Performance analysis of the MICRO-V (Multifunctional, Integrated, Climate-responsive, Opaque, and Ventilated) façade with different ventilation modes

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Abstract. Climate-responsive facades (CRFs) are a potential solution to respond to transient energy exchanges in buildings to control and enhance the indoor environmental quality (IEQ). In addition to space heating and cooling, adequate ventilation within a thermally comfortable range is critical in new and retrofit constructions, particularly as current high-performance facades maximize airtightness. In this study, an opaque multifunctional CRF (MICRO-V) was investigated to regulate the flow of heat and air into buildings with daily and seasonal responses. This façade is made of phase change materials (PCMs), an adjustable insulation system, and an embedded ventilation unit to provide conditioned fresh air. The effect of different ventilation modes (balanced, only-exhaust, only-supply) on the overall thermal performance of the façade was studied. A CFD simulation study in the context of Toronto, Canada, in the cooling season was performed. The study showed a correlation between increased airspeed and overall heat recovery in the façade, with an average of 75-80% heat recovery between the indoor exhaust air and fresh supply air. The results showed how the façade’s operational modes could be adjusted based on the outdoor climate conditions. MICRO-V is a decentralized façade system with simultaneous air supply and exhaust, the findings showed the interconnected behaviour of the components in the façade and how it can provide conditioned fresh air.

1. Introduction
In a highly technology-oriented world, the need for innovative high-performance building façades that excel in performance compared to the existing super-insulated and super-airtight facades is evident. Dynamic and adaptative facades are promising alternatives that have gained attention in the past decade. Typical static building facades have a constant performance that does not change with time. This leads to a lack of direct management of changing weather conditions and occupant preferences daily, seasonally, and annually. Therefore, applying dynamic facades that could change their performance over time, depending on the building and climate context, is a promising solution [1,2]. Climate-responsive facades (CRFs) can reversibly change their behaviour over time in response to changing indoor and outdoor boundary conditions to fulfil specific indoor environmental quality (IEQ) and energy efficiency requirements [1,3].

The design of dynamic facades can be classified into material, component and full-façade scales based on the level of responsiveness in the façade [4]. On the material scale, the application of smart materials such as phase change materials (PCMs) and thermochromic coatings that can inherently or actively change their properties has been widely studied [5]. CRFs with a dynamic performance on the full façade and component scales have also been the focus of various research projects. Solar facades
that combine solar radiation with other functionalities for solar gain or electricity generation purposes are the most prominent example of CRFs [4]. One of the limitations of the literature on CRF design is the lack of studies on opaque CRFs, with the main focus on transparent facades [1,5]. Designing facades that can respond to broader boundary conditions can ensure higher resiliency in building performance. Their transient behavior is advantageous in the context of changing climate projections in urban areas, which leads to a considerable shift in the daily and seasonal weather profile of cities that could make static facades vulnerable to sudden outdoor conditions [6]. The shift in building façade design also relies on the need for facades to become an active part of the energy system in buildings by integrating multiple functionalities and building services [7]. In this line, ventilated building façades have shown a high potential in improving building energy savings and IEQ. Adding multifunctionality to decentralized façade designs could expand their application and operation in diverse climates and different seasons [8]. The importance of ventilation in individual building zones has been highlighted in the current situation caused by the COVID-19 pandemic. A well-designed, ventilation system can reduce the risk of virus spread in indoor spaces by diluting the concentration of potentially infectious aerosols through air exchange with outside air [9]. Several studies have shown positive outcomes attributed to ventilated and multifunctional facades that exceed fresh air provision. The convective airflow inside such facades affects their thermal behavior that can be positively used to improve IEQ in buildings through surface temperature regulation [7,10]. Typical designs in the literature include integrated ventilation channels or air cavities behind the glazing to either provide supply air or pre-condition the recirculated indoor air. There is a research gap on ventilated facades that can provide a simultaneous fresh air supply and removal of stale indoor air [8]. The performance analysis of multifunctional CRFs is complex given the interconnected nature of the materials, systems and active controls involved. Thus, simulation studies or long-term experiments should be performed considering both active control and design parameters [9,10]. In this study, the performance of a multifunctional CRF with integrated ventilation is evaluated in the climate context of Toronto, Canada. The multifunctional, integrated, climate-responsive, opaque and ventilated (MICRO-V) façade was designed as an alternative to high-performance building façades to perform in different climate conditions with variable operation. The MICRO-V provides pre-conditioned fresh air and acts as a buffer to control environmental loads to enhance IEQ in buildings. The main objective in this paper is to assess the thermal performance of the façade, and its efficiency to pre-condition the fresh air under different ventilation scenarios.

