Integration of a sorption collector coupled with a decentralized mechanical ventilation unit in curtain wall module

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Abstract

Over the last few years, a growing attention has been given to the integration of active solar technologies into the building envelope, so to increase the renewable energy production share and contribute to reach the goal of net-zero energy buildings.

In this context, the layout of an air based solar cooling system integrated into a façade module was designed and assessed in [1] [2]. This solution utilizes a triple state absorption module within a Sydney type vacuum tube solar collector to thermally condition an airflow directed to the internal space reducing the thermal load covered by traditional technologies.

A further development consists in the integration of this solar collector with a decentralized ventilation machine, so that the hygienic airflow can be heated up or cooled down by the sorption collector. In addition, the ventilation unit is equipped with a heating/cooling coil to guarantee the thermal comfort of the room occupants.

The implementation of this system in façade modules would thus replace a centralized ventilation system and a fan coil and allow harvesting the solar radiation to produce renewable energy.

The effectiveness of the sorption collector in this layout and the energy performance of the system are assessed through dynamic simulations for a set of climates and building envelope characteristics.

The results show that a combination of active and passive cooling can greatly limit the use of cooling coil even though the performance varies significantly with climate and façade orientation. On the contrary, the performance in heating have been found quite poor for all configurations studied.

Keywords: Solar active envelope, Heating and cooling systems, Solar sorption collectors, Solar cooling.

1. Introduction

Unitized metal-glass curtain walls offer a great opportunity to create new applications in the field of active solar facades. Such façade modules can be largely prefabricated, integrating components in the production line and manufacturing easy-to-install modules. The proposed concept aims to exploit the synergy between an air-based solar sorption collector and a decentralized ventilation unit to create a multifunctional plug-and-play façade module. It can be applied in new constructions or retrofitting applications of typical tertiary buildings.

The sorption collector exploits solar radiation on vertical façades throughout the year, which represents an easy-to-access but still unexplored energy potential. It is exploited to thermally precondition (both in cooling and heating modes) the hygienic airflow. An air-handling unit (AHU) is connected in series to the sorption collectors, on the one hand supplying fresh air to the office zone and on the other covering the remaining fraction of the heating and cooling loads through a water coil. This solution substitutes a centralized ventilation system with a decentralized façade-integrated AHU with the further advantage of replacing the use of an external fan-coil unit.

The main advantages of decentralized ventilation systems have been reported in several studies [3] [4] [5] [6]. They can be summarized in fan electricity savings, greater flexibility in the control of the ventilation system, higher user satisfaction and reduction of false ceiling height. However, greater efforts for filter replacement and maintenance, costly humidification/dehumidification and higher sensitivity to wind pressure and temperature of the building envelope must be taken into account.

Focusing on the sorption collector, its working principles have already been presented in literature [1] [2] [7] [8]. The collector is composed of a number of “sorption tubes”, which are sealed glass tubes under vacuum divided into two compartments, called reactor (“RE”) and condenser/evaporator (“CE”) (see Figure 1). Within these tubes, the working pair LiCl-water solution runs in a batch process of absorption and desorption (see Figure 2). The processes are made possible by thermally linking the reactor side of the sorption tube to a solar absorber and connecting the reactor and the condenser/evaporator to two dedicated heat exchangers.

Figure 1: View of the prototype of the sorption collector [source: ClimateWell].

