSCs to the renovation of residential and commercial buildings by over-cladding in which the over-cladding panels are large flat steel cassettes that are perforated to allow air to be drawn through the perforations.

TSCs were invented in the mid-1980s by John Hollick (CEO of Conserval Engineering) and Dr. Rolf Peter (a Scientist from Switzerland) as a method of using solar radiation to pre-heat ventilation air for buildings (Hollick, 1994, Kutscher, 1996). Since the first commercial installation of a TSC on the Ontario (Canada) Ford Motor Company assembly plant in 1990 (Conserval Engineering Inc., 2009a), over 1000 TSCs have been installed in more than 30 countries (Conserval Engineering Inc., 2009b). The first TSC system in the UK was installed in 2006 on the south wall of a single storey industrial building and since then a number of TSCs have been installed and are now operating.

TSCs are constructed by attaching perforated metallic sheets to the envelope of a building. This creates an air gap between the perforated sheet and the building envelope (plenum). Using a fan, the exterior air is drawn into the plenum though thousands of perforations in the surface of the metallic sheet 'absorber'. As the air passes over the outer surface of the perforated sheet, heat is transferred by convection from the sheet to the air. The solar heated air is then drawn out of the plenum though the outlet hole and is ducted inside the building (see Figure 1). When solar heated air is not required, TSCs have a by-pass opening so that the ventilation air stream can circumvent the perforated metallic absorber .To direct the air to flow through the perforations, the plenum is sealed around all its edges.

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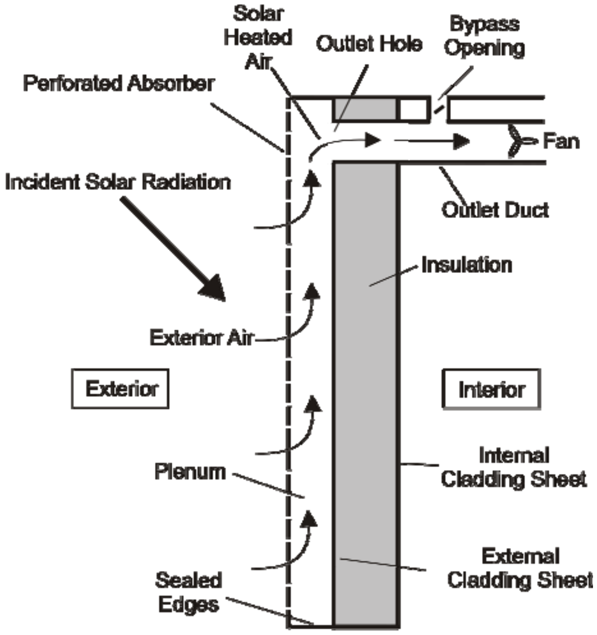

Figure 1 *A schematic view of a transpired solar collector*

TSCs were shown to be competitive in many applications and achieve instantaneous thermal efficiencies of over 70 % with low capital investment costs. These two factors create the potential of simple economic payback of less than two years for large installations (Conserval Engineering Inc., 2009a)).

Basic Energy Balance Equations for TSC

The instantaneous thermal efficiency of the TSC can be described using the standard flat-plate solar collector efficiency equation, which is the energy transferred to the outlet air stream divided by the total solar radiation incident on the perforated absorber surface:

$$n_i = \frac{mC_p\left(T_{out} - T_{amb}\right)}{AG_T} \tag{1}$$

where C_p is the specific heat of ambient air (ambient air is the term used in the solar thermal literature for exterior air (ASHRAE, 2010)), A is the projected area of the perforated absorber, m is the mass flow rate though the perforated absorber, T_{out} is the air leaving the perforated absorber, G_T is the total solar irradiance incident on the absorber surface, and T_{amb} is the exterior air temperature. Equation (1) can be rearranged to find the temperature of the air leaving the TSC (Duffie and Beckman, 2006: p.278-289).

Similar to flat-plate solar collectors, T_{out} can be determined by performing an energy balance of the perforated absorber (Duffie and Beckman, 2006: p.239). This energy balance is illustrated in Figure 2, and shown mathematically in Equation 2.

