Energy evaluation of an horizontal open joint ventilated façade

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Abstract

The term "open-joint ventilated façades" refers to a building system in which an external layer of slabs or tiles (metallic, ceramic, stone or composite) is hanged by means of a metallic-frame structure to the exterior face of the brick wall, creating an air cavity between wall and slabs. The arrangement of slabs is such that it forms open gaps between them, allowing the surrounding air to enter and leave the cavity all along the façade. In addition to aesthetic and constructive reasons, the main interest of open joint ventilated façades is their ability to reduce cooling loads. This is done by the buoyancy effect created by solar radiation inside the ventilated cavity. This paper focuses on the energy performance of a typical open joint ventilated façade, comparing its temperatures and heat transfer fluxes with those of a conventional sealed air cavity façade. The thermal and fluid-dynamic behaviour of both designs have been analysed with CFD techniques and the results of the simulations conclude that open-joint ventilated façades can help to achieve substantial energy savings in climates with hot summers and mild winters.

Keywords: *Ventilated façade, CFD, Energy-efficient building, Solar passive design.*

1. Introduction

1.1. Motivation

In the global final energy consumption, the household sector accounts for a 29% share, which corresponds to a 21% share of CO2 emissions [1]. Inside this sector, space heating and cooling remains the most important factor and it is responsible for more than half of the energy expenditure. These indicators underline the growing importance of the evaluation of buildings thermal behaviour and the pressing need to increase their energy performance.

The buildings envelope (façades, roofs, walls, windows, etc.) plays an important role in energy efficiency. The exterior building elements, among them the façades, act as barriers between exterior and interior climatic conditions, but they may also work as passive solar energy systems. This way they can help reducing energy requirements for heating, ventilation and cooling while maintaining adequate comfort (interior temperature and humidity).

Energy efficiency and Bioclimatic Architecture are two of the pillars of the Strategic Singular Project, named ARFRISOL (Arquitectura Bioclimática y Frío Solar ≈ Bioclimatic Architecture and Solar Refrigeration), organized and promoted by the Spanish Education and Science Authority. This project study the energy behaviour of five demonstration-containers (new or renovated buildings) located in five different climatic conditions.

The aim is to prove that by combining passive conditioning systems (ventilated façade, greenhouse, glass corridors, etc.) and renewable energy sources (solar energy, biomass, geothermal energy, etc.) it is possible to reduce more than 80% the conventional energy consumption as well as carbon dioxide emissions to the atmosphere [2]. Three of the five buildings have open joint ventilated façades; the E-70 building located in Madrid, is the subject of the present study (central Spain, continental climate, Köppen climate classification: Csa); the other two are located in Almería (Southern Spain, Köppen: Bsh) and Soria (Northeast of Spain, Köppen: Csb).

1.2. Description

The open joint ventilated façade (OJVF) is a type of exterior closure built over a brick wall (that works as a support) to which a metallic-frame structure is attached. On this structure, the exterior tiles (stone, ceramic...) are hanged, leaving an air chamber between them and the main brick wall. The term "open joint" comes from the small gaps left between the tiles; these horizontal and/or vertical open joints, allow exterior air to enter and to leave the chamber, effectively "ventilating" the façade.

The open-joint façade is a passive conditioning system. The solar radiation on the exterior tiles heats them up and activates convection inside the air chamber, thus generating ventilation with an ascending air current that enters and exits the cavity through the open joints. When this current leaves the chamber by the upper gaps, it extracts thermal energy. In that way, the temperature of the brick wall and the heat flow towards the interior of the building is reduced, cutting down the energy required for air-conditioning. As this ventilation is produced by solar radiation, the OJVF is particularly interesting for areas where the peak of energy demand happens during the summer.

Also, manufacturers of this kind of external protection consider that, by the increased ventilation, humidity problems should be diminished, which is of special value when enhancing old buildings.

1.3. Classification and bibliographic study

The open-joint ventilated façade is a special type of ventilated façade, double envelope, double skin, advanced integrated façade or light façade, etc.: there is not a general agreement on a proper name. These terms form a rather wide range of building façade solutions that can be categorized according to different criteria. The International Energy Agency [3] classifies integrated advanced façades according to the ventilation type, the air's trajectory and the façade's configuration (mainly according to the materials) Different authors use other criteria, for instance Oesterle *et al*. [4] and Saelens [5] who characterize double skin façades based on the cavity's geometry.

These closure designs are quite recent. According to the International Energy Agency [3], the first building with a ventilated façade was erected in 1967 in the Cambridge University, but it was not until the nineties [6] that architects, concerned about energy efficiency in building, begin to integrate these solutions into their designs.

Double skin façades or advanced façades have been developed as time went by, trying to obtain not only aesthetic improvements in the buildings, new or rebuilt, but also the increase of thermal and acoustic isolation, the reduction of conventional energy for air-conditioning, the possibility of night free cooling, etc. This development has generated a great amount of scientific articles. Some of the most analysed characteristics are the properties of the façade components and the building itself (geometric, thermal physics, optical, etc.), the energy performance and the control optimization.

These systems have been studied with experimental and analytical methods, as well as numerical ones. Experimental analysis are limited and they are mostly confined to specific cases: some real working buildings and laboratory models, such as Saelens [5] and Kragh [7,8]. Afterwards they have been commonly used to validate analytical and/or numerical models.

Analytical methods are simple procedures to obtain approximations of the thermal and fluid-dynamic behaviour of this sort of façade solutions. In scientific bibliography there are many articles with rather different approaches. For example, Park [9] studies the thermal behaviour of double skin façades with natural ventilation by using parametric models; Grabe [10] develops a simple algorithm in order to predict the temperature and the flow characteristics in double façades. Both studies have been validated by experimental data. Balocco [11], using dimensionless analysis, obtains the energy performance of double skin façades, with natural as well as mechanically induced ventilation, extrapolating the dimensionless relations obtained at small scale. The network models and the control volume approach are also considered as analytical methods. Referring to the first one, Hensen *et al*. [12], Gratia and Herde [13], and Stec and Paassen [14], incorporate the energy equation into the model thus obtaining the energy performance for complete buildings. These models are only useful during the design stage. The control volumes approximation is usually a simple calculus model that takes into account the energy equation, the radiation model and the air speed in the cavity, solving the flows between the different elements or blocks in which the façade is divided. Faggembauu *et al*. [15, 16] and Saelens *et al*. [17] use this model to obtain the performance of several double skin façades.

Computational Fluid Dynamic (CFD) techniques have also been employed in this field. They allow to obtain a very detailed analysis of the thermal and fluid-dynamic behaviour of this type of building design, the downside is that they are quite complex and require a great amount of computing resources. Manz and Simmler [18] have carried out a comparative analysis of the heat transmission by natural convention in closed vertical cavities of buildings, using CFD and empirical correlations, obtaining a good approximation between the results of both techniques. Safer *et al*. [19] have studied a double skin façade equipped with shading devices and forced ventilation, although they did not take radiation into account, because of the calculation time. That is the reason why authors such as Klems *et al*. [20], choose to consider the radiation separately. The CFD models have also been paired with energy simulation programs of buildings to study the whole building, obtaining good results [21].

Despite the great amount of papers published about "ventilated façades", there are almost no references addressing the specific "open joint" design which is the object of this work. The geometric, thermal and fluid dynamic differences have prevented the prediction of performance and operational behaviour using any kind of similitude. One research using the open joint design is that of Nore *et al*. [22] who have studied the wind induced fluid-dynamics behaviour of the air in the cavity. Also, our research team has already published several articles [23-25], where fluid-dynamic and energy studies on open-joint ventilated façades have been carried out, taking convection, conduction and radiation models into account.

From the economic point of view, there are some references regarding the cost the ventilated façades (not open joint): Hilmarsson [6], who carries out an exhaustive analysis of the types of costs (operation, maintenance, construction, etc.) of these façades, compared with traditional designs; and Jager [26], who has published data about the initial investment and the maintenance costs in double skin façades (with different configurations) and conventional façades in Central Europe. Despite this, it is still very difficult to find data to compare the costs in specific cases.

