Technical feasibility of a façade integrated solar cooling system for commercial buildings

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Abstract:
To reduce peak demand and electricity consumptions for cooling of office buildings under tropic weather conditions, a façade integrated solar cooling system has been proposed. The system consists of evacuated tube solar collectors (ETSC) installed in the cavity of the double skin façades (DSF) to collect solar energy to be used in an Organic Rankine Cycle (ORC) turbine which drives the compressor of the vapour compression cycle (VCC). The collected solar energy during the weekends is stored in a hot water storage tank for use during the operating hours of the office building. The system is backed up by a gas fired water heater. TRNSYS 16 was used to evaluate the technical performance of the integrated system. The system is able to meet the cooling demand for the operating hours selected. It was found that the annual solar fraction of the system is about 13.25%.

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1. Introduction

Concern for decreasing consumption of traditional energy resources and reducing environmental pollutants, while the demand for electricity has increased dramatically due to population increases and economic growth, people have paid more attention to renewable energy and energy efficiency. The International Institute of Refrigeration (IIR) has reported that electricity consumption for air-conditioning systems of commercial buildings accounts for 15% of total electricity generated in the world. Meanwhile, the demand for air-conditioning systems has been increased with a 17% growth rate annually (Pridasawas 2006). It was observed that lower cooling energy demand has significant benefits for reducing greenhouse gas emissions (Wang, Chen & Ren 2010).

Multifunctional façades have been an important concept in terms of building energy efficiency, particularly in the European Union. Fuschillo (1975) first realised the topic of semi-transparent solar collectors. The major problems of transparent façades are solar collector slope angle and transparency. Bari (2000) stated that the optimal slope of a solar collector varies between -10° to 35° in tropical climate area. The transparent glazing limits the solar collection area. ETSC was selected to be installed in the cavity of the double glazing façade to collect solar energy. ETSC has been proved to have relatively higher thermal efficiency at higher temperature due to lower heat loss coefficient, by having selective coating and vacuum insulation, than unglazed/glazed flat-plate solar collector (Shah & Furbo 2004).

Nowadays, chillers are commonly used in large commercial buildings with a large range of cooling capacity from 10 kW to more than 2 MW. A vapour compression cycle chiller was selected for the study. The power source to drive the VCC is from an ORC, which has been proven to have excellent performance for power generation in small-scale applications (< 5 MW) since the process allows the use of a low-grade heat source (McMahan 2006). Compared to other renewable energy sources, solar energy has the highest capacity and lowest replenishment in order to be an excellent heat source for ORC (Rayegan & Tao 2011). Solar ORCs have been studied since the 1970s based on both theories and experiments. The
reported overall electricity efficiency is 4.2% when ETSCs (71.6% efficiency) were utilized in the system (Wang et al. 2010).

The coupling of ORC and VCC systems to produce cooling using organic working fluids was first proposed by Goswami (1995). However, this concept had not attracted much attention until recently (Wang & Peterson 2011). In the coupled system, the vapour expands in the ORC turbine to produce shaft work to drive the compressor of the VCC instead of using an electrical motor. Therefore, the conversion losses from the electric generator and the electrical motor can be eliminated. The coupled system not only provides advantages in terms of overall efficiency, it also provides flexibility for producing electricity when cooling is not needed.

From a recently published work (Wang, Peterson & Herron 2011), the performance of the ORC-VCC driven by renewable energy has been studied comprehensively both theoretically and experimentally. Meanwhile, there is no systematic analysis to take into account the performance of solar thermal energy collection system and interactions with the double skin façade. The purpose of this study is to analyse the feasibility of this fully coupled system in terms of technical performance.

2. System description

The basic concept of the proposed low-temperature solar cooling system is shown in Figure 1. This integrated system mainly consists of façade integrated ETSCs, a hot water storage tank, pumps, an auxiliary heater, an ORC subsystem and a VCC subsystem. The water is pumped into the tubes of ETSCs to transfer the heat. The heated water is stored in the tank and transfers solar energy to evaporate the working fluids of the ORC to drive the turbine, which produces shaft power, which is used to drive VCC for cooling. The auxiliary heater is used for back up when solar energy collected is not sufficient to meet the temperature required.