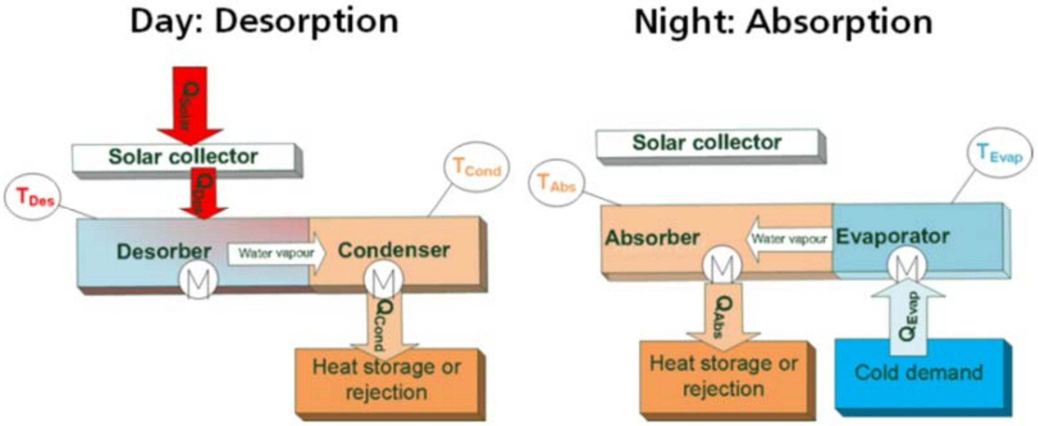

Figure 2: Fundamental operation cycles of the sorption tubes integrated in the sorption collector [8].

Two main processes can be distinguished. Desorption occurs when the solar radiation captured by the solar absorber heats up the solution in RE generating water vapor, which tends to flow in the CE. Heat rejection at the CE allows keeping the water vapor pressure low, condensing the vapor. During the absorption process, water evaporates at low temperature in the CE thanks to low-pressure conditions (i.e. vacuum). Removing heat from the RE and supplying low temperature heat to the CE (i.e. cooling the operation fluid) through the heat exchangers let the water at the CE evaporate and be absorbed in the salt matrix in the RE.

In this work, particular care is paid in the development of control logics that optimize the exploitation of solar renewable energy and guarantee at the same time thermal comfort and hygienic air change, so to create a healthy and comfortable indoor environment. With respect to previous studies, the present paper focuses on the synergic coupling between the ventilation system and sorption collectors.

2. Façade concept

2.1 General description

The reference zone is a generic office space of a typical high-rise building. It is 4.5 m wide, 6 m deep and 3 m high, resulting in 27 m^2 floor surface. The façade can be then composed of three 1.5 m wide façade modules (see Figure 3). Each module consists of a glazing and two opaque panels located at the top and at the bottom of the façade-element. The sorption collector is installed in correspondence of the lower opaque panel, while movable blinds are hosted upon the upper opaque panel. An 8 mm single glazing frontally covers the collector for safety reasons and gives to the façade a uniform appearance.

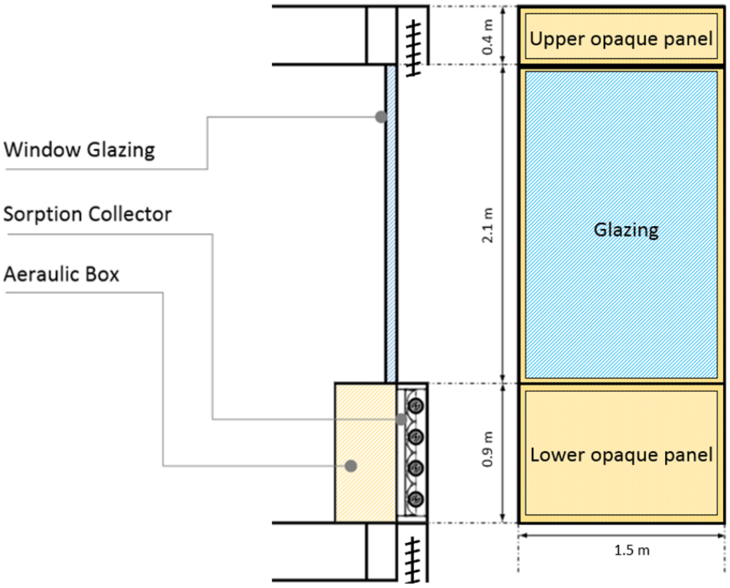

Figure 3: Schematic of the façade-integrated ventilation unit and sorption collector.

The analyzed configuration of the system includes multiple sorption collectors (one for each façade module), which are connected in series to an AHU (one for each office room). The link between the sorption collector and the AHU is realized by means of "aeraulic boxes", which are able to direct the fresh and exhaust airflows using motorized dampers. The aeraulic boxes are located in the rear side of each sorption collector so to simplify the design and the connections (see Figure 4).

