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Plaster ventilated façade system for renovating modern and ancient buildings. A CFD analysis

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Abstract. In the past decades several researches have been related to energy saving and emissions reduction. The technologies that exploit passive natural ventilation, like ventilated roofs and façades, have been recognized as the effective methods to provide energy saving and comfort. Ventilated façades represent dry assembled coating systems for buildings, traditionally made of panels in different materials. Very few ventilated façade systems with plaster finishes are already present on the building market. The potentiality of their design solution can be considered, e.g., when an historic building has to be recovered, since they can enhance the energy efficiency of building without changing its appearance. CFD simulations have been carried out by the authors in order to analyze the thermal energy behavior of a ventilated façade system with a plaster finishing and for comparing the benefits derived from its use to the corresponding unvented insulated façade. The ventilated façade shows a relevant energy saving thanks to the effect of ventilation: a reduction of 70% of heat flux was achieved, furthermore, a reverse conductance calculation showed relevant differences with the same calculated by thermo-physical material properties, since in this last calculation the heat and mass transport effect are not considered.

Keywords – ventilated façade; plaster; CFD; refurbishment; energy saving;

1. Introduction

In the last decades CO2 emission reduction, renewable technology penetration and energy efficiency increase have been the main aims of different nation policies worldwide.

An analysis of present building stock led to an imperative necessity: the implementation of both passive and active systems, thus achieving an increase of energy efficiency and greenhouse gas (GHG) emissions reduction, as demanded by the United Nations Framework Convention on Climate Change (UNFCCC) [1]. In particular, most of the researches carried out by scientists specialized in different disciplines -with the aim to quantify the benefits derived from the use of different strategies/products for retrofitting the building heritage of the Mediterranean Basin and to reduce its energy consumption- are focused on passive systems. Among these, the technologies that exploits natural ventilation, like ventilated roofs and façades, have been recognized as effectively able to enhance the building performances with low installation costs [2, 3]. The application of a ventilated facade let to reduce the effects of direct solar radiation by 27.5 %[4] and the ventilation of roofs can reduce significantly the heat fluxes (up to 50%) during summer season [5]. Several efforts are aimed to enhance the ventilation in the ventilated structures also by developing innovative building components. In [6] the experimental results show that the introduction of a novel roof tile shape in ventilated roofs let to increase the ventilation in the "above sheet ventilation" layer, and, consequently, to achieve better results in terms of energy savings than ventilated roofs equipped with standard tiles.

The building envelope provides the primary conditioning factor to heating and cooling loads and the inevitable ensuing energy cost for users [7]. A refurbishment must ensure balanced efficiency by overseeing “comfort per cost,” and maximum benefits from investments, while also safeguarding economic returns within the solutions lifespan: all of this combined factors must set the strategy [8].

Ventilated façade contribute to the thermal insulation of existing buildings, lowering energy needs, and GHG emissions [9]. These solution should differ by country and region conditions, explicitly considering the available energy sources and climate features [10]. It is composed by the following elements: an opaque vertical wall with an external coating constituted by finishing elements such as slabs, panels and others, separated from the opaque wall by a ventilated cavity. Actually, the ventilated cavity acts as a passive cooling element and, therefore, let to avoid thermal bridges and condensation problems.

Nowadays, on the building market it is possible to find ventilated façade systems that adopt different materials as finishing layer. They usually use panels made of ceramic, metal, plastic and so on as cladding solution that allow to reduce time and costs of installations. Very few ventilated façade systems already present on the building market use plaster finishing. The potentiality of this solution can be considered when, e. g., an historic building has to be recovered, as it can enhance the energy efficiency of building without changing its appearance testified by its original plastered façades.

CFD simulations have been carried out by authors in order to analyze the thermal energy behavior of a ventilated façade system with a plaster finishing and compare the benefits derived from its use to the corresponding unvented insulated façade.