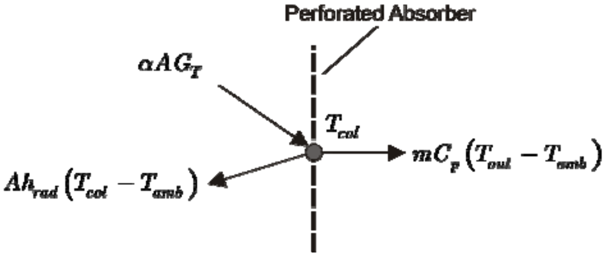

Figure 2 – *Simple energy balance on the perforated absorber*

$$mC_p\left(T_{out} - T_{amb}\right) = aAG_T - Ah_{rad}\left(T_{col} - T_{amb}\right) \tag{2}$$

In Equation (2), α is the absorptance of the perforated absorber (Duffie and Beckman, 2006: p.174-177), T_{col} is the temperature of the perforated absorber and h_{rad} is the linearised radiation heat transfer coefficient (linearising the radiation heat transfer coefficient is an effective means of converting the temperature to the power of 4 as described by the Stefan-Boltzmann law to a linear formula over a narrow temperature range). Equation 2 assumes that the wind heat loss can be neglected (Gawlik and Kutscher, 2002).

Given that the energy transferred to the outlet air stream is a function of the design of the perforated absorber, a heat exchange effectiveness (HEE) ratio (ε_{HX}) is used to describe the relationship between the actual temperature rise against the maximum possible temperature rise:

$$\varepsilon_{HX} = \frac{\left(T_{out} - T_{amb}\right)}{\left(T_{col} - T_{amb}\right)} \tag{3}$$

where HEE is determined experimentally (Brunger et al., 1999: p.109). By rearranging Equation (3) for T_{out}, Equation (2) is transformed into:

$$mC_p e_{HX}\left(T_{col} - T_{amb}\right) = aAG_T - Ah_{rad}\left(T_{col} - T_{amb}\right) \tag{4}$$

The mass flow rate is expressed in terms of the suction-face velocity (v), which is defined as the velocity of air if it were to travel though whole surface area of the absorber:

$$v = \frac{m}{A\rho_{air}} \tag{5}$$

where ρ_{air} is the density of ambient air. The resulting equation for instantaneous thermal efficiency is obtained (Kutscher et al., 1991, Carpenter et al., 1999, Brunger et al., 1999:):

$$n_i = \frac{\alpha}{\left(1 + \dfrac{h_{rad}}{\varepsilon_{HX}\rho_{air}C_P v}\right)} \tag{6}$$

Equation (6) shows that the efficiency of the TSC is proportional to its absorptivity. Broadly speaking, absorptivity is highest in darker colours and as TSCs tend to cover large sections of the building's south wall, careful design is required to balance aesthetics and thermal efficiency. Depending upon the application; colours such as blue, red, green and grey can be considered as having good solar absorptance characteristics (Corus Colors, 2010).

Figure 3 demonstrates that TSCs are able to achieve instantaneous efficiency of over 70 % when operating at suction-face-velocities above 0.02 m/s. Operating a TSC at suction-face-velocities below 0.02 m/s results in lower instantaneous thermal efficiencies but higher air temperature rises.

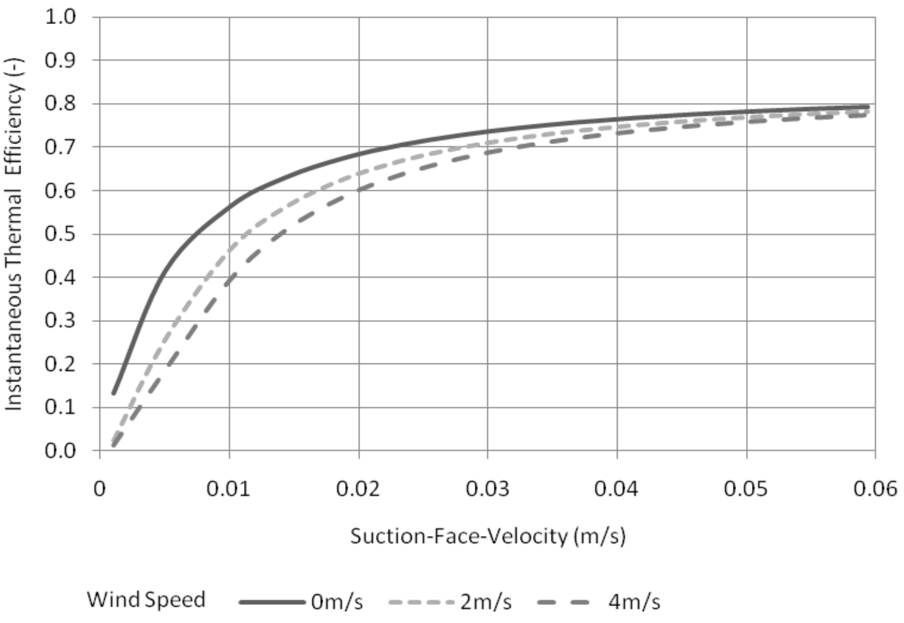

Figure 3 – *Instantaneous thermal efficiency against flow rate for 3 wind velocities (based on the assumptions in RETScreen® V3.1 (Carpenter and Meloche, 2002) and using an absorptivity of 0.9)*

