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EXPERIMENTAL MONITORING OF AUTONOMOUS CURTAIN WALLING FACADE MODULE

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Abstract. This paper introduces an innovative concept for active wall-curtain façade modules aiming at high level of energy autonomy. The façade module consists of two opaque panels and one transparent panel integrating building integrated photovoltaics supported by façade integrated battery Peltier air-conditioning unit, active shading, and LED lighting. The developed demo-protype was deployed at testing facility and subjected to long-term experimental monitoring to assess the energy performance in real environment. The complex monitoring system captured key power and thermal fluxes, temperatures, mass flows and other operational states of the active wall-curtain façade modules. These measurements were assessed in form of monthly overview depicting total electricity consumption, on-site energy production, heating and cooling delivery as well as self-sufficiency and self-consumption indicators.

Keywords: Active facades, energy autonomy, BIPV, in-façade energy systems, Peltier air-conditioning.

1. Introduction

The EU committed in the European Green Deal to decarbonize the building sector by 2050 [1]. However, according to BPIE [2], over 97 % of buildings around EU have to undergo the retrofit to achieve this vision. They also stated that 75 % of the building stock are built before 1990 in outdated envelope standards leading to insufficient energy performance. This situation calls for high-performance façade solutions enabling to achieve nZEB standard for new or retrofitted buildings. The building envelope must cope with daily and seasonal variation in both interior and exterior environment due to the occupancy requirements and given weather conditions. However typical envelope has usually static properties, with lack of flexibility to reflect these variations or harvest the incident solar radiation.

This paper introduces compact façade solution embedding multiple energy systems within the wall-curtain façade module aiming at high level of energy autonomy. The current research proposes an innovative active façade solution integrating BIPV panels, flat battery, Peltier air-conditioning (AC) unit, active shading system and artificial lighting embedded into one direct current (DC) microsystem developed by Czech Technical University in Prague. This DC microsystem has been integrated into prefab curtain-walling module manufactured by Wieden s.r.o., the industry partner within the project.

The active façade solution may improve the local energy management, where the solar energy is locally utilized for the space-conditioning or other integrated energy systems. The current work represents experimental research, where the research institution and industry partner closely cooperated in the development of a demo-prototype of the active multi-functional façade curtain walling unit. The demo-prototype was deployed on testing facility located at the UCEEB, CTU in Prague (see in Figure 1) and energy behaviour of the façade unit is being monitored and tested in real environment. So far, the current version of the demo-prototype does not represent a marketable product. The presented façade unit is developed mainly for demonstration purposes of the compact in-façade solutions and embedded energy system cooperation. The development is still in progress to reach the marketable level, that the active curtain walling module, complies all required standards.

The demonstration façade unit is compounded from three main modules: an opaque module with BIPV and integrated flat-plate batteries, an opaque module with BIPV and façade integrated Peltier AC unit and a transparent module with BIPV and active shading device. The technical specification of these panels is provided in sections below. Hereunder, the applied technologies are briefly discussed.

The BIPV technology was utilized as a main source of energy to supply the active façade unit. This technology represents the best-practice building component, that has been already established at the market as a promising solution for building stock decarbonization. For further information, this technology has been already comprehensively reviewed in several publica-

Figure 1. Demonstration façade curtain walling unit deployed at testing facility.

tion e.g. recently in [3, 4]. The intermittent operation of the BIPV panels is in our concept supported by

(i) prioritizing the direct use by the other energy systems within the façade unit and then

(ii) storing the surplus energy in the flat-plate battery array integrated in the inner wall of the unit.

The battery integration into the facade has not been as heavily researched as BIPV. There are only limited literature sources available regarding such integration. E.g. Kim et al. [5] reported integration of a solar power bank for user appliances. The reason is likely due to several practical issues related with questionable fire safety as well as high sensitivity of battery performance for operational conditions. These practical issues were neglected in this research in order to arrive to a compact solution demonstrating the potential of the energy autonomous concept.

