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ACTIVE ALUMINUM WINDOW-FRAME INTEGRATED PROTOTYPE WITH A THERMOELECTRIC HEAT RECOVERY SYSTEM FOR VENTILATION AND AIR CONDITIONING

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ABSTRACT

Research interest in the integration of thermoelectric systems in the building envelope have increased during the last years. Studies show that regardless of a low COP compared to vapor compression systems; thermoelectric systems present other remarkable features for heating, cooling and ventilation on buildings. Among those studies, a few prototype experiences incorporate thermoelectric systems on windows.

Alternatively, standard air conditioning systems often require additional equipment installed on façade or wall surfaces that compromise the use of space in the case of building refurbishment. Thus, the integration of thermoelectric systems on window framing is presented here as a decentralized alternative for air conditioning support, whose performance aims at balancing out the heat losses in windows.

The purpose of this communication is to present the development of an active aluminum window-framing prototype with a thermoelectric heat recovery system for heating and cooling. In a typical single-floor house scenario, the active window-frame works in two different modes: pre heating/cooling mode applying forced convection through a mechanical fan and pre heating/cooling mode with natural convection. The impulsion airflow rate meets ventilation requirements according to Spanish Technical Building Code (CTE) for indoor air quality.

KEYWORDS

Active window; peltier; thermoelectric; façade; heating; cooling.

1. INTRODUCTION

Reducing the energy consumption of buildings has been a major concern in recent decades. According to the United Nations Environmental Program, the energy consumption demand around the construction and operation of buildings in 2015 was equivalent to 38% of the global energy demand. Research on the application of thermoelectricity in buildings for heating, cooling and ventilation has emerged as an alternative to conventional systems.

Thermoelectricity encompasses the direct conversion between temperature differences and electrical voltage through two related mechanisms called Seebeck effect and Peltier effect. Peltier cells are devices that allow for heat transfer when the electric current flows through its circuitry composed by two types of semiconductor materials (n-type and p-type). The heat transfer allows for cooling on one of the sides of the cell while heating on the other. Likewise, the change in the direction of the applied current produces a change in the direction of temperature transfer, giving them the capacity for working as heat pumps (see Figure 1).

Thermoelectricity has been widely applied in the fields of electronics, military, automotive and industry however; their application in energy systems for buildings is a barely developed area. The application of thermoelectric systems in buildings have several advantages over conventional HVAC systems including great versatility of the modules due to their capacity for heating and cooling in a single device. Moreover, the technology's high reliability reduces the need for maintenance. The greatest advantage, however, is the avoidance of refrigerant fluids, present in conventional vapor compression systems, which have a negative impact on the environment and demand large amounts of space.

This paper aims to present an ongoing experimental study carried out in partnership between Hydro Extrusion Spain S.A.U. and Universidad de Navarra, that focuses on the activation of a window frame using thermoelectricity in order to pre-heat and pre-cool the supply air in a residential building. Foremost, a brief background on the integration of thermoelectricity in buildings is presented, including previous experimental studies carried out by the thermoelectricity research group of the University of Navarra. Afterward, design parameters and considerations are described including different operating scenarios and building requirements for TEM integration and window activation and lastly, discussion and conclusions.

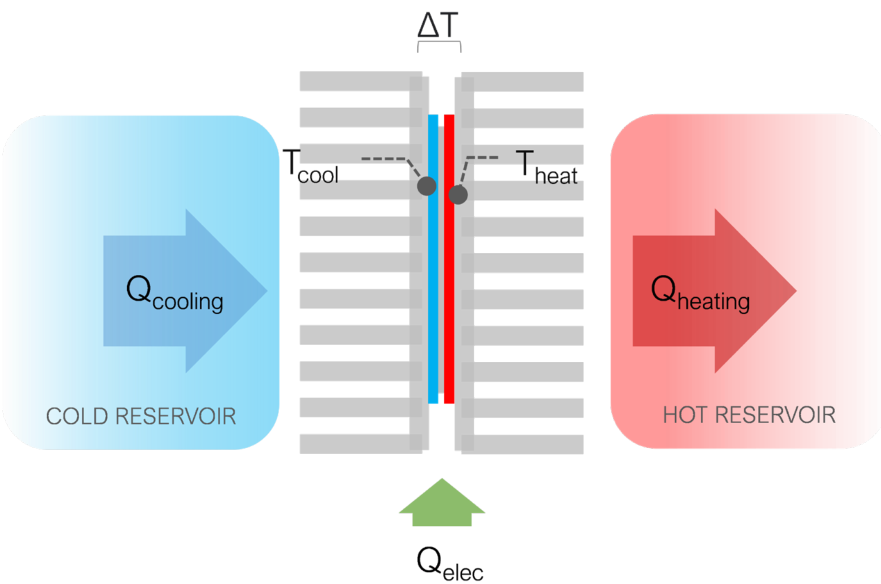

Figure 1. Concept schematic of the operation of a Peltier cell

2. BACKGROUND

Thermoelectricity for air conditioning in buildings has two different applications: through integration of TE modules in different parts of the building or through independent (not integrated) systems. Considering the integrated TE modules, it is possible to find them on the envelope system, mainly façades, in interior suspended ceilings for cooling purposes, in roofs, in heat recovery systems and windows (Figure. 2). Not integrated TE systems are those such as ventilation systems, TE combined with phase-change materials, dehumidifiers, and other devices (Zuazua-Ros et al. 2019).

