A Review: Ventilated Double-skin Façades

Safaa Lahayreh\textsuperscript{1,2,*}, Monica Siroux\textsuperscript{2}, Anas El Maakoul\textsuperscript{1}, Ismail Khay\textsuperscript{1} and Alain Degiovani\textsuperscript{1}

\textsuperscript{1}International University of Rabat, LERMA Lab., Morocco
\textsuperscript{2}INSA Strasbourg ICUBE, Strasbourg University, France

*sa@uir.ac.ma

Abstract. In the aim of reducing the effect of climate change on the environment, multiple energy efficient solutions have been developed in all energy-consuming sectors around the world, especially smart building design strategies in the building sector. One of these technologies are Ventilated Double-Skin Façades (VDFs), which use the thermal interaction between the external environment and the internal space of a building in order to reduce its heating or cooling loads and thus reduce the greenhouse gas emissions. They also offer multiple other benefits, depending on several parameters, including improving the building’s thermal and acoustic insulation, and providing natural ventilation and exposure to daylight. The goal of this paper is to provide a review of the available research on VDFs in literature, namely their thermal behavior, the parameters that influence it, and the main criteria used to categorize VDFs.

1. Introduction
In recent years, due to climate change and energy saving obligations, high energy efficiency has become one of the main priorities to consider when designing a building, along with human comfort and healthy working environment.

The residential and tertiary building sector is known to consume 40% of the European Union’s final energy \cite{1}. Moreover, a considerable part of this energy is wasted due to thermally and energetically inefficient and obsolete building designs, construction materials, and cooling/heating systems. These losses can be reduced thanks to effective passive and active solutions including innovative building designs and space heating and cooling methods. We cite for instance optimized building orientation, natural ventilation and solar systems, thermal mass walls \cite{2,3}, efficient insulating envelopes and construction materials, mechanical ventilation and HVAC systems \cite{4}.

One of the many different construction techniques that have been studied over the years and which can combine passive and active solutions to reduce the energy needs of a building is Ventilated Double-Skin Façades (VDFs).

A ventilated double-skin façade consists of two skins or layers, a glazed or opaque external wall and an internal thermal mass wall separated by an air channel, which is also named in literature cavity or gap, that collects or evacuates the solar radiation absorbed by the external layer of the façade \cite{5}. In addition, air inlet and outlet openings, often called vents, are placed on the walls typically at the top and the bottom. VDFs can also have different orientations, configurations and diverse skin and insulation materials can be used depending on several parameters like climate context \cite{6}. The use of this technique can either be used to effectively lower envelope heat gains \cite{7-9} or reduce heating loads of a building.
1.1. VDF thermal behavior

The three heat transfer mechanisms that govern the heat exchanges between the façade’s walls and the inside of the building are convection, conduction, and radiation.

In a typical configuration of a VDF, convection inside the air cavity of the façade is basically generated thanks to the air-flow velocity (wind) and the temperature gradient between the façade’s surfaces and the air. In the absence of wind, the external wall absorbs and stores solar radiations. The air in the channel thus heats and becomes less dense. Thanks to the stack effect (buoyancy force), the air then arises, flowing inside the room and then through the top outlet vent. This creates a pressure drop at the bottom of the air channel, which brings in cold air into the cavity through the inlet vent. (figure 1. (a)). This is what is called natural convection [10]. Otherwise, in the presence of wind, the ventilation in the air gap is caused by the chimney effect and the mechanical force of the wind.

VDFs also provide heat to the inside of the building. Giving that there is still a temperature gradient between the internal and external air, the outer wall releases the heat it absorbed and stocked during the day through radiation mechanisms. This phenomenon being not immediate depending on the thermal mass of the wall, it gives the indirect heat gain the advantage of providing heat during nighttime when temperatures usually drop, and air vents are closed.

![Figure 1. Working principle of a VDF [10].](image)

Thanks to VDFs, heat gains allow the reduction of the energy needed for space heating in the winter season. And in the summer, natural ventilation and the buoyancy effect decrease the energy needed for space cooling.

