Design and Testing of Autonomous Curtain Walling Façade Unit

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Abstract

This paper presents an innovative concept of autonomous unitized curtain walling façade with integrated functions of heating, cooling, lighting, shading as well as renewable energy generation (photovoltaics) and storage (battery) within the façade system. The autonomous unitized façade unit has been designed, manufactured and tested in real environment. The façade unit achieves high level of autonomy in summer when solar shading is applied even though the efficiency of thermoelectric cooling resulted in significantly lower values than predicted.

Keywords: photovoltaics, thermoelectric cooling, Peltier cooling, curtain walling façade

1. Introduction

In most applications the prefabricated unitized curtain walling façades are passive elements which ensure thermal resistance between indoor and outdoor environment and solar shading of transparent parts. Efforts for increasing of renewable energy supply in buildings result in application of building integrated photovoltaic (PV) systems (Shukla et al., 2017). Advanced solutions of adaptive façades with various mechanical, electrical, thermal or chemical concepts have been investigated for last decade but the implementation in practice represents a challenging task (Loonen et al., 2017). The presented autonomous concept of curtain walling façade integrates in-façade thermoelectric air-conditioning unit together with renewable energy system consisting of PV panels and flat-plate battery within the façade structure. The target is to achieve a high degree of self-sufficiency in the energy balance for thermal conditioning of indoor space adjacent to façade (Zavrel, V. et al., 2019), especially in summer season for solar cooling. The demonstration unit for autonomous operation has been designed and manufactured in collaboration with industrial partner and its energy performance has been monitored for one year at test cell in central Europe climate to provide indoor comfort (space heating and cooling).

2. Design of Autonomous Curtain Walling Façade Unit

The developed prototype of façade module with size 3,06 x 2,75 m consists of three parts: part (1) with Peltier air-conditioning (heating/cooling) unit, part (2) with flat-plate battery unit and part (3) with triple glazed window and shading device (see Fig. 1). The construction of curtain-wall structure has been designed according to the standards of industrial partner WIEDEN s.r.o. with total *U*-value in opaque part 0,152 W/m^{2}K. PV panels cover the whole available area of the module except the glazed part and air intake-exhaust openings. In total 8 polycrystalline PV panels are mounted at module considering efficiency 17,0 % with total peak power 920 W_p. Thickness of curtain walling unit assembly is 246 mm and the total thickness of the entire façade unit including ventilated cavity behind PV panels is 406 mm. To comply with the standard thickness of the curtain walling module structure was critical for the integration of energy components.

Part (1) of the façade module integrates the air-conditioning (AC) unit using thermoelectric Peltier elements. It was designed with 10+10 thermoelectric elements in two rows with considered operational cooling power 320 W each row (at operating point 12 V, 7 A). Only 10 elements were finally operated, rest of them were considered only as a back-up. The thermoelectric elements were thermally connected to fin heat exchangers at both so-called cold and hot sides of the elements. The remaining surface of the dividing plane between both sides is filled with immersed thermal insulation to eliminate the thermal bridging across the air channels. Fig. 2 (left) shows the

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aluminium heat exchangers coupled to thermoelectric elements within the AC unit. Air circulation in channels at both hot and cold side is provided by small radial fans with variable speed control. While maximum airflow of both fans was considered at 800 m^3/h, the speed levels of the exterior and interior fans were set differently for winter and summer regime. The winter regime was set at 3800 rpm (approx. 600 m^3/h) for interior fan and 1900 rpm (approx. 300 m^3/h) for exterior fan. The summer regime was set at 2800 rpm (aprox. 450 m^3/h) for interior fan and 4200 rpm (approx. 650 m^3/h) for exterior fan. AC unit can be operated in heating and cooling regime only by switching the polarity of the thermoelectric elements. In summer, the air from adjacent air-conditioned space enters the interior channel, where it is cooled down and delivered back to the conditioned space. The waste heat from the hot side of the thermoelectric elements is removed to the ambient environment via the exterior channel. The winter operation is reversed.

