

QUANTIFICATION OF BUILDING ENERGY EFFICIENCY IMPROVEMENT WITH INNOVATIVE SYSTEMS BASED ON VENTILATED FAÇADES

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ABSTRACT

In recent years, the approach to building construction in Europe has been under review with a view to constructing and refurbishing buildings in a more energy-efficient way. In this context, the development of innovative building envelopes that enable building thermal performance to be enhanced is of major importance. However, the energy performance of such construction systems upon their integration into an actual building is not easy to evaluate.

At present, the LIDER application is the computer implementation of the general verification option of the energy demand limitation requirement (HE1), established in the Basic Document on Habitability and Energy of the Technical Building Code (TBC). On the other hand, CALENER is the tool chosen by the TBC for the building energy rating.

Though these tools are valid for regulatory proposes, they only provide an approximation to building energy efficiency because they solely envisage standard construction solutions. Therefore, if the goodness of the design of a particular, innovative (hence non-standard) solution for the reduction of a building's energy demand or energy consumption needs to be assessed, more versatile tools, which analyse the solution's contribution to the overall energy balance of the building, will need to be used. Energy efficiency simulation programs are available in building construction, such as EnergyPlus,

which was used in this study, which provide greater versatility though they are not without their limitations. In particular, in the case of EnergyPlus, it may be noted that, though it allows new modules developed from zero to be integrated, their integration is no simple matter. In fact, knowledge of the internal workings of the program is required in order to be able to develop and, subsequently, to integrate these modules into the program.

The main contribution of this study consists of a methodology that allows innovative systems to be incorporated in EnergyPlus in a relatively simple way for the evaluation of the energy efficiency of the buildings into which they are installed. In addition, this methodology has been used to implement in EnergyPlus both a conventional ventilated façade (this only being considered in an approximate form by LIDER) and new construction solutions that improve the energy efficiency of the ventilated façade in cooling (evaporative cooling) or in heating (hot air recovery as support for the ventilation/heating system).

The energy efficiency of these new, upgraded ventilated façades was evaluated by simulating two realistic buildings (a block of flats and a school). The results obtained demonstrate that both solutions could contribute to reducing the energy demand of buildings refurbished with a ventilated façade.

1. INTRODUCTION

The growing social awareness regarding efficient energy use has led to more stringent regulations in the context of building energy efficiency (Technical Building Code, Directive 2002/91/EC on the energy performance of buildings, Royal Decree 47/2007 on the energy certification of buildings). These requirements include an energy evaluation of buildings using calculation software. The reference computer programs in the regulations (LIDER and CALENER) are publicly available for free use.

One limitation of the reference programs is that they only work with conventional construction systems. Consequently, when an innovative construction system is considered, its influence on building energy consumption cannot be evaluated by these programs, unless considerable simplifications are applied. Such is the case of the ventilated façade, which, despite being a relatively common system, is simply simulated in LIDER by means of an equivalent thermal resistance [1].

In contrast, open source programs, such as TRNSYS and EnergyPlus, allow new modules that simulate the thermal performance of innovative systems to be incorporated and can, therefore, evaluate their influence on the overall energy consumption of the building in which they are installed.

The present study examines the influence of several innovative construction systems on the energy efficiency of two realistic buildings (for civic and residential use, respectively). In this study, the mathematical models that describe the thermal performance of these systems were integrated into EnergyPlus. EnergyPlus was selected because it is a free, open source program that contains an extensive collection of construction systems and systems of thermal conditioning/ventilation components [2].

The studied construction systems were based on the ventilated façade. In addition to the conventional ventilated façade, the incorporation of an evaporative cooling system in this façade and the recovery of hot air from the ventilated cavity to the thermal conditioning/ventilation systems were considered.

2. INNOVATIVE CONSTRUCTION SYSTEMS BASED ON VENTILATED FAÇADES

2.1. CONVENTIONAL VENTILATED FAÇADE

The ventilated façade is a building envelope that is fundamentally characterised by including a ventilated cavity, bounded by two leaves: an inner leaf that provides thermal insulation and airtightness for the building, and an outer leaf that forms the actual air cavity. The energy from solar radiation is partially absorbed by the outer leaf, which becomes warm and transfers energy by convection to the air inside cavity and by radiation to the surface of the inner leaf. The heat transferred to the air in the cavity causes this to rise by natural draught, thus dissipating heat in relation to this appreciable heat flux.

Although the conventional ventilated façade is not an innovative system, a mathematical model was also developed for this system. This was because, on the one hand, its treatment in the energy simulation programs for buildings is excessively simplified, as noted above. On the other hand, as mathematical models needed to be defined for innovative ventilated façades, it was considered convenient to use a conventional ventilated façade model based on the same approximations as a reference.

2.2. VENTILATED FAÇADE WITH EVAPORATIVE COOLING

Evaporative cooling is a simultaneous heat and material transfer process that occurs as a result of the interaction between water and air streams. The net effect of the process is a decrease in temperature and an increase in air humidity.

The evaporative cooling system considered for ventilated façades consisted of generating a thin film of water on the surface of the inner leaf (Figure 1). The evaporation of part of this water entailed consumption of the latent vaporisation heat; this gave rise to additional energy dissipation, which contributed to building cooling. The system's effectiveness is, therefore, especially favoured in warm, dry climates.