![Figure 1: Schematic diagram of the combined ETSC-ORC-VCC system](image-url)
2.1 Integrated evacuated solar collector

A commercially available ETSC was used in the simulation. ETSC consists of two borosilicate glass tubes with selective coating on the outer layer surface. The space between the two tubes is vacuum, which is significant to reduce thermal loss due to negligible conductive and convective heat transfers. A U-tube is placed inside the vacuum and attached to a black copper fin to transfer heat from the selective surface. The dimensions and technical data of an ETSC array are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length (m)</td>
<td>1.68</td>
</tr>
<tr>
<td>Width (m)</td>
<td>0.781</td>
</tr>
<tr>
<td>Absorber material</td>
<td>Copper</td>
</tr>
<tr>
<td>Absorber area (m²)</td>
<td>1.938</td>
</tr>
<tr>
<td>Coating</td>
<td>Selective</td>
</tr>
<tr>
<td>Maximum operation pressure (kPa)</td>
<td>600</td>
</tr>
<tr>
<td>Intercept efficiency</td>
<td>0.498</td>
</tr>
<tr>
<td>Negative of first order efficiency coefficient (WK⁻¹m⁻²)</td>
<td>1.61</td>
</tr>
<tr>
<td>Negative of second order efficiency coefficient (WK⁻¹m⁻²)</td>
<td>0.0027</td>
</tr>
</tbody>
</table>

The integrated façade consists of three glass layers; one is at the front and two at the back of the cavity, where ETSCs are located. The ETSCs are placed 45 mm away from the front glass panel. The back panel is a sealed double-glazing window. The proposed façade system is to maximise the conversion of the incoming solar energy into useful heat as well as minimising the indoor heat gain, without significantly reducing the visible transmittance. To collect maximum solar energy, the ETSCs cover the entire depth of the cavity. The tube layouts of the proposed integrated façade for east and north side of the building are illustrated in Figure 2.

![Figure 2: Layouts of ETSC integrated façades](a) facing east (b) facing north)

2.2 ORC coupled with VCC

To achieve a higher overall efficiency, a two-fluid system is adopted. The ORC and VCC use different working fluids corresponding to their own thermal characteristics. Not like a single-fluid system, a two-fluid system allows each condenser temperature to be optimized to provide individual best performance.
In the ORC, the organic working fluid in the liquid state is compressed by a pump, which allows the fluid to flow through a recuperator. The presence of the recuperator is to utilise the residual heat to preheat the working fluid, which can improve the ORC efficiency significantly (Quoilin 2011). The preheated working fluid is then evaporated in an evaporator/boiler and expanded in a turbine. The low pressure vapour flows out of the expander and to the condenser where it is liquefied by rejecting heat to ambient air. The liquid from the condenser is pumped back and starts a new cycle. The selection of working fluid is an essential step in the ORC design process since the working fluid plays a critical role to achieve high thermal efficiency (Mago et al. 2008). Several researches have investigated the selection and performance of several commonly used organic substance (Bruno et al. 2008; Chen, Goswami & Stefanakos 2010; Saleh et al. 2007). Since the efficiency of ETSCs decreases with increased temperature, 75°C was selected as the evaporating temperature of the ORC in this study. Tchan et al. (2009) have suggested that R134a is the most suitable working fluids for low-grade heat source ORC up to 90°C evaporating temperature. The condensing temperature was assumed to be 35°C. In the ORC, expander or turbine is a key component. A scroll expander was adopted in the ORC, which is one type of displacement expander and has been proven to be good option for small-scale ORC, while having excellent partial-load performance (Lemort et al. 2009; Schuster et al. 2009). In order to directly couple with the ORC, a scroll compressor was applied in VCC to match the ORC’s turbine rotator speed.

