Experimental Assessment of the Façade-Integrated Thermoelectric Air-Conditioning Unit towards Development of the Autonomous Curtain Walling Module

T Matuška¹, V Zmrhal², V Zavřel² and P Slanina³

¹Czech Technical University in Prague, UCEEB, Czech Republic
²Czech Technical University in Prague, Faculty of Mechanical Engineering, Czech Republic
³SKANSKA a.s., Department of Curtain Walling and Facades, Czech Republic

Corresponding author’s e-mail: vojtech.zavrel@fs.cvut.cz

Abstract. This paper introduces an innovative concept for adaptive wall-curtain façade modules. The façade module integrates functions of heating, cooling, ventilation, lighting, shading as well as renewable energy storage and generation in order to enable autonomous adaptation of each individual façade module to local outdoor and indoor conditions. This paper is focused on the development of the façade-integrated air-conditioning system. Since the wall-curtain façade construction offers only limited space, the solution requires minimalistic size of the air-conditioning system. For this purpose, the application of thermoelectrical cells was investigated and the first prototype of thermoelectrical air-conditioning (mock-up) unit was developed and tested. This paper demonstrates the energy performance of the experimental setup and provides recommendations for further development process.

1. Introduction
In order to improve the building performance, an alternative approach of façades with adaptive physical properties has been researched for the last decade. The aim is to develop such an adaptive façade system, which actively responds upon the local outdoor and indoor conditions reaching desired energy and comfort outcomes. To enable the adaptive façade behaviour, various mechanical, electrical, thermal or chemical concepts have been investigated for past years, however any of these concepts has not yet been considered as mature technology. Despite of the theoretical benefits of adaptive approach, the implementation to practice represents a challenging task. Therefore, the end goal of the current research is to develop prefabricated façade module, which can be economically competitive with current façade systems. To arrive to the final result, the academic and industry partners closely cooperates in the development [1],[2],[3].

2. Concept of autonomous curtain walling façade module
Our concept is to apply the state-of-the-art technologies for heating, cooling ventilation and shading within the standard curtain walling module. Specifically, the application of thermoelectric cells is investigated to provide the HVAC functions within the extremely limited space. In addition, all integrated building service systems are completely powered by façade-mounted renewable energy system consisting of photovoltaic (PV) panels and flat-plate batteries. Thus, the embedded systems
represent a direct current (DC) microsystem with integrated control actuating based on local outdoor and indoor conditions. The façade module with the additional functions ensures optimal energy performance and thermal comfort with high degree of autonomy. The decentralized HVAC system can satisfy individual needs of each façade module and related working or living space, while local PV system ensures high coverage of demand from renewable sources.

The case-study representing an office was conducted for analysis and demonstration of the façade module performance. The case-study office has dimensions 5.4 x 3.5 x 4 m with two window areas with size of 1.9 x 2.8 m. The opaque area occupies approximately 10 m² of the façade module with maximal thickness of 0.2 m. This part of the façade module is available for integration of the building service systems and renewable energy sources. In brief, the opaque construction includes the air canals delivering the supply and the exhaust air to the integrated thermoelectric AC unit, that is described in the detail in following section. Also, the outside opaque area is used for façade-mounted PV panels. The thin-plate batteries are located in the inner side of the opaque part in order to guarantee suitable operational conditions (stable temperatures in the range of 20 to 30 °C).

3. Façade integrated thermoelectric air-conditioning unit

In order to develop a compact façade module, the AC unit must be integrated within the curtain walling structure. In fact, the space requirements for the unit are very strict. The traditional refrigerant based solutions can barely fit to the extremely limited space. Other issue with the standard cooling devices is a risk of possible leakage of the refrigerant to the façade structure. Alternatively, the thermoelectrical cells working based on the principal of the Peltier effect can be used for this application [4].

The utilization of the thermoelectric cells has several advantages such as (i) minimalistic size, (ii) no motion parts, (iii) reliability without risk of leakage and related low maintenance requirements (iv) direct current device suitable for energy supply from PV panels and (v) universal application, where the same device can be used for heating and cooling purpose by switching of the flow of the electric current. The main disadvantages are lower efficiency in comparison to refrigerant based solutions and limited temperature drop [5],[6].