2. Design and analysis of the case study

The building chosen as case study is part of the Cappuccinelli Social Housing district in Trapani. The project of this particular neighbourhood, designed by Michele Valori [11], dating back to 1956. The design is based on an ante litteram holistic approach aimed at ecology, sustainability and energy retrofit.

Actually, the original project derived from the idea of courtyards similar to those of the agricultural communities in Trapani surroundings. Inside the large courtyards there was an extensive vegetated space, with some tall trees and vegetable gardens. Courtyard buildings are made of duplex apartments symmetrically coupled. Inside the apartments the space is distributed as following: on the ground floor, a hall where is located the staircase, a kitchen and a dining room; on the first floor, three bedrooms and a toilet. The apartments have a private garden located on the back.

Figure 1. A courtyard during its construction.

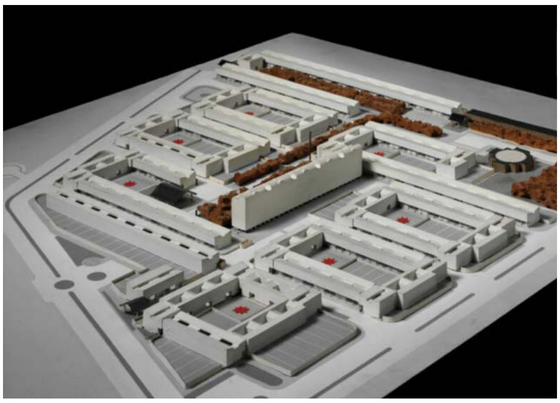

Figure 2. The original model of Cappuccinelli.

Today all Cappuccinelli’s buildings are particularly degraded: starting from the reinforced concrete structures up to the external finishing plasters which show serious flaking due, also, to the proximity to the see. Actually, the SH district is 150 m far from the waterfront and it is located near the cultural heritage site named “Tonnara Tipa” located just along the coast. Most of the buildings have been changed by tenants during the last years and by Autonomous Social Housing Institute (IACP); actually, the firsts have changed the original design of buildings by adding new volumes without licenses; the second changed building details, through (e.g.) the modifications due to the consolidations of pillars.

A recovery project is going to be designed by authors in the field of their research activity. It foresees to recover these buildings by retrofitting them through the use -among other systems and strategies- of a ventilated façade system with plaster finishing. This will let to improve the energy performance of buildings without changing their original appearance, as well as designed by Valori.

3. Metodology

CFD simulations for comparing the energy behavior of ventilated façade with an unvented insulated have been carried out by authors.

3.1. Domain description

A model of the described ventilated façade system has been implemented in the finite-elements software Comsol Multiphysics V 5.4 [www.comsol.com]. The effect of the ventilation channel, at the expense of a simplification to the external fluid flow problem has been investigated in detail. Hence, a 2D domain was modelled as a section of the case study building, thus neglecting the 3D heat and mass transport effects due to the interaction between building and wind. This method, adopted by several authors, let to focus the analysis on a significative section whose behaviour is analogous to the other ones [12, 13, 14]. The thermo-fluid steady state problem was solved by coupling three physics: heat transfer in solids and liquids, turbulent flow, radiation surface to surface. For the turbulent flow the k-ε model under the Boussinesq approximation [15] was implemented, the effects of the buoyancy forces were considered.

For the environmental conditions, a data set based on historical measured data was used for wind, air temperature and solar radiation.

Cappuccinelli's case study building is 7.2 m height and 12.6 m large; it is covered by a flat roof and it is surrounded -in the scheme used for the simulations- by an air domain composed as follows: 2 m large in front of the ventilated façade, 10 m high above the roof and 10 m large in the back side (figure 3).

