Doctoral School on Engineering Sciences
Università Politecnica delle Marche

Extended summary

Experimental and analytical assessment of vertical opaque envelopes: optimization in warm temperate climates

Curriculum: "Architecture, Buildings and Structures"

Author

Ambra Vegliò

Tutor

Prof. Alessandro Stazi

Date: 30-01-2013

Abstract. The current research is aimed at identifying, experimentally and analytically, the energy performance of several vertical opaque envelopes, in warm temperate climates.
The aim of the research regarding the *traditional envelope* is to verify the dynamic performance of 3 different wall constructions (masonry wall, cavity wall and insulated cavity wall). In each case, the optimal retrofit solution in terms of comfort, energy consumption and environmental impact is identified. To that end, contemporary experimental comparisons were made between buildings which are characteristic of the existing building heritage (1940-1980). Dynamic parametric analyses (EnergyPlus software) were carried out in order to verify the impact of different retrofit solutions. The results show that the behaviour of the 3 envelopes differs greatly. The use of considerable thicknesses of thermal insulation sometimes causes problems of overheating. The introduction of an external ventilated insulation layer was found to be the optimal solution.
The aim of the research regarding the *ventilated envelope* is to assess the effective thermal performance of the ventilated façades with a thermo-fluid dynamic analysis. To that end, contemporary experimental comparisons were made between ventilated façades with different external cladding (clay cladding and zinc-titanium), various heights of the ventilation channel (4, 6, 8 and 12 m) and different exposure (east, south and west). Fluid-dynamic parametric analyses (ANSYS-Fluent software) were also carried out. The results show that variations in the height of the ventilation channel cause an increase in the velocity and temperature values in the channel. The air flow rate also rises considerably when the height of the channel increases. Both the ventilated façades, with different external cladding, perform well even if there is a chimney effect at different times, during the daytime in one case and during the night in the other.

Keywords. Traditional wall constructions, ventilated façades, experimental study and parametric analyses, thermal performance, optimal retrofit solutions.

1 Problem statement and objectives

Recent years have seen a rise in energy consumption in European countries, in particular due to a greater number of air-conditioning systems. For this reason, the energy efficiency Directives [1,2] promote the improvement of the energy performance of buildings, requiring the member states to identify buildings which can act as reference standards for energy efficiency according to their function, geographical position and outdoor and indoor climate conditions.

The aim of the current research is to evaluate, experimentally and analytically, the energy performance of several *vertical opaque envelopes*, in warm temperate climates.

Traditional envelope

An analysis of the literature shows that, traditionally, for buildings in temperate climates 3 different wall constructions have been used for the outdoor climate conditions:

- capacity: typical of traditional buildings where envelopes with high thermal mass act as heat storage, leading to temperature mitigation. Many authors [3–6] have demonstrated the efficiency of this system even compared with modern envelopes [7];
- stratification: typical of buildings from the 1960s onwards, where multi-layer envelopes with air cavities slow down the heat flux because each layer provides a slight resistance to heat transfer [6,8–10];
- resistance: typical of buildings in the 1990s, where the insulation is carried out using materials that act as thermal barriers against heat loss. Several authors have shown the efficacy of this strategy, particularly when the insulation layer is placed on the external side of the wall [6,11–13].

Over the years there has been a transition from traditional capacity buildings, which adapt dynamically to the climate without the use of heating systems, to buildings with envelopes which act as a thermal barrier to the outdoor climate conditions.

Energy saving regulations, which originated in cold climates, have adopted the latter strategy of resistance insulation, using increasing thicknesses of insulating material. In Italy, following the European trend, this strategy of super-insulation has been applied to both new constructions and when retrofitting existing buildings, setting limits for stationary and periodic parameters (D.Lgs. 192/05 [14] and subsequent decrees). The Italian temperate climate is strongly dynamic because characterised by a considerable range of daytime and seasonal temperature variations. In many cases the use of these envelopes has led to the problem of overheating and to high levels of humidity, and consequently to the need to install expensive heating and cooling systems and mechanical ventilation in order to regulate the temperature of the indoor environment. In temperate climates mixed solutions should be identified which, while using considerable thermal resistance (for the winter), are able to exploit the dynamic behaviour of the mass.

The current study is aimed at identifying the optimal retrofit for the climate, in terms of comfort, energy consumption and environmental impact.