The connections between different aeraulic boxes are realized through air ducts that pass from one module to another taking advantage of the façade thickness. The overall thickness of the façade module that contains the AHU, the aeraulic box and the sorption collector is estimated to be about 0.6 m. Nevertheless, there is space for reducing the façade thickness by developing ventilation units and collectors tailored for the application.

The AHU is able to supply up to 320 m^3/h. It is a double-flow unit that integrates a recirculation damper and sensible heat recovery unit (η_{sens} = 80%). It is always active when the room is occupied and when free cooling is convenient. A bypass damper prevents the use of the heat recovery unit in case of free heating/free cooling. The AHU also integrates a water coil, so to provide enough heating and cooling power to replace the installation of an external fan-coil unit. The specific fan consumption is assumed to be constant and equal to SFP = 0.36 Wh/m^3. Filters are installed both on the fresh and return air streams as prescribed by [9]. A schematic of the façade integrated energy system is shown in Figure 4.

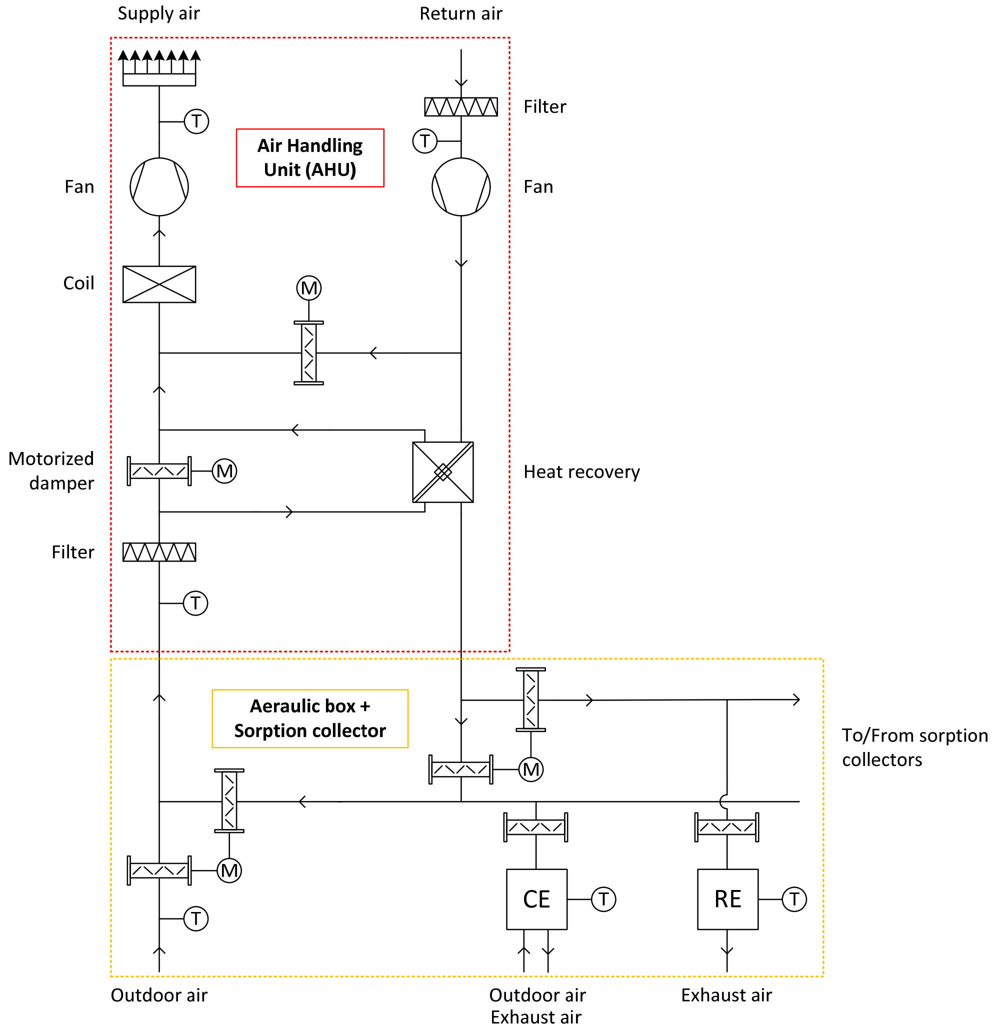

Figure 4: Layout of the AHU coupled with the façade-integrated aeraulic box and sorption collector.

