Importance of thermal stack effect in ventilative cooling concepts for residential buildings

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ABSTRACT

This paper investigates the impact of ventilative cooling in residential buildings constructed from light-weight cross-laminated timber. Different temperature-controlled ventilative cooling concepts such as single sided ventilation, cross-ventilation and thermal stack based chimney ventilation concepts are simulated and compared in terms of impact on indoor temperature and robustness to external conditions such as the surroundings and the building orientation. Chimney ventilative cooling which makes use of the thermal stack effect has the largest impact on indoor temperature and is least affected by the external conditions.

KEYWORDS

Ventilative cooling, single-sided ventilation, cross-ventilation, chimney ventilation, thermal comfort, thermal stack, cross-laminated timber

1 INTRODUCTION

This paper investigates the impact of ventilative cooling in residential buildings constructed from light-weight cross-laminated timber and evaluates the robustness of different concepts with respect to environmental conditions such as the building orientation and the surrounding environment. Light-weight timber-based construction of residential buildings has received growing attention, and is increasingly implemented in order to realize serial prefabricated homes that can be installed on-site in a matter of days and to reduce the environmental footprint by use of sustainable materials. At the same time, these prefab construction styles also present new design challenges and questions on which heating, cooling and ventilation systems that should be used in order to realize low energy consumption and good thermal comfort, while also matching well with the serial production process. Ventilative cooling is an energy-efficient approach to cool buildings by utilizing natural airflow to regulate indoor temperatures. By harnessing cool outside air during favourable conditions, ventilative cooling reduces the need for active cooling, leading to cost savings and a smaller environmental footprint. Ventilative cooling solutions can be easily integrated in prefab walls and are considered an interesting concept for serial residential building production.

2 SIMULATION SETUP

2.1 Simulation environment

The simulations in this paper are carried out using Matlab/Simulink in a co-simulation setup where the building dynamics are modeled in the Modelica IDEAS library (Jorissen, et al., 2018) and the installation and control algorithms are implemented in Matlab/Simulink.

2.2 Inhabitant behaviour

Inhabitant profiles are generated using the StROBe model (Baetens & Saelens, Modelling uncertainty in district energy simulations by stochastic residential occupant behaviour, 2016;

Baetens, On externalities of heat pump-based low-energy dwellings at the low-voltage distribution grid, 2015; Baetens, StROBe, sd) which includes room occupancy, CO2, humidity and heat generation by occupants. Window opening behaviour is taken into account using an extension of this model (Verbruggen, Delghust, Laverge, & Janssens, 2021; Verbruggen, Window Use Habits as an Example of Habitual Occupant Behaviour in Residential Buildings, 2021; Verbruggen, EROB, sd). In this paper, only one inhabitant profile consisting of 2 full-time working adults with a school-going child is generated and used in the simulations.

2.3 Building geometry and properties

The building geometry considered is based on a terraced house used in the Dutch standards for ventilation calculations (VLA, TNO, Peutz BV, & Nieman Raadgevende Ingenieurs BV, 2018; ISSO 92, 2009). The 3 floors plan is shown in Figure 1 and the front and back view is shown in Figure 2. In this study, the building walls are modelled as layers of light-weight cross-laminated timber panels on the inside and outside with insulation material in between.