3. Detailed simulations

The system performance is evaluated by computer simulations and the annual solar fraction was estimated. The proposed system was modelled by using TRNSYS 16 simulation studio with standard Types to represent the major components of the system. The fraction of total energy required which is covered by solar energy for a specified set of solar collector array area and water tank volume. The outputs not only include the amount of power required for cooling system, but also the annual solar fraction of the system to indicate the technical performance of the façade integrated ETSC coupled with ORC-VCC subsystems.

3.1 Orientations of ETSCs

The case study building is located in Darwin, Australia (12.42S, 130.83E), which is in a tropical climate zone with 28°C yearly average temperature. To find the best locations for the ETSCs on the walls, yearly total radiations on a vertical surface in various orientations were simulated. Typical Meteorological Year (TMY) weather data, which has been proven to give a reliable estimate of the long term average annual performance of a wide range of solar thermal systems (Morrison & Litvak 1999), was used. Figure 3 shows the east orientation has the highest annual total solar radiation (5.36 GJm$^{-2}$). The second highest is north-east orientation followed by north orientation.

3.2 Coupling ETSC with building

The building selected was a typical 50-storey office building with 42 m × 42 m square floor plan and 3 m floor height; the core area is 282.4 m$^2$ for service facilities. The sketch of the floor plan is illustrated in Figure 4.

ETSCs are placed on both east and north side of the building. The building was modelled by using Type 56, in which the properties of building envelope, infiltration rate, ventilation rate, cooling setting temperature, internal gains and schedules are defined meeting the Building Code of Australia requirements. Table 2 lists the characteristics of each layer of the building fabric. In the analysis, one middle level of the building was selected to model. The whole
floor is divided into six zones to represent offices facing different orientations, corridors and services cavity above the ceiling.

Figure 3: Comparison of yearly total radiation incident on a vertical surface

Figure 4: Floor plan of modelled office building

Table 2: Properties of layers of building’s key components

<table>
<thead>
<tr>
<th>Component</th>
<th>Layer</th>
<th>Key property</th>
<th>U-factor Wm⁻²K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall</td>
<td>Plaster boards</td>
<td>Thickness = 0.026 m Density = 950 kgm⁻³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cellulose insulation</td>
<td>Thickness = 0.080 m Density = 43 kgm⁻³</td>
<td>0.437</td>
</tr>
<tr>
<td></td>
<td>Precast concrete</td>
<td>Thickness = 0.100 m Density = 2000 kgm⁻³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminium cladding</td>
<td>Thickness = 0.004 m Density = 2700 kgm⁻³</td>
<td></td>
</tr>
<tr>
<td>Shear wall</td>
<td>Plaster boards</td>
<td>Thickness = 0.013 m Density = 950 kgm⁻³</td>
<td>2.264</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>Thickness = 0.400 m Density = 2400 kgm⁻³</td>
<td></td>
</tr>
<tr>
<td>Partition</td>
<td>Plaster boards</td>
<td>Thickness = 0.013 m Density = 2700 kgm⁻³</td>
<td>3.980</td>
</tr>
<tr>
<td>Floor below</td>
<td>Plywood</td>
<td>Thickness = 0.019 m Density = 540 kgm⁻³</td>
<td>2.501</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>Thickness = 0.150 m Density = 2400 kgm⁻³</td>
<td></td>
</tr>
<tr>
<td>Floor above</td>
<td>Plaster boards</td>
<td>Thickness = 0.130 m Density = 950 kgm⁻³</td>
<td>3.099</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>Thickness = 0.015 m Density = 2400 kgm⁻³</td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>Double glazing</td>
<td>SHGC = 0.598</td>
<td>0.860</td>
</tr>
</tbody>
</table>
The front cover glass, ETSCs and double-glazing back panel are modelled separately. The equivalent normal radiation \( G_{eq} \) transmitted through the front cover is determined by correlation provided by (Bosanac & Nielsen 1997):

\[
G_{eq} = K_{\tau a,b} \times G_b + K_{\tau a,d} \times G_d + K_{\tau a,g} \times G_g \text{ ................. (1)}
\]

