Experimental Study of a Modular Unglazed Transpired Collector Façade for Building Refurbishment

Abstract:

The use of renewable energy sources available for buildings to reduce energy consumption and emissions has become extremely important over the last few decades. Unglazed transpired collector (UTC) façades absorb solar radiation to preheat the ventilation air at a low cost and with minimum intervention for existing buildings. In this study, a UTC façade module was built and monitored in the field in winter during the continental cold and dry climate of Cordoba, Spain. With the data obtained, the feasibility of the installation of this façade system was evaluated. The values of efficiency, effectiveness and temperature increase measured during the experiment were analysed statistically, and the influence of solar radiation and ambient temperature on them were studied. The values of efficiency and effectiveness presented widespread cumulative distribution functions with mean values similar to those reported in other controlled experiments found in literature. A case study was carried out to analyse the feasibility of installing a UTC façade to reduce the energy consumption of the ventilation load in a typical apartment. It was found that in 74.6% of the days considered in this study the ventilation heating demand would be covered. Refurbishment of building façades using this UTC modular approach could be considered an alternative to reduce ventilation and heating energy consumption.

Keywords: Unglazed Transpired Collector, Ventilated façade, air preheating, opaque ventilated façade, façade refurbishment

1. Introduction

In recent years, the performance of active building façades has been widely studied, especially those façades in which the use of renewable energy sources reduces the building energy consumption. Unglazed transpired collector (UTC) façades can provide ventilation preheating in the winter and night free cooling in the summer (Peci et al. 2019; Kassai et al. 2018). Unlike other more sophisticated systems, this is an inexpensive and minimally invasive solution for refurbishment of the façades of existing buildings. A UTC façade consists of a perforated metal layer that absorbs solar radiation, an air plenum and an insulation layer, which may be the existing façade of the building. Ventilation air is heated as it passes through the holes in the solar absorber layer and then is introduced into the building, figure 1. In this way, the thermal boundary layer is sucked into the air plenum and the heat loss to the exterior is minimised. The absorber layer should be painted in a dark colour with high solar radiation absorptance and preferably with a low long wave emissivity, (Hall and Blower 2016). Due to the constructive characteristics of this system, in some cases, the refurbishment of the façade would only need the installation of the absorber layer and the ventilation system, or the connection with the existing HVAC system (Badescu et al. 2019).

UTC façades have been installed in new and refurbished buildings for decades (Hollick 1996; Brown et al. 2014; Al-damook and Khalil 2017; Fleck, Meier, and Matovic 2002). They have also been used for industrial processes like crop drying or venting of livestock barns (Cordeau and Barrington 2011; Love et al. 2014). Furthermore, they can be used for cooling when combined with other systems, such as absorption or desiccant cooling systems, (Pesaran and Wipke 1994), (Peci, Comino, and Ruiz de Adana 2018). Energy saving was achieved in all cases, although the efficiency varied according to the weather conditions, especially wind velocity. However, there is still a lack of field measurements to quantify the actual energy saving under ambient weather conditions.

The efficiency and feasibility of UTC façades have been studied by several authors (Collins and Abulkhair 2014). On the one hand, the heat loss to the exterior due to natural convection, that could be the main drawback of this system, has been found to be negligible, (Kutscher, Christensen, and Barker 1993). On the other hand, one of the most influential variables on the performance of a UTC was found to be the wind velocity and many authors concluded that this affects the efficiency of the UTC as a solar collector (Al-damook and Khalil 2017; Fleck, Meier, and Matovic 2002; Vasan and Stathopoulos 2014). Due to the variety of weather conditions during a season, an estimation of the efficiency should consider the values over an extended period, and there is a lack of experimental data in the literature with respect to this. This study supports theoretical and experimental research by providing experimental evidence of the performance of the system.

In this study, the ventilation temperature was controlled using an on/off control strategy to prevent cold air from entering the building. A similar control strategy was proposed by (Moon et al. 2017; Gagliano, Aneli, and Nocera 2019; Giovanardi et al. 2015).

This study proposes a modular approach. A prototype of a UTC module was built and installed on the façade of a test cell under ambient weather conditions in Cordoba, Spain. The effect of ambient temperature and solar radiation on its performance was studied, and the values of the COP, effectiveness, efficiency and temperature increase over almost one month were analysed. With the data obtained, a case study was carried out to estimate the ventilation and ventilation heating energy consumption savings. The aim of this study was to characterise the UTC module prototype behaviour using experimental data measured over a period and to assess the feasibility of its installation to refurbish a residential building in this location based on the experimental results.

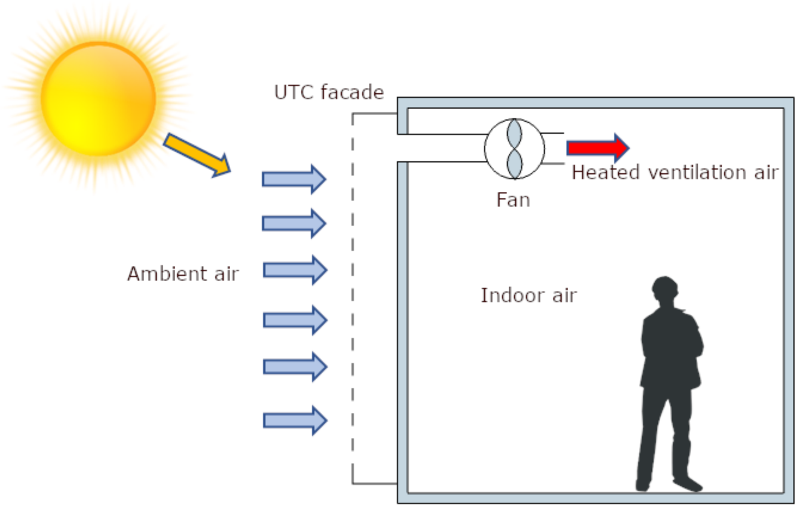

Figure 1. Schematic of a UTC façade system

Nomenclature:

A_c UTC collector surface area (m^2)

C_p Specific heat of air (J/kg K)

COP Coefficient of performance

$\dot{E}_v$ Ventilation sensible heat load (W)

I_T Total irradiance on the collector (W/m^2)

$\dot{m}$ Air mass flow rate (kg/s)

$\dot{Q}_{conv,ext}$ Convection heat transfer rate from the collector to the ambient air (W)

$\dot{Q}_{conv,int}$ Convection heat transfer rate from the collector to the plenum air (W)

$\dot{Q}_{conv,sw}$ Convection heat transfer rate from the insulation panel to the plenum air (W)

$\dot{Q}_{rad}$ Energy rate absorbed by the collector surface by radiation (W)

$\dot{Q}_{rad,long,ext}$ Long wave radiation interchange between the collector and the surroundings (W)

$\dot{Q}_{rad,long,int}$ Long wave radiation interchange between the collector and the insulation panel (W)

t_{on} Daily time with the fan running (s)

T_{amb} Ambient temperature (K)

T_{col} Collector surface temperature (K)

T_i Indoor temperature (K)

T_{out} Collector outlet air temperature (K)

T_p Plenum air temperature (K)

V_r Daily ventilation air volume required by regulations (m^3)

$\dot{W}_{fan}$ Power consumption of the fan (W)

ε_{HX} Collector effectiveness

η_{col} Collector efficiency

ρ Air density (kg/m^3)

2. Methodology

2.1 Experimental set up

A prototype of a UTC façade module was installed in a test cell under exterior weather conditions in Cordoba, south of Spain, coordinates 37˚54’51.19’’N 4˚43’34.8’’W. This location corresponds to a typical continental climate with mild winters and many sunny days, and therefore can be considered suitable for installing any kind of solar collector system. The façade was oriented to the south and there were no obstacles to the beam solar radiation nearby. The system was monitored in order to measure the temperatures of the different layers and the inlet air, the ventilation heat transfer rate to the cell and the main weather variables.