According to the status of Li-Cl-water solution in the compartments, the sorption collector may transfer useful heating or cooling power from the CE to the air stream and so the hygienic airflow is pre-heated or pre-cooled. If this is not the case, fresh air can still be taken from outdoor bypassing the sorption collector and exhaust air is expelled either through the CE heat exchanger (“CEx”) or the RE heat exchanger (“REx”). This means that the CEx can be crossed by fresh air or exhaust air, whereas the REx can be crossed only by exhaust air, which is then expelled into the atmosphere.

2.2 Control strategy

The aim of the control strategy of the aeraulic box is to manage optimally the airflows, in order to exploit heating and cooling gains from the sorption collector. Two motorized dampers control the connections between AHU, sorption collector and external environment. The three main working schemes are described in the following figures (Figure 5 to Figure 7). These schemes are alternative to each other and they are triggered by combinations of signals, which are elaborated from temperature measures taken within the sorption collector and the aeraulic box.

Scheme 1 is activated when the sorption collector has to be cooled down. When the CE reaches a high temperature (T_{CE} > 50°C), fresh air is taken from outside bypassing the sorption collector. Doing otherwise could cause damages to the AHU components and thermal discomfort to the room occupants.

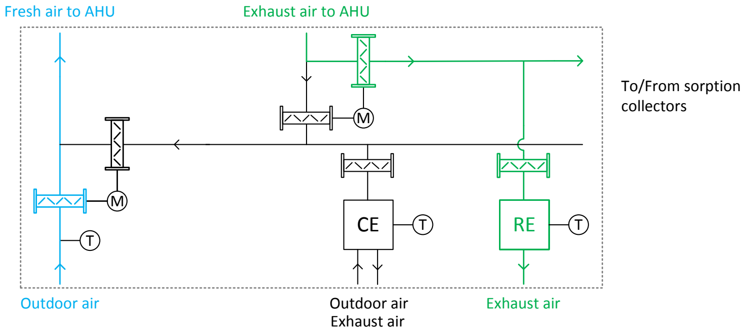

Figure 5: Scheme 1, airflows pattern (blue line: fresh air, green line: exhaust air).

Scheme 2 is activated when neither heating nor cooling gains from sorption collectors are requested or available. Fresh air is taken from outside bypassing the sorption collector, whereas exhaust air is rejected through the CEx.

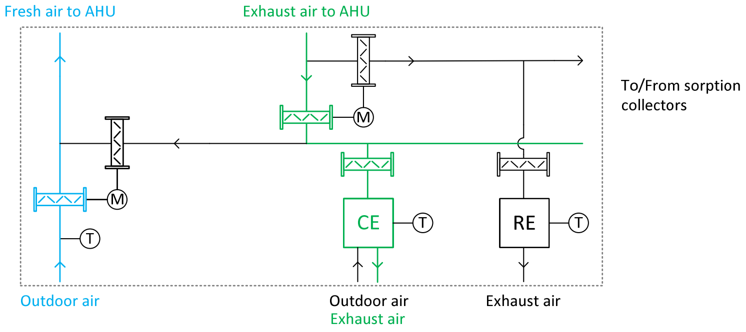

Figure 6: Scheme 2, airflows pattern (blue line: fresh air, green line: exhaust air).

Scheme 3 is activated for both heating and cooling purposes when heating or cooling power that can be transferred to the fresh air supply is available at the CEx. Exhaust air is rejected through the REx.