Ventilated envelope

The ventilated façades with an opaque external cladding were designed in order to save energy during the winter and to resolve problems of durability due to the atmospheric agents and aggressive solar radiation [13]. These walls proved to be excellent during the summertime thanks to the chimney effect, leading to the development of several numerical models which identify the range of temperature and the air velocity in the gap and estimate the thermal performance [15,16].

Few researchers have presented experimental analyses on ventilated façades of real buildings [17,18]. Some experimental studies develop mockups, aimed at the validation of a simulation model [19,20] while others present analytical models validated through laboratory measurements taken from the literature [21].

Numerous experimental studies have been carried out on double skin façades [22-25], on walls with light exterior panels [26] or with PV panels [27]. There are several studies on the energy performance obtained using ventilated façades with different external cladding, but without integrating the analytical study with the experimental measurements. To analyse the energy performance of ventilated façades, computational fluid-dynamic (CFD) modelling has proved to be the most appropriate simulation method [28]. The advantage of ventilated façades, characterised by dynamic behaviour in warm temperate climates, has induced some researchers to suggest dynamic insulation [29-31] with an external porous insulating material which allows the air filtration inwards.

There are no studies regarding the use of a ventilated external insulation layer: this is a system which adapts dynamically to the outdoor climate conditions, with two configurations, one for the summer and one for the winter. The system originated in Northern Europe [32-34] but has been rarely applied owing to its installation complexity and the poor winter thermal performance of the air vents, which are generally made of thin aluminium plates. For this reason, our research group has studied a preassembled system with air vents made of insulating material (registered trademark MUnSTa®).

The aim of this study is to experimentally assess the efficiency of ventilated façades with different external cladding during operating conditions and to verify the real airflow and the range of temperatures in the various layers for different chimney heights and exposure.

2 Research planning and activities

2.1 Traditional envelope

The research on the traditional envelope considered 3 multi-storey buildings, chosen (through typological, constructive and statistical analyses [35,36]) as reference buildings for each of the 3 traditional wall constructions identified: building 1 with solid brick masonry (capacity), building 2 with unfilled brick-block cavity wall (stratification) and building 3 with unfilled brick cavity wall with a 5 cm external insulation layer (resistance).

2.1.1 Experimental methods

Summertime (20th June – 6th July 2010) and winter (12th December – 27th December 2010) simultaneous monitoring was performed on the case studies. The following measurements were carried out according to UNI EN ISO 7726 [37]:

– outdoor environmental conditions: a weather station with a global radiometer, a combined sensor for the speed and the direction of the wind and a thermohygrometer was used;

– indoor climate conditions: some indoor microclimate stations that included a globe thermometer and a thermohygrometer were used;
– envelope performance: dataloggers coupled to thermoresistances and heat flux meters were used;
– specific tests on the envelope (blower door test and thermo-graphic survey) provided data which were useful for both the calibration of the dynamic models and for identifying the thermal bridges.

2.1.2 Analytical methods

The buildings chosen as case studies were reconstructed as virtual models using EnergyPlus dynamic software. By comparing the values measured during monitoring with the calculated ones it was possible to develop realistic virtual models.

During the first stage, an optimal retrofit was performed on the calibrated models involving all the construction components (pitched roof, first floor slab and window) except the external vertical wall to conform them with Italian energy saving legislation ([14] and subsequent decrees). Parametric variations were made on the external vertical wall changing the position of the insulating material and using thicknesses and materials which provided (in all cases) the same stationary thermal transmittance. Retrofitting with a ventilated external insulation layer was also carried out: it is made up of external insulation in expanded polystyrene (9 cm thick) separated from the internal wall by a channel which can be either ventilated during the summer or closed hermetically during the winter.

During the second stage, an in-depth study on the cavity wall was performed. Parametric analyses were carried out for different types of insulating material in order to identify a retrofit solution optimised in terms of comfort, energy consumption and environmental impact.

The ventilated external insulation layer, which proved to be an optimal solution, was subjected to a subsequent in-depth study using a software program for dynamic thermo-physical analysis (ANSYS-Fluent) based on the air velocity in the ventilation channel. This last study aims to identify the optimum time for opening the vents.