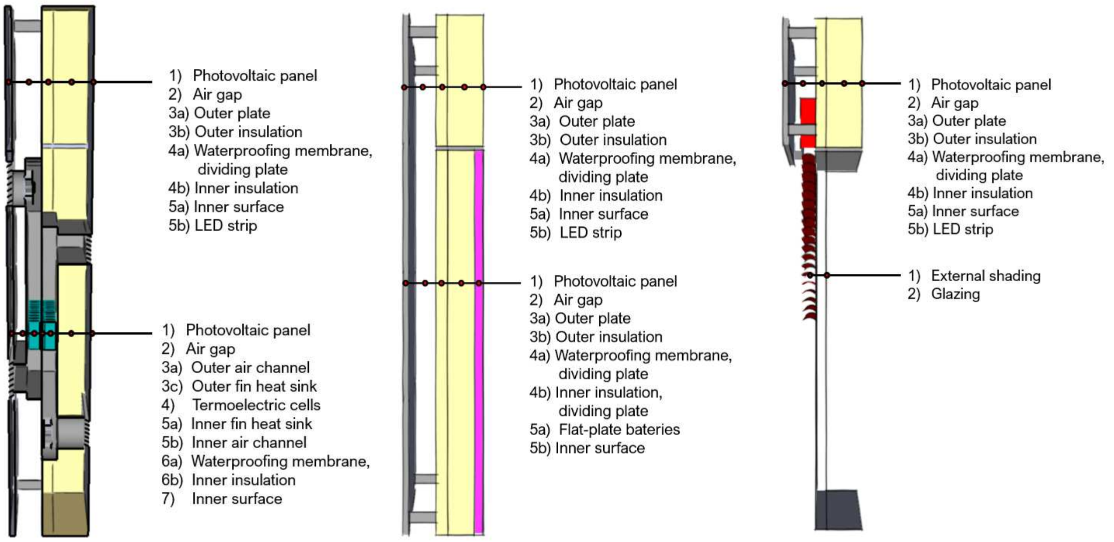

Fig. 1: Section view of three parts of autonomous curtain walling façade module covered by PV panels: (1) integrated AC unit with thermoelectric elements, (2) integrated flat-plate battery unit, (3) window with solar shading device

Fig. 2: Peltier AC unit with finned heat sinks (left), flat-plate battery layout (right)

Part (2) of the façade module reflects the standard layout of opaque curtain walling facade but it integrates a flat-plate battery unit in cavity at interior surface of the module. This location ensures satisfactory operational conditions as well as good access for the maintenance from the interior. The flat-plate battery unit is composed from 2 sections, each contains 8 LiFePO4 cells (3,2 V; 60 Ah), see Fig. 2 (right). The whole battery unit is only 25 mm thick and its nominal energy capacity is 3,1 kWh. Individual battery cells are connected to battery management systems to control uniform charging/discharging and monitoring of battery cells status. The whole system PV – battery – AC unit is connected into the direct current (DC) circuit and operated at nominal voltage 24 V.

Last part (3) of the façade module represents a standard glazed curtain walling structure with controllable shading system according to the standards of the industrial partner. The triple glazing unit (U_g = 0,5 W/m^2.K, g = 0,5) is applied to introduce a natural daylight into the adjacent space. The external louvers with servomotor powered by DC current were located in the upper part.

3. Testing and long-term monitoring

The manufactured façade module has been installed to a test cell (see Fig. 3) for demonstration of the function and monitoring of operation parameters in September 2020. The test cell is divided to air-conditioned space (with floor area 3 x 3 m and height 2,6 m) and technical room with auxiliary cooling and heating circuits, thermal storage and detailed monitoring equipment to evaluate the energy flows within the testing cell and the tested façade system. Conventional indoor air temperature settings have been used for control (21 °C for heating, 27 °C for cooling, hysteresis 1 K) of the thermoelectric AC unit. Auxiliary space cooling and heating systems have been operated with shifted settings (18,5 °C for heating, 28,5 °C for cooling, hysteresis 1 K) to evaluate the thermoelectric AC unit capacity to cover the space heating and cooling load. Auxiliary space cooling has been provided by water/air fan-coil supplied with chilled water. Electric fan-coil provided the auxiliary space heating. Ambient air temperature and solar irradiance have been monitored as outdoor climate conditions, indoor temperatures were monitored in several places for control and to obtain an information about capability of façade module to keep the required conditions in the air-conditioned room.