3.1. Experimental setup of thermoelectrical AC unit

In frame of the current research, novel in-façade thermoelectrical air-conditioner is being developed. The development was divided into three technological steps: (i) mock-up unit development for energy performance verification, (ii) in-façade unit integrated to small scale façade module as functionality
sample, (iii) final in-facade unit for the full-scale facade module with all integrated functions as prototype. This paper deals only with the testing of the mock-up unit, since the current research is being still in progress.

The construction of the mock-up unit is limited within the available space of 0.2 x 0.2 m available in the façade module. An assembly was compiled from high-performance thermoelectrical cell (TE Technology, HP-199-1.4-0.8) and the two heat sinks (SK623, Fisher Elektronik). The assembly was encapsulated to a polystyrene housing and inserted into a duct representing the façade cavity. The duct with the embedded assemble is arranged to create two separate so-called hot and cold canals.

![Figure 2. Photo of the mock-up thermoelectrical unit](image)

Via the hot canal, the waste heat from thermoelectrical cell is removed to the exterior. Via the cold canal, the internal air is cooled down by the thermoelectrical cell. The forced air flow through the system is served by the two inline duct fans (Elektrodesign TD500/160). Photos of the mock-up unit construction can be observed in Figure 2. The scheme and illustrative photo of the entire experimental setup are shown in Figure 3.

The entire experimental setup is also equipped by several sensors and measurements instruments. The temperatures, airflow and electrical power are measured. More into detail, three temperature points are inserted in each inlet and outlet air to the thermoelectrical air-conditioner. Two temperature points are located on the internal surfaces of the two heat sinks. All temperature sensors (PT100 type TF 101N) are connected to the central measuring station (Alborn type ALMEMO 5690), where the measured data are stored. The orifice plate track was used for airflow monitoring, where the pressure drop is monitored via inclined manometer and the electrical power was measured via the laboratory electrical source (Statron type 3256.4). In addition, the inlet air to the both canals may be pre-conditioned by electrical heaters to ensure the desired boundary conditions for the measuring purposes.
3.2. Experiments definition

The aim of the experimentation is to verify the energy performance of the entire assembly representing the in-façade thermoelectrical air-conditioner using single cell. In this paper, four experiments are presented and summarized in Table 1. These experiments were executed to assess the energy behavior of the single-cell assembly for various boundary conditions. For each experiment, these boundary conditions represented by the inlet air temperatures and airflows in both canals were set to be constant. However, several disturbances (e.g. actual weather situation, laboratory indoor conditions etc.) influence the experiment inputs (especially inlet temperatures), therefore the inlet air is conditioned via electrical heaters with manual control to eliminate the major fluctuation of these temperatures. Nevertheless, some level of uncertainties related with boundary conditions is present and it is quantified within the experimentation.

The desired inputs for experimentation are shown in Table 1. The first experiment is considered as reference case, where the inlet temperatures to the hot and cold side are both identical at 27 °C. The airflow was assumed in proportion to nominal cooling and heating load of the thermoelectrical cell at 40 m³ h⁻¹ for cold canal and 80 m³ h⁻¹ for hot canal. The other experiments evaluate variation of the boundary conditions. Experiment nb. 1 demonstrates the influence of the raised temperature level applied for both canals at 30 °C. The experiment nb.2 demonstrates the influence of raised temperature only for the hot canal at 32 °C. In this case, the temperature difference between canals is about 5 °C. Experiment nb.3 demonstrates the lower level of the airflow through the both canals, where 30 m³ h⁻¹ for cold canal and 60 (m³h⁻¹) for hot canal is set.

| Id  | Cold Canal (CC) | Hot Canal (HC) | TE cell |
|-----|----------------|----------------|---------|
|     | t_{in, c} (°C) | V_c (m³ h⁻¹)  | t_{in, h} (°C) | V_h (m³ h⁻¹) | I (A)            |
| Ref | 27             | 40             | 27       | 80          | \{0;2;4;6;8\}   |
| Exp. 1 | 30            | 40             | 30       | 80          | \{0;2;4;6;8\}   |
| Exp. 2 | 27            | 40             | 32       | 80          | \{0;2;4;6;8\}   |
| Exp. 3 | 27            | 30             | 27       | 60          | \{0;2;4;6;8\}   |

In each experiment, the energy performance of the thermoelectrical cell were tested in range of electrical current from 0 to 8 A. The electrical current was switched every 20 minutes about 2 A to examine the

![Figure 3. (a) Scheme of the experimental setup (b) photo of the experimental setup](image)
entire operational range of the thermoelectrical cell. The length of the period for switching was selected empirically based on the initial inspection of the experimental setup, where the time constant of the system was observed about approximately 5 minutes. It means that each experiment captured both dynamic and steady-state behavior of the measured system. For current assessment, the goal is to evaluate the characteristic behavior, therefore only the steady-state data were analyzed here.