1.4. How it works

In a façade exposed to solar irradiation there is heat exchange by conduction, convection and radiation. Figures 1 and 2 show details of these energy transfers (for clarity, conduction through walls is not represented). In Sanjuan e*t al*. [25], the heating transmission in the open-joint ventilated façade has been studied on detail, finding that the exterior and interior layers behave very similarly as in a conventional façade with sealed air cavity, the differences been mainly on the air behaviour inside the cavity.

In the conventional sealed cavity façade shown in Fig. 1 a convective loop is formed. The air closer to the exterior layer which receives solar irradiation heats up by convection and rises; the air closer to the interior wall is cooled because of the lower temperature of this this inner wall and descends.

The air behaviour in the ventilated façade is quite different. As can be observed in Fig. 2, the air rises along the whole cavity height gaining heat by convection from the tiles as well as from the interior wall. In the tile area the exterior air enters through the bottom joints and keeps rising as it heats up. When it reaches a sufficient temperature (higher than environment temperature) the air begins to exit the cavity -through the top joints-, extracting thermal energy from inside the cavity. The air closer to the brick wall rises by chimney's effect absorbing heat from such wall. The air average temperature in the cavity is between exterior air temperature and the temperature of the solid surfaces (tiles and brick wall) on both sides of the chamber. In this façade, the cavity air temperature is lower than the temperature reached in a conventional façade with a sealed air chamber.

The thermal energy extracted by ventilation depends on the mass flow rate of air that circulates inside the cavity. This flow, been driven by natural convection, is a function of the temperature field. The effectiveness of the ventilated façade relays on the amount of energy absorbed by the air as it rises in the cavity. This extracted energy does not enter the building and therefore the cooling thermal load is reduced. In areas of high solar irradiation the described mechanism can be quite intense, although the angle between the sun position and the façade (time of day, season, latitude) is also a major factor.

1.5. Objectives

This article describes a numerical analysis of the thermal and fluid-dynamic behaviour of an open-joint ventilated façade throughout the year. The façade belongs to a demonstration-container of the ARFRISOL project located in Madrid, which can be seen in Fig. 3. Because of its characteristics and climatic conditions, it has been considered is a good study case. It is divided by windows on each floor, has only horizontal joints between tiles, and the climate is continental with hot summers and cold winters. The photograph of Fig. 4 allows to inspect the inside cavity showing the brick wall, the insulation layer, a glimpse of the metallic frame and the exterior ceramic tiles. A close-up can be seen in Fig. 5, with the details of horizontal open joints, or gaps between the tiles.

The aim of this type of composed exterior wall is to generate a convective current of air, not unlike a solar chimney, which helps to dissipate part of the thermal energy accumulated inside the building, thus reducing the energy need for air-conditioning in summer. A general purpose computational fluid dynamics code has been used (FLUENT) with a quasi-steady 2D model. Results were obtained to describe the energy behaviour of the air flow generated inside the chamber and also to calculate the heat transfer with the surroundings all year round. A comparative analysis of the open-joint ventilated façade and an equivalent sealed air chamber façade has been carried out, in order to obtain the energy saving achieved with the use of the OJVF.

In contrast to the previously published papers of this research group [23-25], this investigation has been done on a specific commercial open joint ventilated façade, with a stair shape joint (to avoid water rain entering the gap). Also a certain validation has been performed using infrared measurements. In addition, data corresponding to the four seasons of the year has been analysed, not only from an energy point of view but also from an economic one.

2. Methodology

As previously mentioned, the numerical simulation uses a commercial Computational Fluid dynamic code (CFD): Fluent version 6.3. This code allows the simultaneous analysis of a heat transmission and a fluid dynamic problem, solving the Navier-Stokes equation (including the energy equation), with the finite volumes method.

The reasons to generate a 2D geometry instead of a 3D one are:

- The vertical joints between the tiles are sealed and the vertical support brackets impede the lateral movement of air between adjacent gaps
- The frontal tile width is an order of magnitude higher than the cavity depth
- Because of the small size of the joint gap and its staggered shape, the 2D modelling allows to obtain a resolution almost an order of magnitude higher than the obtained with a 3D model, with a reasonable number of cells.

For each of the two constructive solutions a model has been generated, with the only difference of the external layer. Fig. 6 shows a sketch of the numerical domain geometry. The domain represents a vertical plane of the façade between two windows. Apart from brick wall, insulation, air cavity and exterior tiles it includes also a broad layer of the surrounding air, thus enabling to calculate the heat flow between the outside air and the tiles without assuming any given transmission rate.

In both cases the closure is built, from outside to inside with ceramic tiles (FAVETON, 28 mm thickness, 206.7 mm height), either ventilated (10 mm separation between tiles) or sealed, 50 mm thick air cavity, a 60 mm layer of insulating material (rock wool) and an interior wall made of a layer of damp-proof mortar (15 mm thickness), "one feet" hollow brick and gypsum plaster (20 mm thickness). In the simulations the insulating layer and the composite mortar-brick-plaster interior wall have been represented together.

A structured meshing has been generated, refined in the air cavity, near the tiles and the open joints. The grid dependence has been studied obtaining fairly good results from 100000 cells up (the variations in the mass flow rate inside the gap are below 2%). Fig. 7 represents a detail of the mesh used in the OJVF, which has about 400000 cells.

The Discrete Ordinates model has been chosen for radiation [27, 28]. This model allows introducing the solar radiation as radiation itself, instead of simulating it as a thermal load on solid surfaces (confront with Coussirat [29] P1 model or Baldinelli [30] solar load model-). The discretization of the solid angle has been analysed, finally selecting a value six times higher than the one used by default.

Turbulence effects have been included using a K-epsilon approach (RNG) [31], including buoyancy effects. Chen [32] and Coussirat *et al*. [29] have found out that this model obtains better results than others in cases with similar features to one in this article.

The fluid (air) is considered as ideal gas. The properties of the solid materials forming the closure have been taken from the buildings standards, and from technical papers of manufacturers. The ceramic tiles have a thermal conductivity of 0.20 W/mK and the insulated brick wall has an average thermal conductivity of 0.0965 W/mK. Both are considered opaque to radiation and they were assigned an emissivity of 0.85 and 0.9, and a diffuse reflection of 1.5% and 1% respectively.

Referring to the boundary conditions:

- Convection and radiation towards the room have been taken into account in the inner brick wall. Following UNE-EN-673 and current Spanish normative for buildings, heat convection coefficient is 7.69 $W/m^2 \cdot K$, room air temperature is 21ºC when central heating is working (spring, autumn and winter) and 26ºC when air conditioning is connected (summertime).
- The external air has constant hydrostatic pressure (atmospheric) and enters the cavity at exterior air temperature. The same temperature is considered for radiation exchange with the environment.
- Only the incident radiation perpendicular to the façade component has been considered.

About the solution procedure, a second order discretization scheme has been used in the energy, turbulence and radiation equations and a second order – pressure staggered scheme in the momentum equations. Also the SIMPLE algorithm has been utilized in the pressure-velocity coupling.

To obtain the results of a typical day, a quasi-steady approximation has been performed. The solar radiation and exterior temperature change is quite slow, its time derivative is about two or three orders of magnitude smaller than the air temperature variation along the gap and it can be discounted in the fluid and thermal flows calculations. This allows the results of a certain instant of time to be obtained with a steady state simulation using only the appropriate boundary conditions for that moment.

About solution convergence, enough iterations have been computed so that the normalized values of all the residuals are lower than 10^{-6}.