2. Methodology
The MICRO-V façade was designed to dynamically regulate the flow of heat and air into buildings using daily and seasonal responses. This façade module is a multifunctional dynamic façade with different components, each targeting a specific environmental load. The façade was designed to have a fixed and dynamic set of responses. The fixed responses relate to the annual and seasonal changes of the façade for overall heat transmittance, and the dynamic responses relate to the daily and real-time changes, namely to pre-condition the fresh air.

2.1. MICRO-V design
The MICRO-V façade was conceptually designed using a performance-based design framework [1] and optimized through parametric CFD simulation modeling. The final design of the MICRO-V module, which is 60 cm × 90 cm, is shown in Figure 1. The façade is comprised of multiple components, including a core heat recovery unit designed to exchange heat between the indoor return air and fresh outdoor air. Phase change materials (PCMs) integrated inside an air-cavity act as additional components to pre-condition the fresh air and affect the overall thermal performance of the façade. This pre-conditioning is achieved with incident solar radiation and thermal energy storage similar to a Trombe wall system. Two types of PCMs macro-encapsulated in aluminum channels store thermal energy annually in both heating and cooling seasons using different melting temperatures
(\text{T}_\text{mp}). Overall, 4.5 liters of each PCM was integrated, divided into six aluminum channels. Table 1 shows the material properties of the MICRO-V façade.

![Figure 1. a) Plan and section views of the MICRO-V; b) 3D view of the façade in COMSOL©.](image)

The dynamic operation of MICRO-V is directly related to the operation of the integrated ventilation system. The base operation mode in MICRO-V is balanced ventilation with simultaneous fresh air (FA) supply and return air (RA) exhaust having the same airflow rate of 10 m³/hr with an airflow speed of 0.5 m/s operated by separate fans for each stream. The ventilation module in the façade has a six-channel configuration considering a width of 3 cm per channel, which are separated by thin aluminium walls for maximized heat exchange. Aluminium fins (Figure 1a) were embedded in each channel for heat transfer and arranged to create a counterflow air exchange in the unit. Considering the integration of the ventilation module in the insulation panel and the counterflow air exchange, the thermal transmittance of the insulation can be adjusted.

| Material          | Properties                  | Unit         | Values       |
|-------------------|-----------------------------|--------------|--------------|
| PCM_A             | \text{T}_\text{mp}          | °C           | 29           |
|                   | Specific heat capacity      | J/kg.K       | Solid: 2300  |
|                   | Latent heat                 | KJ/kg        | Liquid: 1400 |
| PCM_B             | \text{T}_\text{mp}          | °C           | 15           |
|                   | Specific heat capacity      | J/kg.K       | Solid: 2000  |
|                   | Latent heat                 | KJ/kg        | Liquid: 1900 |
| Insulated glazing unit | Thermal transmittance   | W/m². K     | 1.2          |
| Insulation panel  | Thermal resistance          | m². K/W      | 5            |

The fixed and dynamic operation of the MICRO-V depend on the material properties and the active control of the façade, which governs the ventilation scenarios daily and seasonally. Therefore, it is necessary to quantify how MICRO-V’s performance changes in regulating environmental loads when subjected to various operational scenarios.

2.2. Numerical simulations

To assess the effects of changing the operation scenario on the overall heat transfer of the façade with active ventilation, a three-dimensional, time-dependent simulation model was prepared in COMSOL Multiphysics©. Heat transfer, solar radiation, and CFD for airflow studies were performed on an hourly basis. The objective of this numerical analysis was to quantify how the MICRO-V works on a component scale exposed to different boundary conditions and operation scenarios. In this study the MICRO-V faces the south in the climate of Toronto, Canada. The boundary conditions were determined at the exterior and interior faces of the façade with adiabatic conditions at the sides (Figure1b). The 20-year historical climate data for Toronto (ASHRAE Zone 5) was used for the
exterior boundary conditions [13]. The simulation study was performed for three consecutive days in the summer. Table 2 shows the average weather profile for the summer days used in the model. The indoor boundary conditions were set to a constant temperature set point ($T_{in}$) of 23 °C.