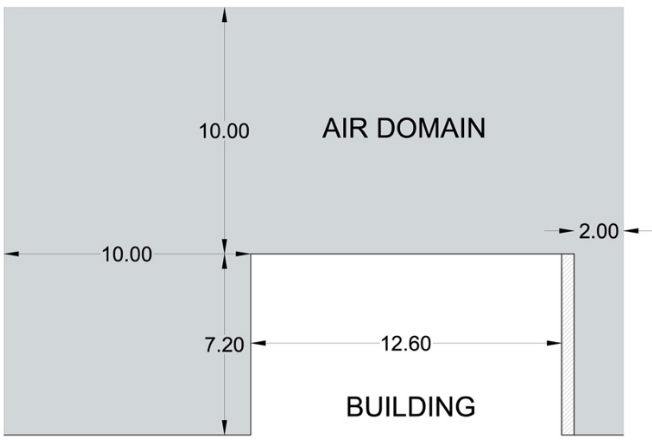

Figure 3. Building section scheme with geometrical domain set in Comsol Multiphysics.

The ventilated façade has an upwind exposition, the chosen size of the upwind domain (on the right side of the building, figure 3) is sufficiently large to consider the fully developed wind fluid flow. The downwind and upper domains (on the left and upside of building) were sized by considering the turbulent effects induced by the building shape.

The unvented insulated façade is composed by calcarenite blocks with an air cavity interposed between the two ashlars; a plaster layer; a rockwool layer and a final external plaster layer (figure 4).

In the ventilated façade system, a ventilated air cavity and a finishing plaster layer were added on the external side (figure 5).

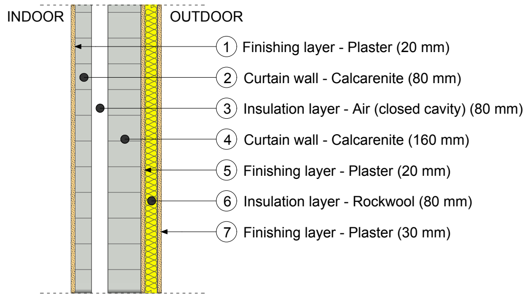

Figure 4. Unvented insulated façade section.

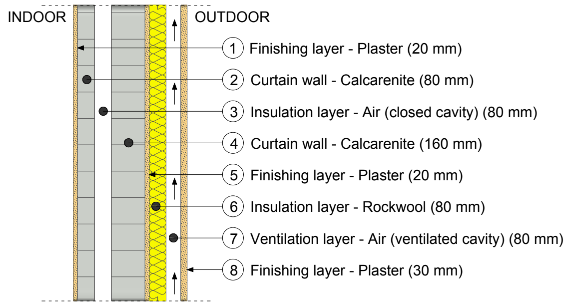

Figure 5. Ventilated façade section.

The thermo-physical properties of materials are indicated in table 1; the calculated thermal conductance for unventilated wall is 0.32 W/m^{2}K, for ventilated one is 0.28 W/m^{2}K

Table 1. Thermo-physical properties of materials.

Materials	Dimensions [cm]	λ [W/mK]	$\boldsymbol{\rho}$ [kg/m^3]	c_p [J/kgK]
Plaster	2	0.7	1400	840
Calcarenite	8	0.63	1500	840
Air	8	0.19	1.2	1005
Calcarenite	16	0.63	1500	840
Plaster	2	0.9	1800	840
Rock woll	8	0.035	70	1030
Finishing plaster	3	0.9	1800	840

Size and layout of ventilation inlet and outlet sections were set according to technical products widely used by manufacturer (figure 6).

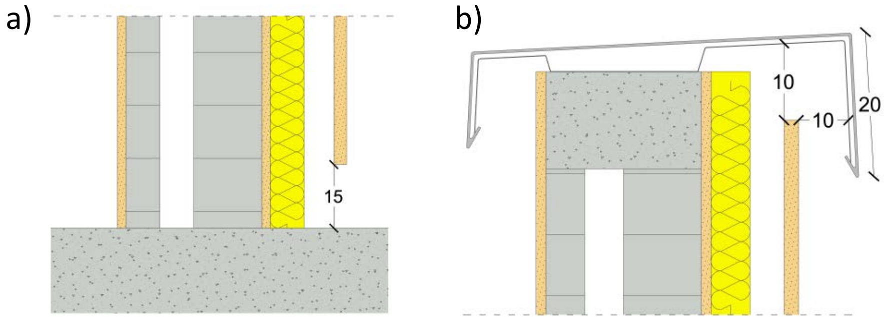

Figure 6. Inlet (a) and outlet (b) sections of ventilated facade. All measures are expressed in cm