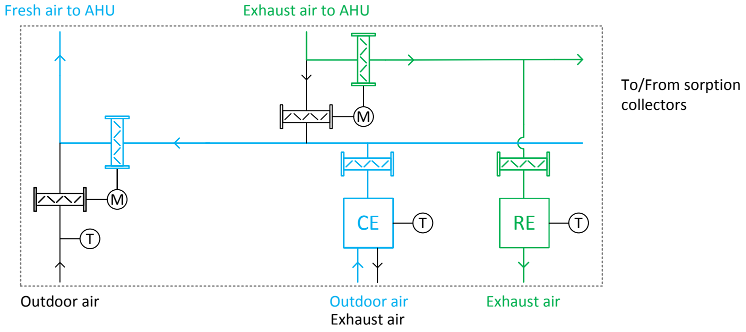

Figure 7: Scheme 3, airflows pattern (blue line: fresh air, green line: exhaust air).

Furthermore, a free cooling mode is implemented. In this case, a fresh airflow higher than the minimum required for hygienic purposes is used and either Scheme 2 or Scheme 3 is activated depending on the temperature measured at the CE.

3. Numerical modelling

3.1 Description of sorption collector and decentralized AHU models

A numerical model of an AHU is developed in TRNSYS. Circulating fans are modelled with Type 111a, while the sensible heat recovery unit is modelled with Type 760. Although there is a unique water coil in the AHU, two separate Types (Type 753 and Type 508) are used in heating and cooling modes.

The sorption tubes are modelled with Type 827 [7] [8], which is an equivalent R-network able to model both the vapour exchange within the sorption tubes and the heat transfer in REx and CEx. This Type has been validated against measurements [7] and showed a very good agreement between experimental and simulated results. Type 827 is coupled with Type 832 [10], which is responsible for the detailed calculation of the heat transfer of the solar collector and treats the modelling of the short-wave radiation separately.

The model used to simulate the interaction between the sorption collector and the interior environment is decoupled. The heat transfer through the opaque façade surface is not affected by the presence of the sorption collector and vice-versa. A multi-step analysis was carried out in [2] on the interaction between the rear side of the sorption collector and the indoor environment. It shows that the presence of a sufficient thick insulation layer (i.e. 10 cm) allows to greatly reduce the effects on the yearly space heating/cooling demand. Because of the similarities between the present system and the one studied in [2], this conclusion is here applied.

3.2 Reference room and building modelling

The reference office zone is modelled with Type 56. It consists of a single-zone single-airnode model. The thermo-physical and optical properties of building assemblies are listed in Table 1 and Table 2. In particular, two glazing typologies and two different Window-to-Wall Ratio (WWR) are analyzed (62% and 36%). Such WWR values permit to evaluate the impact of different sorption collector sizes, which vary from 1.35 m^2 to 2.70 m^2 on each façade module. The four resulting scenarios are listed in Table 3.

Construction	**Boundary cond.**	**U-value [W/(m^{2}K)]**		
		Rome	**Stuttgart**	**Stockholm**
Internal wall	Adiabatic	1.97	1.97	1.97
Internal floor / ceiling	Adiabatic	1.86	1.86	1.86
Facade opaque part	External	0.30	0.15	0.15
Facade frame	External	3.01	3.01	3.01

Table 1: Thermal properties of the building assemblies.

		Glazing #1	**Glazing #2**
Layers	[mm]	8/1.5/8/16/10	4/16/4/16/4
Fill gas	[-]	Air / Argon	Argon / Argon
U_{gl}	[W/(m^{2}K)]	1.17	0.59
g-value	[-]	0.448	0.451
U_{fr}	[W/(m^{2}K)]	2.44	0.70

Table 2: Thermal and optical properties of the transparent surfaces.

Scenario	**WWR**	**Glazing type**
1	62%, Four tubes collectors	Glazing #1
2	62%, Four tubes collectors	Glazing #2
3	36%, Eight tubes collectors	Glazing #1
4	36%, Eight tubes collectors	Glazing #2

Table 3: Scenarios for the building envelope facade.