To analyse the fluid-dynamic and thermal behaviour of the two constructive solutions considered (OJVF and conventional façade), the simulations have been carried out varying the external temperature and the solar radiation for two orientations of the façade (north and south). The climate data correspond to the site of Madrid, Spain [33], where the E70 building is located. Madrid has Mediterranean Continental climate (Köppen climate classification: Csa; [34]) with cold winters, hot dry summers and high levels of accumulated annual solar radiation.

3. Results

3.1. Validation

In order to validate the CFD model some thermographs of the OJVF south façade were taken with an infrared camera as shown in Figures 8 and 9. They were shot at 14 hours in springtime (16th may), with a solar radiation perpendicular to the façade of 779 W/m^2 and exterior air temperature of 15.6ºC. In the analysis of these thermographs the different emissivity of the materials has been taken into account, as well as the angle between façade and line of vision, and the distance from the objective and each point of the façade.

As it can be seen in Fig. 8, the lower part of the façade is the apparently hottest one, with temperatures of more than 50ºC, due to the ground reflection and also the reflection from the cars parked in front of the building. With height the temperature decreases, although in Fig. 8 this effect is exaggerated because of the increasing distance from the infrared camera and the vision angle. The window sun shadings are photovoltaic modules (see also Fig. 3). Their temperature is higher than the surrounding façade because of their higher absorption coefficient and because the photovoltaic cells, having a low overall efficiency, reject most of the solar energy as heat. These modules apart from their main function (obtaining electric current from solar radiation) have been located just above the windows to provide shading below, which is evident in Fig. 8.

For a more accurate validation data, thermographs at medium height of the exterior wall have been used (Fig. 9), well above the ground to avoid reflection. The emissivity has been corrected with temperature measurements made for that purpose with PT100 sensors; as a result, colours, particularly in the centre of Fig. 9, accurately represent the scale of temperatures. From those corrected thermograms it has been deducted the temperature of the external surface in a vertical line, between windows and not shaded. In Fig. 10 this experimental temperature is plotted against height and compared with the results of the simulation with the same external conditions.

Two details have to be taken into account in the analysis of this figure: the joints and the higher tile. At the joints, the infrared data shows the temperature at the inner step of the tile rim (if there is resolution enough) while the numerical data shows the air temperature between the tiles, which is much lower than the tiles surface temperature. At the topmost tile (about 1.5m), the infrared data displays a lower temperature than the predicted by the numerical simulation. The reason for this divergence is not clear, but it has been attributed to the window sill (not included in the numerical simulation) and the shadow of the photovoltaic modules over part of the tile.

Leaving aside these deviations, the relative error calculated as the root mean square of the temperature differences at the slabs centre, with respect to the temperature difference with the exterior air temperature, is only of 1.3%.

About the conventional façade, there are quite a number of papers about the validation of numerical codes for the simulation of closed cavities, and the methodology above mentioned has been found to obtain good results on them [35]. In fact, this kind of test has even been used to validate the first CFD codes [36].

3.2. Fluid and thermal characteristics

A representative case has been selected to highlight the qualitative analysis of the thermal and fluid dynamic phenomena in both façades. The conditions of this case corresponds to summer with south orientation, at 14 hours (T_{ext} = 28.3ºC and solar radiation perpendicular to the surface 432 W/m^2).

The air flow behaviour in the open joint and closed cavity façades is quite different. Fig. 11 shows the air velocity vectors in the bottom, medium and top parts of the cavity for the sealed façade. The phenomenon generated is characterized by the formation of a convective loop. The air in contact with the exterior part of the closure (at a higher temperature because of solar radiation) heats up and ascends while the air in contact with the brick wall part descends as it cools off. In the central figure we can observe the symmetry in the ascending and descending air movement, around the middle of the cavity.

Tall closed cavities with high aspect ratio are known to exhibit multicellular flow patterns. This has been mainly investigated on double glazed windows [37], and the critical conditions can be found in reference [38]. Although some of the cases studied in this work could fall inside that region (considering the conditions at middle height), a single convective cell has been found in all of them. This is probably due to the temperature increase with height produced by the solar radiation on the tiles, in contrast with the constant temperature imposed on double glazed windows. In any case, with respect to the heat transfer characteristics, there are little difference whether the flow is single or multicellular [39,40].

Fig. 12 shows the air velocity vectors in the interior of the cavity of an OJVF. In this case the velocity profile is not symmetric, the airflow always rises and the air behaviour at the joints depends on their height. In the lower joints the external air enters the cavity with a jet structure corresponding to the entrance of air through a fairly narrow slot. Then, the airflow straightens and from the middle of the panel the flow has almost only a vertical component and is quite uniform. As it ascends its speed increases due to the rise of temperature (the incident radiation heats the tiles and the tiles heat the air of the cavity). Also, the transversal uniformity is partially lost, as the velocity and the temperature of the airflow close to the tiles increase more than those of the flow close to the brick wall. Around the middle of the cavity height the air starts to exit through the slots, evacuating heat.

Fig. 13 shows the variation of the air velocity vertical component plotted against height in a vertical axis situated in the middle of the cavity of the OJVF in summer conditions. The steps are related to the entrance of air through the joints of the bottom tiles and its exit at the top ones. Maximum velocity is achieved at middle height although there is not symmetry. The entry and exit flow rate is higher at the bottom and top decreasing progressively towards the central area. The peaks observed at the bottom half of the figure, are due to the air jets entering through the joints.

In Fig. 14, the velocity profiles are compared at middle height in the transversal direction: from the inner wall to the tiles. The profile of the convective loop that characterizes the sealed cavity, ascendant near the tiles and descendant near the inner wall, can be clearly seen. The velocity is around five times less than in the OJVF. It can be deduced that the flow uniformly rising and the higher velocity are two of the main fluid dynamic characteristics that favour heat evacuation in the OJVF.

The thermal behaviour of both construction solutions can be analysed in Figures 15 and 16 that show the contours of temperature, and also in Fig. 17 where the temperature variation with height is represented, allowing the comparison of temperature curves corresponding to different areas: interior and exterior tiles surfaces, air chamber and interior wall. The three figures are for summer conditions. In the sealed façade it may be seen that although there are important temperature differences between exterior air, tiles and cavity air, the temperature only varies slightly with height. Maximum temperature is reached at the upper part of the tiles, approximately 49ºC. The air temperature in the cavity is always intermediate between the temperature of the tiles and that of the brick wall and the differences are barely around 5ºC. The convective loop produces transference of thermal energy from the hottest surface (generally the exterior side, heated by solar radiation) to the coldest one. In the temperature map of Fig. 15 a gradual increase with height of the temperature of the air in contact with the exterior face of the façade can also be observed, together with an increase of the thickness of the thermal boundary layer, which is consistent with natural convection on a vertical surface.

Figures 16 and 17 show that in the OJVF all the temperatures also rise with height and that the increase is bigger than in the sealed cavity. The difference in temperature between the inner sides of the cavity is about 3ºC, but the difference of the inner wall to the exterior of the tiles is around 10ºC. The air in the cavity keeps a temperature lower than both the tiles and the brick wall. The difference in temperature between the air and the brick wall is only of the order of 2ºC, but the difference with the tiles is about 5ºC, which means that the air is mainly extracting heat from the tiles. All the temperatures are lower than the equivalent in the sealed façade, except for the top area of the exterior surface of the tiles which is more or less the same. As the air in the cavity and the interior surface of the tiles have a lower temperature than in the sealed façade, there is a smaller heat transmission towards the interior of the building. The temperature distribution of the exterior air can be seen in Fig. 16. The variation with height in the lower tiles of the OJVF is smaller than in the sealed façade, because the air that enters at every joint reduces the thermal boundary layer. From the middle of the height the hot air reverses such behaviour. In this case the fluid thermal distribution does not adjust to a pure natural convection.

Fig. 18 represents the heat flux transmitted towards the interior of the room, also for the same summer conditions. The heat flux in the sealed cavity façade is more or less uniform all along the height of the façade, while in the OJVF, it increases in the same proportion as the air temperature and its distribution is not as smooth due to the higher complexity of the airflow inside the cavity. The total heat flux (integrating in height) is clearly much bigger in the sealed cavity façade.