3.2. Case study

The present study is focused on the effects of the wind speed, air temperature and solar radiation on the thermal behaviour of the facade, in terms of ventilation, heat flux and temperature. The simulations were carried out in steady-state for summer environmental conditions. A solar radiation flux of 500 W/m^2 is applied on the vertical external layer through the software interface "Surface to surface radiation" directly exposed to the sun, the external air temperature was set to 30°C. A uniform wind speed profile defines the inlet boundary condition in the domain, applied to the external boundary layer of the upwind air domain. Wind is supposed entering from the right side of the domain with horizontal direction, perpendicularly to the facade. The wind speed profile is variable with the altitude, according to the following power law

$$v = v_0 \left(\frac{z}{z_0}\right)^{\alpha} \quad (1)$$

where:

- v_0 is the wind speed (v_0=5 m/s) at the reference height z_0 (z_0=10 m);
- α is an empirical factor depending on the surface roughness, for a urban area like Trapani was considered α = 0.3 [16].

An equivalent convective heat transfer coefficient equal to 4 W/(m²K) is applied on the internal wall surface; it considers the heat transfer from the wall surface to the room (indoor air at 24 °C).

The chosen environmental parameters are representative of the typical summer project conditions for the indicated location. All the boundaries of air domains were considered as open boundaries to let the air free outflow. It's important to underline that the buoyancy effects were considered also in the closed air cavity (layer n. 3 in figure 4 and figure 5), the heat transfer is affected since in this layer both heat and mass transport occur. The whole mesh is composed of triangular linear elements with 42525 degrees of freedom for the insulated unvented façade model and 53338 in the ventilated one. To improve the solution, the elements are more concentrated within the ventilation channel and in the near areas (figure 7).

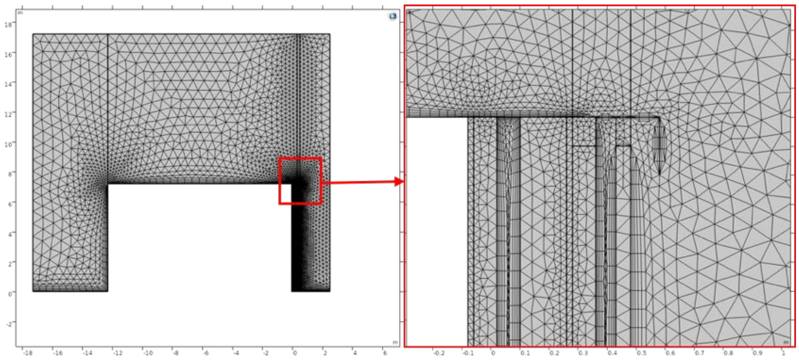

Figure 7. Physics-controlled mesh with free triangular geometry.

4. Results and discussion

The multiphysics approach let to evaluate the global energy performance of the analysed ventilated façade. The main aim of the simulations is to underline the effect of the ventilation on the thermal insulation in hot climate conditions. The most representative parameter is the net heat flux inward into the conditioned room. In figure 8 the inward heat flux variation on the building height is reported; a comparation between ventilated and unvented simulation case is showed.

The ventilation cavity shows an evident heat flux decrease thus enhancing the passive energy saving. The peak showed from the unventilated heat flux curve is due to the air velocity gradient; the heat transport due to wind is lower at low height.

Ventilated façade shows an average heat flux reduction of 70% if compared to the unvented one. The mitigation effect of ventilation cavity is well visible also in terms of surface temperature (figure 9): the external façade of ventilated case is always cooler than the unventilated one; the average difference between 1.5 m and 6 m height is 4°C. This difference is evident on the internal wall surface and positively affects the indoor comfort due to mean radiant temperature in the ventilated case.