2.2 Ventilated envelope

The research on the ventilated envelope was performed on 2 office building characterised by ventilated façades with different external cladding (clay cladding and zinc-titanium), various heights of the ventilation channel (4, 6, 8 and 12 m) and different exposure (east, south and west).

2.2.1 Experimental methods

The following investigations were carried out on the case studies with clay ventilated façades (22 July - 7 August 2009) and with zinc-titanium ventilated façades (22 July – 29 August 2011, according to UNI EN ISO 7726 [37]:
– outdoor environmental conditions: weather stations mounted on the vertical façades with global and vertical radiometers, a combined sensor for the speed and the direction of the wind and a thermohygrometer were used;
– detailed analysis of the thermo-physical behaviour of the façades by means of:
  - a set of thermo-resistances to measure the surface temperatures of the different layers;

- a set of hot-wire anemometers placed in the ventilation channel to analyse the velocity and the temperature of the air in the gap;
- a set of heat flux meters to measure the incoming and outgoing heat flux through the ventilated façade and to calculate the transmittances;

the measurements were carried out at the inlet openings and at half the height of the ventilation channel;
– indoor climate conditions: some indoor microclimate stations that included a thermo-hygrometer were used;
– specific tests on the envelope (thermo-graphic survey) provided data which were useful for both the calibration of the dynamic models and for identifying the thermal bridges.

2.2.2 Analytical methods

Numerical models of the ventilated façades studied were carried out, through the software ANSYS-Fluent, to simulate the fluid-dynamic behaviour in the ventilation channel. Experimental data were necessary for the set-up and the validation of the models: they allowed us to define the profiles of the boundary conditions to define the ventilated façade models.

Dynamic parametric analyses were carried out in order to identify the impact of different parameters (thickness of the ventilation channel and thickness of the insulation layer) on the behaviour of the ventilated façades.

3 Analysis and discussion of main results

3.1 Traditional envelope

The experimental data on the 3 case studies demonstrated that:
– in the summer, masonry walls and cavity walls behave well, with lower internal temperatures, compared with insulated cavity walls;
– in the winter, all the traditional walls perform badly and never conform to comfort standards because the occupants of the buildings use the heating system for a very few hours in the day. However, the resistance–insulated wall performs better than the others (owing to its lower thermal transmittance).

Energy retrofitting, carried out according to current legislation standards which require the use of considerable thicknesses of insulating material, has a very different effect on the 3 types of walls, above all as regards comfort:
– with the masonry walls the use of super–insulation (in any position) has a negative effect in the summer since it causes considerable problems of overheating. On the contrary, in the winter the insulation positioned externally proves to be a good solution. It is very convenient to refurbish with a ventilated external insulation layer, which offers benefits both in the summer and in the winter;
– with the cavity walls thick insulation leads to a great improvement in both the summer and the winter, with external insulation being preferable. The use of a ventilated rather than a traditional external insulation layer further reduces the summer surface temperature and increases the winter values;

– adaptation to current legislation for walls which are already lightly insulated, through the addition of a further layer of insulation, has a slightly negative effect in the summertime and there is little improvement during the winter.

As regards energy consumption the different insulation strategies were beneficial in all the studied wall constructions during the winter while the retrofit worsens the initial situation during the summer except when it is applied to the cavity wall.

From the point of view of environmental impact, the ventilated external insulation layer was found to be the best system due to its ability to adapt to outdoor conditions, because of the presence of the ventilation channel.

3.2 Ventilated envelope

The experimental data on the 2 case studies, with various ventilated façades, have allowed us to demonstrate that the different external cladding (clay cladding and zinc-titanium) and the inertial characteristics of the materials that mark the boundary of the channel, affect the chimney effect: during the daytime for clay ventilated façades and during the night for zinc-titanium ventilated façades.

The study of the influence of the height of the ventilation channel on the velocity and temperature profiles showed that a higher ventilation channel, for both the external claddings, increases the air overheating effect and the subsequent cooling. Moreover, if the external surface temperature of the external cladding is the same, an increase in the height of the ventilation channel leads to higher air velocity values in the channel.

Analysis of the Reynolds number and of the air flow rate in the ventilation channel showed that, as found with the air velocity values, the air flow rate also increases considerably with the height of the ventilation channel, with different air flow (laminar flow for the low façades and turbulent flow for the high façades).