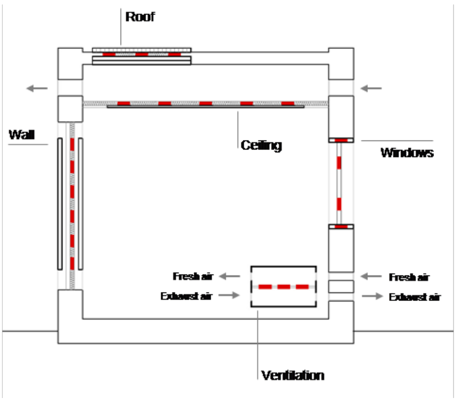

Figure 2. Diagram of the different thermoelectric integration options in buildings. Source: (Zuazua-Ros et al. 2019)

The research group on thermoelectricity at the Department of Construction, Building Services and Structures of the Universidad de Navarra designed and built three experimental prototypes for the integration of thermoelectric systems in the building envelope (Figure 3). A first approach developed by Martín-Gómez et al, consisted of a façade-integrated prototype with 84 Peltier cells (Martín-Gómez et al. 2016). Despite a low COP, the results of the performance analysis served to prove the capacity of the thermoelectric system for heating or cooling of a 6.7m^2 space unit. Additionally, it helped to determine some constructive parameters regarding the integration of thermoelectric systems in the building envelope. Subsequently, Ibañez-Puy et al. presented in 2017 the design of a Thermoelectric Heating and Cooling Unit (TCHU) (Ibáñez-Puy et al. 2017). The prototype was installed in a ventilated façade, using the exterior air cavity to dissipate heat from the TEMs, thus achieving a complete integration of the thermoelectric system. Researchers improved the insulation and aesthetic parameters of the construction. Higher COP values were achieved in comparison to previous experiences. Lastly, Martín-Gómez et al. presented in 2019, a full-scale prototype of a Ventilated Active Thermoelectric Envelope (VATE). The prototype consisted of two modules of 8 Peltier cells each, 2 tangential fans, finned heatsinks and an electrical panel located in between the modules (Martín-Gómez, Zuazua-Ros, del Valle de Lersundi, et al. 2021) The prototype was installed in an actual office space and it was tested under real conditions. It presented some improvements concerning construction parameters, and the optimization of the electrical system allowed for the reduction of volume space of the prototype on the facade. Among other studies that integrate thermoelectric technology in window frame or glass, Xu, et al developed an active window prototype, mounting the thermoelectric modules (TEMs), in two aluminum tubes on both sides of the window, analyzed in laboratory conditions (X. X. Xu, Van Dessel, and Messac 2007). Following up, they built a prototype and tested it under real conditions (X. Xu and Van Dessel 2008a) and subsequently a steady state model of this prototype was validated (X. Xu and Van Dessel 2008b). A similar study was proposed (Birthwright et al. 2008), the TEMs installed on the window compensated for the heat flow through the window obtaining a COP greater than three. Other studies used active thermal insulators (ATI) applying solar energy to compensate for heat losses through the window. The system

Figure 3. Images of façade integrated thermoelectric prototypes developed in the School of Architecture in chronological order from left to right. Left (Martín-Gómez et al. 2016), center (Ibáñez-Puy et al. 2017), right (Martín-Gómez, Zuazua-Ros, Del Valle de Lersundi, et al. 2021). Source: authors

integrates photovoltaic panels (BIPV) that power the TEMs, located between the glazing panes in the façade assembly. In this case, a model was developed to test the performance (Harren-Lewis et al. 2012). The study of an active window concluded that, "The ATI design is a significant improvement over the energy efficient windows. It can reduce heat gain through a window by up to 67% powered only by incident solar radiation. By reducing the heating and cooling load, the economic and environmental cost associated with the building's energy consumption will decrease. Although evaluating only summer cooling option, they deliberated on the option of including a battery to make winter heating a viable option. However, they did not consider the aesthetics of the prototype, concluding that closer examination of the design of the heat sinks would of the heat sink design would lead to a more commercially viable element.