The experimental set up was used in a previous study (Peci et al. 2019). This set up consists of a modular site office of 6x2x2,5 m with a 3 cm sandwich panel cladding, see figure 2. The cell remained closed during the experiments, although leakage through cracks around the door and a small window existed. The air temperature inside the cell was kept within a normal range using an electric heater and an air conditioning system, with a set temperature of 23 ˚C. Figure 3 shows the position of the measurement probes. Temperatures were measured at three different heights for the four layers of the façade. The global solar radiation on the façade plane was measured using an analogue second class (<1.8%) pyranometer SR05-A1 installed on the façade itself. The ambient temperature was measured in a shielded case to avoid any solar radiation influence.

Figure 2. The test cell with the position of the UTC façade module and the protected ambient temperature probe (right).

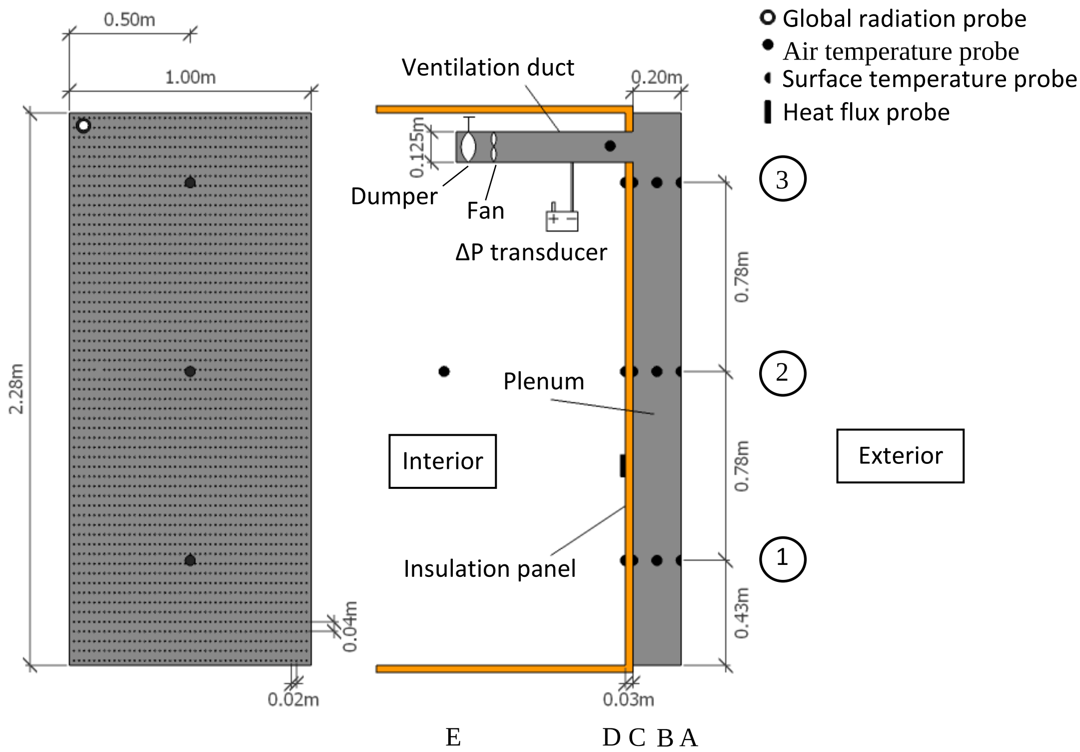

Figure 3. UTC experimental module dimensions and temperature probe locations. Probes were installed at three heights (1,2 and 3) in the steel plate (A), the plenum (B), the outer sandwich panel surface (C) and the inner sandwich panel surface (D).

The UTC fan was controlled throughout a hysteresis cycle. It was automatically turned on when the inlet air temperature was above 23 ˚C and turned off when this temperature was below 21 ˚C. When the fan was on, the average air flow rate was constant with a value of 220 $m^3 h^{-1}$. The suction velocity for this flow rate was 0.027 m/s. The average electric power consumption of the fan was 34 W. Further information about the experimental set up can be found in (Peci et al. 2019).

2.2 Theoretical model

A theoretical model based on energy balance equations was used to analyse the UTC façade performance. The energy balance in the collector surface, equation 1, and the overall energy balance, equation 2, gives the net energy entering the building (Leon and Kumar 2007).

$$\dot{Q}_{rad} = \dot{Q}_{conv,ext} + \dot{Q}_{conv,int} + \dot{Q}_{rad,long,ext} + \dot{Q}_{rad,long,int} \quad (1)$$

$$\dot{m}C_p(T_{out} - T_{amb}) = \dot{Q}_{conv,int} - \dot{Q}_{conv,sw} \quad (2)$$

The ventilation sensible heat load of a building can be evaluated as the difference between the energy of the inlet and outlet air streams, equation 3.

$$\dot{E}_v = \dot{m}C_p(T_i - T_{amb}) \quad (3)$$

Effectiveness and efficiency were assessed with equations 4 and 5. The temperature increase was evaluated using equation 6, (Leon and Kumar 2007).

$$\varepsilon_{HX} = \frac{T_p - T_{amb}}{T_{col} - T_{amb}} \quad (4)$$

$$\eta_{col} = \frac{\dot{m} C_p (T_{out} - T_{amb})}{I_T A_c} \quad (5)$$

$$\Delta T = T_{out} - T_{amb} \quad (6)$$

The coefficient of performance, COP, of the UTC collector can be evaluated with the equation 7. The only energy consumption of the system was that of the fan motor.

$$COP = \frac{\dot{m} C_p (T_{out} - T_{amb})}{\dot{W}_{fan}} \quad (7)$$

2.3 Case study

A typical apartment consisting of a living room, three bedrooms and two bathrooms was considered to study the rate of ventilation and ventilation heating achieved by the UTC façade module. The ventilation requirements for this case according to regulations ("Código Técnico de La Edificación (CTE) Documento HS 3 - Calidad de Aire Interior" 2017) are listed in table 1. The total daily flow rate required was 3283 m^3/day. The percentage of the daily required ventilation achieved, and the percentage of daily ventilation heating requirements covered with the UTC module tested were evaluated with equations 7 and 8, respectively. From these data the area of UTC modules needed in each case was calculated. The south façade length was 15 m with a height of 3.25 m. Windows covered 5.5 m^2 of the façade and the area available for installing UTC modules was 47 m^2.

$$\%\, Ventilation\ achieved = \frac{\dot{m}\, t_{on}}{\rho V_r} \cdot 100 \quad (7)$$

$$\%\, Ventilation\ heating\ achieved = \frac{\dot{m}\, C_p (T_{out} - T_{amb})\, t_{on}}{\rho V_r\, C_p (T_i - T_{amb})} \cdot 100 \quad (8)$$

Table 1

Room	Ventilation requirements (m^3/s)
Living room	0.010
Main bedroom	0.008
Bedrooms	0.008
Bathrooms	0.012

3. Results and analysis

3.1 Hourly results

The typical behaviour of the UTC system during the day is shown in figures 4 to 7. They show the experimental UTC outlet air temperatures for four typical days with combinations of high and low global radiation and ambient temperature levels. The inlet air temperature is only represented when the fan was on.