1.2. Parameters that influence VDFs thermal behavior

1.2.1. Weather parameters: solar radiation and wind speed. The thermal performance of a VDF strongly depends on weather conditions, especially solar radiation and wind speed.

Indeed, the more intense solar radiations are, the more considerable energy savings can be [11], due to the better ventilation rate in the air channel (stack effect). Therefore, the orientation of the façade in relation to the sun is an important parameter to take into consideration when designing a VDF. It should make sure that sun rays are orthogonal to the surface of the façade, and that sun exposure periods are maximised [12].

Similarly, regarding the wind speed, the more important wind speed is, the higher are ventilation rates in the air gap [12].
The effects of these two parameters were compared during summer and it was concluded that the natural ventilation (stack effect) is unimportant compared to the wind-driven ventilation if wind velocity values are greater than 1.5 m/s. E. Gratia and A. De Herde also concluded in their study that the ventilation inside the air gap is actually mixed. It is caused by the wind on the top of the buildings, and by the stack effect towards the bottom due to the greater buoyancy forces. [13].

1.2.2. Design parameters: cavity width and construction materials. The thermal performance of a VDF also depends on parameters that are related to the design of the façade, like the width of the air cavity, which is the distance between the façade’s two layers, and the construction material of the external thermal mass wall. E. Oesterle and al. present an extensive description of the changes that occur in the type of the ventilation inside the cavity when design and construction characteristics of the façade are varied. The authors found that the stack effect starts to become significant when the air cavity’s width is narrow and less than 40 cm [14]. In the same context, it also has been found that heat recovery is more likely to be efficient for small air channel widths as they heat transfer coefficients are higher due to high air velocity inside.

Regarding the outer skin material, many authors agree that façades with a glazed external wall are preferred for the summer season conditions. In fact, the use of materials with high specific heat, low thermal conductivity, low absorptivity coefficient and low density are favourable when it is wanted to reduce overheating of the absorbing wall. For opaque façades, F. Stazi and al. conducted an experimentation to compare the performances of metallic material and clay [15]. They concluded that the use of metallic materials for the external layer leads overheating during the day. However, contrariwise, they boost space cooling at night. They concluded that for opaque façades, materials with high reflectivity like white aluminum are more adapted. Very few authors studied the use of biomaterials as construction materials for VDFs, despite their multiple advantages. Bio-based materials are known to be renewable, with low production and transport costs and lower CO2 emissions than conventional construction materials, which can improve the impact our buildings have on the environment. They can also improve the thermal performance of building façades. For instance, timber is known for its low thermal conductivity, and thus is a good material for envelope insulation [16]. E. Pujadas-Gispert, and al., created their own tiles using recycled materials and bio-based polyester resin. tiles made of sanitary paper, grass reeds, recycled textiles, drinking-water treatment waste, and a bio-based polyester resin [6]. The tiles they created were tested experimentally in a VDF system as insulation layers and the results were positive. The heat was dissipated during the day when solar radiations are important, and the internal space temperature was conserved at night.

2. Classification of VDFs

The classification of VDFs has been discussed on several papers and studies. To do so, three major determining criteria have been identified in literature by the reviewed authors: the type of ventilation used in the façade, the structure of the VDF and the mode of ventilation of the cavity.

2.1. Ventilation type

(i) Naturally ventilated façades - don’t use any ventilation system and are often called passive [17]. As explained in section 1.1, natural ventilation is basically caused by two forces: buoyancy (chimney or stack effect) and the wind [18]. During periods with solar irradiation and due to solar heat gains, the air in the channel is warmer than the outside air. Thus, it is expelled towards the outside of the façade and lets in the cooler outside air, thus reducing the cooling loads. Naturally occurring wind patterns can also help with cooling and ventilating the building. Naturally ventilated façades are not suitable for countries with hot climates.

(ii) Mechanically ventilated façades - are described as active walls because they use ventilation systems such as air handling units, fans, HVAC systems. In periods with solar heat gains, mechanical ventilation systems are used to get rid of the absorbed energy. In colder periods where space heating is necessary, heat exchangers can be used to recuperate the solar heat [17].
(iii) **Hybrid or mixed-mode ventilation** - combines both natural mechanical ventilation, thanks to a controlled automated system that allows the shift to mechanical ventilation when natural ventilation is not possible anymore. Hybrid ventilation is suitable for countries with hot climates [17,18].