Barreto et al. presented a heat recovery system based on heat-pipes that aims at reducing the heat losses caused by ventilation. On the other hand, to improve indoor air temperature and air quality, as well as thermal comfort. The heat recovery system is coupled to the window frame. The heat exchange between the incoming air and the exhaust air takes place through centrifugal fans (Barreto et al. 2022).

Based on previous experience measuring the capacity of the thermoelectric system to air-condition an entire space, researcher at the Universidad de Navarra found that the integration of thermoelectricity in buildings has several drawbacks, the most important being the difficulties encountered in ensuring the energy demand for heating and cooling.

On the other hand, keeping a constant airflow favors air circulation inside and allows heat transfer. Moreover, heat losses caused by thermal bridges are constant drawbacks despite all the improvements made along the previous experiences.

3. DESIGN APPROACH

Architecture and building need to comply with many mandatory regulations, which can be considered the minimum requirements. However, many other factors must be added to these minimums that are part of the design process such as aesthetics, consideration of ease and simplicity of construction and assembly, low maintenance of all its systems and components (Torres-Ramo et al. 2009)

The component under study in this research is an active window that serves as a decentralized ventilation system with a contribution of heating and cooling to the supply air. Both ventilation systems and windows themselves are sources of energy gains and losses. Thus, the activation of these elements through an integrated TE system aims to balance out those energy gains and losses.

Windows are one of the most industrial and modular elements of buildings. They are technically precise, easy to assemble, easy to customize (i.e. specific glass panes), they offer a variety of solutions depending on the needs and they are dry construction. All these features mean that windows can be considered an affordable system to which another industrialize system can be attached or integrated to.

When conceptualizing the active frame, the initial step is to consider the ventilation operations that the frame can accomplish. Thus, as a starting point, attention has been focused on ventilation requirements established in the Spanish Building Code (exactly CTE HS3). Then, the requirements of the integrated TE system were considered for a final conceptual solution to be developed. The next two subchapters present these steps.

3.1. TEM integration: building requirements and operating scenarios

Given that it is a decentralized system, this equipment must be installed in each room of a house. As a starting point for the initial design, the bedrooms have been considered. In order to meet the requirements for constant flow ventilation in living spaces, the Spanish Technical Code (*Código Técnico de la Edificación)* CTE HS3 "Air Quality" establishes a constant minimum air supply flow of 8 l/s (28.8 m^3/h) for the case of a main bedroom within a house.

According to this, the air inlets can be made in different ways, prioritizing the vents associated with windows due to their ease of execution. Thus, this constant natural ventilation is guaranteed due to aerators installed in windows, which provide a constant micro ventilation air inlet. The natural ventilation is ensured due to exhaust air openings located in kitchen and bathrooms. This will be the first scenario where the active frame prototype will be tested.

The second scenario corresponds to those cases in which there is a controlled mechanical ventilation system with a heat recovery unit. In this case, the minimal renewal air is not only assured, but it is preheated to reduce the energy demands of the indoor space.

3.2. TEM integration: activating the window

The integration of TE systems in buildings supposes the consideration of new factors in the constructive design such as wiring, Peltier modules appearance, ducts, and fans in the first place, and power supplies, sensors and control system in a second place.

As explained before, the Peltier cells will pre-heat or pre-cool the fresh air renewing the indoor air. Therefore, the system will be composed of two chambers, one at each side of the cells, that will drive cooled or heated fresh air indoors.

In heating mode, the fresh air at lower temperature will enter the inner side chamber and will be preheated at desirable 21 ºC to be supplied to the indoor space. At the same time, the indoor exhaust air will be drawn to the outer chamber. The temperature of the exhaust air, being higher that the outdoor temperature, will increase the outer chamber temperature, thus, the temperature difference of the two sides of the Peltier cell will be reduced. This heat recovery system will improve the performance of the Peltier cell, since at lower temperature difference, higher coefficient of performance.

In cooling mode, the operation will be similar, the outdoor air will be pre-cooled when entering the inner chamber, and then supplied to the indoor space. At the same time, the indoor air will be cooler than the outdoor air, thus, it will reduce the temperature difference of the two sides of the Peltier cell.

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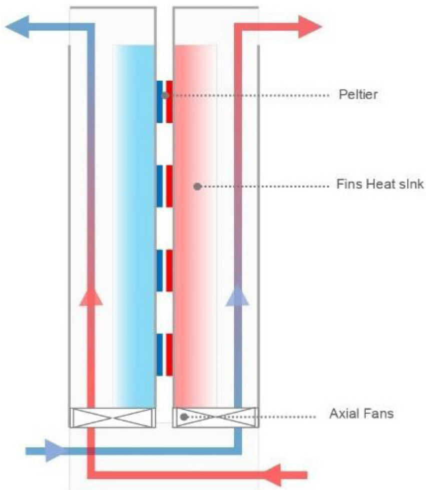

Figure 4. Initial concept schema of the active window frame operation.