3.3. Energy performance of the OJVF

The simulations presented in this section have been carried out in quasi-stationary conditions using the data (exterior temperature and solar radiation) of typical days for each of the four seasons of the year in Madrid, and for façades oriented to the north and to the south, which in the northern hemisphere correspond to the shadow and sunny sides respectively. The typical day can be defined as the average of all the days of each season and can be taken as a fair representative of the season as far as energy requirements are concerned.

It can be stressed that the temperature and solar radiation data do not represent extreme conditions, because the "Typical meteorological year" used is an average of 10 years data [33]. The exterior air temperature varies between 6.7ºC and 17.2ºC in spring, from 19.1ºC to 27.4ºC in summer, from 4.4ºC to 14.4ºC in autumn and between 7.2ºC and 14.4ºC in winter. The maximum solar radiation perpendicular to the wall is 779 W/m^2 in springtime, 432 W/m^2 in summer, 819 W/m^2 in autumn and 834 W/m^2 in wintertime (notice the influence of the sun inclination in each season).

Figures 19 and 20 compare the energy performance in both façades along a typical day for each season of the year. The heat flux is shown (positive when from exterior towards the interior room) for both façades and both orientations. They also include the solar radiation perpendicular to the façade and the exterior air temperature.

For the selected typical days there are about 14 hours of day light in summer, 12 hours in spring and autumn and 10 hours in winter.

In summertime, the OJVF oriented to the south has a better performance than the sealed façade during the day, reducing the heat gain. At night at the south side, and during all day in the north façade, the heat flux both entering and exiting is almost non-existent, because exterior and interior air temperatures are quite similar.

In the rest of the seasons, at the south side during the day, the heat gain reduction obtained with the OJVF with respect to the sealed façade is even larger, since the solar radiation perpendicular to the wall is higher because of the lower solar altitude. On the other hand, there are significant heat losses at the northern façade – and the southern at night-, because the exterior temperature is lower than the interior room temperature. These losses are more or less the same in both the ventilated façade and the sealed one.

To quantify more accurately the differences between closures, the energy requirements of the 4 typical days have been integrated. Table 1 shows heating and cooling requirements for each façade, at the two orientations, the four typical days. Also, an approximate total value is calculated adding the heating and a third of the cooling energy required. This has been done assuming that the same kind of energy (electrical) is used in heating and cooling, and that a COP of around 3 can be expected in a good refrigerating plant. From the values in this table, a detailed comparison can be made between both façades. In summer, at the south side during solar radiation hours, less thermal energy is transferred to the room with the OJVF, so the cooling load decreases by about 29% compared to the sealed cavity façade. At night the heating loads are small and very similar. Integrating all the thermal energy requirements for a typical summer day, the south side OJVF requires approximately 15% less energy. Regarding the orientation to the north, both closures behave in a similar way: during the day a small amount of heat is transferred to the room and at night there are some small loses. The global energy requirements are basically the same for both façades.

In winter, the energy losses are substantially higher and the OJVF behaves a bit worse without solar radiation. The thermal energy required for heating on the south side at night and on the north side all day is between 4 and 5% higher than the sealed façade. However, on the south side during the day the solar radiation makes possible the existence of an energy gain even despite the low exterior temperature. In this situation, the ventilated façade behaves better than the sealed one reducing the cooling loads All in all, the energy required in a typical winter day on the south side is 7% smaller if we use an OJVF.

In spring and autumn the trends are the same as in winter with very small differences due to the variation of the exterior temperatures and the solar radiation in the three seasons. The heating loads are smaller in spring and bigger in autumn- in Madrid the typical autumn day is colder than in wintertime (remember that autumn includes 21 december days an winter ends the 21th of march). On the other hand, in spring as well as in autumn the solar radiation has a higher effect than in winter (higher solar altitude but more hours of natural light and higher rate of sunny days). Comparing the total energy required yearly, the sealed façade is about 4% better for northern orientation, while for south orientation the OJVF attains energy savings around 9 %.

These results prove that the open joint ventilated façade here described, achieves a not trivial energy saving and the corresponding reduction in contaminants emission.

For the subsequent economic study several factors are to be considered, among them costs of materials, construction works, maintenance and the price of the energy used for the building thermal conditioning.

Maintenance and operation are believed to be equivalent for both façades, and not very costly; therefore they may be omitted for comparison. However these maintenance costs are quite important in double skin façades as stated by Poizaris [41] [35] and Hilmarsson [6].

In the cases here studied the initial capital investment is very dependent of the materials specifically used and the location of the building. Offers obtained from several construction companies throw a buying cost of 150 to 200 €/m2 for a sealed cavity façade and from 200 to 240 €/m2 for an OJVF with components of similar thermal properties.

Nowadays the difference in cost is important but it is expected that the economic installation gap will decrease in the near future. The façades composed of tile layers are becoming more popular every day, which means a foreseeable reduction in manufacture costs.

Considering a south façade, the total energy requirement deducted from table 1 by multiplying the daily year average requirement by 365 days, gives 50,19 kWh/m^2 per year for the OJVF compared with 54,84 kWh/m^2 per year for a conventionally sealed cavity façade.

If electrical energy cost is assumed to be around 0,14 €/kWh, the economic annual saving in thermal conditioning would be in the order of 0.65 €/m^2 in favour of the OJVF, which is too small to compensate the difference in capital costs, at least at present prices; the expected price evolution of both building and energy could situate the OJVF in a better position in a few years. It is also expected that zones with cooling loads much higher than heating loads (lower latitude than Madrid…) the difference in annual energy requirements could favour the OJVF design.

A parametric analysis of thickness and thermal properties of the different components has not been carried out in this work; it might be an interesting subject to try to improve OJVF behaviour both in southern and northern façades.

4. Conclusions

A bidimensional CFD model has been developed to analyse the fluid-dynamic and thermal behaviour of an open joint ventilated façade along the whole year. This model has been validated with infrared measurements of the exterior surface of the actual façade.

The energy efficiency of the modelled façade has been compared with a conventional, sealed cavity, façade. The climatic data employed has been the corresponding to a typical meteorological year of Madrid, where the façade is situated. This climate is classified as Continental Mediterranean with cold winters, hot summers moderate raining and high annual solar radiation.

The simulations results show that the behaviour of both façades is strongly related with orientation and climatic conditions. But, in general terms, it can be said that the higher the solar radiation and surrounding air temperature, the bigger the eventual energy saving with an OJVF.

The flow pattern of the air inside the cavity is completely different for open and sealed façades. While in a sealed cavity façade the flow is characterized by a convective loop, in an OJVF the airflow is always upward and its velocity has been found to be around five times the sealed cavity magnitude. Also, the flow behaviour is strongly dependant on the height position. The air enters the open cavity by the lower joints increasing its velocity and temperature as it rises. From the middle to the top, the air leaves the cavity through the joints, evacuating heat.

About the thermal behaviour, it has been ascertained that, under radiation conditions, OJVF temperatures are lower, especially the air inside the cavity, and this results in a lower heat flux transfer towards the interior of the building.

At the location studied, the energy saving estimation of the OJVF is around 9 % for the south façade while, for a north façade, the energy requirements are about 4 % higher. This reduction helps to compensate the higher costs of an OJVF although, nowadays, the economic reasons cannot be the only ones for choosing this design.

5. Acknowledgments

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Figures and Tables.