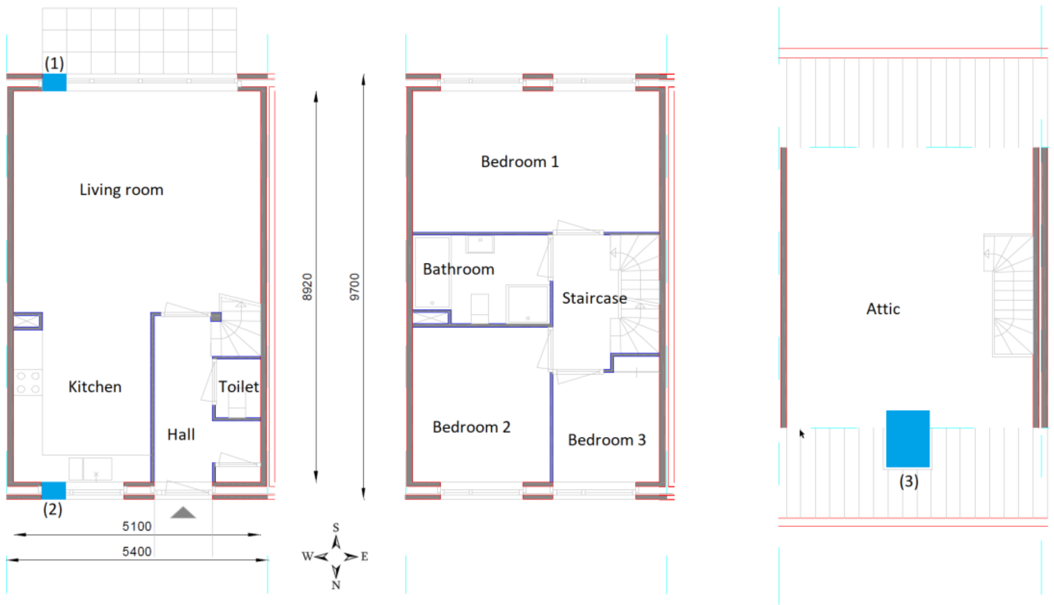

Figure 1: Terraced house floor plan

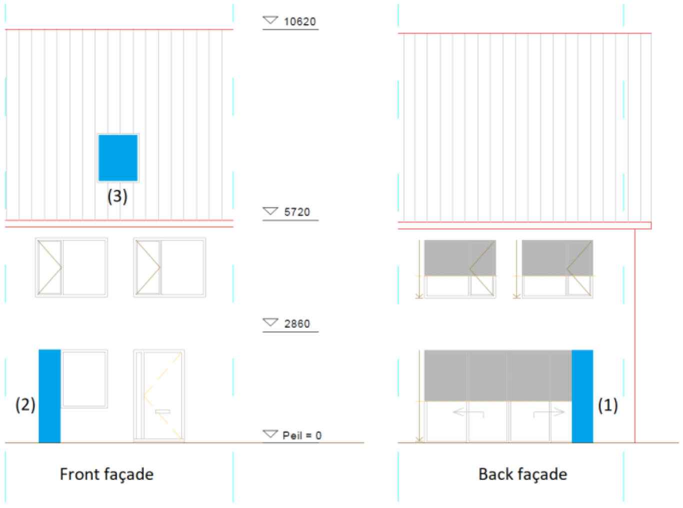

Figure 2: Terraced house front and back view

2.4 Environmental conditions

The climate data used in the simulations is based on data measured in Uccle, Belgium between 2000 and 2009, that is combined into a single climate file with some extremes including a hot summer to test the effect of challenging weather conditions. To evaluate the robustness of the ventilative cooling, the building is simulated in four different orientations and both in a suburban and urban environment. The effect of the surrounding environment on the wind speed is taken into account using a power-law correction (ASHRAE Handbook - Fundamentals, 1993). In the default orientation as shown in Figure 1, the front façade is facing north and the living room with the largest window is facing south.

2.5 Ventilative cooling concepts

The effect of three ventilative cooling automatic temperature-controlled concepts is investigated:

- Concept 1: Single-sided ventilation, where only one ventilative cooling component (1) of dimensions 2 m x 0.5 m with discharge coefficient of 0.2 in the living room is used (see (1) in Figure 1 and Figure 2). As this component is used on the ground floor, it is also burglary and insect-proof (Duco Louvres and grilles, sd).
- Concept 2: Cross-ventilation, where two ventilative cooling components (1) and (2) similar as above in the living room and kitchen are used (see (1)-(2) in Figure 1 and Figure 2).
- Concept 3: Chimney ventilation, where ventilative cooling component (1) similarly as aboven is located in the living room and a roof window (3) located in the attic (1.4 m x 1 m) are used and whereby an open staircase is assumed (see (1)-(3) in Figure 1 and Figure 2).