During the day shown in figure 4, despite the intermittent radiation levels on the façade, the ventilation was running for most of the daytime, due to the high ambient temperatures. In the midday periods, the temperature increase inside the UTC reached more than 5 ˚C, reaching maximum values of about 30 ˚C. When there was not enough beam solar radiation, the ventilation was turned off, so ventilation with low air temperature was not possible.

In the most unfavourable case, with cloudy sky and low temperatures, figure 5, the maximum UTC outlet temperatures obtained were between 20 and 25 ˚C. The air flow rate was very intermittent, only running when there was some beam solar radiation. During this kind of day, the UTC system was not able to ventilate, as the temperature was not high enough to be introduced into the rooms.

As expected, UTC outlet temperatures increased with high global radiation on the façade. In the most favourable case, figure 6, outlet air temperatures above 35 ˚C were measured. However, the inlet temperature values were not as high as in the case when ambient temperature was low at the time that solar radiation was high. For this case, high radiation and low ambient temperatures, figure 7, maximum inlet temperatures between 25 ˚C and 30 ˚C were measured.

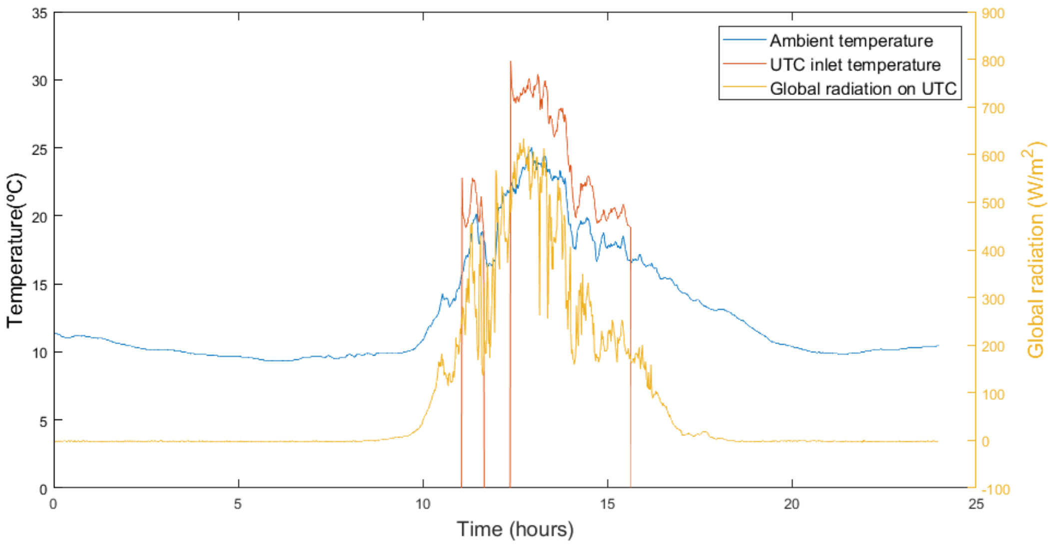

Figure 4. Measurements over a typical day with low radiation and high temperature levels.

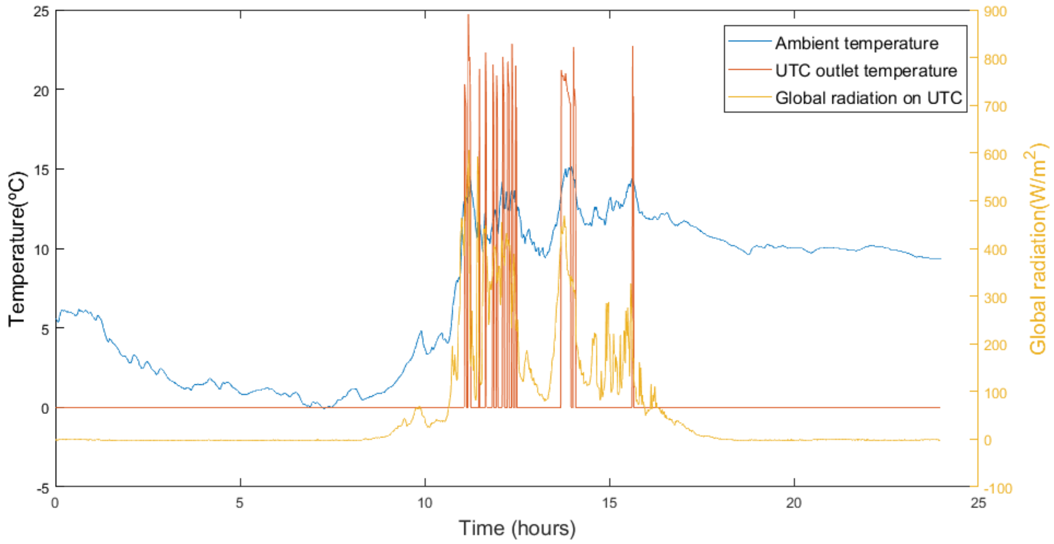

Figure 5. Measurements over a typical day with low radiation and low temperature levels.

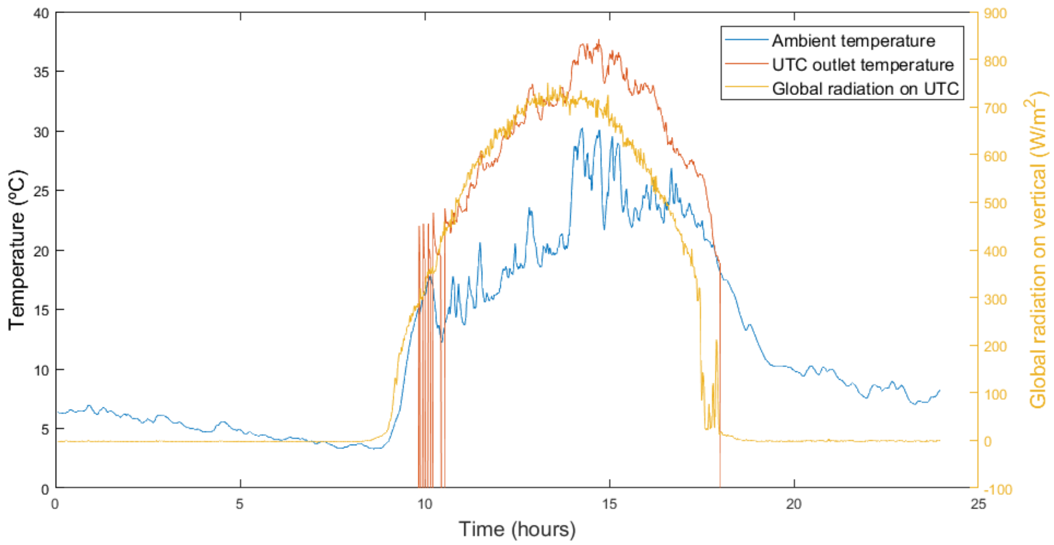

Figure 6. Measurements over a typical day with high radiation and high temperature levels.