### 2.2. Façade geometry and cavity partitioning

Ventilated double skin façades can be categorized by considering their structure and type of construction, which is related to the partitioning of their air cavities [14,17,19].

This criterion tells us how the air cavity is physically divided. The partitioning configurations reviewed in literature are box, shaft-box, corridor, and multi-storey VDFs. (figure 2)

![Figure 2. Air cavity configurations. (a) Box, (b) Shaft-box, (c) Corridor, (d) Multi-storey [20].](image)

(a) **Box type VDF**, also defined as storey with juxtaposed modules – is described in literature as a façade partitioned horizontally on each floor, and vertically in a way that divides it into small juxtaposed independent boxes [14,17,19]. The vents or openings that serve as air inlets and outlets are placed at each floor. (figure 2a)

(b) **Shaft-box type** – In this type of façade, multiple boxes (box type VDF) are separated by a long vertical ventilation canal placed in the channel for air outlet (figure 2b). Thanks to natural ventilation, the air naturally goes through the vertical shaft and goes through the outlet vent placed at the top of the façade.

(c) **Corridor façade**: The air channel in the corridor configuration is only partitioned along the horizontal length and not limited vertically, which is for acoustical, fire security or ventilation reasons [20]. Thus, each floor of the façade has an extended air cavity, which is generally large enough for people to walk in for cleaning or maintenance [17]. (figure 2c) Also, in each floor, the air inlet and outlet vents are located in the outer wall of the façade, close to the ground and ceiling to encourage separate intake and exhaust of the air [21].

(d) **Multi-storey VDF**: literature describes the cavity in a multi-storey façade as one large volume. In fact, unlike the box, shaft-box, and corridor type, it is not fractioned. Each floor or storey can have one uninterrupted air channel. Big openings are placed at the bottom and the top of the building for cavity ventilation. [14,19, 20,21]. Floors can be added and installed at the level of every storey for cleaning and maintenance reasons. (figure 2d)

X. Lancour and al. also add a fifth configuration of VDF, which they call the **multi-storey louver** type. The main thing that differentiates this configuration from the multi-storey type are the rotating slats placed on the outer wall to allow air to escape or pass through even when they’re in closed position [17].

The buoyancy force (stack effect), and thus the height of the façade, are important when studying the performance of VDFs. Therefore:

- the multi-storey type and the shaft-box configurations are ideal for using natural ventilation to limit solar heat gains, thanks to the important stack effect in the air gap. [22].
- the box and corridor types aren’t suitable for natural ventilation because the distance that separates the inlet and outlet vents is less considerable, but are very suitable for tall buildings because they prevent overheating in the upper levels.
2.3. Ventilation mode

Table 1. Experimental and numerical work reviewed.

| Author/year        | Work done experimental and numerical                                                                 |
|--------------------|-------------------------------------------------------------------------------------------------------|
| [23] Saelens and Hens, (2001) | Numerical model to assess the behavior of active double skin façades and comparisons with experimental results and measurements. |
| [24] Shiou Li, (2001) | Experimental work to assess the performance of a south facing double glass envelope system with natural and mechanical ventilation |
| [25] Saelens, (2002) | 2D numerical model for box type double or multiple-skin façades with mechanical and natural ventilation. |
| [26] Manz, (2003) | Numerical simulation model of heat transfer in cavities with natural convection                        |
| [27] Manz and Simmler, (2003) | 2D CFD model in transient state on FLOVENT for a ventilated double glass façade with a shading device and mechanical ventilation. |

The ventilation mode criterion basically corresponds to the direction of air in the channel (its origin and destination). Five ventilation modes have been identified to classify VDFs. (figure 3)

(1) Outdoor Air Curtain - In a traditional outdoor air curtain, outdoor cool air is goes through the inlet vent at the bottom of the channel, and thanks to the stack effect leaves the cavity through the outlet vent. Therefore, an air barrier is generated around the external layer. (figure 3(1))