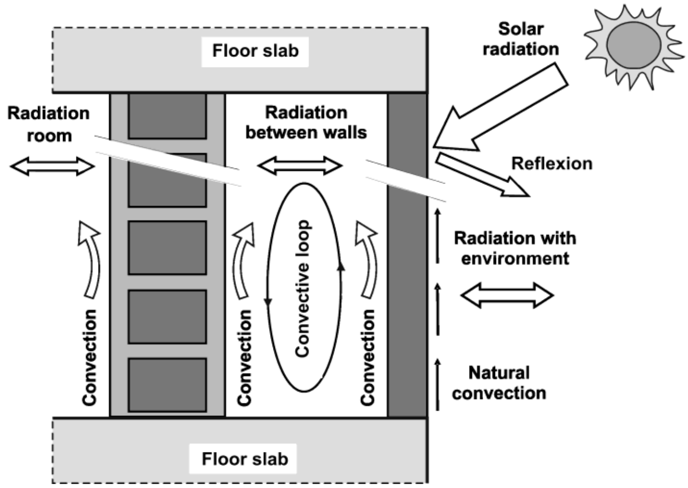


Fig. 1. Heat transfer processes in a conventional sealed cavity façade.

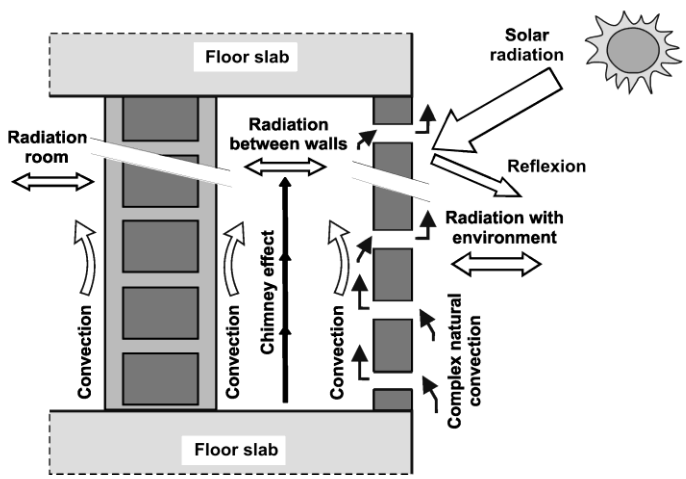


Fig. 2. Heat transfer processes in an OJVF.

Fig. 3. Photograph of demonstration container in Madrid (South façade).

Fig. 4. Photograph of the open-joint ventilated façade structure.

Fig. 5. Photograph of the horizontal joints detail.

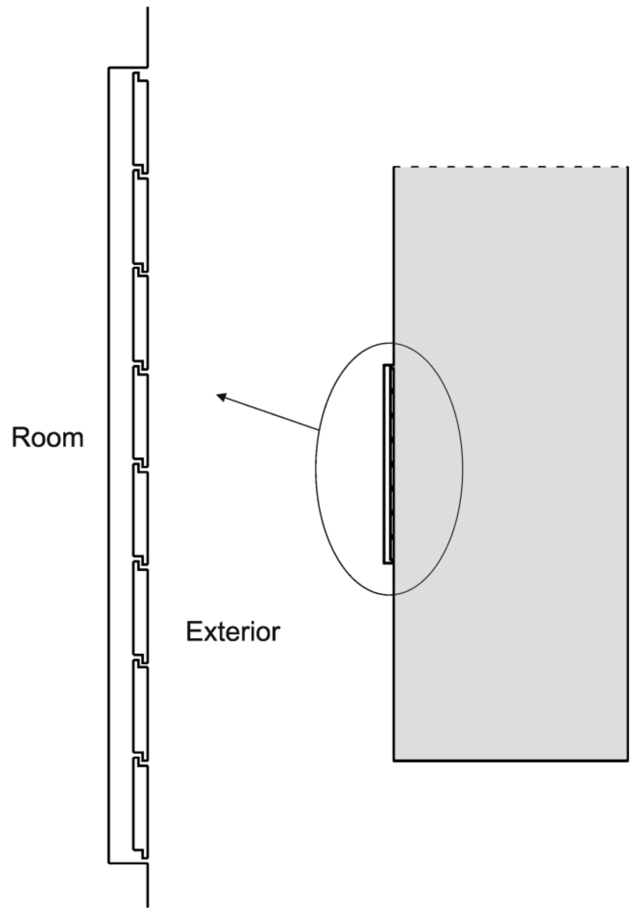


Fig. 6. Sketch of the model domain.

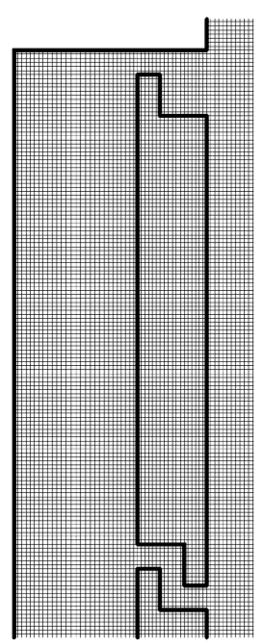


Fig. 7. Detail of the mesh on the cavity, slabs and joints.

Fig. 8. Thermograph of the south façade of Madrid building, springtime, 14:00 (perpendicular solar radiation 779 W/m^2, exterior temperature 15.6ºC).

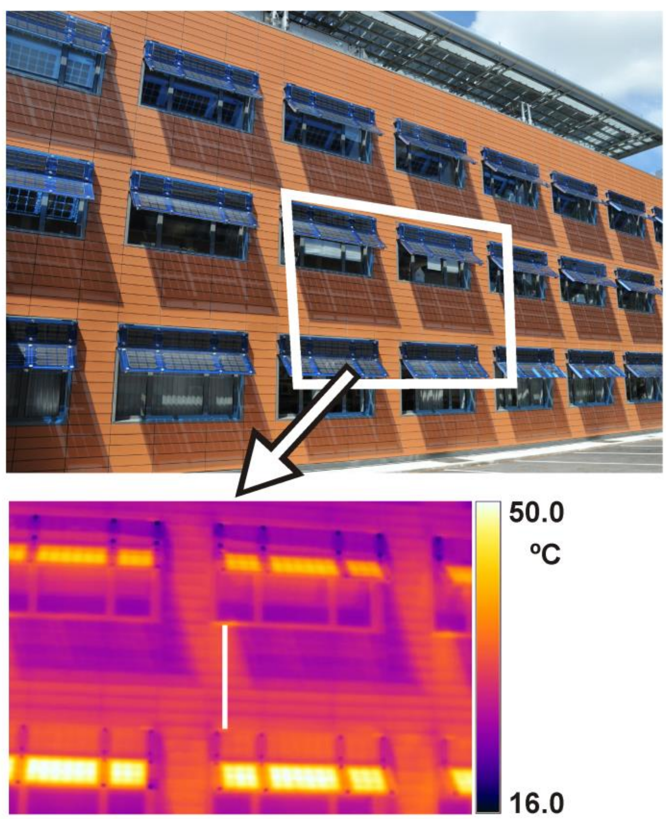


Fig. 9. Detail of the thermograph of the south oriented OJVF; 14:00, springtime, perpendicular solar radiation 779 W/m2, external air temperature 15.6ºC.

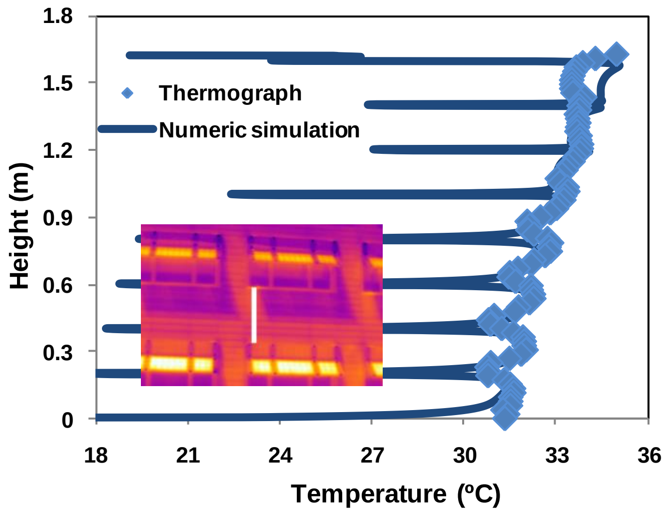


Fig. 10. OJVF external surface temperature: experimental thermographic data compared with numerical simulation results. Climatic conditions: solar radiation perpendicular to vertical plane 779 W/m^2, surrounding air temperature 13.5ºC, springtime, 14:00.