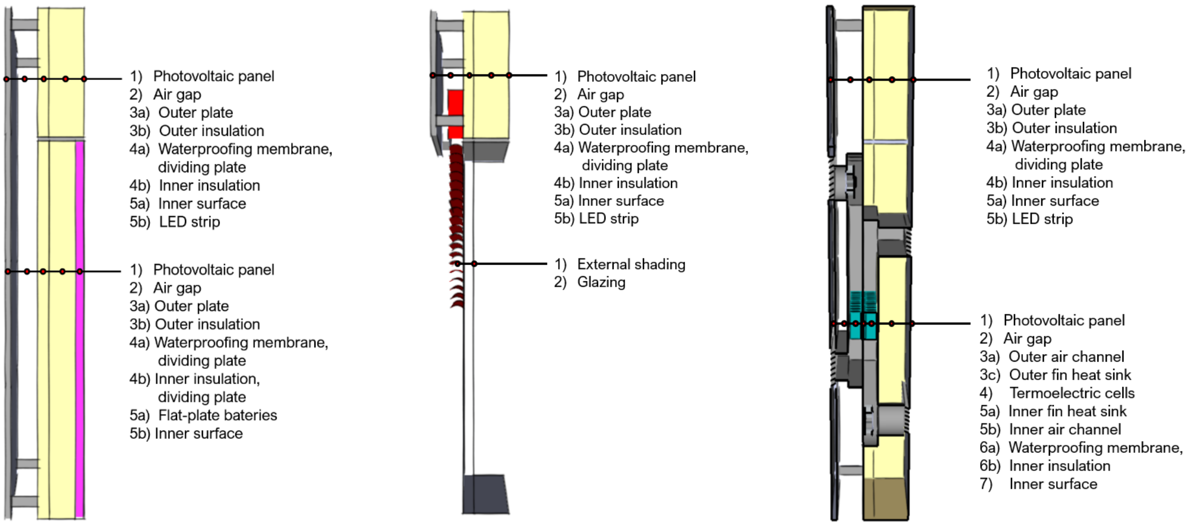
The next integrated system is façade integrated air-conditioning system. The design of façade unit assumes the integration of air-conditioning device into the curtain walling structure despite the fact, that the potential space for the unit is very limited. The conventional compressor systems cannot fit into the façade structure easily and vibro-acoustic properties together with limited possibilities for maintenance of mechanical components finally exclude such solution from design.

Peltier cells compiled from thermocouples can be regarded as promising alternative for such application. Peltier cells with use of electricity absorb heat on cold side of the thermocouple and reject the heat on hot side [6]. Such non-mechanical heat pump offers number of advantages such as minimal dimensions, no mechanical parts, no maintenance, no risk of leakage, suitability for direct current supply from PV system and simple control (heating and cooling mode based on electric current polarity). Compared to compressor system, lower efficiency and a limited temperature drop is referenced as main disadvantages [7, 8]. Peltier technology utilization in building technical systems has been researched in last decade and number of prototypes has been developed. The first Peltier system for heating and cooling purpose integrated into building façade has been developed in 2016 [7]. The combination of a façade-integrated Peltier air-conditioning device with PV system has been reported a year later [9].

2. Autonomous façade curtain walling unit design

2.1. Module 1: Building-integrated PV with flat battery

The section view of module 1 is depicted in Figure 2a. The BIPV panels are integrated into a standard design of curtain-walling unit structure. The thickness of the curtain walling unit together with ventilated cavity is about 400 mm. The allocated place for the flat battery is within the 25 mm thin cavity at the inner side. PV system consists of 8 polycrystalline panels considering 17 % efficiency with total peak power about 920 $\mathrm{W_p}$. The BIPV operation is supported by flat battery array accounting 2 sections, each with 8 $LiFePO_4$ battery cells. The nominal voltage of each cell is at 3.2 V and capacity 60 Ah. In total, the array is designed for maximum voltage 25.6 V and storage capacity of 3.1 kWh. In addition, the LED strip is located at the inner side.



(A). Module 1 with integrated flat-plate battery.

(B). Module 2 with glazing and active shading.

(C). Module 3 with façade integrated Peltier AC unit.

FIGURE 2. Unit design – section view of modules.

2.2. MODULE 2: GLAZING WITH EXTERNAL SHADING SYSTEM

The section view of module 2 is depicted in Figure 2b. This module represents transparent structure for natural daylight combined with mechanical shading system in the front of the large-format triple glazing. Servomotor for external louvers is powered by DC current. The shading system emplacement is covered by the PV panel. The shading system is controlled automatically by the embedded smart controller with respect to outdoor environment to prevent the high cooling load in summer season or harvest the solar gain in winter.