The performance is indicated by temperature difference between inlet and outlet of the hot and cold canals and COP for each level of the applied electrical current. In addition, the energy fluxes for cooling and heating are evaluated with respect to electrical load of the thermoelectrical cell. These indicators provide complete overview regarding the energy performance of the mock-up unit.

4. Functionality assessment of thermoelectrical AC unit

4.1. Results

Figure 4 shows three plots, where each plot reveals the part-load characteristic of the tested mock-up unit according to the performance indicator. Each line in the plot represents results from the given experiment, thus the experiments can be compared with each other. In addition, both results from cold and hot canals are depicted in each plot. It also worth to notice the error bars in all figures, which indicate the aforementioned uncertainty of the boundary conditions in the laboratory (e.g. variation of the inlet temperatures due to ambient situation).

In Figure 4a, the temperature difference of inlet and outlet air temperatures for each canal is assessed. For the reference case, the temperature difference in the cold canal was observed in range of 1 to 2.5 °C for the tested operational range. As expected, the highest temperature difference was found for the case with lower level of airflow through the canals, that was in range of 1.5 to 3.2 °C. The lowest temperature difference was in the experiment nb.2, where different temperature level for each canal was applied. In this case, the range was only between 0.8 to 2.1 °C. The same pattern in terms of performance was seen for temperature difference in the hot canal. Here, the temperature difference of the reference case was observed in range of 0.6 to 3.6 °C, the case with lower level of airflow in range of 0.8 to 4.9 °C and the case with different temperature level for each canal in range of 0.4 to 3.3 °C. The experiment nb.1, where both inlet temperature levels were raised, behaved almost identically with the reference case.

In Figure 4b, the COP indicator for cooling and heating is demonstrated (negative COP values are dedicated for cooling). Both cooling and heating COP part-load characteristic revealed a peak for lower utilization rate of the thermoelectrical cell (around 2A). When the utilization rate of the thermoelectrical cell grown up, the COP rapidly decreased. For instance, the cooling COP for reference case diminished from 2.5 (-) to 0.35 (-) according to utilization rate. Similarly, the heating COP decreased from 3.3 (-) to 1.2 (-). Analogous behaviour can be observed for all experiments except experiment no. 2 (different inlet temperatures settings for cold and hot canals), where the cooling COP was in range 1.3 to 0.35 (-).

In Figure 4c, the thermal fluxes with respect to power load of the thermoelectrical cell are shown. The maximal cooling and heating load for the reference case are 33W and 96W, respectively. Again, the experiment no.2 provided the lowest cooling load as was already indicated in previous figure. Experiment no.2 performs the worst also in terms of heating load from the tested experiments.

4.2. Discussion

First, the results revealed the sensitivity of the performance efficiency on the temperature drop between hot and cold side. The higher temperature drop increases the convective heat flux between hot and cold side of the assembly (thermoelectric cell plus heat sinks). In fact, part of the dissipated heat is shortcut back to the cold side, which reduces the performance. This “thermal shortcut” is present in each experiment, however the experiment no. 2 and no.3 are affected more than the reference case. Each of these experiments has different symptoms of this “thermal shortcut” based on given boundary conditions.
In the experiment no.2, the temperature drop between hot and cold sides is generated by setting of various inlet temperature. The influence of the inlet temperature is observed mainly for the lower utilization rate (electrical current 2A). For the higher utilization rate (electrical current 8A), it can be assumed that the temperature drop between cold and hot side is mainly driven by the thermoelectrical cells, therefore the influence of the inlet temperatures is less significant (compared to the reference case).

In the experiment no.3, the temperature drop between hot and cold sides is generated by setting of the airflow. Lowering the airflow throughout the unit increases the temperature differences between the inlet and outlet. However, as Figure 4a depicted, the increase is not proportional to the other experiments. The temperature difference of inlet and outlet grows gradually with the utilization rate of the thermoelectrical cell. While the tested air-conditioner performed similarly to the reference case considering the lower utilization rate, for the higher utilization rate, the temperature drop between hot and cold side raised up to 8.2°C. The temperature drop of the reference case was approximately 6.0°C. To have a completed figure, the temperature drop for the previous experiment no.2 was approximately 10.6°C including the inlet temperature variants. The gradual increase of the temperature drop explains the reduction of the performance for higher utilization rate.