As a reference situation, manual ventilation by window opening of inhabitants is also simulated. It is important to remark that the results in this reference situation may depend heavily on the chosen inhabitant profile. This paper focusses mainly on the mutual comparison of the automatically controlled ventilative cooling, which is not directly affected by the absence or behaviour of inhabitants. In the simulations, it is assumed that the presence of the automatic ventilative cooling does not affect the window opening behavior of the inhabitants.
For the control of the ventilative cooling, a setpoint of 22 °C with a hysteresis of ±2 °C is used and the ventilative cooling components are only opened when there is a cooling demand (above 22+2 °C) and when there is cooling potential, namely when the outside temperature is lower than the inside temperature. Conversely, the ventilative cooling is closed when there is no more cooling demand (below 22-2 °C) or when the outside temperature is higher than the inside temperature. Since the purpose of ventilative cooling is actually to reduce the temperature of the building mass and not just the air temperature, an estimate of the wall surface temperature of the building is used as the inside temperature.

3 SIMULATION RESULTS

In total 32 simulations are carried out ranging from May to September with four different building orientations, for a suburban and urban surrounding, and with manual window opening as the reference situation and as well as with the three temperature-controlled ventilative cooling concepts.

3.1 Impact of ventilative cooling on indoor temperatures

Figure 3 shows the influence of the ventilative cooling during a hot July week for a suburban environment with outside temperatures reaching 36 °C. With only window ventilation by inhabitants, the operative temperature in the living room is reaching 33 °C during the hottest day. With temperature-controlled ventilative cooling, the operative temperature is considerably reduced to 30.4 °C with single-sided ventilation, 29.3 °C with cross-ventilation and 28.5 °C with chimney-ventilation. With cross-ventilation and chimney ventilation, temperatures at night go down with the outside temperature and the heat built up during the hottest day on July 20 is also evacuated more quickly during the following days. In bedroom 1, the operative temperatures with window ventilation, single-sided and cross-ventilation are quite similar, whereas only chimney ventilation is able to remove heat from the bedroom. However, even with chimney ventilation, the temperature in bedroom 1 is quite high and going up to 32.4 °C on the hottest day. An explanation for this is that the window opening in the inhabitant profile from the StROBe/EROB models is not dependent on the climate data and the temperatures in the building. In reality, inhabitants will also open their windows during hot summer nights which will enhance the ventilative cooling considerably.

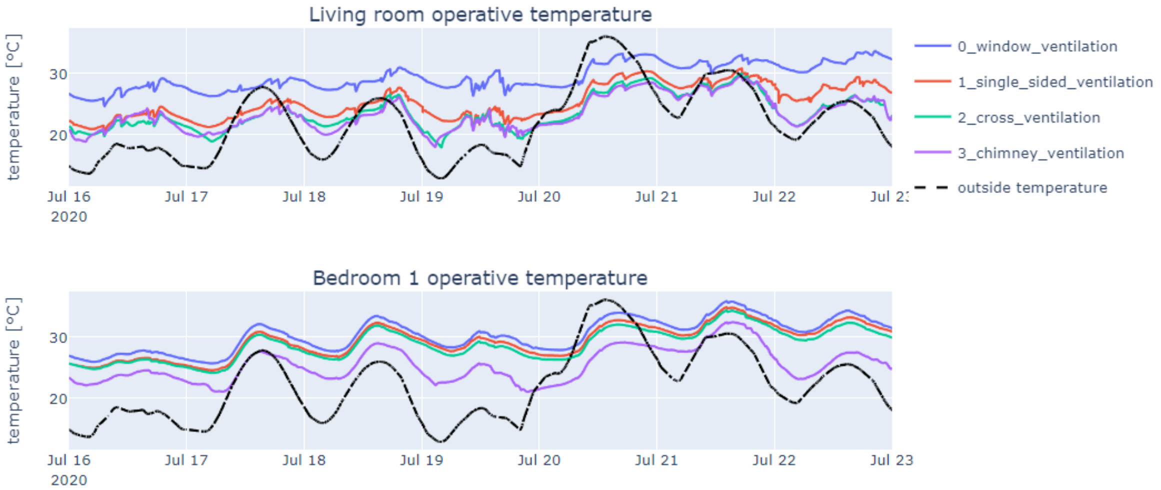

Figure 3: Living room and bedroom 1 operative temperature during a hot summer week