2.3. MODULE 3: FAÇADE INTEGRATED PELTIER AIR-CONDITIONING UNIT

The section view of module 3 is depicted in Figure 2c. This module is specific by the façade integrated air conditioning unit using Peltier cells. The space-conditioning is provided by 20 pcs of high-performance Peltier cells arranged in two rows with design cooling and heating capacity 640 W, 1280 W, respectively. The rows can be operated separately in two stage control manner. The nominal electric power load is assumed at 750 W. The heat is absorbed/removed from cell surfaces by finned heat sinks located at both side of the cells. The heat is then transferred to the air circulating in exterior and interior duct channels. The circulation of the air is provided by two variable speed control fans. The highest airflow is considered at 800 m^3/h. The entire AC unit fits into cavity with thickness of 165 mm.

Voltage polarity of Peltier cells defines the operation mode of AC unit (heating, cooling). The air from indoor space enters to the interior channel and cooled down is delivered back to the space. The extracted heat is rejected to the ambient environment through the hot side of Peltier cells via the exterior air channel. The operation in winter mode is reversed.

2.4. MONITORING SYSTEM

The demo-prototype is equipped with complex monitoring system. This system measures main energy flows within the embedded energy systems of the façade unit, outdoor and indoor climate conditions (temperature and relative humidity of the air, solar irradiance). The thermal output of the Peltier AC unit has been measured indirectly based on fan speed vs mass flow mapping and inlet-outlet temperature difference measured directly. The mapping was performed as one-at-time measurements using velocity probing. The outcome of this preparatory experiment was correlation curve between fan speed vs mass flow, that was further used in the energy performance assessment. In addition, the monitoring system as well as logged consumption of secondary heating and cooling systems in the testing facility. The secondary systems serve as back-up energy sources in case of limited heating or cooling capacity of the Peltier AC unit. The measured variables are listed in Table 1.

3. ENERGY PERFORMANCE ASSESSMENT

The demo-prototype was deployed at testing facility in September 2020. The installation was followed by commissioning period to configure the control and monitoring system. During commissioning period, a faulty behaviour of the on-site power system was found. The battery system was being overloaded every time, when the second stage of the Peltier AC unit was triggered. The electrical current required by Peltier cells exceeded the nominal level of the battery system.

Metering definition	Unit	Metering definition	Unit
Peltier cells consumption	kWh	Peltier AC unit inlet – interior	°C
Fans consumption	kWh	Peltier AC unit inlet – exterior	°C
Back-up heating consumption	kWh	Peltier AC unit outlet – interior	°C
Back-up cooling – fan consumption	kWh	Peltier AC unit inlet – exterior	°C
Monitoring system consumption	kWh	Back-up cooling – inlet water temperature	°C
LED lighting consumption	kWh	Back-up cooling – outlet water temperature	°C
Total electricity consumption	kWh	Back-up cooling – water mass flow	°C
PV production	kWh	Indoor temperature	°C
Battery supply	kWh	Indoor relative humidity	%
PV surplus metering via electric heater	kWh	Outdoor temperature	°C
		Outdoor relative humidity	%
		Solar irradiance on façade - exterior	W/m^2

Table 1. List of measured variables.

Year / Month	Missing data [%]	Total el. consumption [kWh$_{el}$]	PV system production [kWh$_{el}$]	Heating supply and coverage factor [kW$_{ht}$]	[%]	Cooling supply and coverage factor [kWh$_t$]	[%]
10/2020	3	268	nan	16	59	0.4	17
11/2020	0	322	24	24	71	0.0	N/A
12/2020	0	361	15	145	90	0.0	N/A
01/2021	17	352	21	192	95	0.0	N/A
02/2021	21	273	33	135	74	0.0	N/A
03/2021	2	278	43	136	96	0.8	100
04/2021	0	193	45	73	95	0.4	100
05/2021	0	102	49	13	75	0.0	N/A
06/2021	0	166	51	0	0	4.1	15
07/2021	0	48	42	0	55	0.1	100
08/2021	0	59	34	2	70	0.2	100
09/2021	0	44	25	3	80	0.0	N/A

Table 2. Energy performance of the façade module: monthly overview.

Thus, the presented results were obtained without using second stage of the AC unit.