Where \( K_{\tau a,b} \), \( K_{\tau a,d} \) and \( K_{\tau a,g} \) are incidence angle modifier for beam, diffuse and ground respectively. \( \theta \) is incidence angle and \( r \) (0.24) is coefficient for fitting the incidence angle modifier derived from transitivity with different incidence angle. \( G_b \), \( G_d \) and \( G_g \) are beam, diffuse and ground reflected radiation.

The ETSCs collect solar energy from the transmitted \( G_{eq} \) and it was modelled by Type 71 in TRNSYS. The 2-D incidence angle modifier (IAM) data provided by the manufacturer was used. The solar radiation received on the double glaze window (inner panel of the façade) depends on the shading caused by adjacent collector tubes. In this study the shading effect of the ETSCs on the double glaze window was taken into consideration.

The distance between the centres of tube is 70 mm and the outer radius of each tube is 30 mm. And the distance to the glass panel is assumed to be 15 mm. When incidence angle is between 0° and 31°, the internal glass panel will be exposed to the beam radiation. The beam radiation reaching to the back panel is proportional to the exposed area. The shading area varies with the incidence angle.

### 3.3 ORC-VCC cycle

The collected solar energy by the ETSCs is stored in a buffer tank (100 m³) and provided for the evaporator to drive the ORC when the cooling is required at the building. To cover the entire cooling load; a gas auxiliary heater is required. In order to reach 75°C boiling temperature in the evaporator of the ORC, the auxiliary heater is set to 85°C. It was assumed that no pressure drops in the evaporator, condense and pipes and the process in the turbine and pumps are isentropic (Mago et al. 2008). When water flows through the evaporator heat exchanger, the water temperature drops from 85°C to 70°C.

The mass flow rate of water flows into the evaporator was determined by:

\[
\dot{m}_w = \dot{Q}_{ev} / (C_{p,w} \times (T_{in} - T_{out})) \text{ ................. (4)}
\]

\[
\dot{Q}_{ev} = \frac{P_t}{\eta_{ORC}} \text{ ................. (5)}
\]

\[
P_t = \frac{L_{cool}}{COP_r} \text{ ................. (6)}
\]
Where $Q_{ev}$ is heat transfer rate at the evaporator (kW), $m_w$ is mass flow rate ($\text{kg s}^{-1}$) for water, $C_{p,w}$ is the specific heat of water (kJkg$^{-1}$K$^{-1}$), $T_{in}$ and $T_{out}$ are water temperatures at the inlet and outlet of the evaporator respectively (K). $L_{cool}$ is cooling load for one storey of the building (kW), $COP_r$ and $\eta_{ORC}$ are the coefficient of performance of the VCC and the efficiency of the ORC. $P_t$ is power generated from the turbine (kW). Pump power is neglected in this analysis since it is much less than the total power required for cooling.

The coefficient of performance (COP) of VCC and efficiency of ORC vary with partial load ratio (PLR). The design full load COP 3.5 for VCC and full load efficiency 12% for ORC were assumed. The relationships between PLR and COP & efficiency were derived from the experiments by Le, Bansal & Tedford (2004) and Obernberger, Thonhofer & Reisenhofer (2002) (Figure 5).

$$\text{PLR} = \frac{\text{Load}}{\text{Available full load capacity}}$$(7)

$$\text{PLF} = \left[ \frac{\text{Partial load efficiency}}{\text{Full load efficiency}} \right]_{\text{ORC}} = \left[ \frac{\text{Partial load COP}}{\text{Full load COP}} \right]_{\text{VCC}}$$$(8)

![Figure 5: Relationship between partial load ratio and partial load fraction](image)

4. Simulation results

The solar thermal subsystem starts operating whenever the solar radiation can heat water in the ETSCs 1°C higher than its inlet temperature. The ORC-VCC combined subsystem is switched on when the indoor temperature goes beyond 24°C between 8am and 6pm during weekdays. Water in the storage tank is pumped to the evaporator when cooling is required and flows back to the tank. The auxiliary heater makes sure that the supply water temperature to the ORC is 85°C.