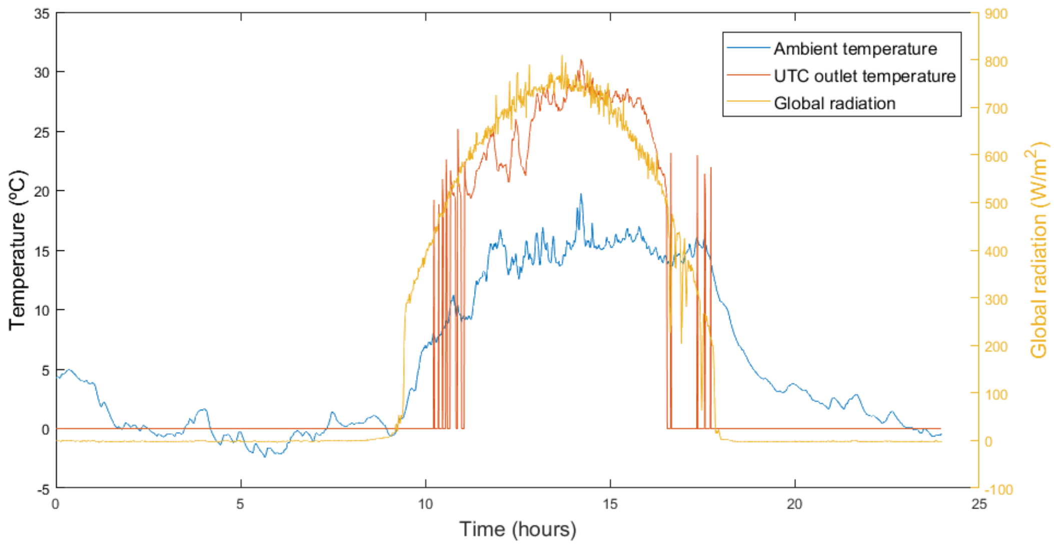

Figure 7. Measurements over a typical day with high radiation and low temperature levels.

According to these data, the more days with high solar radiation, the more heating energy saving will be obtained. Therefore, locations with many hours of beam solar radiation and low ambient temperature would benefit more from installing a UTC façade for heating. During cloudy days there would not be any ventilation, or the ventilation heat load would be higher if a ventilation system were working in the building. In any case, the installation of a UTC façade system does not imply an increase in the heating loads. In the experimental tests there were more days like those shown in figures 6 and 7.

3.2 Efficiency and Effectiveness

The cumulative distribution function (CDF) of UTC efficiency and effectiveness measured during the test are represented in figures 8 and 9. The efficiency mean value was 0.40 and 90% of the efficiency values were found to be 0.46 or less. Effectiveness was found to be greater than 0.48 for 90% of the measurements, with a mean value of 0.52. The CDF of the effectiveness became steeper from values around 0.30, and it can be seen that 90 % of the effectiveness values fall between 0.30 and 0.60. The values of efficiency were more spread, with 90 % of the values between 0.21 and 0.48.

The values of efficiency and effectiveness obtained are in agreement with those found in literature. In (Collins and Abulkhair 2014), a comparison between numerical analysis and the results of other authors was carried out. In this study, values of effectiveness between 0.6 and 0.8 were found for a suction velocity of 0.027 m/s. Other authors, (Van Decker, Hollands, and Brunger 2001), found numerical and experimental values in the same range. Values of efficiency between 0.20 and 0.75 were found in (Badache, Hall, and Rousse 2012) for high and low levels of absorptance, irradiation and flow rate.

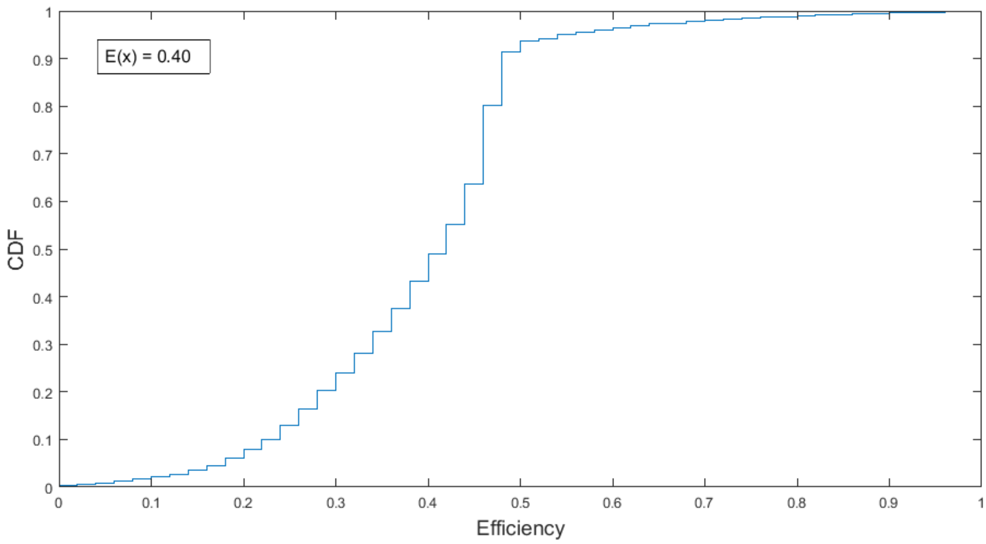

Figure 8. Cumulative distribution function of the UTC module efficiency.

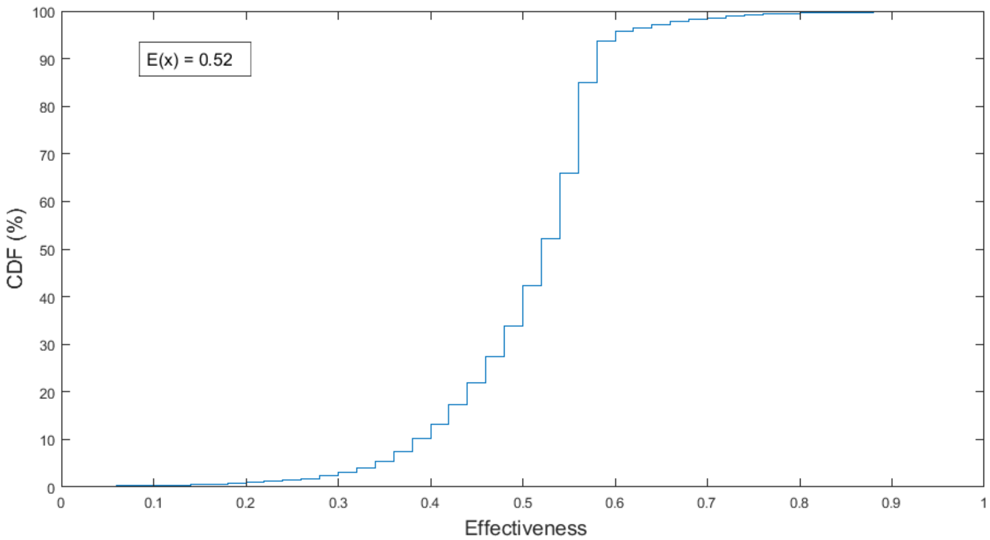

Figure 9. Cumulative distribution function of the UTC module effectiveness

From these results it can be concluded that, given the high dispersion of both efficiency and effectiveness, which is dependent on the weather variables, the study of the energy savings for a specific building should take into account the typical climate of its location. The effects of the weather variables on the performance of the UTC façade are analysed in the followig paragraphs.