**Table 2. Average historical weather used in the simulation model.**

| Climatic parameter                  | Unit | Summer days |
|-------------------------------------|------|-------------|
| Ambient temperature (avg.)          | [°C] | 21.4        |
| Ambient temperature (max.)          | [°C] | 28.3        |
| Ambient temperature (min)           | [°C] | 13.9        |
| Direct normal irradiance            | [W/m²]| 284.7      |
| Relative humidity (avg.)            | [%]  | 69.5        |
| South wind speed (avg.)             | [m/s] | 3.5         |

In this study, two operation modes were defined for the ventilation unit in the façade, as shown in Figure 2. The airflow speed was the main parameter varied in the ventilation scenarios, which directly affected the amount of air getting into each channel. The conditional mode was assessed based on the temperature difference between outdoor and indoor air. For instance, the effect of lowering the airspeed of the FA will be investigated in periods of high outdoor temperatures in the summer days. Additionally, four cases were modelled to assess the tempering of air temperature in the air cavity using PCMs and solar radiation. First, the case with no PCM was tested, and then the $T_{mp}$ of PCM_A was changed to 24 °C and 21 °C.

**Figure 2.** Scenarios tested in the simulation model.

2.2.1. Governing equations and Key performance indicators. The Navier-Stokes equation (Equation (1)) was used for energy equilibrium calculations. The Reynolds number calculations performed for each airspeed in the ventilation scenarios showed a laminar flow in the channels was achieved. The initial conditions in the façade were set to a temperature of 15 °C and an airspeed of 0 m/s.

$$\rho C_P \frac{dT}{dt} + \rho C_P u \cdot \Delta T + \Delta q = Q$$  \hspace{1cm} \text{Equation (1)}

By applying the ventilation modes in each season, the following parameters were assessed in each iteration shown in Figure 2:

- Pre-cooling efficiency of the ventilation unit (Equation (2));
- Supply air temperature of the pre-conditioned fresh air ($T_{SA}$);
- Air and surface temperature gradient in the façade;
$$\eta = \frac{q}{q_{\text{max}}} = \frac{T_{FA} - T_{SA}}{T_{FA} - T_{RA}}$$ \hspace{1cm} \text{Equation (2)}$$

3. Results

3.1. Ventilation Scenarios

3.1.1. Balanced ventilation. In the first ventilation scenario, both supply (SA) and return air (RA) streams had the same airflow speed entering the ventilation module. Figure 3 shows the impact of changing the airflow speeds above and below the reference case of 0.5 m/s on $T_{SA}$ entering the room. The trend of the temperature changes in the figure clearly shows the rise in $T_{EA}$ when leaving the room, indicating the heat exchange between the two channels. The temperature of the supply air entering the room is decreased as the airspeed is increased. While the $T_{SA}$ gets close to the $T_{in}$ of 23 °C in all cases, particularly when the airspeed is set to 0.7 m/s, further cooling down is required to meet the indoor setpoint temperature. It must be noted that the temperature difference between the SA and the EA streams was highest in the lowest speed scenario with the airspeed of 0.05 m/s.

The pre-cooling efficiency of the façade with regards to the SA outlet and RA inlet temperatures and the outdoor temperature was measured to an average of 75-80%. The ventilation unit’s efficiency was mainly assessed in relation to the temperature difference between indoor and outdoor air in each ventilation scenario. The pre-cooling efficiency increases considerably by increasing the speed from 0.05 m/s to 0.7 m/s. Particularly as temperature difference ($\Delta T$) between $T_{out}$ and $T_{in}$ grows, a linear trend of enhanced efficiency is observed in all the ventilation scenarios. For instance, when the $\Delta T$ is 5 °C, the heat recovery efficiency of the façade increases from 76% with the airspeed of 0.05 m/s to 97%, with the highest airspeed of 0.7 m/s. In contrast, when the $\Delta T$ is low, such as 0.7 °C at night, the lowest efficiency of the façade is recorded in all the scenarios ranging from 54% to 60%.

Figure 4 presents the temperature and airspeed variation within the cross-section of the façade at 3 pm on the second day, (39 hr) which experienced the highest outdoor temperature of 32 °C. The in-depth analysis of temperature and airspeed in the façade shows a direct relation between airspeed variation and the air cavity temperature rise. As shown, when the airspeed is gradually increased from the off mode to the speed of 0.7 m/s, the higher airflow rate in the cavity increases cavity’s temperature and inside the air channels. Interestingly, the façade shows better performance when the airspeed is 0.7 m/s compared to the airspeed of 0.5 m/s in managing $T_{SA}$. The relation between the airspeed variation and temperature profile of $T_{SA}$ can be explained from the airspeed contours and Figure 3. In all the cases except for the off mode, the airspeed is increased rapidly as soon as it enters the fresh air channel with a smaller width and then directed to the interior SA vent. This suggests that the higher speed and better heat exchange efficiency makes up for the higher air cavity temperature as the SA entering the room.
with a speed of 0.7 m/s has a lower temperature. The temperature gradient shown in the off mode is also promising as it shows a very low temperature profile in the hottest time tested with no airflow present, preventing overheating. Meanwhile, the ventilation’s operation could be further optimized using active speed control to ensure an acceptable pre-conditioned fresh air is received.