In Figure 4, the position of the ventilative cooling components during the hot July week is shown. Firstly, it can be seen that the ventilative cooling systems are open when the outside temperature is lower than the inside temperature and when the inside temperature is higher than 22±2 °C. Secondly, the chimney ventilation is closing quicker than the other concepts when the outside temperature is rising above the inside temperature, because it is slightly better in evacuating the heat during the hot summer days.

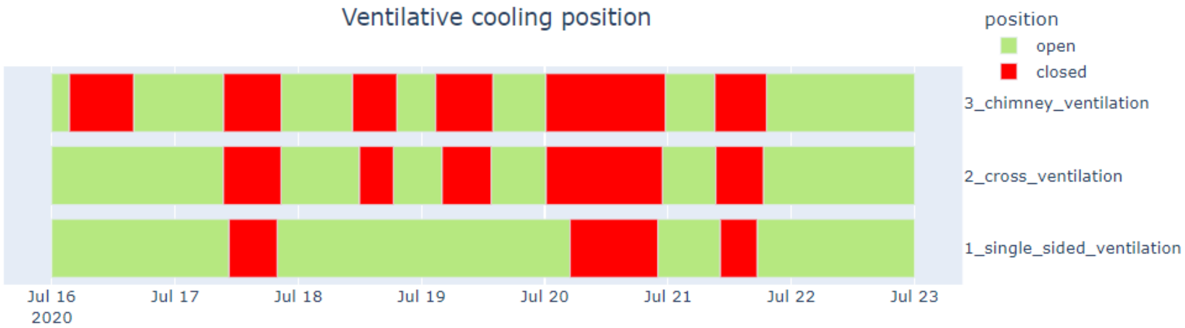

Figure 4: Ventilative cooling position for the different concepts during a hot summer week

3.2 Robustness of the ventilative cooling to external conditions

Figure 5 shows box plots of the daily average operating temperature in the living room for the different ventilative cooling concepts, aggregated from May until September over the different orientations with suburban surroundings on the left and urban surroundings on the right. Compared to manual window opening, which depends on the presence and behaviour of inhabitants, the temperature-controlled ventilative cooling concepts allow to keep the temperature in the living room under control most of the times. Single-sided ventilative cooling performs worse than the other two concepts, whereas chimney ventilation performs best and is able to keep the temperature well around the setpoint of 22±2 °C. In an urban environment, where wind speeds are reduced compared to unshielded or suburban surroundings, the cross-ventilation concept performs slightly worse than the thermal stack driven chimney ventilation.