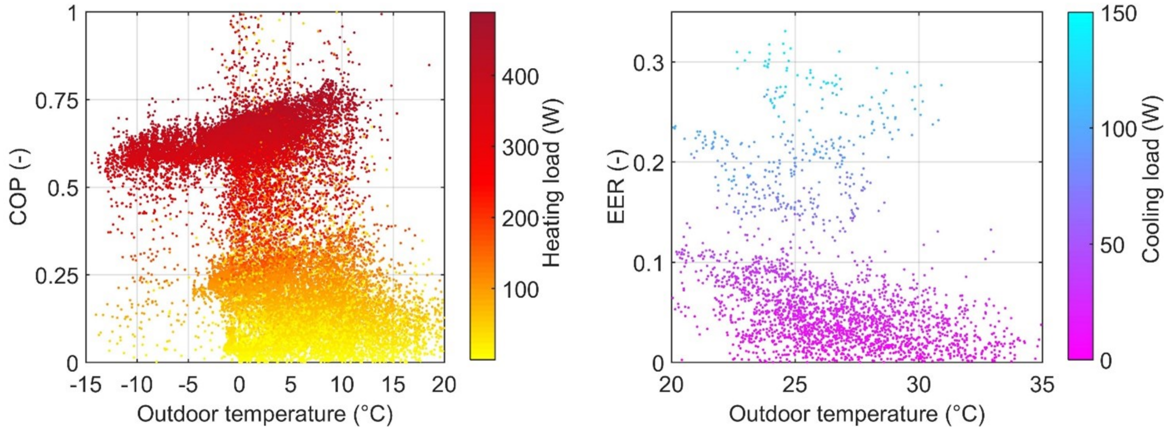
Regarding the operational regime, the heating setpoint of the Peltier AC unit was set to 21 °C. The cooling setpoint 27 °C to keep the indoor environment of the testing facility within this range. Flowrate through interior and exterior channel of Peltier AC unit were different for winter and summer operation. The winter flowrate was approx. 600 m^3/h (3800 rpm) for interior channel (fan) and approx. 300 m^3/h (1900 rpm) for exterior channel (fan). The summer flowrate was approx. 450 m^3/h (2800 rpm) for interior channel (fan) and approx. 650 m^3/h (4200 rpm) for exterior channel (fan). In this experiment, secondary energy sources were also in operation. The settings aim to switch on the secondary heat sources only if the Peltier AC unit reach its maximum capacity. Therefore, the heating setpoint was set at 18.5 °C and cooling setpoint was 28.5 °C. The resulted energy performance is depicted as monthly overview in Table 2. The table summarizes the total electrical consumption, measured PV system production and heating/cooling supply and associated coverage factor. Remark on share of missing data due to lost internet connection in January and February 2021 is also added.

The time-step of the monitoring data acquisition was 30 s and data were logged into cloud archive. Detailed energy balance has been monitored for period from October 2020 to September 2021. The PV system electricity production was not measured in October 2020 due to fault of the battery system. Various operation parameters have been adjusted within the monitoring and evaluation period. In November 2020, the winter flowrates for channels have been finally set. The summer flowrates for channels wre set in the beginning of May 2021. External mechanical shading was shut in June and the back-up system for cooling was switched off.

The level of autonomy and energy efficiency was further processed using following energy performance metric. Self-sufficiency SS indicator and self-consumption indicator SC were used to indicate the level of energy autonomy. Some literature denotes these indicators also as on-site energy fraction (OEF) and on-site energy matching (OEM). Indicators SS and SC are defined between 0 to 1, where SS indicates

Year / Month	Missing data [%]	SS [%]	SC [%]	SCOP [-]	max. COP [-]	SEER [-]	max. EER [-]
10/2020	3	N/A	N/A	0.08	0.99	0.34	0.39
11/2020	0	8	98	0.10	0.46	0.05	0.17
12/2020	0	4	100	0.46	2.16	N/A	N/A
01/2021	17	6	100	0.62	3.32	N/A	N/A
02/2021	21	12	1.0	0.57	1.13	N/A	N/A
03/2021	2	16	99	0.58	1.75	0.17	0.22
04/2021	0	24	99	0.46	1.91	0.20	0.24
05/2021	0	48	97	0.18	0.64	0.00	0.17
06/2021	0	31	99	0.16	0.38	0.05	0.33
07/2021	0	86	90	N/A	N/A	0.01	0.11
08/2021	0	56	91	0.08	0.26	0.01	0.11
09/2021	0	57	92	0.09	0.25	N/A	N/A

TABLE 3. Energy autonomy and efficiency: monthly overview.