Suction-face-velocities of 0.04 to 0.05 m/s are recommended for field installations to ensure the wind heat loss and ‘outflow’ does not compromise the performance of the TSC (Gawlik and Kutscher, 2002, Kutscher et al., 2003). Outflow is where the heated air in the plenum exits through a section of the TSC absorber, thus losing the heat generated. Gunnerwiek et al. (2002) identified that if the site wind speed reached 5 m/s, outflow would be prevented if the TSC were operating with suction-face-velocities of:

- 0.0125 m/s under typical operating conditions;
- 0.017 m/s for long buildings facing into the wind;
- 0.026 m/s for cubical buildings with the collector facing the wind;
- 0.039 m/s for cubical buildings with the wind incident on the collector at 45 °.

Types of Transpired Solar Collectors

TSCs are of three basic types: 1) a stand-alone; 2) a south-facing wall; and 3) the roof-top mounted TSC. A stand-alone TSC is one where both the perforated absorber and the non-perforated sheets are exposed to the ambient environment and the TSC is supported independently of the building. This type of TSC is used for commercial drying applications (Leon and Kumar, 2007).

Figure 4 shows a south-facing wall type of TSC, also known as a envelope mounted TSC (Kozubal et al., 2008). In this construction type, the perforated metallic absorber is fixed to the building façade of either a new or existing building. As the TSC is incorporated onto the facade, the additional components of the TSC are a metal sheet (the perforated absorber) and the spacer system.

The roof-top mounted TSC (Conserval Engineering Inc., 2010a) sits on the roof of the building and can be used when there is no suitable south-facing wall area. This construction type has the potential to achieve higher energy yields than the south wall type due to the greater freedom to optimise the tilt, orientation and coating of the absorber (Kozubal et al., 2008).

Figure 4 *SolarWall® TSCs installed on the south wall of Beaconsfield service station (UK), where the TSC preheats the ventilation air for the food court*

Photovoltaic / Transpired Solar Collector

TSCs can also be combined with photovoltaic panels to create a hybrid photovoltaic/solar thermal panel (PV/T) (Hollick, 2000a), that is a photovoltaic/transpired solar collector (PV/TSC). The aim of creating a hybrid PV/TSC system is to simultaneously convert solar radiation into economical heat and electricity when available collector area is at a premium (Charalambous et al., 2007), or simply to improve the economic performance of the PV system by cooling the PV cells (Naveed et al., 2006).

There are two broad types of PV/TSC:

1. Bonded type - PV cells/modules are bonded directly to the absorber (Hollick, 1998, Delisle, 2008);

2. Fixed type - PV modules are fixed to the absorber (Naveed et al., 2006, Conserval Engineering Inc., 2010b).

The bonding of PV cells directly to the perforated metallic sheet has been studied by Conserval Engineering Inc. (Hollick, 1998) and Delisle (2008), who verified that the PV/TSC was able to lower the temperature of the PV cells, but the PV cells also resulted in a reduction in the thermal efficiency of the TSC when compared to a standard TSC. The effect was attributed in part to the reduced absorptivity of the PV cells compared to the absorber. When bonding PV cells to the corrugated absorber, an important consideration is the location of the PV cells on the corrugations. When investigating the effect of two potential PV cell configurations; 1) bonding just on the ridge, or 2) across the whole sheet, Delisle (2008) was able to conclude that there would be shading of the PV cells if bonded over the whole surface of the sheet. Thus, careful design of the PV cell configuration would be required. Currently, there is no commercial PV/TSC of the bonded type, thought to be primarily due to the difficulty in manufacturing suitable PV cells that can be economically bonded to the absorber.

The fixed type PV/TSC, where conventional PV modules are fixed to the absorber, has been commercialised with both the south wall form and modular form (Conserval Engineering Inc., 2010b, Hollick and Barnes, 2007). In one study, the forced ventilation of polycrystalline silicone PV modules using a TSC system was able to reduce the operating temperature of the PV modules by 3 to 9 ^{o}C. This cooling of the PV modules resulted in a reduction in simple economic payback time from 23 years (PV without TSC) to 15 years (PV/TSC) (Naveed et al., 2006).