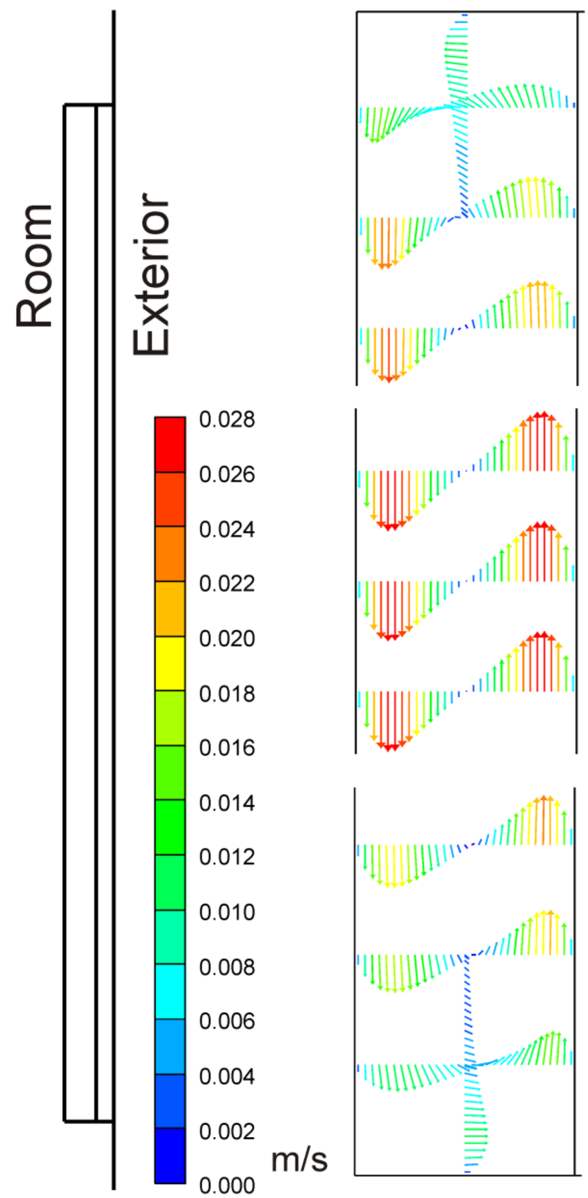


Fig. 11. Air velocity vectors in the bottom, medium and top parts of the cavity for the sealed façade. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.

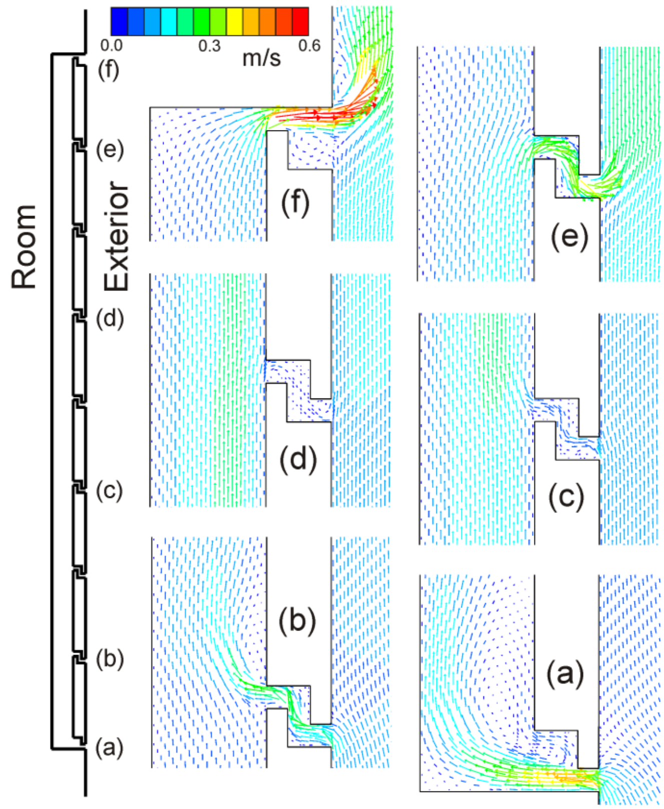


Fig. 12. Air velocity vectors in the interior of the cavity of an OJVF. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.

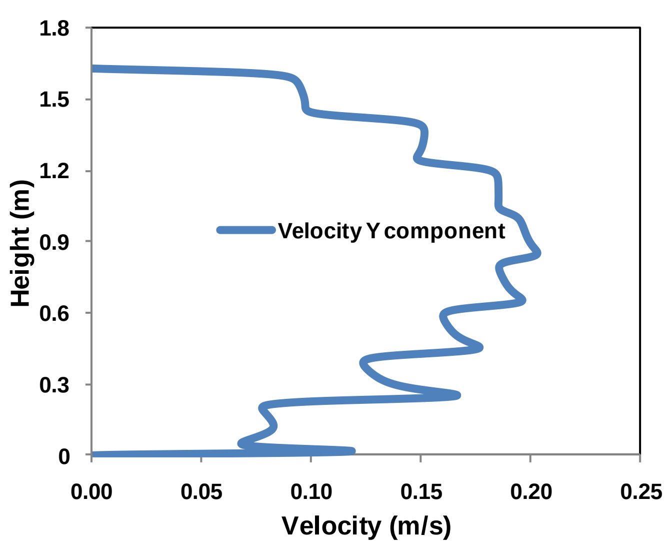


Fig. 13. Vertical component of air velocity in the middle vertical plane of the OJVF. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.

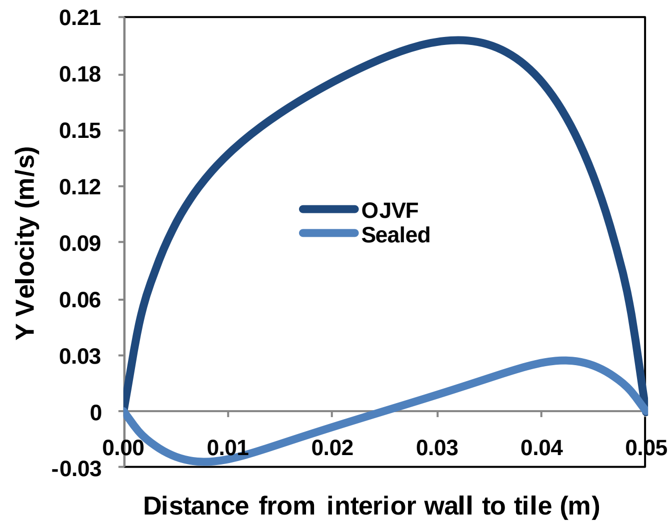


Fig. 14. Vertical air velocity component in a transversal section of the cavity at middle height. Comparison of OJVF vs. close cavity façade. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.