(A). COP factor and heating load.

(B). EER factor and cooling load.

FIGURE 3. Peltier AC unit efficiency vs outdoor air temperature.

the portion of power consumption, that is covered by the on-site source and SC indicates the portion of generated energy from the on-site source that is used within the system, rather than exported or dumped.

The Peltier AC unit provides the heating and cooling in the testing facility. This device also represents the major electricity consumer of the active facade unit. Therefore, this study is focused on evaluation of the energy efficiency using COP for heating and EER for cooling. The monthly summary is shown in Table 3. This table contains timestamp, percentage of missing data, self-sufficiency and self-consumption indicators and COP and EER factors. COP and EER factors were evaluated in two forms:

(a) as ratio of "seasonal" (monthly) sum of thermal energy delivered/removed by the unit vs its electricity consumption accounted in kWh denoted as SCOP and SEER in Table 3 and

(b) as ratio of nominal heating/cooling load vs its power load accounted in W. Maximal values for given months are also depicted in Table 3 denoted as max. COP and max. EER.

Both forms (a) and (b) include fans power.

The efficiency of Peltier AC unit was further investigated with respect to outdoor air temperature. Figure 3 shows a scatter plot, where each dot represents a measured state for which COP or EER was evaluated related to outdoor temperature at the time of the measurements. In addition, each dot was coloured in scale representing the thermal load of the unit at the time of the measurements to give whole information regarding the energy performance of the Peltier AC unit. The maximum COP = 3.2 was reached January 2021. The maximum EER = 0.39 was obtained in October 2020 during the full load. The unit in part-load performed at considerably lower efficiency. The seasonal COP is between 0.46 and 0.62 for winter season and the seasonal EER is between 0.11 and 0.33 for summer season.

4. LESSONS LEARNED

After successful laboratory testing of functional samples, the demo-prototype of the façade curtain walling unit was designed, constructed, and deployed at testing-facility located at UCEEB (CTU) site, Buštěhrad. The energy performance of the façade unit was experimentally evaluated within one year long monitoring campaign to assess the façade curtain walling unit operation in the real environment. Hereunder, the presented results are summarized from perspective of:

(i) energy autonomy expressed by power self-sufficiency and self-consumption of the testing facility including local PV,

(ii) thermal demand coverage by the façade integrated Peltier unit,

(iii) efficiency in terms of COP and EER of Peltier unit (as main power consumer).

(a) In terms of energy autonomy, self-sufficiency during summer season and potential for solar assisted cooling has been evaluated. The highest self-sufficiency indicator was reached in July 2021, power load covered by the on-site energy generation was 87 % due to application of external shading. On the other side, high power self-sufficiency indicator in winter season was low, only around 10 % as indicated already in preliminary simulations.

(b) The thermal demand coverage was limited due to second stage disallowance in operation of the Peltier AC unit. The missing capacity was especially noticeable in cooling mode without shading. As an example, only about 15 % of cooling load in June 2021 was covered by the Peltier system. On the other hand, operation within the transition season or with use of external shading resulted in possibility to cover the demand of testing facility space and it reduced the hours of space overheating. Although the total capacity of the Peltier AC unit was half of originally assumed, the coverage of heating load was high at approximately 80 % in average during the whole winter season (from October 2020 to March 2021).

(c) Peltier AC unit performed bellow the expectations. Based on laboratory measurements, the COP was expected in range of 1.2 to 2 and the EER in range of 0.6 to 1. The unit in the real-life scenario could not reach the expected energy performance. The COP was found between 0.8 to 0.6 for nominal load and EER around between 0.1 to 0.2. The efficiency is worsened due to part-load operation as well as due to higher temperature difference between ambient and interior air temperature. The energy efficiency could be improved by several measures:

  (i) enabling the full-capacity,

  (ii) optimization of current-voltage settings of the Peltier,

  (iii) optimization of fan speed.

  Particularly the constant fan speed setting was found inappropriate. As first step, the variable fan speed control needs to be applied to reflect the regime of the unit and ambient temperature. The design of the optimized fan control is the ongoing work.

To conclude, this paper introduced demo-prototype of active façade curtain walling unit, that integrates various energy systems. The demo prototype was successfully deployed at testing facility and long-term monitoring campaign was executed. The detailed monitoring system allowed to assess the level of energy autonomy and energy performance of the innovative façade components.

Acknowledgements

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