Once the concept of the system is defined, the next steps are related to the integration of each element in the frame design. In general, the main items to be addressed are the following:

- Outline of airflows: There is a critical point between the two chambers at each side of the Peltier cell, since at some point both ducts must cross. Figure 5 shows some of the different solutions considered by the research group to solve this issue.
- Heat dissipation: As literature review and previous experiences support, the heat dissipation is a key issue for the optimal performance and efficiency of the Peltier cells. In this case, aluminum fins extruded together with the frame are considered as a heat dissipation system. In order to ensure the best dissipation, axial fans are integrated in the design at both sides of the cells.
- Power capacity: The Peltier cells generally used for building integration experimental research have a maximum power capacity of around 50W. In this case, considering that the system is focused for new building construction or refurbished scenario, in both cases a low energy demand is assumed. Therefore, the integration of 4 Peltier cells (maximum power capacity of 200 W per living space) is considered as starting point.

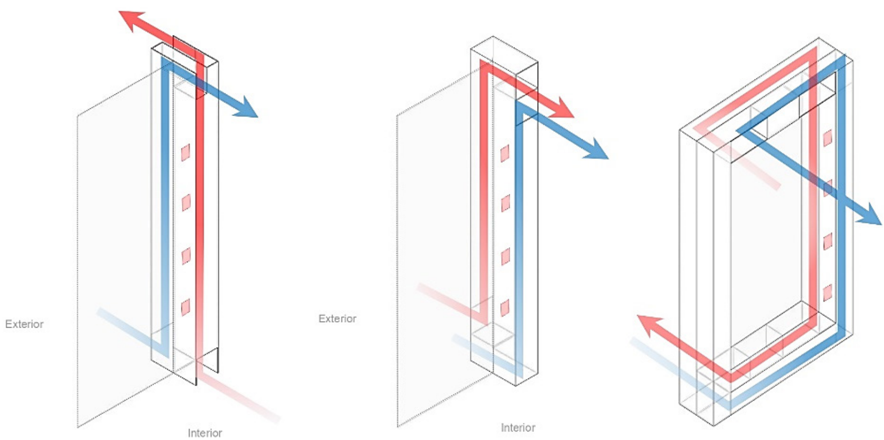

Figure 5. Concept drawings of air flow alternatives

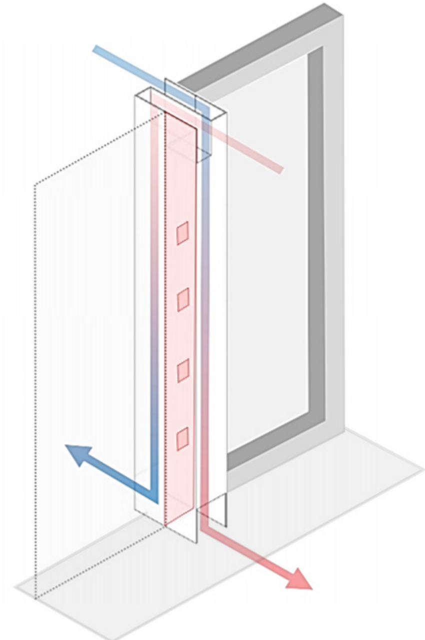

Figure 6. Concept axonometric of the final result.

As a result, the final concept diagram that will be prototyped is shown in Figure 6. The air ducts will be crossed in the lower part of the profile, to ensure the air supply from the upper part of the window frame. This configuration allows the adaptability to any type of window, since it can be extruded and later cut to the desired length.

4. DISCUSSION AND CONCLUSIONS

This paper presents the initial steps towards an active aluminum frame integrated in windows. The active frame under study in an ongoing project will include thermoelectric modules and will operate as a heat recovery system to precool and preheat the supply fresh air to the indoor space.

Since windows are among highly industrialized elements for buildings, the advantages of the integration of thermoelectric systems in window frames ranges from measurement and shape precision to a more simple and specialized installation. Moreover, the experimental prototype presented here, has aluminum-extruded components, which allows for easy integration with windows.

Previous experiences and performance analysis of façade integrated thermoelectric systems demonstrate the feasibility of this technology to pre-heat and pre-cool the airflow, thus helping to improve the indoor thermal comfort and reducing the energy consumption. Among the challenges that will be studied through this experimental prototype are the complete integration of the thermoelectric system with the window frame, which implies meeting the technical requirements of windows in terms of water and air tightness, thermal bridges and condensations. In addition, forced ventilation is required to keep a continuous airflow, and the noise of the fans is another drawback.

Moreover, optimal location of filters on the inlets, would favor an optimal particle filtering which allows for supplying a cleaner fresh air. As for future steps, researchers at the University of Navarra are working on the construction of an adiabatic box where the prototype will be tested under controlled temperature conditions.

ACKNOWLEDGEMENTS

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