E3S Web of Conferences **172**, 09007 (2020) http://doi.org/10.1051/e3sconf/202017209007
NSB 2020

Curtain Wall with Solar Preheating of Ventilation Air. Full Scale Experimental Assessment

Roberto Garay-Martinez[1,*], Beñat Arregi[1]

[1]TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo bidea 700, 48160, Derio, Spain

Abstract. Heating load in Commercial buildings is highly related with ventilation systems, while at the same time local discomfort in the vicinity of glass walls occurs due to overheating. In this paper, a novel double envelope curtain wall is presented, which extracts heat from the façade by means of a ventilated cavity which is then incorporated to the ventilation air intake. A substantial reduction of heating loads is achieved. Whenever solar gains are not sought, a bypass element allows the natural ventilation of this air cavity, acting as a ventilated façade. An integrated control system with embedded electronics and actuators allows for a smart control of the system. The system is designed for integration with existing rooftop ventilation systems. Design considerations are discussed, and the outcomes of a full-scale experiment conducted in Bilbao (Spain) along 2019 presented.

1 Introduction

European policy and regulations aim at a substantial reduction of greenhouse gas emissions and primary energy use, as well as an increased share of renewable energy [1]. The construction sector is considered to have a great improvement potential, considering that energy use in buildings is 40% of the energy consumption of the EU [2].

Also, indoor air quality issues are increasingly relevant due to greater scientific knowledge and improved airtightness. This has led to increased requirements for ventilation and indoor air quality in national regulations, and the increase of heat loads in buildings.

In a context with increased envelope insulation and airtightness, ventilation energy losses become much more significant, yielding up to 50% of space heating or cooling needs in some cases. Considering greater human density in these buildings, office and commercial buildings have traditionally been more intensive in energy use for ventilation.

Although implementations of curtain walls in commercial buildings have been relatively common in the last 50-70 years, glazed envelopes are an increasingly popular envelope system in these buildings. In fact, adoption of glazed façades is increasingly common in public buildings, and even for high-end residential projects.

The energy performance of the average curtain wall is commonly insufficient, with high transmission heat loss in winter and overheating problems in summer. Modern components such as additional glass panes, gas-filled cavities, low emissivity coatings and thermally broken framing elements have been developed to partially mitigate these problems.

Also, comfort-related issues are reported by building occupants in the vicinity of glazed envelopes. Low surface temperatures in winter periods and direct solar radiation or high surface temperatures during irradiated periods and hot periods are known issues of these systems.

Considered the exposed twofold issue with energy use and comfort , a technical solution is proposed, where a double envelope curtain wall (DECW) is used to pre-heat ventilation air.

This system reduces radiant asymmetries and occupant discomfort due to greater heat absorption in the glass, and delivery to a ventilated cavity. The cavity is connected to the intake of and Air Handling Unit (AHU).

The effect of the system is threefold:

- With regards to heat and shortwave radiation exchange in the building envelope, the DECW substantially reduces local overheating in the vicinity of the building envelope. The double-glazing configuration with the ventilated cavity produces a highly solar-selective envelope, which is cooled down by the ventilation air.
- With regards to the distribution of captured heat throughout the building, it is now distributed by means of the ventilation system. Thus, it allows to re-distribute heat to colder areas in the building (i.e. areas close to not sun-exposed façades).
- The absorbed heat also reduces the heating load of buildings. The DECW system performs an initial temperature increase and reduces the required heat input to the ventilation stream at the air handling unit.

* Corresponding author: roberto.garay@tecnalia.com

The presented system is in line with previous research in multiple-skin building envelopes [3], solar radiation in curtain walls & glazed envelopes [4], solar energy utilisation in ventilated cavities [5-7] and double envelope systems or atria.

The proposed solution presents several differences from other previously existing systems. With regards to its architectural concept, it is designed and constructed as a slim system, adaptable to state-of-the-art curtain wall design and construction methods. With regards to its ventilation and energy interaction with the building, this system differentiates from others in its configuration as a primary air system, in serial connection with the AHU, where the cavity is continuous for the full façade height.