Fig. 3: Installation of autonomous curtain walling façade unit at test cell (CVUT UCEEB)

Energy balance of the system (PV and battery electricity supply, façade load, back-up energy demand) has been monitored in detail to evaluate on-site energy fraction (OEF) and on-site energy matching (OEM) indicators. The OEF indicator is defined as the ratio of energy production from the PV system (including the battery) which covers the total energy consumption of the façade module and expresses the solar fraction or self-sufficiency of the façade module. The OEM indicator represents the ratio of the energy from the PV system (including the battery) used for local consumption to the total production of PV energy and expresses self-consumption of façade module. Efficiency indicators for thermoelectric heating and cooling (AC unit) has been also evaluated, namely coefficient of performance (COP) and energy efficiency ratio (EER) as the ratio of heating or cooling output to electric power input. Beside the PV panels as a part of the façade module, electricity from grid has been used as for back-up in case that battery state of charge will drop under 20 %. Following power quantities were monitored:

- electric power supplied from PV panels;
- electric power supplied from flat-plate battery;
- battery state of charge;
- total electric load of facade module;
- excess PV power exported out of system (heating rod in water storage);
- electric load of thermoelectric elements (negative - cooling, positive - heating);
- electric load of fans;
- back-up electricity from grid;
- back-up heating power;
- back-up cooling power (based on water flowrate and temperatures);
- cooling and heating power of AC unit (based on air flowrate and temperatures in air ducts).