(2) Indoor Air Curtain – The internal air goes through the cavity and then, thanks to mechanical ventilation, goes back inside. Therefore, an air barrier is generated around the internal layer of the VDF. (figure 3(2))

(3) Air Supply - Ventilation openings are at the bottom of the external wall and the top of the internal skin. External air enters the cavity, rises and goes inside or into a ventilation system. (figure 3(3))

(4) Air Exhaust – Ventilation opening are at the bottom of the inner layer and at the top of the external one, and warmer internal air to the external environment through the air gap. (figure 3(4))

(5) Buffer Zone – The cavity is airtight. The façade layers are sealed, and a neutral barrier-like area of air is generated. Therefore, there is no ventilation, but this mode has been proven to improve the thermal performance and protect internal shading devices of the façade. (figure 3(5))

3. VDF modelling

Studying the thermal performance of a VDF is important in order to ensure an acceptable and comfortable indoor climate in a building. In the interest of assessing the influence of the factors discussed above on the thermal efficiency of VDFs, several methods can be used.
In fact, different modeling approaches have been used in literature including experimental work (real test houses, full or reduced-scale test rooms, guarded hot box (GHB) [28], calibrated hot box (CHB) [29]), CFD numerical models and analytical methods.

Table 1 reviews some of the experimental and numerical work done in literature.

CFD modeling consumes a lot of computing time (CPU), and thus the numerical simulations and configurations possible for a VDF are limited. Therefore, it is more useful to use analytical models on software like MATLAB.

Numerical and analytical methods have been studied more in depth throughout the years. A. De Gracia and al. described in detail the different typologies of numerical modelling (airflow network models, control volume approach, zonal approach, CFD simulations…) and highlighted their benefits and limitations. [30]

4. Conclusion

In order to reach the EU’s net zero carbon emissions target by 2050, scientists and researchers have been studying energy efficient systems and designs to implement to the building sector. To this end, many authors have investigated the role of Ventilated Double-Skin Façades in minimizing energy consumption in buildings.

Indeed, numerous experimental protocols and numerical models have been proposed for that matter. VDFs have proven to play an effective role in reducing cooling loads during summer. M. Ciampi and al. affirm that the use of carefully designed VDFs will allow energy savings exceeding 40% in the summer [31]. However, research on the impact of VDF incorporation in buildings for heating purposes is still relatively limited. Furthermore, the use of bio-based materials in VDFs has not been discussed enough in literature either, which could be an interesting aspect to develop.

5. References

[1] E. Doroudchi, K. Alanne, Ö. Okur, J. Kyyrää, M. Lehtonen, Approaching net zero energy housing through integrated EV. Sustain. Cities Soc. 38, 534–542 (2018)
[2] M.M. Antonio, T.A. Isabel, S. Cho, J.L Vivancos, Energy efficiency and thermal comfort in historic buildings: A review. Renewable and Sustainable Energy Reviews, 61(), 70–85 (2016).
[3] T. Blázquez, S. Ferrari, R. Suárez, J.J. Sendra, Juan, Adaptive approach-based assessment of a heritage residential complex in southern Spain for improving comfort and energy efficiency through passive strategies: A study based on a monitored flat. Energy, 181(), 504–520 (2019).
[4] A. Aslani, A. Bakhtiar, M. Akbarzadeh, Energy-Efficiency Technologies in the Building Envelope: Life Cycle and Adaptation Assessment. Journal of Building Engineering, (), S235271021830319X–. (2018).
[5] D. Faggembaau, M. Costa, M. Soria, A. Oliva, Numerical analysis of the thermal behavior of ventilated glazed facades in Mediterranean climates. Part I: development and validation of a numerical model, 75(3), 217–228 (2003).
[6] E. Pujadas-Gispert, M. Alsailani, K.C.A van Dijk, A.D.K Rozema, J.P ten Hoope, C.C. Korevaar, S.P.G. Moonen, Design, construction, and thermal performance evaluation of an innovative bio-based ventilated façade. Frontiers of Architectural Research, (), S2095263520300170–. (2020)
[7] F. Mootz; J.-J. Bezian, Numerical study of a ventilated facade panel. 57(1), 29–36 (1996).
[8] C. Afonso, A. Oliveira, Solar chimneys: simulation and experiment. 32(1), 71–79 (2000).
[9] C. Balocco, A simple model to study ventilated facades energy performance. 34(5), 469–475. (2002).
[10] A. Gagliano, S. Aneli, Analysis of the energy performance of an Opaque Ventilated Façade under winter and summer weather conditions. Solar Energy, 205(), 531–544 (2020).
[11] R.F. De Masi, S. Ruggiero, G.P. Vanoli, Hygro-thermal performance of an opaque ventilated façade with recycled materials during wintertime. Energy and Buildings, 245, 110994 (2021).
[12] M. Ibañez-Puy, M. Vidaurre-Arbizu, J.A, Sacristán-Fernández, C. Martin-Gómez, *Opaque ventilated Façades: Thermal and energy performance review*, Renew. Sustain. Energy Rev. 79, 180–191 (2017).