Three people are hosted in the office with a daily schedule from 07:00 to 20:00. The internal gains are due to human presence, artificial lighting and appliances. The human occupation determines latent (0.059 kg/h/person) and sensible gains (70 W/m^2, [11]). The use of the electronic equipment causes sensible gains for 3 W/m^2 [12], while lighting (LED) generates 7 W/m^2 sensible gains. A generic solar shading device is implemented to simulate movable external blinds (shading factor of 70% when pulled down). No influence of the urban or environmental context in terms of unwanted shading on the active solar façade is taken into consideration.

With regard to air leakages and ventilation, a constant infiltration rate of 0.15 1/h is simulated and a hygienic fresh airflow equal to 39.6 m^3/h/person is delivered during occupation hours [9]. The thermal comfort is guaranteed by the joint contribution of sorption collectors and water coil. The heating and cooling temperature set points are fixed to 20°C and 26°C during working hours. Three different façade orientations (East, West and South) and three representative European climates (Rome, Stuttgart and Stockholm) are analysed for each scenario.

4. Results and discussion

4.1 Performance indicators

The assessment of the performance of the sorption collector in this configuration is based on key indicators that consider the capability of the system to cover the zone load with clean energy.

In order to do so, the energy seasonally transferred to the supply airflow through the system components is calculated. Looking at the fresh air stream in heating mode, positive gains are provided by the sorption collector (Q_{sc}^{heat}), the heat recovery unit, the heating coil (Q_{hc}) and the circulating fan. The share of energy purposely delivered to the supply airflow represented by the sorption collector in heating mode is calculated defining the solar fraction SF_{heat} as shown below:

$$\mathrm{SF}_{\mathrm{heat}} = \frac{\mathrm{Q}_{\mathrm{sc}}^{\mathrm{heat}}}{\mathrm{Q}_{\mathrm{sc}}^{\mathrm{heat}} + \mathrm{Q}_{\mathrm{hc}}}$$

During summer operation, cooling contributions are provided by the sorption collector (Q_{sc}^{cool}), the heat recovery unit and the cooling coil (Q_{cc}), whereas the circulating fan increases the air stream temperature. Additionally, the free cooling effect is calculated (Q_{free}^{cool}).

In this case, the solar fraction SF_{cool} is defined considering also the passive contribution of free cooling:

$$\mathrm{SF}_{\mathrm{cool}} = \frac{\mathrm{Q}_{\mathrm{sc}}^{\mathrm{cool}} + \mathrm{Q}_{\mathrm{free}}^{\mathrm{cool}}}{\mathrm{Q}_{\mathrm{sc}}^{\mathrm{cool}} + \mathrm{Q}_{\mathrm{free}}^{\mathrm{cool}} + \mathrm{Q}_{\mathrm{cc}}}$$

4.2 Heating performance

The heating energy delivery of the sorption collector to the supply air (Q_{sc}^{heat}) is quite poor, as shown in Table 4. This is mainly due to the need of expelling exhaust air either through the CEx or the REx. In fact, the sorption collector is not capable of heating up effectively since heat is continuously removed. During wintertime, the heat recovery of the ventilation unit is active and the exhaust air is close to outdoor ambient temperature. The combined effect of heat losses to the ambient and the heat removal due to expulsion of cold exhaust air prevents the solar collector to reach temperatures high enough to start effectively desorption, especially in Northern climates.

It is also found that the heat transfer in the heat recovery unit is influenced by the presence of the sorption collector. When the sorption collector is used in heating mode, the fresh air supply enters the heat recovery unit with higher temperature levels and thus the heat transfer within the recovery unit is reduced. A specular problem arises in cooling mode, but its effects are negligible in the studied climates because of the very low amount of recoverable cooling energy.

In general, the heating performance is enhanced in case of southern exposures because of the higher irradiation during wintertime. This leads to heating energy deliveries that are in average three times higher than for other orientations.

At lower latitudes (Rome), the heating demand is not a major problem, especially in office buildings. Here solar fractions SF_{heat} are much higher than in Stockholm or in Stuttgart as the low heating load can be easily covered with renewables. Conversely, average SF_{heat} values do not exceed 8% in Stuttgart and 4% in Stockholm.