4.1 System component sizes

In the proposed solar thermal system, the ETSCs fully cover the east and north external walls, except spandrel area. The total collect area is 113.4 m$^2$ for each side.
The total annual energy consumption for cooling is 367 MJ/m². The peak cooling load reaches 86.91 kW for whole floor and only occurs 3 hours for the whole year. An appropriate VCC capacity selection is determined by using the relationship between effect coverage and energy coverage defined by Banks (2008) (Equation 9 & 10).

\[
\text{Effect coverage (\%)} = \frac{\text{Rated output of VCC (kW)}}{\text{Peak cooling load of building (kW)}} \times 100\% \quad (9)
\]

\[
\text{Energy coverage (\%)} = \frac{\text{Total energy supplied by VCC (kWh)}}{\text{Total energy required by building (kWh)}} \times 100\% \quad (10)
\]

The relationship between effect coverage and cooling energy coverage for the building in Darwin was considered. The capacity of VCC can be selected at 85% of the peak load, which is able to cover more than 90% of cooling energy requirement. Table 3 summarized the component sizes and operating conditions.

<table>
<thead>
<tr>
<th>Table 3: Summary of system characteristics and operation conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ETEC</strong></td>
</tr>
<tr>
<td>Total area (m²)</td>
</tr>
<tr>
<td>No. of parallel collector arrays</td>
</tr>
<tr>
<td>Flow rate (L/h)</td>
</tr>
<tr>
<td>Operation temperature (°C)</td>
</tr>
<tr>
<td><strong>ORC</strong></td>
</tr>
<tr>
<td>Capacity (kW)</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Working fluid</td>
</tr>
<tr>
<td>Evaporating temperature (°C)</td>
</tr>
<tr>
<td>Condenser temperature (°C)</td>
</tr>
<tr>
<td><strong>VCC</strong></td>
</tr>
<tr>
<td>Capacity (kW)</td>
</tr>
<tr>
<td>COP</td>
</tr>
</tbody>
</table>

4.2 Energy flows

The ETSCs integrated façade on north and east side received 461 GJ and 605 GJ solar energy respectively in total from 4397 hours day time. However, the ETSCs operated for 2587 hours to provide 221.5.2 GJ useful energy. Apart from thermal losses from the ETSCs, the front cover reflected and absorbed a small proportion of solar radiation as well.

The gained useful energy is stored in the water tank, while tank loss occurring in it. During the cooling period, 1450 GJ energy goes into auxiliary heater to obtain 85°C. To achieve constant temperature heat source for the ORC, gas is required for auxiliary energy (90% efficiency). To drive the VCC, 1501.83 GJ energy is provided to ORC. The energy flows of the system are shown in Figure 6.
It is impractical to design a system operated solely by solar energy. Annual solar fraction used to indicate the contribution of the solar energy. It is determined as a function of total useful energy gain from the ETSCs and total thermal energy required to run the ORC. It was found that the solar fraction is about 13.25% for the modelled office building in Darwin, based on the system characteristics and operation conditions.

5. Conclusions
A fully coupled solar cooling system is proposed in this study to enhance the function of facades for commercial office buildings. This integrated system consists of ETSCs, water storage tank, auxiliary heater, ORC and VCC with low-temperature heat source from solar energy. TRNSYS 16 is employed to evaluate its feasibility in terms of cooling provision for a high-rise office building in Darwin. The annual cooling energy required is 544 GJ. The designed capacity of the system can achieve 92% of the cooling energy. The operating temperature in ETSCs varies between 66°C - 88°C. Solar and gas are the main energy suppliers in this system (pump power is negligible), which attribute 13 % and 87% respectively.

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