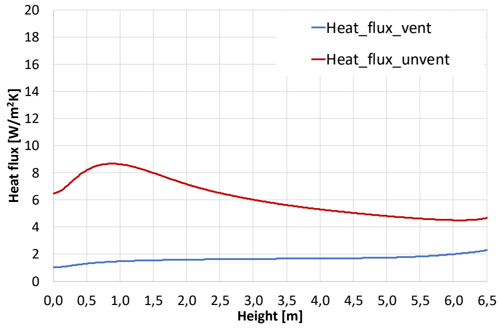

Figure 8. Heat flux trend.

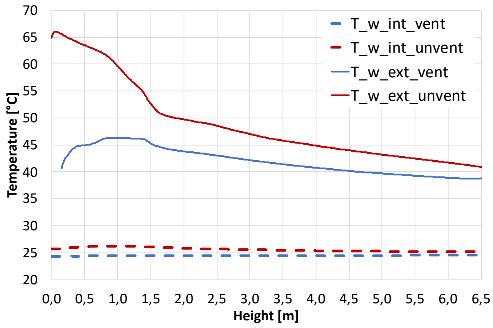

Figure 9. Surface temperature of wall.

In figure 10 a 2D plot of temperature distribution on different section sketches is showed.

On the base sections the overheating, due to radiation effect, is more marked in unvented façade: a temperature difference of more than 15°C are reported on the external layers. Significant differences on temperature distribution are evident also on the average height section far from boarder heat transfer effects: the ventilation channel removes heat from the external plaster layer; moreover, the radiation heat transfer between the plaster layer and the rockwool one is clearly showed. Finally, on the top of the façade, the temperature distribution in the air flow outlet from ventilation channel is evident.

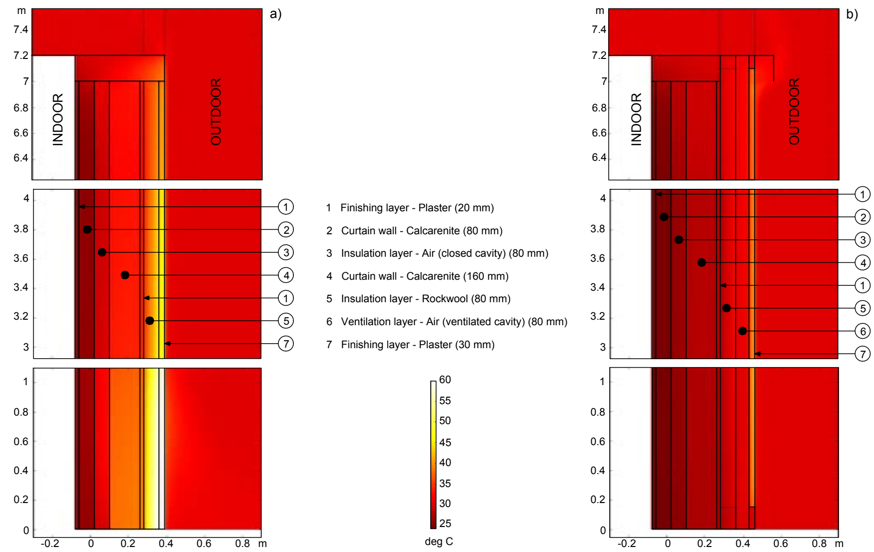

Figure 10. 2D temperature distribution of unvented (a) and ventilated (b) façades.

In figure 11 the distribution of air velocity is showed. Forced convection is predominant on buoyancy effects in presence of external wind: the effect of the outlet section geometry is evident. With the described environmental boundary conditions, a flow rate of 0.33 m^3/s and mass flow rate of 0.39 kg/s for 1m of cavity section depth have been calculated.