Transpired Solar Collector Design

The most common application of a TSC is to pre-heat the ventilation air, and the heated air is then generally heated further as it passes through the building's HVAC system to reach the desired delivery temperature. In the summer, when there may be no requirement to heat the ventilation air supply, TSC systems have a means of by-passing the absorber (see Figure 1).

A number of alternative system types have been explored with various degrees of success:

- Cooling ventilation air (Hollick, 2007) – at night, the temperature of the TSC absorber will be lower than the ambient air temperature due to radiant heat losses to the sky, thus enabling the TSC absorber to cool ambient air at night (Summers, 1995);

- Pre-heating water for a district heating network – TSC heated air is passed over an air-to-water heat exchanger (Frank et al., 2006);

- Hot water preheating - for example, at the Correctional Facility, Inuvik or the WIWOG Wohnbaugesellschaft, Germany (Conserval Engineering Inc., 2009a);

- Desiccant regeneration for cooling applications (Pesaran and Wipke, 1992);
- Diurnal cycle energy storage – for example, at the St. Lawrence College excess heated air is ducted through a hypocaust energy storage radiant flooring system (Conserval Engineering Inc., 2009a);
- Drying of agricultural products - for example cocoa and tea (Leon and Kumar, 2007).

The predicted integrated environmental and economic performance of TSCs is primarily determined using either RETScreen® V3.1 Solar Air Heating Project Model (Conserval Engineering Inc., 2009b) or in the UK the Simplified Building Energy Model (SBEM) 2010 (Version 4.0.a onwards) for Building Regulations Part L compliance (Hall, 2010).

RETScreen® V3.1 Solar Air Heating Project Model is a Excel spreadsheet application which is designed to model pre-heating of ventilation air. It uses NASA surface meteorology and solar energy weather data to calculate energy savings on a monthly average time-step using an efficiency equation similar to Equation (6), which takes into account the dominant variables of absorptivity, airflow rate and wind speed. The energy saving calculated is the sum of the active absorber solar gain and wall heat recapture (heat loss through the wall is recaptured into the air stream). The RETScreen® V3.1 Solar Air Heating Project Model has been validated against SWift™, which is a free dynamic simulation model for TSCs (Carpenter et al., 1999, Carpenter and Meloche, 2002).

When the National Renewable Energy Laboratory (NREL) in the USA compared the Solar Air Heating Project Model against their NREL *TRNSYS* TSC model, they found that the NREL TRNSYS model predicted 14% less delivered energy than the RETScreen® V3.1 Solar Air Heating Project Model.

The simplified energy yield model uses the efficiency algorithms researched in the IEA Solar Heating and Cooling Programme Task 14 (Brunger et al., 1999) and can model preheating of ventilation air for most building types. TSC energy yield models are however not currently included in many of the building energy dynamic simulation software. Crawley et al. (2008) reviewed the capability of whole building energy modelling software in 2008 and found that TSCs were only included in the EnergyPlus simulation engine (EnergyPlus, 2009) and research tool TRNSYS (Summers, 1995, Langensiepen and Morhenne, 2010).

Internationally, TSCs appear to be able to generate economic payback periods (number of years required to pay back the capital costs) of around 2 to 10 years (Conserval Engineering Inc., 2009a), depending upon the application, and less than 1 year to payback their embodied GHG emissions (IEA, 2000).

The UK-based integrated performance investigations are providing evidence to suggest that the performance of TSCs experienced in USA and Canada over the past 20 years could be replicated in Europe. In 2007, a post-occupancy evaluation (POE) was undertaken to determine the actual first year integrated performance of the TSC installation in County Durham, UK (Pearson and Anderson, 2007). The POE found that the TSCs delivered 21 % of the total heating demand of the building in the first full year of operation (2006-2007).

When DSA Engineering compared a range of renewable energy technologies for use on a building in the UK, they calculated that the TSC option could meet a 10 % renewable energy planning policy requirment at a capital cost significantly less than the alternatives. Finally, in a study of typical and low energy distribution centres, Battle McCarthy (2007) calculated that TSCs can make a “significant contribution” (p.9) to the operational energy demand of these types of buildings.