A comparison of the external surface temperatures of the ventilated façades with different exposure (east, south and west) allowed us to notice that the east- and west-facing façades reach higher temperatures because of the solar radiation which, in the early and late hours of the day, strikes the façades with a low angle. This causes a small time lag in the chimney effect.

Both the ventilated façades, with different external cladding, perform well in a warm temperate climate even if there is a chimney effect at different times. A façade with a high ventilation channel is preferable in terms of air velocity and air flow rate, regardless of the exposure.

4 Conclusions

This doctoral thesis has provided a detailed analysis of various opaque external envelopes. The research was based on an integrated strategy between measurements carried out on real buildings and parametric analyses.

In the case of a *traditional envelope*, experimental activities allowed us to quantify simultaneously the performance of different types of traditional wall constructions. The study involved parametric analyses to identify a retrofit solution optimised in terms of comfort, energy consumption and environmental impact. The introduction of an external ventilated insulation layer was found to be the optimal retrofit solution.

In the case of a *ventilated envelope*, experimental activities allowed us to quantify simultaneously the performance of different types of ventilated façades. The study involved the fluid-dynamic simulations to identify the incidence of different parameters. Ventilated façades with different external cladding and different exposure perform well while ventilated façades with a high ventilation channel considerably increase the velocity and the air flow rate in the channel.

References

[1] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC.

[2] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

[3] A.S. Dili, M.A. Naseer and T. Zacharia Varghese. *Passive control methods of Kerala traditional architecture for a comfortable indoor environment: A comparative investigation during winter and summer*. Building and Environment, vol. 45, pp. 1134–1143, 2010.

[4] Z. Yilmaz. *Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate*. Energy and Buildings, vol. 39, pp. 306–316, 2007.

[5] F. Stazi, F. Angeletti and C. Di Perna. *Traditional Houses with Stone Walls in Temperate Climates: The Impact of Various Insulation Strategies*. In: Effective Thermal Insulation – The Operative Factor of a Passive Building Model, Edited by A. Almusaed, InTech, ISBN: 978–953–51–0311–0, pp. 45–60, 2012.

[6] E. Reid. *Understanding buildings: A multidisciplinary approach*. MIT Press, ISBN: 0–262–68054–8, 1984.

[7] S. Martín, F.R. Mazarrón and I. Cañas. *Study of thermal environment inside rural houses of Navapalos (Spain): The advantages of reuse buildings of high thermal inertia*. Construction and Building Materials, vol. 24, pp. 666–676, 2010.

[8] K.J. Kontoleon and D.K. Bikas. *The effect of south wall's outdoor absorption coefficient on time lag, decrement factor and temperature variations*. Energy and Buildings, vol. 39, pp. 1011–1018, 2007.

[9] H. Asan. *Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view*. Energy and Buildings, vol. 32, pp. 197–203, 2000.

[10] E. Kossecka and J. Kosny. *Influence of insulation configuration on heating and cooling loads in a continuously used building*. Energy and Buildings, vol. 34, pp. 321–331, 2002.

[11] P.T. Tsilingiris. *Wall heat loss from intermittently conditioned spaces – The dynamic influence of structural and operational parameters*. Energy and Buildings, vol. 38, pp. 1022–1031, 2006.

[12] C. Di Perna, F. Stazi, A. Ursini Casalena and M. D'Orazio. *Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads*. Energy and Buildings, vol. 43, pp. 200–206, 2011.

[13] F. Stazi, C. Di Perna and P. Munafò. *Durability of 20–year–old external insulation and assessment of various types of retrofitting to meet new energy regulations*. Energy and Buildings, vol. 41, pp. 721–731, 2009.

[14] Decreto Legislativo 19 agosto 2005, n. 192. *Attuazione della Direttiva 2003/91/CE sul rendimento energetico in edilizia*.

[15] M. Ciampi, F. Leccese and G. Tuoni. *Ventilated façades energy performance in summer cooling of buildings*. Solar Energy, vol. 75, pp. 491–502, 2003.

[16] D. Davidovic, J. Srebric and E.F.P. Burnett. *Modeling convective drying of ventilated wall chambers in building enclosures*. International Journal of Thermal Sciences, vol. 45, pp. 180–189, 2006.