3.3 Effect of weather variables

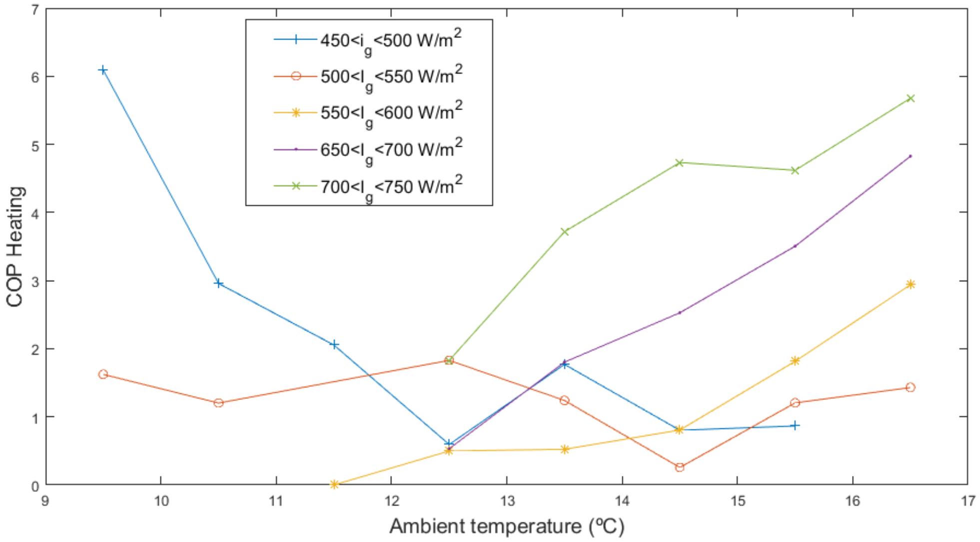

Figure 10. Variation of COP heating values with ambient temperature for different intervals of solar radiation.

Figure 10 shows the variation of heating COP with ambient temperature for different intervals of solar radiation on the collector. It can be seen that for the lowest radiation level COP decreased when the temperatures were below 13 ˚C. For the same range of temperatures, COP remained between 0.5 and 1.8 when irradiation was between 500 and 550 W/m^2. When irradiation was higher than 550 W/m^2 there was a clear trend for the COP to increase as ambient temperature increased.

Figure 11 shows the variation of heating COP with solar irradiation for several intervals of ambient temperature. It can be seen that there was a clear increasing trend of the COP for all the ambient temperature levels when global radiation was above 575 W/m^2. This highlights the importance of solar radiation on the performance of the UTC façade. However, COP increased for global radiation below 525 W/m^2 for ambient temperatures below 12 ˚C, where a small temperature increase has a considerable impact on the COP. Low radiation values usually corresponded to lower temperatures during the day, so the temperature increase was higher compared to those days with higher solar radiation.

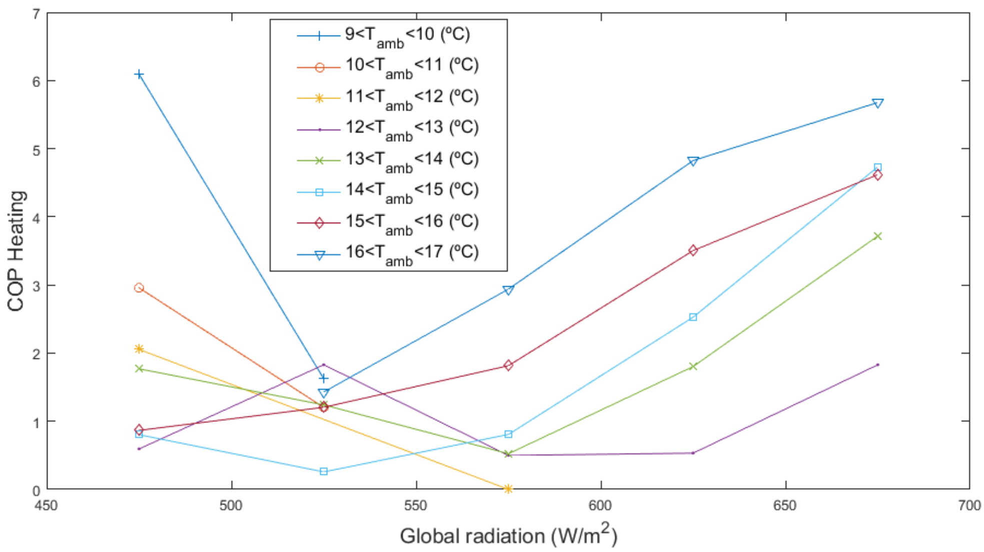

Figure 11. Variation of heating COP with global radiation on the UTC façade for several intervals of ambient temperature.

The effect of ambient temperature on the inlet air temperature increment is represented in figure 12. It can be seen that the higher the ambient temperature, the lower the temperature increase. This trend is more noticeable for the cases with lower solar radiation levels. When the radiation levels were low, the collector surface temperature can not reach high temperatures, so if the ambient temperatures are also high, the temperature increase can not be very high. Figure 13 shows the variation of the air temperature increase with global radiation for several temperature intervals. The temperature increase tended to increase as global solar radiation increased, as expected. However, for low temperatures the trend was the opposite. This may be due to increasing heat loss to the exterior when temperatures were low.

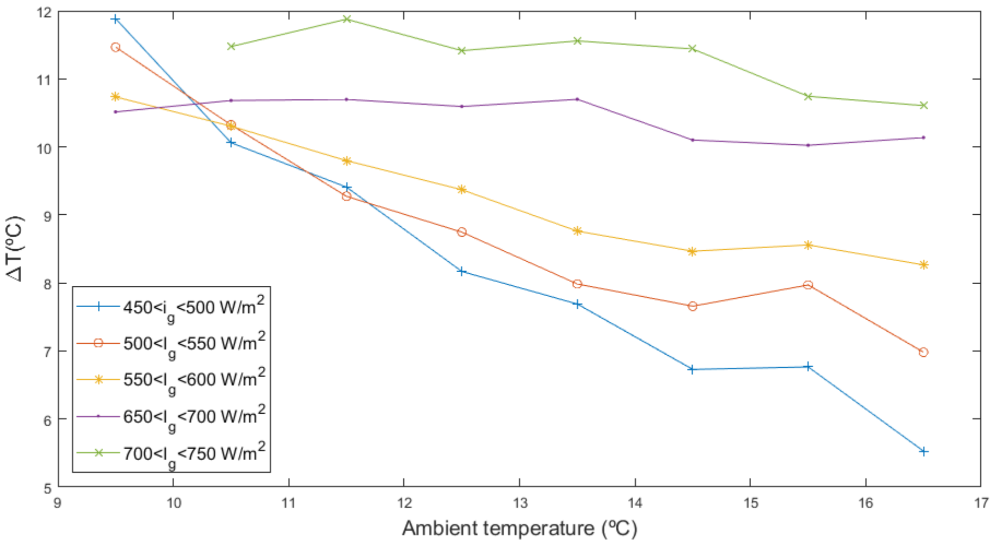

Figure 12. Variation of temperature increase in the UTC façade with ambient temperature for different solar irradiation intervals.