3.1.2. Conditional ventilation. In the balanced ventilation scenario, both supply and exhaust air streams had the same airflow speed entering the ventilation module. Figure 5 shows the impact of varying the airflow speed in each channel, including a switch between only-supply and only-exhaust modes. Comparing the pre-cooling in the façade in two of the conditional cases shows that the ventilation unit’s efficiency is higher when the airflow rate is higher for the SA. However, the best performing case that achieves a stable $T_{SA}$ throughout the test period is the first case in which the airflow rate of the EA is higher, as presented in Figure 5. Comparing the only-supply (EA=0 m/s) and only-exhaust modes (SA=0 m/s) shows that the only-supply scenario is best to be applied on days where $T_{out}$ is not too high, such as the second day. This is to ensure a good heat exchange is achieved between the EA and SA. The indoor air temperature analysis within an enclosed space could better show how the only-exhaust mode is beneficial, such as in periods of high internal gains.
3.2. Benefits of thermal energy storage using PCMs

To further assess the performance of the façade, the effect of the pre-conditioning component in the façade using the air cavity and the PCMs were tested. From the results presented in previous sections, the balanced ventilation mode with an airspeed of 0.5 m/s for each stream was selected for this test. As shown in Figure 2, the main variable tested, the $T_{mp}$ of the PCM_A that corresponds to the cooling season, was varied between 21 °C, 24 °C, and 29 °C and then compared to a case with no PCM present in the air cavity. The temperature gradient within the width of the air cavity at 40 cm height was recorded during the test period and shown in Figure 6 for the hottest time tested (39 hrs).

![Figure 6](image)

**Figure 6.** Temperature changes across the profile of the air cavity at the mid-height of 40 cm.

Considering the outdoor temperature of 32 °C at the time of the measurement, it is expected that all three PCMs are melted, and thus the excess heat in the cavity is increased. Comparing the effect of each PCM scenario on the air cavity temperature and $T_{SA}$ shows that lowering the $T_{mp}$ of PCM from 29 °C to 21 °C would result in a 0.7 °C reduction in the $T_{SA}$ entering the room with an average airspeed of 0.5 m/s. Additionally, a peak shift was observed by adding the PCMs to the cavity, with a 4-hour peak shift from the peak outdoor temperature when applying the PCM with a $T_{mp}$ of 21 °C. A peak shift of 1 hour for the other two $T_{mp}$ cases was achieved. Finally, the higher temperature of the cavity in the PCM integrated cases compared to the No PCM scenario could be explained by the radiation and conductive heat fluxes added due to the aluminium boundary of the PCM channels. This was shown in the total convective heat flux values that ranged between 10 and 15 kW/m² in the case of the PCMs, while the same value was 9 kW/m² in No PCM case. MICRO-V is designed to perform during the year, and the cavity also includes PCMs with $T_{mp}$ of 15 °C already in place, therefore, the annual effectiveness of the PCMs combined should be quantified.

4. Conclusions

In this paper, the performance of a multifunctional CRF with integrated ventilation was evaluated in summer under different ventilation scenarios with variable airspeed for the SA and RA. Additionally, the effect of PCM melting temperature on the overall pre-conditioning of fresh air was tested. It was shown that an increase in the airspeed of both air streams (higher airflow rate) would enhance the ventilation unit’s overall pre-cooling efficiency. While the balanced ventilation scenarios showed lower performance in decreasing the $T_{SA}$ to meet the setpoint temperature, they are easier to manage compared to the conditional scenarios that would require a control logic based on the boundary condition assessment.

The MICRO-V façade provides transient response to regulate the environmental loads and is also a decentralized ventilation system that could be used and adjusted based on individual zone preferences. MICRO-V façade with the simultaneous supply and exhaust modes, and adjustable thermal
transmittance brings a new approach that maximizes the solar radiation efficiency combined with thermal energy storage for both heating and cooling seasons to address the shortcomings of ventilated facades. This study showed how the pre-conditioning could be controlled using the design parameters. This allows the façade to actively switch from the off and on mode, which is beneficial for night ventilation, and cooling during the day. This study, provides a proof of concept on the façade-scale for the MICRO-V façade and how its overall performance can be managed and adjusted to specific contexts. The performance of this façade is further evaluated using on-going experimental tests.

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