To the authors' belief, the system allows for an immediate use of solar gains and, contrary to more complex active façades, it requires neither connection with intricate hydraulic circuits nor the use of additional products or materials with thermal storage capabilities.

This paper presents the system concept, design criteria for the selection of glazed panes, sizing of ventilation flows and connection to the AHU.

An experimental assessment of the concept is presented. In this experimental campaign, a 2-storey-high curtain wall system was constructed and installed into a purpose-specific temporary building. Experimental works were conducted in the vicinity of the KUBIK by Tecnalia [8] test facility, close to Bilbao, Spain.

This location classifies as Cfa under the Koppen-Geiger climate classification and presents roughly yearly 1000 HDD_15 and 200 CDD_20 [9]. According to the same source the daily average solar radiation exceeds 3kW/m2 on 7 consecutive months in the year.

The experimental campaign was performed during the 2019 spring-autumn period. Although there is only minimal heating load in those periods, the actual experimental results were used to calibrate climate-dependent performance indicators, to project such data into colder periods in the year.

2 Definition of curtain wall system & integration in HVAC systems

The DECW is a curtain wall system comprising two glazing units. In between these units, a continuous cavity is generated along the full façade height.

The cavity is used to capture solar heat and recover transmission losses from the indoor space.

The curtain wall is based on a modular concept, achieving both aesthetic and functional integration with the main ventilation system of the building.

The cavity is open to the exterior in its lower end (e.g. ground level) and connected to an air handling unit in its upper end (roof).

A schematic of the system is depicted in Fig. 1 for heating mode.

Ventilation air gets into the system from its lower end and is directed to the Air handling unit through the vertically connected cavity. The air is heated as it rises, primarily by incident radiation from the sun, but also from heat transmitted through the inner glazing (winter periods with low solar radiation). The conditioned air is collected into a plenum at parapet level and supplied to the ventilation system.

A set of dampers at roof level allow to by-pass the cavity, as well as to exhaust excess heat from the cavity. Although not the primary function of the system, these dampers allow for the safe operation of the system and prevents hot air to be fed to the building during cooling periods. When the by-pass is active, the following airflows are allowed by the system:

• Fresh air intake (not pre-heated) is connected to the Air Handling Unit. Thus, cooler air is made available, not to rise cooling needs.

• The DECW plenum is opened to the atmosphere, so that it is cooled down by means on natural convection.

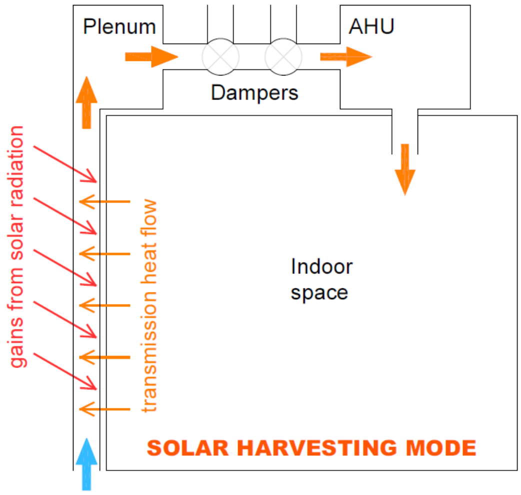

Fig. 1. Schematics of system operation in solar harvesting mode.

The composition of the glazed units has been optimized for solar heat gain into the cavity. It consists of the following units:

• Single glazing to the external side, in order to maximise solar gains,

• Double glazing with a low-emissivity coating to the cavity side, to prevent heat loss from indoor air and deliver the solar gains within the cavity air.

Hygienic issues are considered twofold:

• Filters are installed at the bottom edge of the DECW, in a location with ease of access for cleaning, maintenance & substitution.

• Specific panes (ca. 1/3 of the total surface) can be opened from the internal side for maintenance & cleaning activities.

The design of the system is presented with greater detail in a previous publication [10].

3 Design criteria

The design of the DECW proposed in this paper differs from traditional CW system in a set of issues which need to be considered.