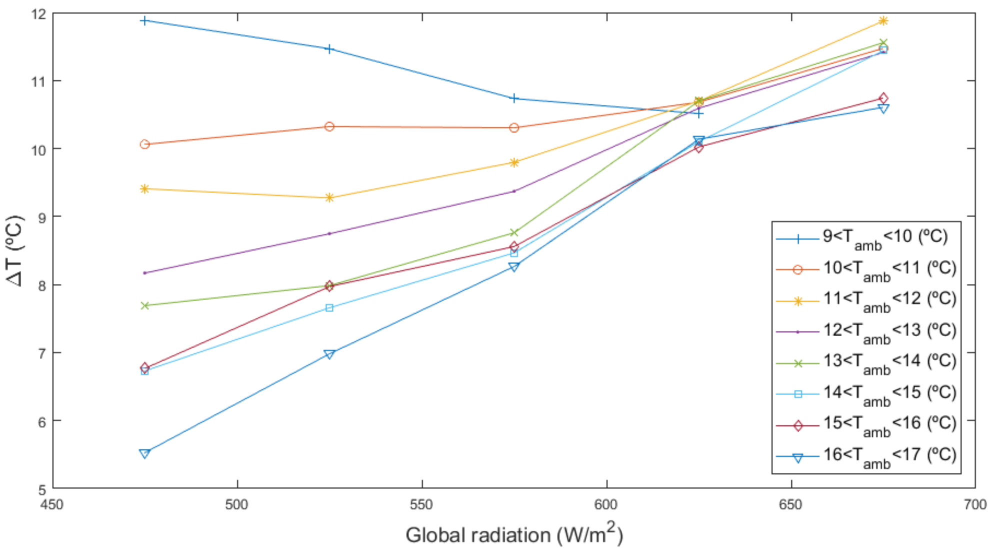

Figure 13. Variation of temperature increase in the UTC with global radiation for different ambient temperature intervals.

The variation of the effectiveness with ambient temperature is shown in figure 14. Effectiveness tended to decrease with temperature for all global radiation levels. As the ambient temperature increased, the temperature difference between the collector surface and the ambient air decreases, and the amount of energy transferred to the air was lower.

Figure 15 shows the variation of effectiveness with solar radiation for several ambient temperatures. The general trend for the effectiveness was to increase with solar radiation. However, for the lowest temperature levels this trend was the opposite. Again, this may be because of the increase of thermal loss to the exterior due to the low temperatures.

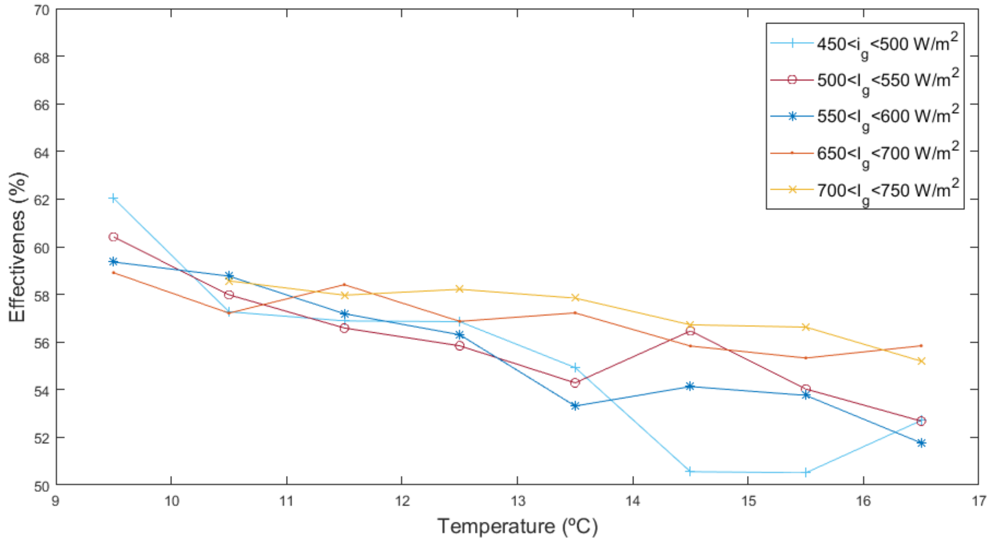

Figure 14. Variation of the effectiveness with ambient temperature for various global radiation intervals.

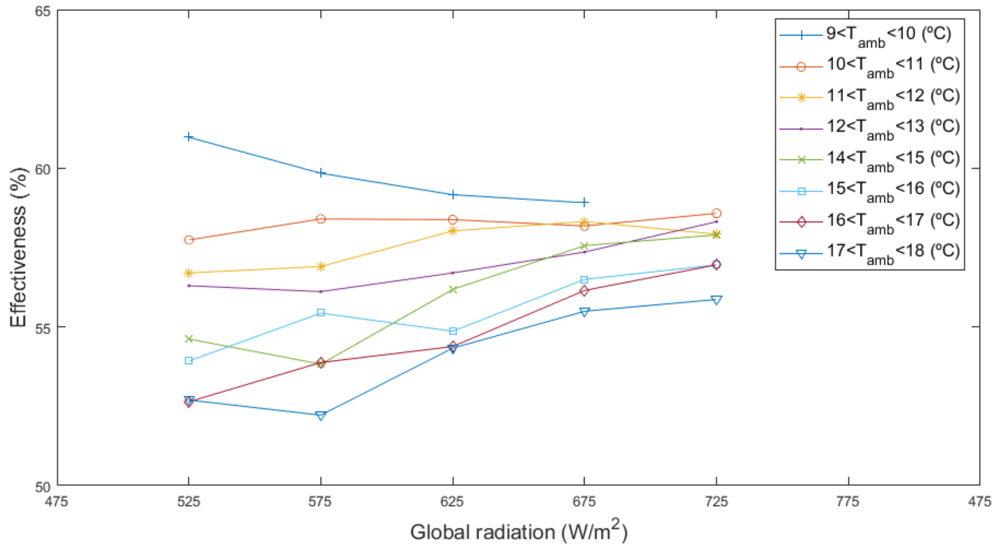

Figure 15. Variation of effectiveness with global radiation for different intervals of ambient temperature.