[17] E. Giancola, C. Sanjuan, E. Blanco and M.R. Heras. *Experimental assessment and modelling of the*

performance of an open joint ventilated façade during actual operating conditions in Mediterranean climate. Energy and Buildings, vol. 54, pp. 363-375, 2012.

[18] F. Stazi, F. Tomassoni, A. Vegliò and C. Di Perna. *Experimental evaluation of ventilated walls with an external clay cladding*. Renewable Energy, vol. 36, pp. 3373-3385, 2011.

[19] F. Peci López, R.L. Jensen, P. Heiselberg and M. Ruiz de Adana Santiago. *Experimental analysis and model validation of an opaque ventilated façade*. Building and Environment, vol. 56, pp. 265-275, 2012.

[20] P. Seferis, P. Strachan, A. Dimoudi and A. Androutsopoulos. *Investigation of the performance of a ventilated wall*. Energy and Building, vol. 43, pp. 2167-2178, 2011.

[21] C. Balocco. *A simple model to study ventilated façades energy performance*. Energy and Buildings, vol. 34, pp. 469-475, 2002.

[22] A. Zöllner, E.R.F. Winter and R. Viskanta. *Experimental studies of combined heat transfer in turbulent mixed convection fluid flows in double-skin-façades*. International Journal of Heat and Mass Transfer, vol. 45, pp. 4401-4408, 2002.

[23] G. Ballestini, M. De Carli, N. Masiero and G. Tombola. *Possibilities and limitations of natural ventilation in restored industrial archaeology buildings with a double-skin façade in Mediterranean climates*. Building and Environment, vol. 40, pp. 983-995, 2005.

[24] V. Serra, F. Zanghirella and M. Perino. *Experimental evaluation of a climate façade: Energy efficiency and thermal comfort performance*. Energy and Buildings, vol. 42, pp. 50-62, 2010.

[25] S.P. Corgnati, M. Perino and V. Serra. *Experimental assessment of the performance of an active transparent façade during actual operating conditions*. Solar Energy, vol. 81, pp. 993-1013, 2007.

[26] P. Mendonça and L. Bragança. *Sustainable housing with mixedweight strategy - A case study*. Building and Environment, vol. 42, pp. 3432–3443, 2007.

[27] M. Sandberg and B. Moshfegh. *Investigation of fluid flow and heat transfer in a vertical channel heated from one side by PV elements, part II - Experimental Study*. Renewable Energy, vol. 8, pp. 254-258, 1996.

[28] A. Pappas and Z. Zhai. *Numerical investigation on thermal performance and correlations of double skin façade with buoyancy-driven airflow*. Energy and Buildings, vol. 40, pp. 466-475, 2008.

[29] A. Dimoudi, A. Androutsopoulos and S. Lykoudis. *Experimental work on a linked, dynamic and ventilated, wall component*. Energy and Buildings, vol. 36, pp. 443-453, 2004.

[30] G. Gan. *Numerical evaluation of thermal comfort in rooms with dynamic insulation*. Building and Environment, vol. 35, pp. 445-453, 2000.

[31] B.J. Taylor, R. Webster and M.S. Imbabi. *The building envelope as an air filter*. Building and Environment, vol. 34, pp. 353-361, 1999.

[32] H. Bartodziej. *Method of heat flow control through an external wall of building and wall assembly for execution of this method*. WO00/60183A1, 2000 (Patent).

[33] G. Anmelder. *Fassadenwärme-Dämm-Verbundsystem*. DE102004001601A1, 2005 (Patent).

[34] R. Güldenpfenning. *Verfahren Herstellung wärmegedämmter Putzfassaden*. DE3238445A1, 1984 (Patent).

[35] V. Corrado, I. Ballarini, S.P. Corgnati and N. Talà. *Intelligent Energy Europe (IEE), Typology Approach for Building Stock Energy Assessment (Tabula)*. Building Typology Brochure, Italy, October 2011.

[36] F. Stazi, A. Vegliò, C. Di Perna and P. Munafò. *Retrofitting using a dynamic envelope to ensure thermal comfort, energy savings and low environmental impact in Mediterranean climates*. Energy and Buildings, vol. 54, pp. 350–362, 2012.

[37] European standard UNI EN ISO 7726. *Ergonomics of the thermal environment – Instruments for measuring physical quantities*. 2002.