With regards of the calculation for the thermal insulation of the building, and accomplishment of requirements as stated in building codes, the authors

http://doi.org/10.1051/e3sconf/202017209007

consider that the cavity should be considered as a well-ventilated cavity, and no thermal resistance should be considered with regards to the cavity and the external glass pane. This leads to a design where the U-value of the curtain wall is specified by the inner glazed unit. With regards to the avoidance of surface condensation, similar considerations should be taken.

With regards to the selection of the location for Low-e coatings, these should be placed towards the cavity, in order to avoid local discomfort and maximize solar heat capture in the cavity. The outer shell should not be too absorbing to avoid heat loss to the ambient.

The sizing of the cavity should be made considering limitations to air speed in ventilation systems, thus airspeed in the range of 2m/s should be considered as a maximum air flow. This is not considered to be a critical issue for large DECW systems, as the large envelope width allows for large ventilation flows in relatively slim configurations.

With regards to air quality and maintenance, the design considers the use of filters in the lower edge of the DECW. This location is considered as the optimal to minimize the introduction of pollution/dust into the cavity and facilitate filter cleaning & replacement processes. In any case, some of the inner panes of the DECW should be openable for cleaning processes.

4 Experimental setup

A full-scale prototype was constructed and installed in a purpose-specific building.

The DECW prototype was composed by a 3x2 module setup. 2 modules were connected in vertical/serial arrangement, and a total of 3 cavities were generated. A total prototype area of 14.8 m^2 was installed.

Details on glazing properties and cavities can be found in Table 1 below.

Table 1. DECW composition.

Item	Details
External glazing	Monolithic, 8mm
Cavity	140mm
Internal glazing	8-16-4.4, filled with Argon

The DECW was connected to an AHU. The AHU was equipped with a variable speed fan and an electric heating coil with several heating levels.

The ventilation air was introduced into a 30.5 m^3 room on the ground floor, in direct contact with the DECW. Considering the physical setup presents a large DECW to volume ratio, ventilation rates were set to be representative of a much larger building. The effective ventilation rate was set at 683 m^3/h. Although an excessive ventilation rate a small room, it allowed to assess the effect of such a system under a (more-realistic) building with a much deeper form factor. The ventilation rate was considered to be reasonable of a building with a 25 m depth.

The setup was located in the vicinity of the KUBIK by Tecnalia test facility [8] in Derio, Spain. Although an independent setup, the weather station and part of the hardware of the control system in the facility was used for convenience.

Fig. 2. Test setup.

5 Experimental campaign & appartus

An experimental campaign was initiated in June 2019. The campaign is ongoing, but experimental results as of November 2019 are presented.

The experimental campaign has been designed to identify the performance of the system for various outdoor & indoor temperature, as well as for solar radiation levels.

For this purpose, the following information was recorded:

- Outdoor temperature
- Indoor temperature
- Temperature in the cavities, at two heights
- Temperature at the outlet of the cavities
- Temperature at the inlet of the AHU
- Temperature at the outlet of the AHU
- Ventilation airspeed
- Electric consumption of the AHU

Temperature records were performed by means of Pt100 sensors, with typical accuracy +-0.2ºC.

Electric consumption of the AHU was performed by means of network analysers, with typical accuracy +-0.5%. Electric measurements considered both ventilation fans and in-line electric heaters.

With regards to ventilation airspeed, and associated measurement such as output power of the DECW, ventilation airspeed was calibrated against the electric consumption of the fan in the AHU as per eq (1) below. By doing so typical measurement errors associated to unsteady airflow and variable density in ducts was avoided. This correlation was validated along relevant periods at the initiation of the experimental campaign, with variable fan energy consumption & inlet temperatures.

$$v \sim C * P_{elec\_Fan} \quad (1)$$

Sun-exposed sensors were shielded against direct solar radiation. Indoor temperature sensors were shielded against radiation with double radiation shields. The location of indoor temperature sensors was selected to adequately represent indoor temperature, avoiding direct placement in the ventilation stream or incorrect placement in corner areas.

Data from solar radiation and windspeed sensors installed in the KUBIK by Tecnalia were used in this study.

6 Results

From the experimental campaign, several relevant data have been extracted and analysed.

An initial output can be taken from the free-floating levels of the indoor temperature. When ventilation air was circulated through the DECW, indoor temperatures were found to be higher even with low solar radiation, as shown in fig. 3.