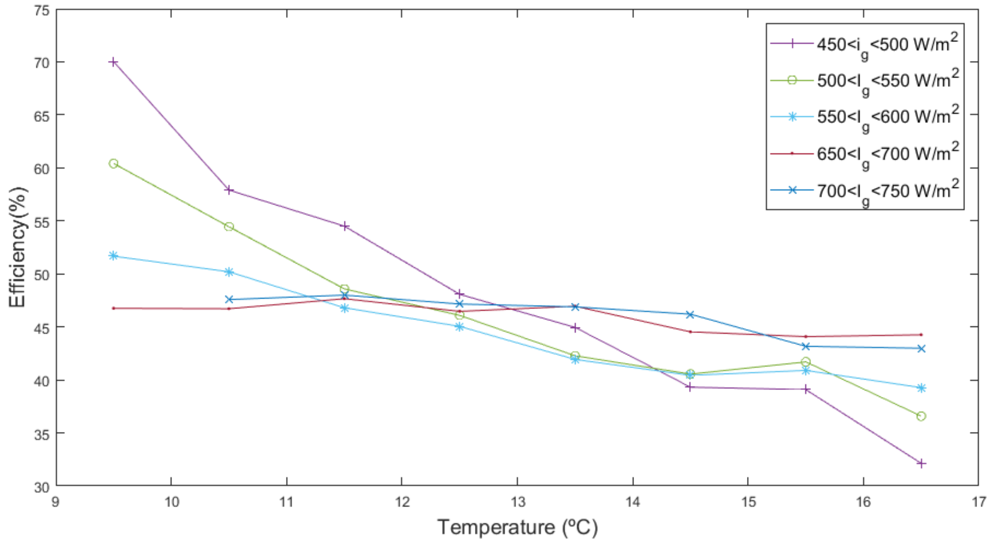

Figure 16. Variation of efficiency with ambient temperature for different intervals of global radiation.

Figure 16 shows the variation of the UTC efficiency with ambient temperature. Efficiency diminished with ambient temperature for every global radiation interval, and the decrement is higher for lower levels of solar radiation. The reason for this is that with high ambient temperatures, the temperature difference between ambient air and the collector decreases, and therefore convection heat transfer reduces. This effect was also pointed out in (Kutscher, Christensen, and Barker 1993). Regarding the dependence on solar radiation, figure 17 shows that efficiency values converge to a value between 0.4 and 0.5 for all ambient temperature intervals. For high solar radiation values, efficiency is independent of the ambient temperature. The decrease in the efficiency with high solar radiation was previously studied in (Fleck, Meier, and Matovic 2002), although the results were represented as a dispersion graph. Figure 17 shows that values are also ambient temperature dependent.

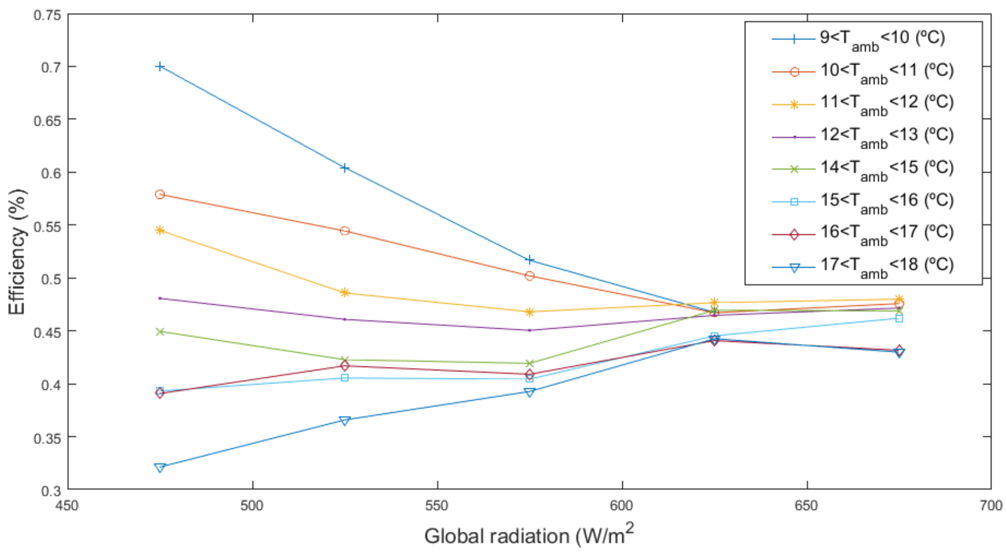

Figure 17. Variation of efficiency with global radiation for different intervals of ambient temperature.

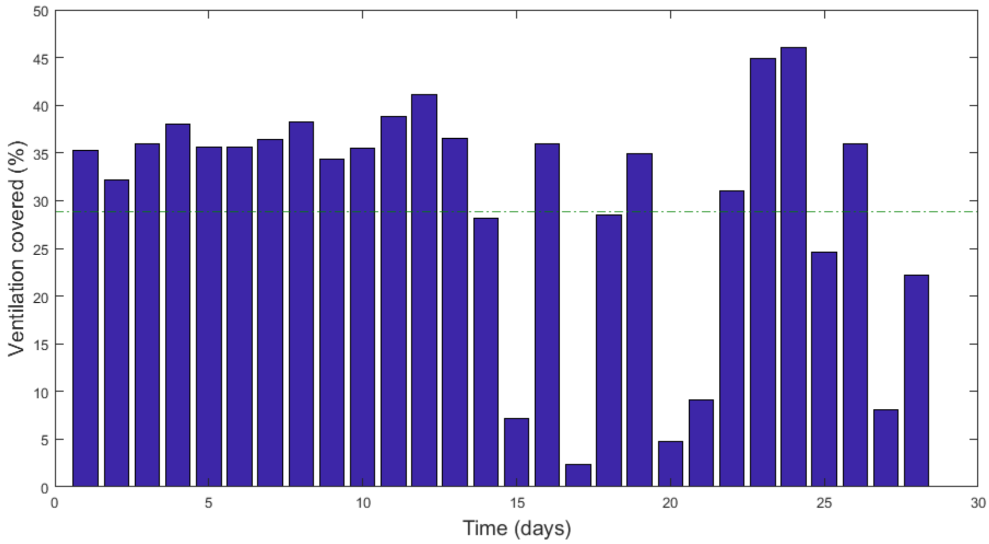

Figure 18. Percentage of daily ventilation covered by the UTC in the experimental tests.

3.4 Case study results

Figures 18 and 19 show the fraction of ventilation requirements and ventilation heating load covered by the UTC module tested if it were connected to the ventilation system of the apartment described in section 2. During sunny days, when the UTC fan is running, the ventilation covered between 28 and 46 % of the ventilation requirements. During cloudy days, these values were between 3 and 10%. The mean value for the 28 days of tests (green dashed line) was 28 %. As for the ventilation heating load covered, values reached a maximum of 44 % during sunny days and minimum of 2% during cloudy days, with a mean value of 26 % for the 28 days of tests. With these data, the minimum area needed to accomplish the ventilation requirements and to cover the ventilation heating load were evaluated and represented in figures 20 and 21 as cumulative distribution functions. The expected area for daily ventilation to cover 100 % of the ventilation requirements was 13.68 m^2, which corresponded with up to 80 % of the cases. To cover the ventilation heating load, the expected area was greater, 15.80 m^2, and it covered 100 % of the heating required by up to 75 % of the cases.

For this case study, the length of façade available to install UTC modules is 9.5 m, so 9 UTC modules could be installed, giving a total UTC façade area of 20.4 m^2. With this area, it can be seen in figures 20 and 21 that the percentage of days in which ventilation and ventilation heating could be covered during the period of the experiments would be 82.2% and 74.8 %, respectively. Therefore, it can be concluded that for a typical apartment, the reduction in energy consumption when installing a UTC façade in this climate is considerable.