ID	Scenario		Rome			Stuttgart			Stockholm		
Nr. [-]	Nr. [-]	Or. [-]	Q_{sc}^{heat} $\left[\frac{kWh}{m^2y}\right]$	Q_{hc} $\left[\frac{kWh}{m^2y}\right]$	SF_{heat} [%]	Q_{sc}^{heat} $\left[\frac{kWh}{m^2y}\right]$	Q_{hc} $\left[\frac{kWh}{m^2y}\right]$	SF_{heat} [%]	Q_{sc}^{heat} $\left[\frac{kWh}{m^2y}\right]$	Q_{hc} $\left[\frac{kWh}{m^2y}\right]$	SF_{heat} [%]
1	1	E	0.39	8.26	5	0.39	29.2	1	0.45	42.7	1
2	1	S	1.08	3.74	22	1.37	23.6	5	1.13	36.4	3
3	1	W	0.34	8.17	4	0.44	28.4	2	0.47	42.4	1
4	2	E	0.09	0.62	12	0.12	3.8	3	0.09	8.6	1
5	2	S	0.10	0.03	74	0.37	1.7	18	0.33	5.2	6
6	2	W	0.07	0.62	10	0.07	3.5	2	0.10	8.6	1
7	3	E	0.74	5.42	12	0.72	20.4	3	0.75	30.2	2
8	3	S	1.92	2.41	44	2.75	16.3	14	2.35	25.9	8
9	3	W	0.69	5.39	11	0.82	19.9	4	1.01	30.0	3
10	4	E	0.22	0.98	19	0.32	5.4	6	0.29	10.2	3
11	4	S	0.37	0.20	65	1.24	3.2	28	1.09	7.3	13
12	4	W	0.23	0.96	20	0.30	5.1	6	0.30	10.2	3

Table 4: Simulation results for heating mode in different climates (Rome, Stuttgart and Stockholm), orientations (East, South and West) and building setup (1-4, see Table 3).

4.3 Cooling performance

As shown in Table 5, the yearly cooling performance of the system is strictly connected to local weather conditions. Cooling loads covered by the coil vary in average from 20 kWh/(m^{2}y) in Rome to 2.4 kWh/(m^{2}y) in Stockholm. The contribution of the sorption collector decreases as well with trends that depend on the orientation.

Desorption and absorption cycles are strongly related to the Sun path and the activation pattern of the ventilation unit, other than the cooling demand of the building. The best conditions to maximize the cooling deliveries are verified in the first place when sorption collectors are able to fully exploit the strong solar radiation available throughout the day to run the desorption process. This means that the ventilation unit must be running in this timeframe, as desorption can effectively take place only with heat rejection at the CEx. In the second place, the sorption collector should deliver the cooling power to the fresh air before the end of the working day so to effectively cover the cooling load and prevent the unfruitful nocturnal discharge of the sorption collector.

In Stockholm, East-oriented collectors do not exploit the early-morning solar radiation since the AHU unit is not running until the start of the working day. Conversely, West-oriented sorption collectors deliver cooling power in the evening, when the cooling load is lower, while the water coil works more intensively during the day. In both cases, the overall performance is worse if compared with southern orientations.

At lower latitudes (Rome), South-oriented facades are characterized by sensibly lower performance with respect to other orientations because of the higher incidence angles of the solar radiation during summer. East-oriented facades experience optimal working conditions (see above) since the strong solar radiation can be well exploited to charge the collector and the cooling delivery occurs in the afternoon.

The solar fraction SF_{cool} ranges 37-62% in Rome, 58-84% in Stuttgart and 69-91% in Stockholm. These results are achieved thanks to the synergic combination of the sorption collectors and the adoption of a free cooling strategy. The contribution Q_{free}^{cool} is larger than the cooling delivery of the sorption collector except for a few cases. The weight of free cooling increases with higher latitudes (Stockholm) and cooling demand.

For all climates and orientations, a lower WWR and a larger collector area significantly decrease the cooling coil energy deliveries, leading to higher values of SF_{cool}. This is due to both a greater contribution of the sorption collectors and lower solar gains in the case of lower WWR. Although the two glazing typologies have similar g-value, the installation of Glazing #2 leads in general higher Q_{sc}^{cool} values as the higher levels of insulation increase the cooling load.