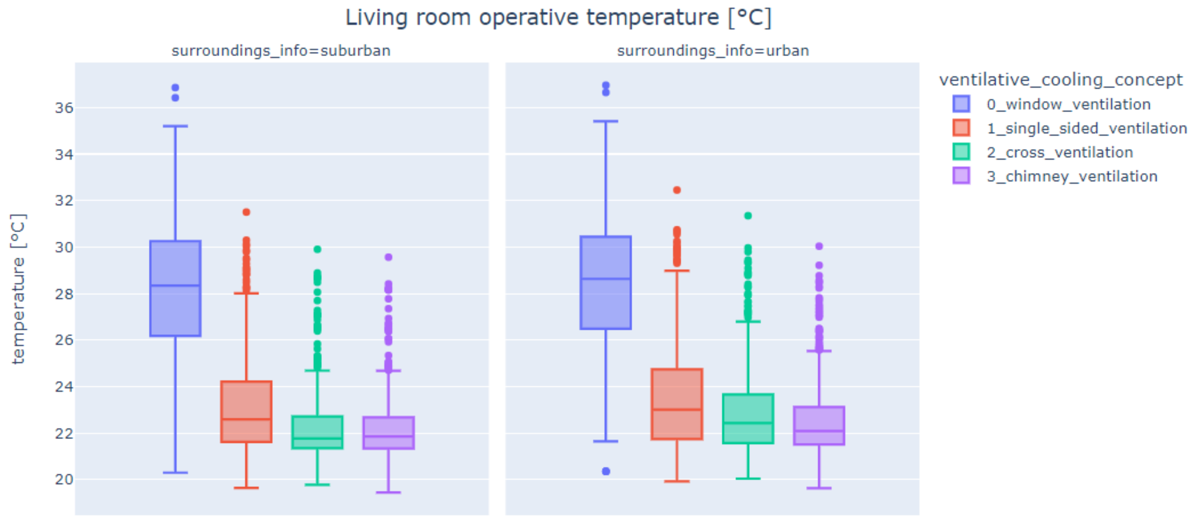

Figure 5: Box plots of the daily average living room operating temperature for suburban and urban surroundings

Figure 6 shows box plots of the daily average operating temperature in the living room for the different ventilative cooling concepts in urban surroundings, aggregated from May until September for the different building orientations from left to right. The orientation refers to the direction of the front façade, whereby 0° means that the front façade is facing north (as in Figure 1), 90° facing east, 180° facing south and 270° facing west. The single-sided and cross-ventilation concepts result in operative temperatures that depend on the orientation, with 270° being the worst case, whereas the chimney ventilation concept exhibits more constant temperatures, because the thermal stack effect is acting more consistently and independent of the orientation and the surroundings.

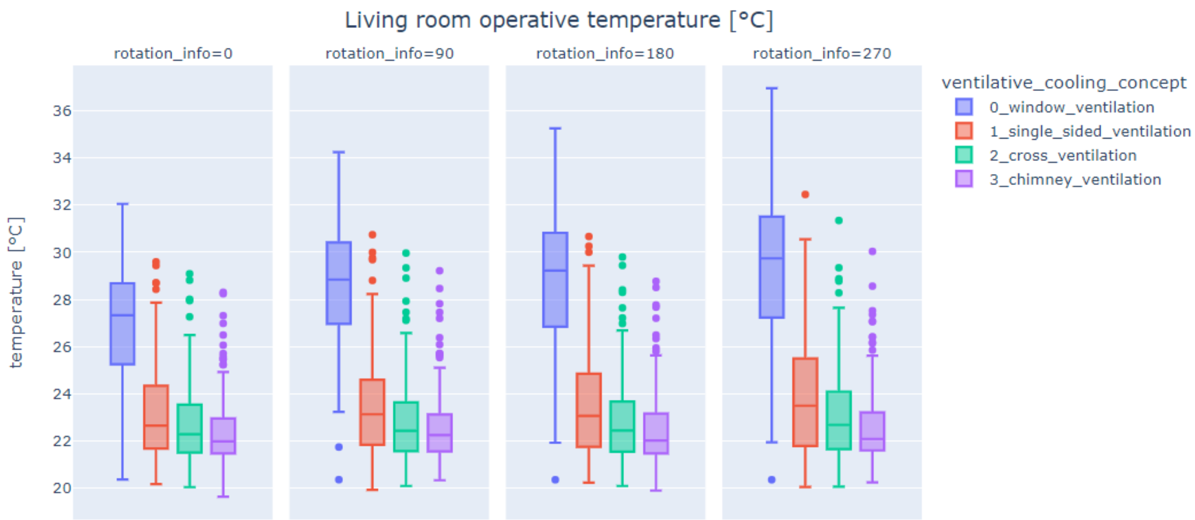

Figure 6: Box plots of the daily average living room operating temperature for urban surroundings and four different orientations

Figure 7 summarize the influence of the ventilative cooling concept, the environment and the orientation on the daily average operative temperature in the living room and bedroom 1. For clarity we focus here on the mutual differences between the three ventilative cooling concepts and therefore the manual window ventilation is omitted from the comparison.

From Figure 7 it is clear that the single-sided ventilation concept with an orientation of 270° in an urban environment has the highest average temperature of around 23.9 °C (top) and the chimney ventilation concept with an orientation of 0° in a suburban environment has the lowest average temperature around 22.2 °C (bottom). It can also be seen that for the cross-ventilation concept in urban surroundings, the 270° orientation (bottom left) results in the highest temperature of the 4 orientations.