[13] E. Gratia, A. De Herde, *Natural ventilation in a double-skin facade*. Energy Buildings, 36(2), 137–46, 45(5), 356–0 (2004).

[14] E. Oesterle, R.D. Lieb, M. Lutz, W. Heusler, *Double skin facades - integrated planning*. Munich: Prestel; (2001).

[15] F. Stazi, F. Tomassoni, A. Vegliò, C. Di Perna, *Experimental evaluation of ventilated walls with an external clay cladding*. 36(12), 3373–3385 (2011).

[16] E. Tapparo, *Engineered wood glass combination - Innovative glazing façade system*, (2017).

[17] X. Loncour, A. Deneyer, M. Blasco, G. Flamant, P. Wouters, *Ventilated Double Skin Façades - Classification & illustration of façade concepts*, BBRI (2005).

[18] M. Kragh, *Building Envelopes and Environmental Systems*. Paper presented at Modern Façades of Office Buildings Delft Technical University, (2000).

[19] S. Barbosa, K. Ip, *Perspectives of double skin façades for naturally ventilated buildings: A review*. Renewable and Sustainable Energy Reviews, 40, 1019–1029(2014).

[20] H. Poirazis, *Double Skin Façades for Office Buildings: Literature Review*, 2004 Report EBD-R--04/3.

[21] B. Brown, *An introduction to the design and application of double skin facades in North American high-rise architecture*, (2016).

[22] M. Torres, P. Alavedra, A. Guzmán, E. Cuerva, C. Planas, R. Clemente, et al. *Double skin facades—cavity and exterior openings dimensions for saving energy on Mediterranean climate*. Build Simul, (2007).

[23] D. Saelens, H. Hens, *Evaluating the Thermal Performance of Active envelopes*, Proceedings of Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes. (2001).

[24] S.S. Li, *A Protocol to Determine the Performance of South Facing Double Glass Façade System*. (2001).

[25] D. Saelens, *Energy Performance Assessments of Single Storey Multiple-Skin Facades*. (2002).

[26] H. Manz, *Numerical simulation of heat transfer by natural convection in cavities of façade elements*. Energy and Buildings. 35, 305–311 (2003).

[27] H. Manz, H. Simmler, *Experimental and numerical study of a mechanically ventilated glass double façade with integrated shading device*. Proceedings of the Building Physics Conference in Belgium, (2003).

[28] D. Sukamto, M. Siroux, F. Gloriant, *Hot Box Investigations of a Ventilated Bioclimatic Wall for NZEB Façade*. Energies, 14(1327), (2021).

[29] Wild, J.A., Moses, P.J., Strom, E.E., *Performance measurements of a phase-change Trombe wall in a calibrated hot box and unoccupied test houses*. Conference: American Society of Heating, Refrigerating and Air-Conditioning Engineers’ semiannual meeting, Honolulu, HI, USA, 91:2B (1985).

[30] A. De Gracia, A. Castell, L. Navarro, E. Orò, L.F. Cabeza, *Numerical modelling of ventilated facades: A review*, Renewable and Sustainable Energy Reviews, 22(1), 539–549 (2013).

[31] M. Ciampi, F. Leccege, G. Tuoni, *Ventilated facades energy performance in summer cooling of buildings*. 75(6), 491–502 (2003).