ID	Scenario		Rome				Stuttgart				Stockholm			
Nr.	Nr.	Or.	Q_{sc}^{cool}	Q_{free}^{cool}	Q_{cc}	SF_{cool}	Q_{sc}^{cool}	Q_{free}^{cool}	Q_{cc}	SF_{cool}	Q_{sc}^{cool}	Q_{free}^{cool}	Q_{cc}	SF_{cool}
[-]	[-]	[-]	$\left[\frac{kWh}{m^2y}\right]$	$\left[\frac{kWh}{m^2y}\right]$	$\left[\frac{kWh}{m^2y}\right]$	[%]	$\left[\frac{kWh}{m^2y}\right]$	$\left[\frac{kWh}{m^2y}\right]$	$\left[\frac{kWh}{m^2y}\right]$	[%]	$\left[\frac{kWh}{m^2y}\right]$	$\left[\frac{kWh}{m^2y}\right]$	$\left[\frac{kWh}{m^2y}\right]$	[%]
1	1	E	6.5	11.0	20.0	47	2.8	6.7	4.0	71	1.7	6.1	1.8	81
2	1	S	5.0	7.2	17.6	41	2.2	4.3	3.4	66	2.6	3.6	1.4	81
3	1	W	6.3	7.8	23.5	37	2.3	5.8	5.9	58	2.0	4.9	3.1	69
4	2	E	7.2	21.3	24.6	54	3.4	19.3	7.1	76	2.8	18.1	3.9	84
5	2	S	6.8	17.1	23.2	51	3.2	16.3	6.9	74	3.8	14.9	3.7	84
6	2	W	7.2	16.8	29.3	45	3.1	17.7	10.0	68	2.8	16.2	6.1	75
7	3	E	10.2	8.4	13.1	59	4.2	4.9	1.9	83	2.5	4.3	0.7	91
8	3	S	6.9	6.1	13.8	49	3.1	3.4	2.3	74	3.3	2.4	0.8	88
9	3	W	9.6	4.9	17.4	45	3.1	4.2	3.9	65	2.7	3.4	1.6	79
10	4	E	11.0	13.8	15.0	62	5.1	10.8	3.0	84	3.6	9.8	1.3	91
11	4	S	8.6	10.7	16.7	54	4.1	8.7	3.8	77	4.5	7.2	1.6	88
12	4	W	10.5	9.1	20.4	49	3.8	10.1	5.4	72	3.5	8.9	2.7	82

Table 5: Simulation results for cooling mode in different climates (Rome, Stuttgart and Stockholm), orientations (East, South and West) and building setup (1-4, see Table 3).

5. Conclusion

The development of this façade concept represents an interesting plug-and-play solution for new and refurbished office buildings from many points of view. It offers heating and cooling power and the hygienic air change through a compact decentralized ventilation system. The installation of the sorption collector pre-heats or pre-cools the airflow through renewable thermal energy. Moreover, the integration of a decentralized ventilation system in the building façade allows to avoid the installation of air ducts in the false ceiling and in technical rooms, leading to higher net living floor area.

The performance of the analysed energy system is significantly influenced by the façade design, orientation and climate conditions. Considering the cooling working mode, simulations show promising results as the cooling load covered by traditional energy generation system is reduced by up to 62% in Rome, 84% in Stuttgart and 91% in Stockholm. Less encouraging results are achieved considering the heating working mode, with average solar fraction SF_{heat} of 25% in Rome, 8% Stuttgart and 4% in Stockholm.

The synergic combination of ventilation unit and sorption collectors leads in most cases to favourable results. Nevertheless, in the current layout the share of heating and cooling load covered by the sorption collectors might compete with the heat recovered by the ventilation unit. This reduces the energy performance of the sorption collector, as presented above.

It should be underlined that the façade-integrated solution is still being studied as prototype and therefore an in-depth economic analysis should be conducted in future in order to evaluate the marketability of the solution in comparison with existing standard façades.

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