Application to Over-Cladding Systems

In this research, a novel Transpired Solar Collector (TSC has been developed for the over-cladding of existing concrete or masonry buildings. This is based on a flat steel cassette panel rather than profiled sheeting, and is the first example of TSC in this type of panel. It could potentially reduce the heating costs of a building significantly when combined with external insulation in a more conventional over-cladding application. It uses steel cassette panels manufactured in lengths of typically 2.9 m and widths of 0.9 m.

Part of the south facing façade of a concrete panel building was over-clad on the lower two levels and this was extended onto the east facing facade. This application is illustrated in Figure 5, in its final form. The metallic panels were manufactured from *Prisma* colour-coated steel with up to 2,500 perforations per m^2 and a porosity of 0.35% when expressed over the panel area (including the panel border). Two of the panels between the windows in each floor level were perforated and the other panels were un-perforated.

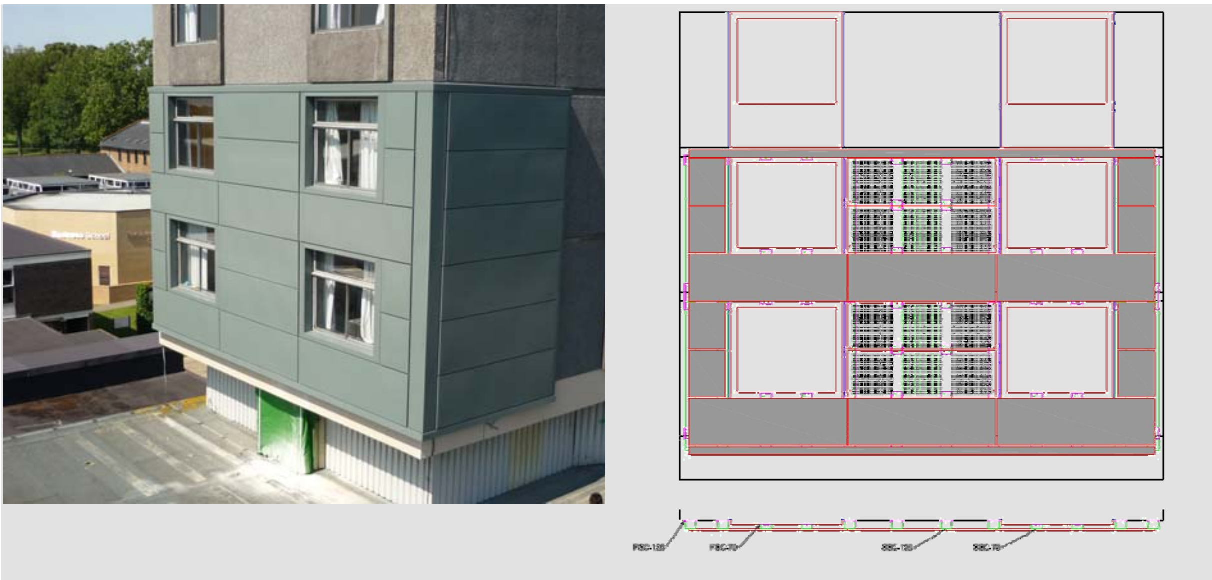

Figure 5 *Application of TSC in over-cladding of a concrete panel building (perforated panels shown on the right)*

Consider the results in Figure 6 obtained in a typical spring or autumn day for a south-facing perforated panel in which the typical heating period was from 11 am until 4 pm. The external steel temperature can reach up to 37°C, although the average during the heating period is 25 to 30 °C. The average in-coming air temperature is approximately 20°C. The reference room temperature is taken as that not influenced by solar gain (ie corridor or north facing room), which is on average 15°C during the heating period. The incoming air temperatures are about 7°C lower than the external temperature of the steel surface. During the heating period, the in-coming air is about 8 °C higher than the room reference air temperature.