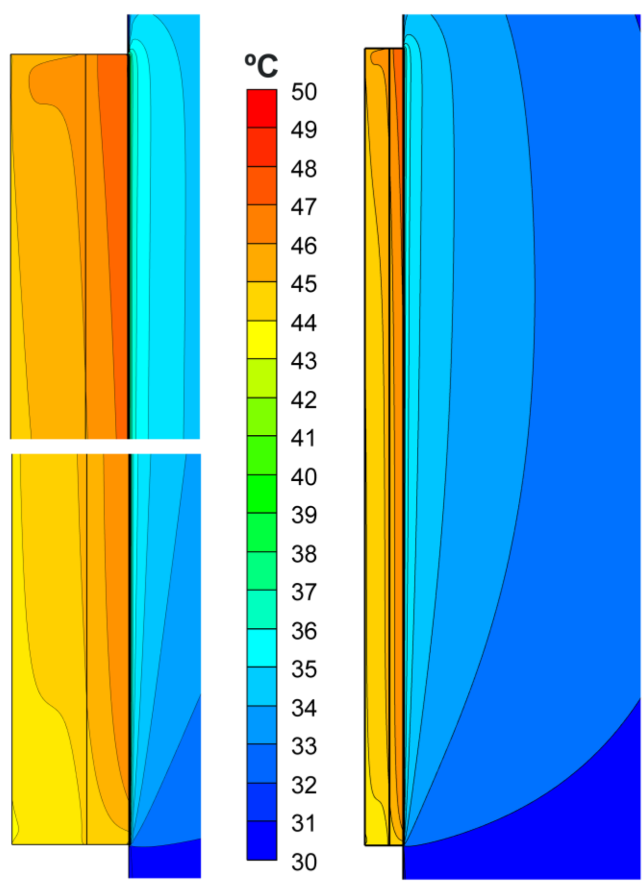
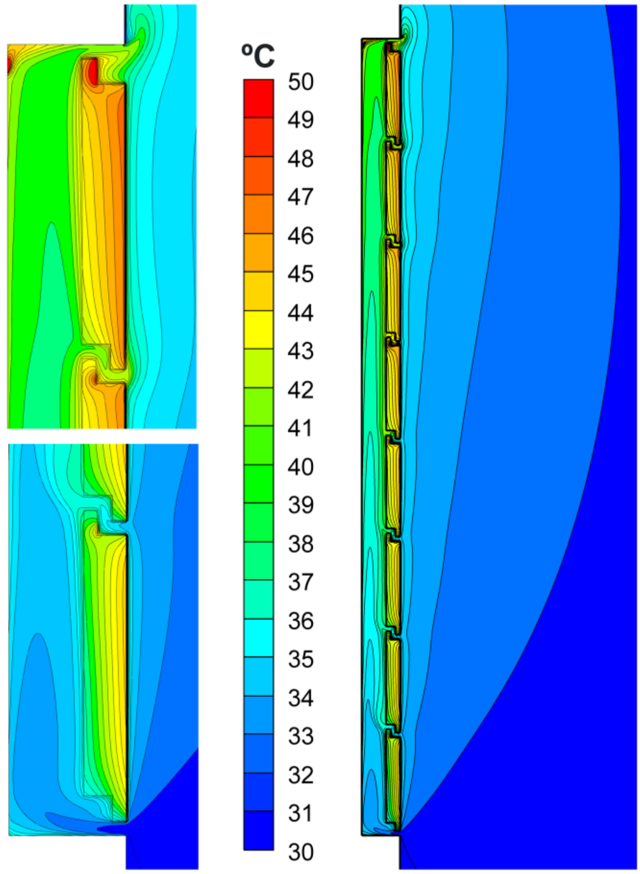


Fig. 15. Temperature contours in the sealed façade. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.



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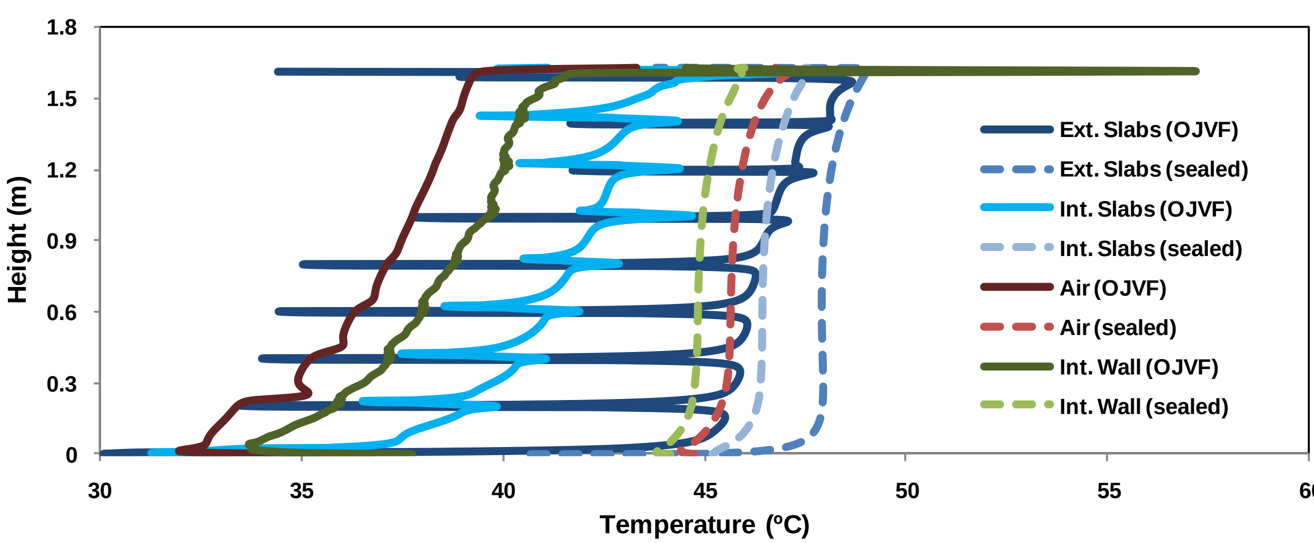

Fig. 17. OJVF vs. Sealed cavity façade temperatures. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.

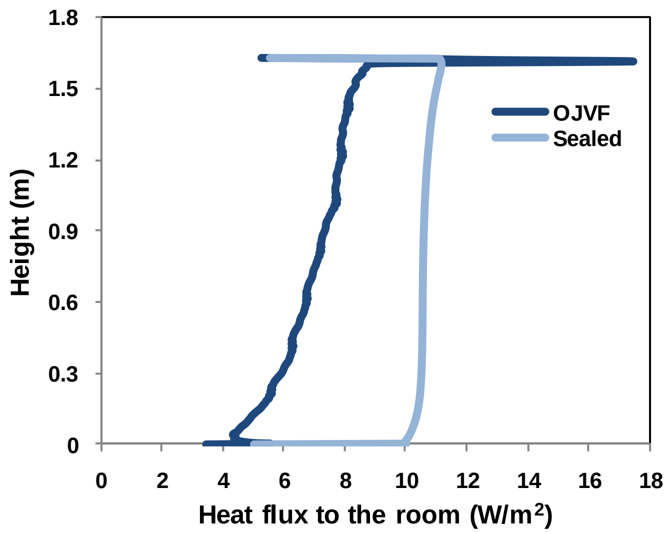

Fig. 18. Heat flux towards the building interior plotted against height. Summertime: 14 h, 26ºC interior, 28.3ºC exterior and 432 W/m^2 perpendicular solar radiation.