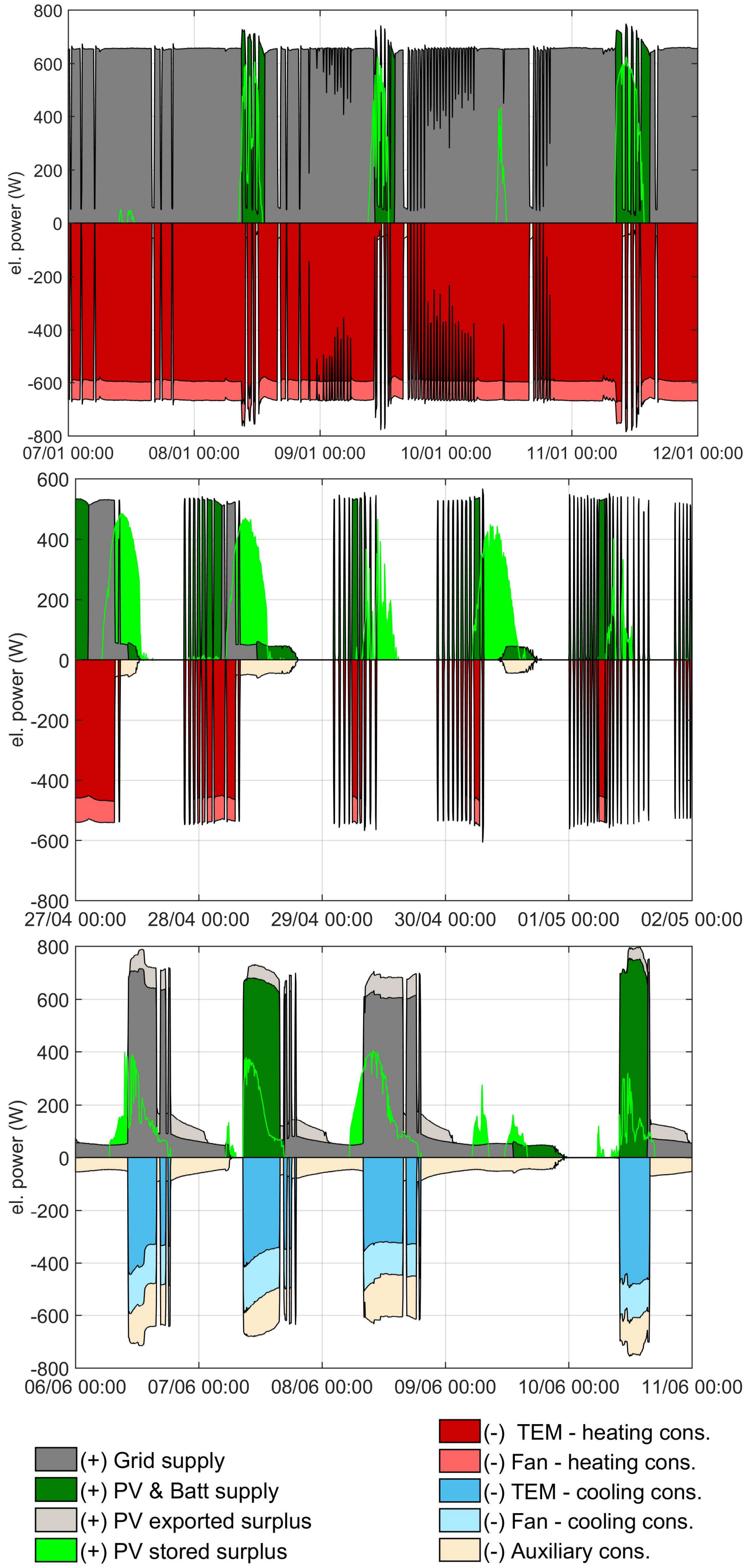

Fig. 4: Course of electric power (production, load) for selected days in winter, spring and summer