Second, the results indicated the heat losses of the tested air-conditioner. In the ideal study-state situation, the dissipated heat should be equal to addition of absorbed heat and inserted electrical power. However, theoretical energy balance was not complied as can be observed in Figure 4c. Two possible sources of these heat losses were identified by the inspection of the experimental setup: (i) heat transfer from the duct representing façade cavity to the ambient environment (laboratory), (ii) air bypass of the heat sinks due to cracks in the polystyrene housing. These sources of the heat loss cannot be precisely quantified from the presented measurements. The investigation of these heat losses is ongoing work in frame of the current research.

![Figure 4](image-url)  
**Figure 4.** Part-load energy characteristic of the mock-up unit (a) temperature difference vs. utilization rate (b) COP vs. utilization rate (c) thermal fluxes vs. power load.
Last, focusing on the cooling performance, the temperature difference in the cold canal caused by the single thermoelectrical cell was found relatively low (around 2.5 °C). Therefore at least two assemblies of thermoelectrical cells and heat sinks must be chained in series next to each other to reach desired supply temperature for cooling purposes. Also, the optimal operation point can be recommended around 6A based on the measured part-load characteristic. At this mid-utilization rate, the COP for cooling reaches still suitable level in relatively narrow range of 0.6 to 0.75 (-). In different words, using the mid-utilization rate is a satisfactory compromise of the COP, the temperature difference and sensitivity to the boundary conditions.

5. Conclusion
This paper introduced the concept of the autonomous façade module with integrated function of heating, cooling, ventilation, lighting, shading as well as renewable energy storage and generation. In order to enable the built-in HVAC functions, the thermoelectric air-conditioner was investigated.

In the frame of the current research, the thermoelectrical AC (mock-up) unit was developed as the first technological step. The aim in this technological step was to verify the energy performance of the mock-up unit. The energy performance of the unit was found in similar range stated in literature [7]. It means that the current construction of the tested unit provides comparable energy performance to the state-of-the-art solutions.

The results shown the part-load energy characteristics depicting in detail the energy performance of the mock-up unit. The analysis of the results revealed the influence of the boundary conditions and indicated possible sources of the heat losses for further investigation. In addition, the optimal operational range in terms of utilization rate of the thermoelectrical unit was identified.

To conclude, the testing of the thermoelectrical AC (mock-up) unit offered valuable outcomes for the development of the next technological step, that is the small-scale functional sample. The experiences from the measurements of the AC (mock-up) unit provided solid ground for the ongoing research and its final goal – autonomous curtain walling module.

Acknowledgment
This work has been supported by the Ministry of Education, Youth and Sports within National Sustainability Programme I, project No. LO1605 and by Technology Agency of Czech Republic within the project TH03020341 Autonomous curtain wall panel.

Reference
[1] Loonen R C G M, Favoino F, Hensen J L M and Overend M 2017 Review of current status, requirements and opportunities for building performance simulation of adaptive facades J. J. Build. Perform. Simul. 10(2) 1940–1493
[2] Frank T 2005 Climate change impacts on building heating and cooling energy demand in Switzerland Energy Build. 37(11) 1175–85
[3] Domínguez S, Sendra J J, León A L and Esquivias P M 2012 Towards energy demand reduction in social housing buildings: Envelope system optimization strategies Energies 5(7) 2263–87
[4] Lineykin S and Ben-Yaakov S Modeling and Analysis of Thermoelectric Module
[5] Martín-Gómez C, Ibáñez-Puy M, Bermejo-Busto J, Fernández J A S, Ramos J C and Rivas A 2016 Thermoelectric cooling heating unit prototype Build. Serv. Eng. Res. Technol. 37(4) 431–49
[6] Liu Z, Zhang L, Gong G, Li H and Tang G 2015 Review of solar thermoelectric cooling technologies for use in zero energy buildings Energy Build. 102 207–16
[7] Irshad K, Habib K, Basrawi F and Saha B B 2017 Study of a thermoelectric air duct system assisted by photovoltaic wall for space cooling in tropical climate Energy 119 504–22