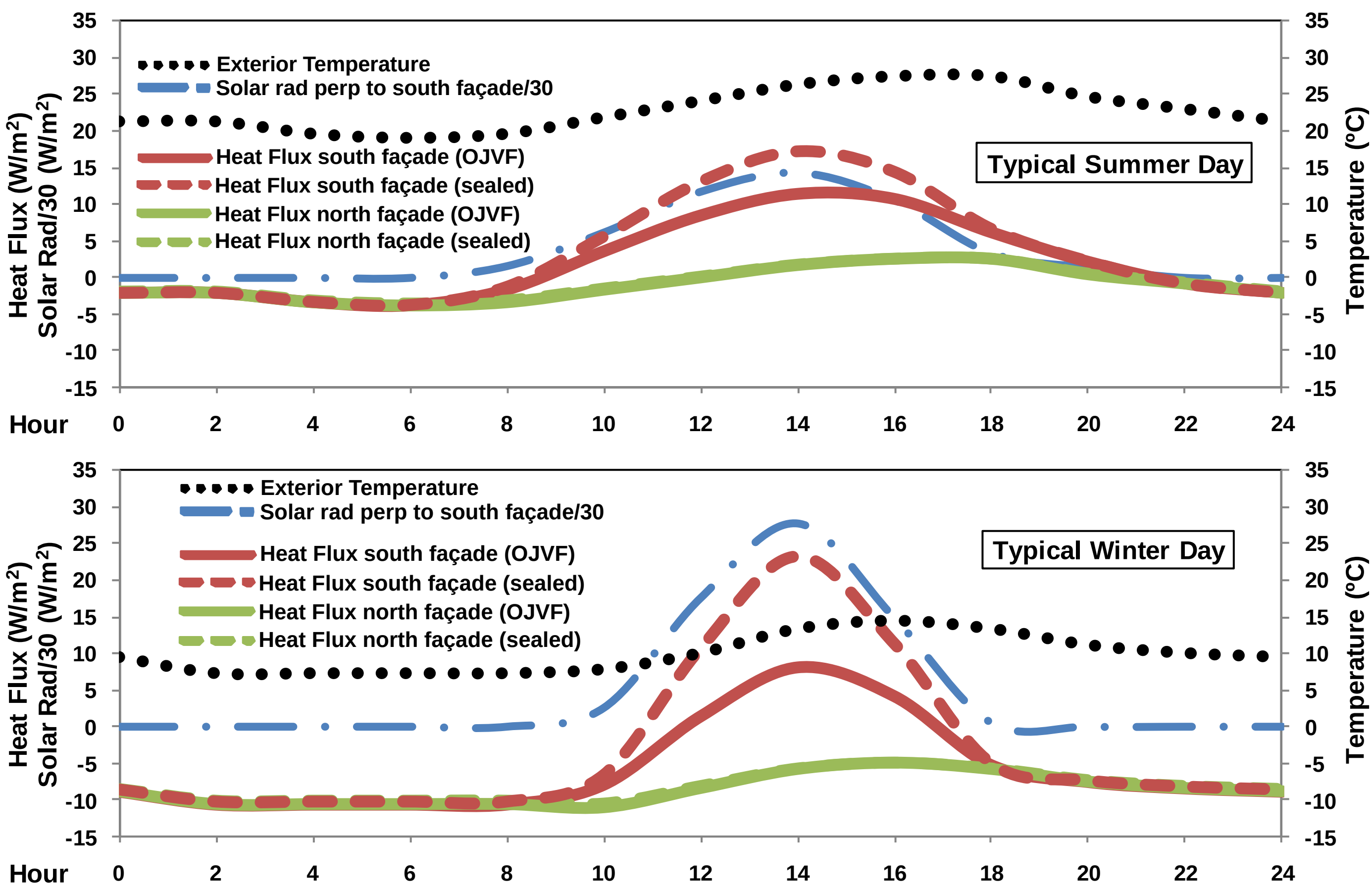

Fig. 19. Energy performance: OJVF vs. sealed façade. Typical summer and winter days.

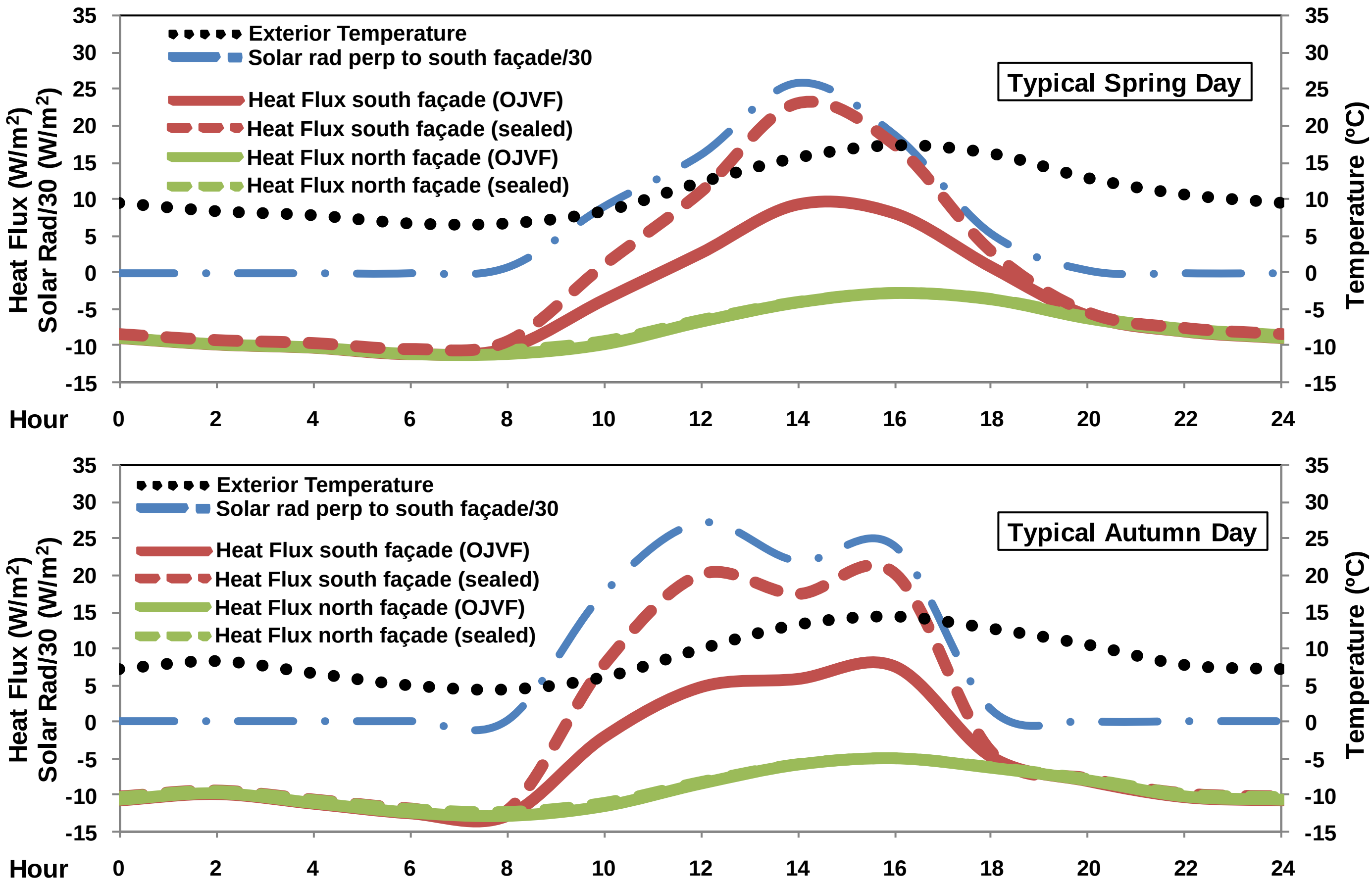

Fig. 20. Energy performance: OJVF vs. sealed façade. Typical spring and autumn days.

Table 1
Heating and cooling requirements in the typical days of the four seasons (Wh/m^2)

	South façade		North façade	
Summer	OJVF	Sealed	OJVF	Sealed
Cooling	85	119	15	14
Heating	27	25	33	33
Daily energy requirements	**55**	**65**	**38**	**38**
Winter	OJVF	Sealed	OJVF	Sealed
Cooling	27	90	0	0
Heating	161	152	207	199
D. energy req.	**170**	**182**	**207**	**199**
Spring	OJVF	Sealed	OJVF	Sealed
Cooling	42	110	0	0
Heating	136	122	185	178
D. energy req.	**150**	**159**	**185**	**178**
Autumn	OJVF	Sealed	OJVF	Sealed
Cooling	37	132	0	0
Heating	163	151	224	214
D. energy req.	**175**	**195**	**224**	**214**
Daily year average	137,5	150,25	163,5	157,25
Yearly percentage	100 %	109,3 %	100 %	96,2 %

Figure and Table Captions

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