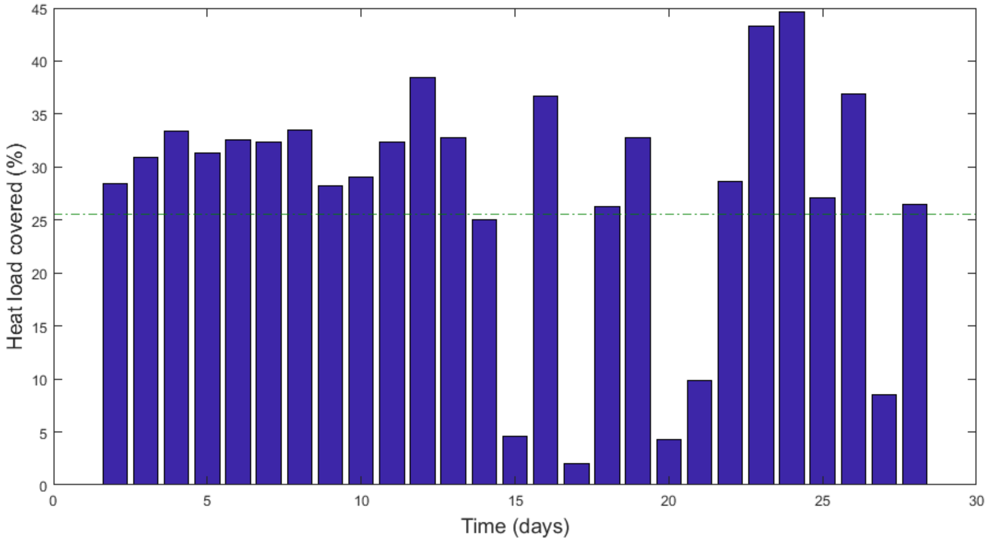

Figure 19. Percentage of daily ventilation heating covered by the UTC.

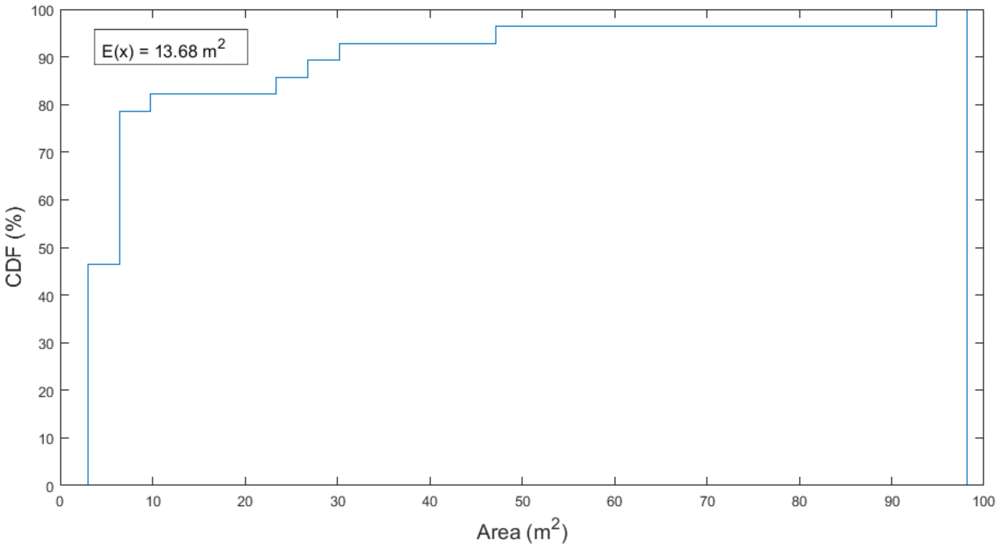

Figure 20. Cumulative distribution function for the UTC surface needed to cover ventilation requirements.

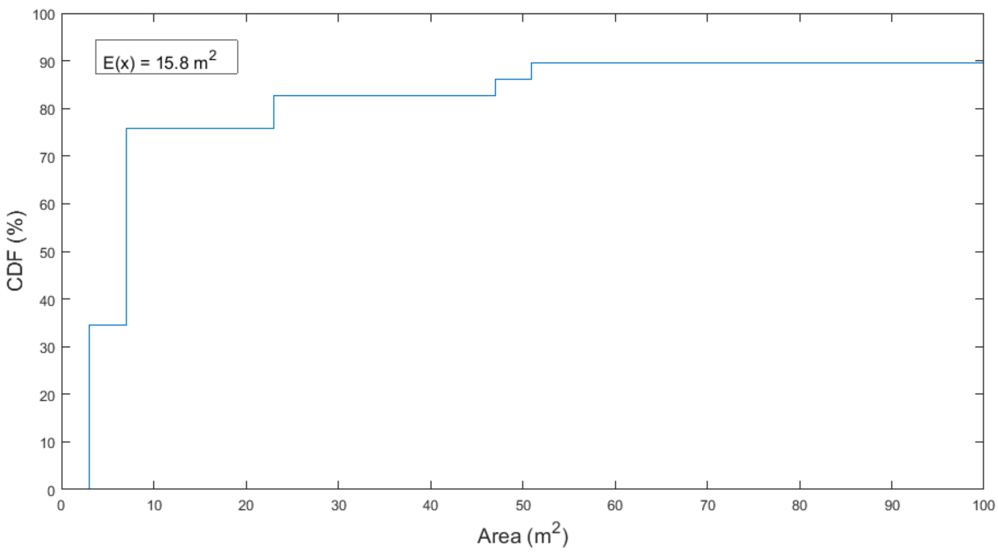

Figure 21. Cumulative distribution function of the UTC façade surface needed to cover the ventilation heating load.

4. Conclusions

A module of a UTC façade was tested under ambient weather conditions and the measurements obtained were analysed. With these data, the number of UTC modules needed in a typical apartment to cover the ventilation flow rate and heat load was estimated.

Values of effectivity and effectiveness agreed with those found in other experimental studies. Therefore, the prototype proposed could be viable as a façade solar collector, although an optimisation of the geometry would be needed. The variation in efficiency and effectiveness with solar radiation and temperature was studied. It was found that effectiveness decreased slightly with an increase in ambient temperature, and it increased with an increase in global radiation. Efficiency decreased with an increase in ambient temperature and converged to a common value when the global radiation reached its maximum values.

High heating COP values were found when solar radiation and ambient temperatures were high. This corresponded to the most favourable scenario with sunny days with mild winter temperatures. The temperature increase inside the UTC rose with solar radiation, and was less and less dependent on ambient temperature as the solar radiation reached it maximum values.

In the case study, it was found that in a typical apartment with the façade orientated to the south, the UTC modules that can be installed would cover a high percentage of the ventilation and heating demand. Therefore, in this location and climate, the use of UTC façades for ventilation and heating was found to be feasible.

Further research would be necessary to assess the performance of several modules installed in combination. Two different approaches could be used for module connection: a complete modular approach where each module is provided with its own fan, and a global approach where the modules are connected to a single fan that provides ventilation to all of them. Both approaches need their own control strategy, each having a different performance.

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