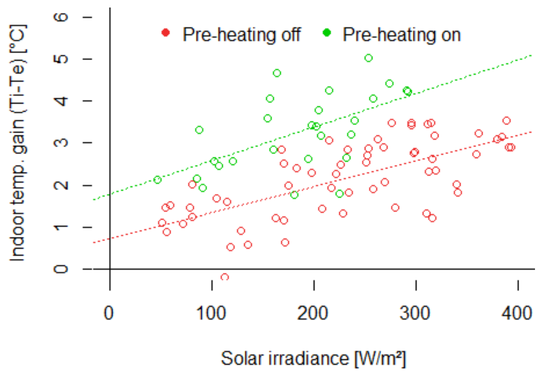

Fig. 3. Daily averaged indoor-outdoor temperature gain, with and without pre-heating of ventilation air.

In terms of heat gain when the DECW is active, radiation-dependent temperature gains were observed in the range of 5 to 15 ºC in the cavity outlet. Fig. 4 presents the output temperature of the cavity against inlet/ambient temperature.

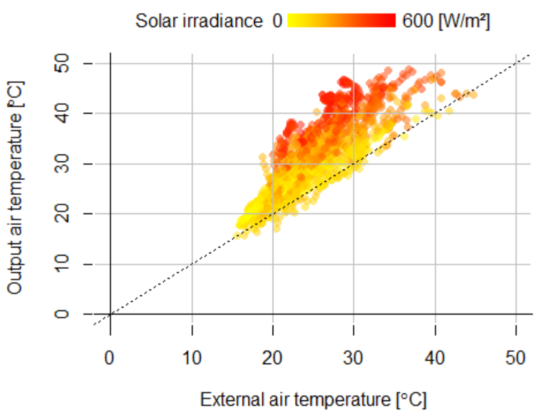

Fig. 4. Inlet-outlet temperature gain in the cavity.

In fact the output power (vertical axis in fig. 5) is affected by both external temperature (horizontal axis) and solar irradiance (colour scale, from yellow to red). A higher output power is achieved for both high indoor-outdoor temperature differences and high solar irradiation. This can be seen in fig. 5.

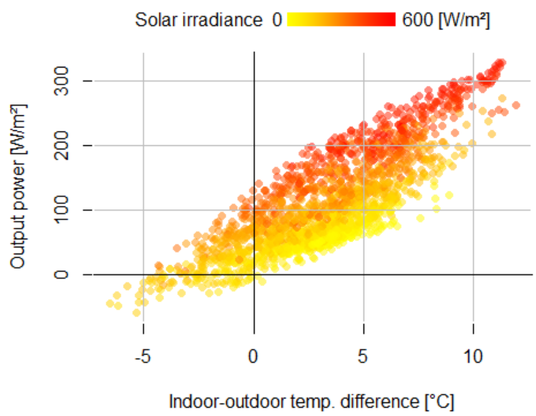

Fig. 5. Output power in the cavity vs Indoor-outdoor temperature difference. Hourly-averaged values.

In fig. 6, the ambient conditions are represented by the position of each data point (indoor-outdoor temperature difference on x axis and solar irradiation on y axis), while the output power is expressed through colour and the dashed lines. The latter indicate that the output power can be expressed as a linear function of temperature and solar irradiance.

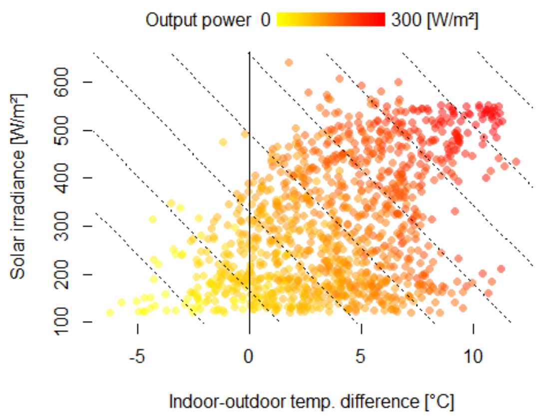

Fig. 6. Output power as a function of solar irradiance and temperature difference. Hourly-averaged values.