Finally, a reverse calculation of thermal conductance was performed as in equation (2)

$$C = \frac{\dot{Q}}{T_{w,ext} - T_{w,int}} \quad (2)$$

An average value of 0.1 W/m^2K was obtained for the entire ventilated façade system (layers from 1 to 7), this value is 65% lower than the thermal conductance calculated from thermophysical properties, this because in the calculation carried out by material properties the effect of heat and mass transport is not considered and the ventilated air cavity is considered as a pure conductive element.

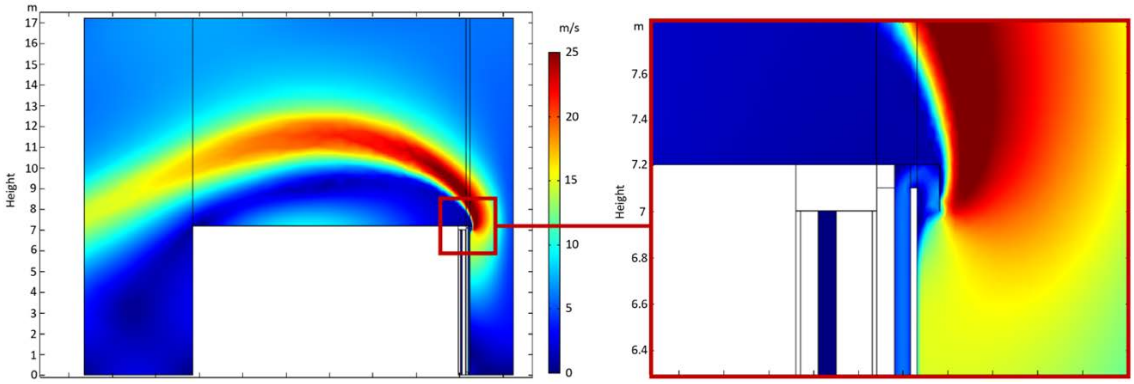

Figure 11. 2D air velocity distribution, a focus of ventilated facade outlet section is showed.

Analogously, the behaviour of the closed air cavity affects the thermal conductance if the convective phenomena are not neglected: for the unvented wall a conductance of 0.28 W/m^{2}K was obtained through the previous expression (reduction of 12% with respect to the thermal conductance calculated from thermophysical properties). In order to better evaluate the benefits of the ventilated wall, a further comparison was made. It was assumed to replace the ventilation chamber with an additional layer of thermal insulation, maintaining the same total thickness of the wall. So, the stratigraphy of the new external wall was defined as follow: 30 mm plaster, 80 mm calcarenite, 80 mm air cavity, 160 mm calcarenite, 30 mm plaster, 160 mm rockwool and finally 30 mm plaster. The resulting thermal conductance is 0.18 W/m^{2}K if the closed air cavity is considered as a pure conductive element, conversely, the value 0.17 W/m^{2}K is obtained by considering the buoyancy effects in the same layer. The heat flow trend of the new configuration shows lower values if compared with the unvented case and higher ones than in the ventilated case, although the thermophysical thermal conductance is lower for the last one. This shows that the thermal conductance calculated by the thermophysical properties cannot be considered as the only significant parameter to evaluate the performances of the ventilated facades. Figure 12 and figure 13 shows the trend of the heat flow and wall temperatures simulated in the new wall configuration with double layer of thermal insulation.

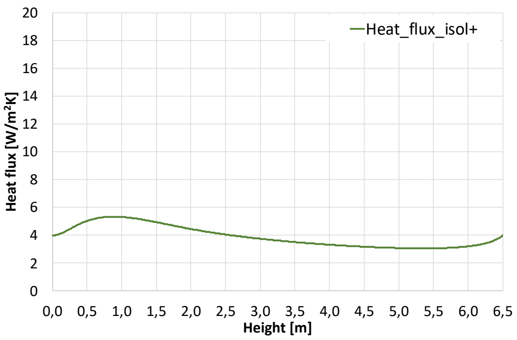

Figure 12. Heat flux trend.