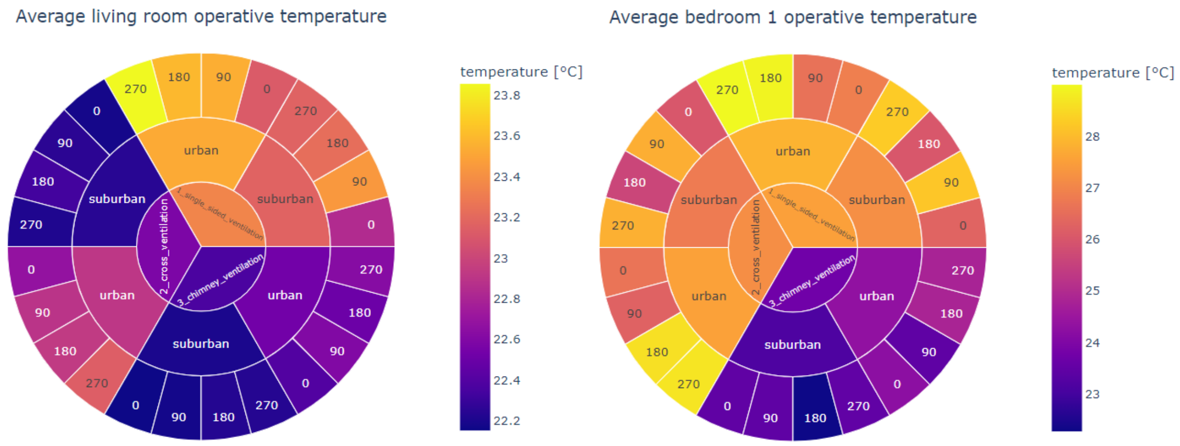

Figure 7: Sunburst plot of the influence of the ventilative cooling concept, the surroundings the orientation on the daily average temperature in the living room and bedroom 1

There are in fact two reasons that explain these results. Firstly, with the orientation of 270°, the living room with the largest window is oriented eastwards and is heating up by high solar gains from the morning until noon. This built-up heat can only be removed when the outside temperature starts to decrease towards the evening. Secondly, in the climate data, the wind is coming predominantly from the south, such that the cross-ventilation and single-sided ventilation concepts can benefit less from wind-driven ventilation when the wind is perpendicular to the ventilative cooling components. The chimney ventilation on the other hand is less impacted by the higher solar gains in the 270° orientation, as the driving thermal stack effect becomes also stronger when the temperature difference between inside and outside increases.

For bedroom 1, the highest average temperature of 28.9 °C also occurs for the single-sided ventilation with a 270° orientation in an urban environment, whereas the lowest temperature of 22.3 °C occurs for the chimney ventilation concept with a 180° orientation in suburban surroundings. The chimney ventilation is the only concept here that contributes significantly to reduction in bedroom temperatures.

4 DISCUSSION AND CONCLUSIONS

This paper investigates the impact of three ventilative cooling concepts in residential building constructed from light-weight cross-laminated timber on indoor temperatures and evaluates the robustness to external conditions such as the surroundings and the orientation of the building.

The ventilative cooling concepts consist of temperature-controlled single-sided, cross-ventilation and thermal stack based chimney ventilation. Compared to manual window opening, automatically controlled ventilative cooling concepts do not require inhabitants to be present and allow to significantly reduce living room temperatures throughout the months of May to September thus avoiding the need for active cooling. The thermal stack based chimney ventilation concept is the only concept that also reduces bedroom temperatures significantly and appears most robust to the external conditions such as the surroundings and the building orientation. From a cost and installation perspective, the chimney concept is also an interesting option, as it requires only one ventilative cooling component to be used in the living room in combination with a roof window that is often already present, but only needs to be automated. Further work will investigate the effect of thermal stack based chimney ventilation in pilot residential buildings.

5 ACKNOWLEDGEMENTS

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