Based on the data from the test campaign, linear correlations were calibrated for the output power and system performance with regards to bounding temperatures and solar irradiation.

$$P = 0.304 * I + 14.54 * (Ti\text{-}Te) \quad (2)$$

$$\eta = 0.304 + 14.54 * (Ti\text{-}Te)/I \quad (3)$$

These parameters were obtained for the specific DECW area, ventilation airflow and building size of the test setup, which are described in Section 4. A graphic representation of eq. (3) is presented in fig. 7. The dashed line indicates the linear regression fit, and the circle represents the average condition during the whole test campaign.

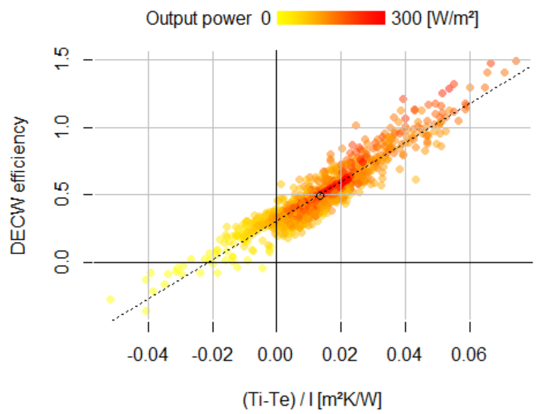

Fig. 7. Efficiency of the solar collector as defined in eq (3). Hourly-averaged values

8. Discussion & Conclusions

In this paper a DECW system is presented, for integration with ventilation systems in buildings. The system concept is presented, along with design considerations. A successful prototyping and experimentation process is presented, which is reflected in operational data over an ongoing experiment. The performance of the system is assessed based on the initial 4 months of data.

The integration performed with the ventilation system is considered to be simple and reliable as it is performed by means of common ducting elements at roof level. Thus, the system is considered to be easy to maintain.

The system reduces the temperature difference between outdoor air and the temperature setpoint of the AHU, thus reducing the energy loads due to ventilation. Although this is a beneficial effect, the design of the overall system should be done with care so that the design criteria for heat recovery steps in the AHU is revisited under this new environment.

The outcome of the experimental campaign shows that glazed envelopes allow for the use of solar heat in the passive heating of buildings. Even in moments where the air in the cavity was not circulated to the inside, the experimental setup showed an increased indoor temperature due to the effect of the sun.

But of course, this effect has been found to be greater in the case of the use of the DECW for the pre-heating of ventilation air. Temperature gains in the range of 3-4 ºC are achieved under medium insolation levels (200-300W/m2).

The output power of the DECW is in the range of 100 to 300 W per m2 of façade. It should be considered that these power levels are in the range or larger of heating terminal units commonly installed in the vicinity of glazed envelopes. Thus, a relevant use of the solar heat is achieved.

The performance of the DECW system as a solar collector can be identified in the intercept of eq. (2). A 30% of performance is achieved. Although this is a medium-level performance (commonly, solar thermal system performance level is in the range of 0.7-0.9), it is important to notice that this performance does not deteriorate with the temperature difference with the outdoor. It actually occurs the opposite way. The performance improves for greater indoor-outdoor temperature differences, as the DECW reduces convection losses to the outdoor, by capturing them into the inbound ventilation airflow. Actually, performance levels greater than 1 are achieved for cases with large temperature indoor-outdoor differences and low irradiance due to a very efficient capture of convection losses in the cavity.

Also, the proposed system delivers heat at comfort conditions, as opposed to other solar systems, which deliver heat at Space heating or Domestic Hot Water temperature levels (45-65ºC). By doing so, DECW performance is in line with typical values for other solar systems.

Considering the limitations of the experimental campaign reported in this paper. The outcomes of this research are being complemented with validation campaigns along 2020, whose outcomes are not yet available.

Also, more detailed analysis of avoidance of summer overheating due to the possibilities to evacuate the captured heat through the plenum needs to be better assessed. This is not fully possible by experimental means, considering that no alternative setup (without DECW) was installed, but can potentially be performed by means of numerical simulation.

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