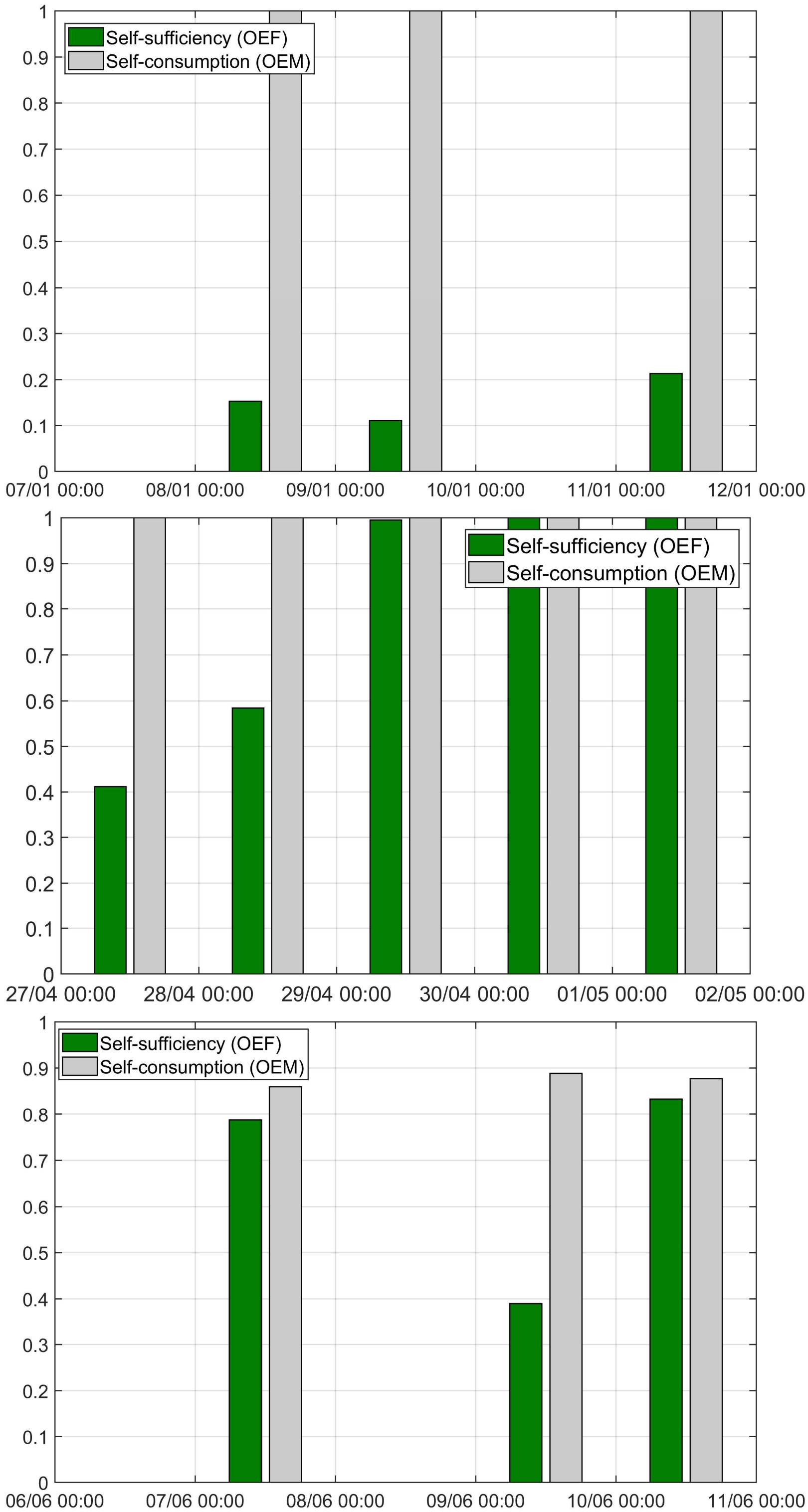

Fig. 5: OEF and OEM indicators for selected days in winter, spring and summer

The measurements have been taken with periodicity of half minute and logged to a cloud repository. Energy performance was evaluated from the measurements for period from October 2020 till September 2021. The PV production could not be measured in first month of the evaluation period due to fault of the battery system. During the long-term monitoring campaign, various manual interventions to the façade module operation were made. In November, the winter regime for fans was set after trial period, when various settings were tested. In January and February, the internet connection was lost for few weeks, that led to higher percentage of missing data. These part of monitoring data was not evaluated. In the beginning of May, the summer regime for fans was set. In the end of

June, the external shading has been applied and the auxiliary cooling system was switched off.

Data for a detailed evaluation have been selected from five working days, when the required temperature conditions were to be met, in three different periods (winter, spring, summer). Fig. 4 shows the course of power supplied and consumed by the curtain walling façade unit. Supplied electric power (production, with a positive sign) is differentiated according to the source: from the grid, supplied from the battery and at the same time the power of the PV system supplied to the battery, or excess power wasted by the electric heater in the heat storage tank. Measured surpluses in the storage tank represent the export of electric power back to the grid. Consumed electric power (load, with a negative sign) is differentiated according to the appliances: consumption of thermoelectric elements (TEM) and fans divided for heating or cooling purposes, and consumption of the power of other measurement and control components. Consumption of auxiliary heating and cooling is not included in the graphs.

In Fig. 5, the indicators OEF and OEM are expressed on daily basis for given periods. The autonomous curtain walling façade unit did not cover a relatively high cooling load with open blinds in the summer months with its cooling capacity and auxiliary cooling was necessary, however, in the case when blinds were used and in the transition period (spring) the results were significantly better. In terms of covering the electricity demand, the results were very good in the transition period and number of days in the summer showed a high degree of autonomy. In winter, due to the low production of the PV system, there is a high utilization of PV production (OEM), but naturally with a very low solar coverage (OEF).

A more detailed analysis of the results showed that the PV facade exposed to sunlight reaches relatively high temperatures around 50 to 60 °C, which causes a reduction in the useful cooling capacity of the AC unit adjacent to outer surface of the facade. Despite the efforts to avoid significant thermal bridges, too large dimensions of the AC unit do not allow to achieve a designed cooling capacity of around 320 W in real operation.

The summarized monthly results are presented in Table 1 which contains timestamp, percentage of missing data, monthly total electrical consumption and PV production as well as heating/cooling delivery and demand coverage. Table 2 shows the monthly values of indicators OEF and OEM and also monthly values of thermoelectric AC unit energy efficiency using COP for heating efficiency and EER for cooling efficiency.