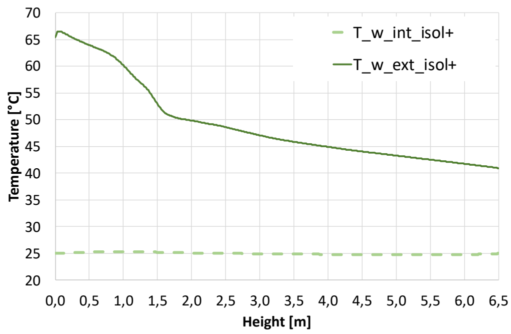

Figure 13. Surface temperature of wall.

5. Conclusions

The ventilated façades were widely studied in literature and are commonly used in design and building technologies; the ventilated cavity mitigates the effect of solar irradiation, especially in Mediterranean climates. An unusual type of ventilated façade system has been analysed in this paper. It is made of a plaster finishing that allow to consider this technological system useful also for retrofitting the historical buildings. This new type of ventilated façade has been considered for the refurbishment of Cappuccinelli SH district in Trapani (Sicily, Italy). A CFD model was implemented in order to compare the energy performance of the new ventilated façade with an insulated and unvented one; the commercial software Comsol Multiphysics was used. A steady state calculation was performed by assuming typical environmental and boundary conditions of the geographical area related to the case study. The ventilated façade shows a strong heat gain reduction thanks to the effect of ventilation: a reduction of 70% of heat flux was achieved. Moreover, the ventilated solution showed lower internal and external surface temperatures, thus enhancing the internal comfort conditions. A mass flow rate of 0.39 kg/s for 1m of cavity depth has been calculated; the fluid dynamic performances of the ventilated cavity could be improved through planning a new design of inlet and outlet sections. A reverse calculation of thermal conductance was performed, the obtained values were compared with the same ones calculated from thermophysical properties. For ventilated façade system a value of 0.1 W/m^{2}K was obtained, 0.28 W/m^{2}K for the unvented one; the respective values calculated from material properties were 0.28 W/m^{2}K and 0.32 W/m^{2}K. This difference was achieved since the effect of heat and mass transport is not considered and the ventilated air cavity is considered as a pure conductive element when the thermal conductance is calculated only by considering the material properties. A last case was considered by replacing the ventilated cavity with an insulating layer. The results show that there are no significative improvements in terms of heat flux reduction in comparison with the ventilated case, figure 14 - figure 15. The results of this study offer promising perspective since the plaster finishing will be widely used in plastered ventilated façade through an experimental campaign in order to better understand its operating and dynamic behaviour in hot climate conditions.

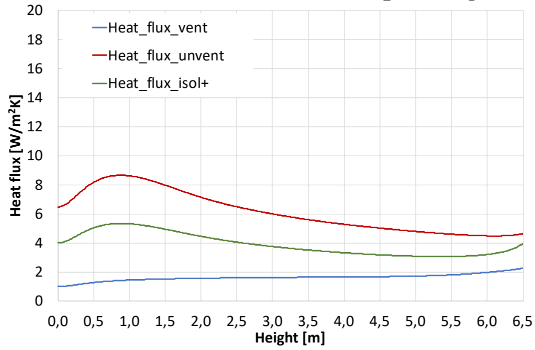

Figure 14. Heat flux trend.

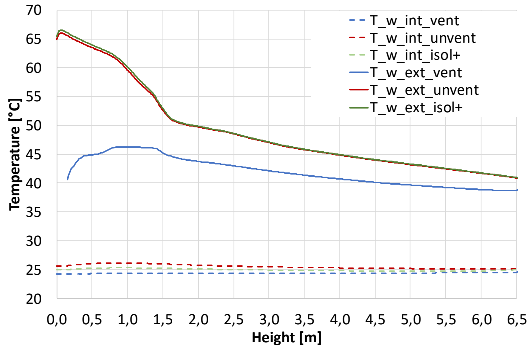

Figure 15. Temperatures of wall.

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