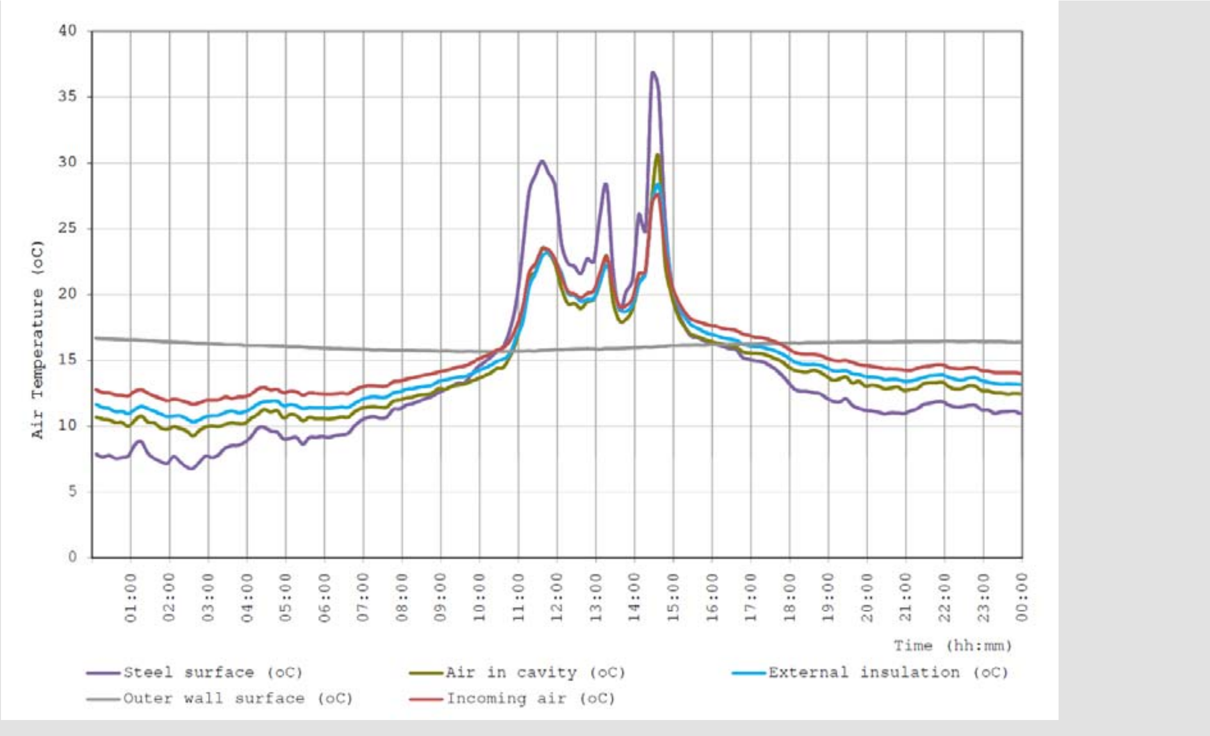

Figure 6 *Typical test results for sunny late autumn day*

Typical measured data are:

Temperature difference between in-coming and the internal air =10°C average	
Heating period (11 am to 4 pm approx.)	5 hours
Air-flow rate through the fan (approximate)	60 litres/sec
Area of perforated panels (per floor)	5.3 m^2

The calculated energy generated per hour was 0.72 kW. Over a 5 hour period per day, this is equivalent to a heating energy of 3.6 kWh. Assume that 150 days per year have this level of solar radiance, this is equivalent to an annual energy input of 540 kWh.

Assume this heating energy is distributed over a building width of 5 m and length of 10 m. The equivalent saving in heating energy, $Q_{\text{nef}} = 540/(5 \times 10) \approx 11$ kWh/m^2 floor area. This is equivalent to about 20% of the heating demand of the over-clad building.

The heating energy provided by is approximately 136 W/m^2, when expressed per unit area of the perforated panel.

The fan energy is rated at 0.1 kW at full flow rate of 120 litres/sec, and so the energy required to operate the fan over 5 years at half this maximum flow rate is about 0.25 kWh per day. This is equivalent to about 7% of the heating energy that is created.

Typical weather conditions over the year may be grouped as shown in Table1 and may be used to predict the total benefit of this form of TSC in terms of reduced annual heating demand for a typical residential building.

Table 1 *Typical weather scenarios used to predict energy savings due to TSC cassette panels*

Condition	Room Reference Temp θ_{room} °C	In-coming Air Temp θ_{cavity} °C	External Temp θ_{ext} °C	TSC Active
Bright cold winter day	15	22	3	Yes
Dull cold winter day	15	5	5	No
Bright spring day	18	27	12	Yes
Dull spring day	18	12	12	No
Warm summer morning	18	30	20	Yes
Warm summer day	22	35	25	No

These typical temperature scenarios may be used to calculate the:

1) Energy generated by *Solarwall* due to solar radiance.
2) Saving in energy loss due to air leakage and conduction through the existing façade.
3) Fan energy when *Solarwall* is in operation.

The night time cooling of the cavity due to radiant effects on the metal surface may be neglected. Similarly, in hot summer conditions, the heated air may be expelled rather than brought into the room.

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