Tab. 1: Energy balance of autonomous facade module

Year	Month	Missing data	Total el. load	PV production	Heating delivery and demand coverage		Cooling delivery and demand coverage	
[-]	[-]	[%]	[kWh_{el}]	[kWh_{el}]	[kWh_t]	[-]	[kWh_t]	[-]
2020	10	3	267,9	nan	15,8	0,59	0,4	0,17
2020	11	0	321,6	24,2	24,4	0,71	0,0	nan
2020	12	0	361,4	15,2	144,5	0,90	0,0	nan
2021	1	17	351,6	21,3	192,1	0,95	0,0	nan
2021	2	21	272,8	33,3	135,4	0,74	0,0	nan
2021	3	2	278,0	43,2	135,8	0,96	0,8	1,00
2021	4	0	192,9	44,9	73,3	0,95	0,4	1,00
2021	5	0	101,5	48,5	13,1	0,75	0,0	nan
2021	6	0	166,1	51,4	0,3	1,00	4,1	0,15
2021	7	0	47,9	41,7	0,2	0,55	0,1	1,00
2021	8	0	59,0	33,7	1,5	0,70	0,2	1,00
2021	9	0	44,2	25,4	2,8	0,80	0,0	nan

Tab. 2: Energy efficiency indicators

Year	Month	Missing data	OEF	OEM	COP		EER	
[-]	[-]	[%]	[-]	[-]	monthly [-]	max. [-]	monthly [-]	max. [-]
2020	10	3	nan	nan	0,08	0,99	0,34	0,39
2020	11	0	0,08	0,98	0,10	0,46	0,05	0,17
2020	12	0	0,04	1,00	0,46	2,16	nan	nan
2021	1	17	0,06	1,00	0,62	3,32	nan	nan
2021	2	21	0,12	1,00	0,57	1,13	nan	nan
2021	3	2	0,16	0,99	0,58	1,75	0,17	0,22
2021	4	0	0,24	0,99	0,46	1,91	0,20	0,24
2021	5	0	0,48	0,97	0,18	0,64	0,00	0,17
2021	6	0	0,31	0,99	0,16	0,38	0,05	0,33
2021	7	0	0,86	0,90	nan	nan	0,01	0,11
2021	8	0	0,56	0,91	0,08	0,26	0,01	0,11
2021	9	0	0,57	0,92	0,09	0,25	nan	nan

4. Conclusion

The energy performance of the unitized curtain walling façade unit designed with integrated energy components to achieve high autonomy was experimentally evaluated in the long-term monitoring campaign to evaluate the operation under real-life conditions. In terms of energy autonomy, the main focus was set on power self-sufficiency in summer season and on potential for so-called solar cooling. The maximum level of self-sufficiency was in July, when 86 % of the power load was covered by the on-site generation. The key factor here was an application of exterior shading, which led to significant reduction of cooling demand and related total electric consumption. The power self-sufficiency in winter season was not expected based on the preliminary calculations and the experiment proved the assumptions. The self-sufficiency in the winter season was only around 10 %.

Use of only 10 thermoelectric elements (nominal cooling power 320 W) was not satisfactory to cover peak cooling loads especially in case without shading. For example, in June only 15 % of cooling load was covered by Peltier AC unit system. Otherwise, in off-season or with external shading, the unit was able to cover the needs of the testing cell and reduce the overheating hours. Although the capacity was reduced, the heating demand coverage was relatively high during winter season (October till March) at approximately 80 % in average, but with electricity taken from the grid.

The Peltier AC unit performed below our expectations in term of energy efficiency. The COP was found between 0,8 to 0,6 (expectation from preliminary laboratory experiments was 1,2 to 2,0). The EER was determined around 0,1 to 0,2 (expectation 0,6 to 1,0). The efficiency is worsened with the reduced operation of the AC unit due to thermal bridges between hot and cold air channels resulting with higher value of temperature of cold air incoming to the room as well as with the thermoelectric elements efficiency reduced due to high temperature of exterior façade surface. The fan speed setting was found also inappropriate therefore the ongoing work will be focused mainly on the optimizing of fan control settings, elimination of thermal bridges and proper control of shading device.

5. Acknowledgments

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6. References

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