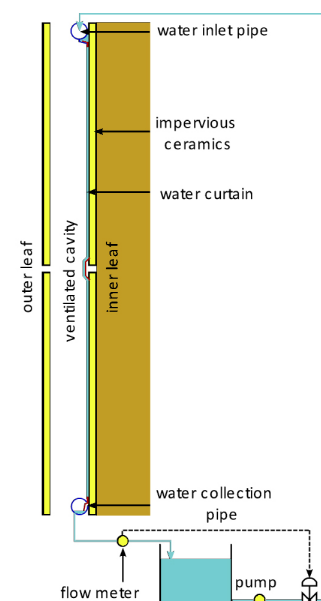


Figure 1. Ventiladed façade with evaporative cooling system.

2.3. VENTILATED FAÇADE WITH HOT AIR RECOVERY

The use of ventilated façades is particularly indicated for warm regions, as it increases the heating demand while reducing the cooling demand [3]. However, an alternative conception of this system could also make it appropriate for reducing the heating demand.

In a conventional ventilated façade, the temperature of the air that circulates inside it increases considerably, especially in winter. This hot air could be used to support the building ventilation system. That is, in this case, the ventilated cavity would be a component of the building ventilation system, which would be used to preheat the air to be introduced into the building. When the building is ventilated with hotter air than that of the outside air, the heating demand should decrease. It may be noted that, unlike the previous cases, in this system, the air circulation is forced and the air volume flow that circulates inside the cavity is established by the ventilation system itself.

3. MODELLING OF THE ENERGY PERFORMANCE OF BUILDINGS FITTED WITH INNOVATIVE CONSTRUCTION SYSTEMS

3.1. MATHEMATICAL MODELS OF INNOVATIVE CONSTRUCTION SYSTEMS

EnergyPlus has a mathematical model for cavities ventilated by natural draught [4]. However, this model treats some of the phenomena that take place in this system in a much too simplified way [3].

The mathematical formulation used in this study of energy transfer in conventional ventilated façades is largely based on reference [5], so that the basic equations need not be repeated here. The main difference with relation to that reference is that the thermal resistance of the outer leaf has not been considered negligible. If this simplification is not adopted, the energy transfer in the outer leaf is given by the Fourier law of heat conduction in an unsteady state, which was solved by means of the transfer functions method [6].

For a ventilated façade with evaporative cooling, in addition to the energy balance for the air in the ventilated channel, the water balance, as well as heat dissipation as a result of water evaporation, must be considered. The incorporation of these effects into the framework developed in reference [5] is relatively easy [7]. A ventilated façade equipped with the devised evaporative cooling system could thus be simulated.

In the mechanical energy balance that determines the air volume flow that circulates inside the ventilated cavity, in references [5] and [7], the temperature of the different leaves was assumed to be uniform. In the present study, however, the ventilated façade is allowed to be made up of several heights at different temperature. This proviso provides greater versatility when it comes to defining buildings in EnergyPlus and is also more realistic.

Finally, the ventilated façade with hot air recovery was essentially governed by the same basic equations as the conventional ventilated façade. However, in this case, air circulation in the cavity was imposed by the ventilation system instead of by natural draught.

3.2. INCORPORATION OF THE MODELS DEVELOPED IN EnergyPlus

If the proposed construction solutions are examined, it could be inferred that they all share the common nexus of dealing with construction elements that modify the external conditions of building envelopes. EnergyPlus contains a feature called *Other Side Conditions Model* (OSCM) that, using a set of variables, allows the temperature and heat flux through an external building surface to be specified. The OSCM was deemed appropriate for the needs of the study, in addition to being sufficiently generic to be used as a first instrument for communication.

On the other hand, one of the proposed solutions incorporates hot air into the building (ventilated cavity with hot air recovery). Generally speaking, it would therefore be convenient for the new components to form part of the thermal conditioning and ventilation system. One of the strengths of EnergyPlus is precisely the wide range of these types of components and their possibilities. In addition, the information transfer between the thermal conditioning and ventilation system components is performed, very appropriately, by so-called data nodes. Nodes may be understood as the connections between thermal conditioning system components.

Therefore, the OSCM and the nodes enabled the identified information transfer needs to the EnergyPlus core to be addressed. It may be noted that it was intended to design a general approach that could be incorporated into future models for building envelopes in a simple way. Therefore, a generic communication interface programmed in FORTRAN (programming language in which EnergyPlus is written) was developed as an additional EnergyPlus module. In contrast, the models of the innovative systems were programmed in C++, as the developed interface was based on the polymorphism of the object-oriented programming.

3.3. STANDARD BUILDINGS

Two standard buildings, for civic and residential use, respectively, were defined in which to incorporate the studied construction systems.

The defined civic building was the secondary education centre shown in Figure 2. This centre had three storeys in the main part, which housed the classrooms and offices. The annex block contained a changing room and a gymnasium. The building was divided into 5 thermal zones with uniform temperature. Each floor of the main block constituted a thermal zone, while the two remaining thermal zones were the gymnasium and the changing rooms.

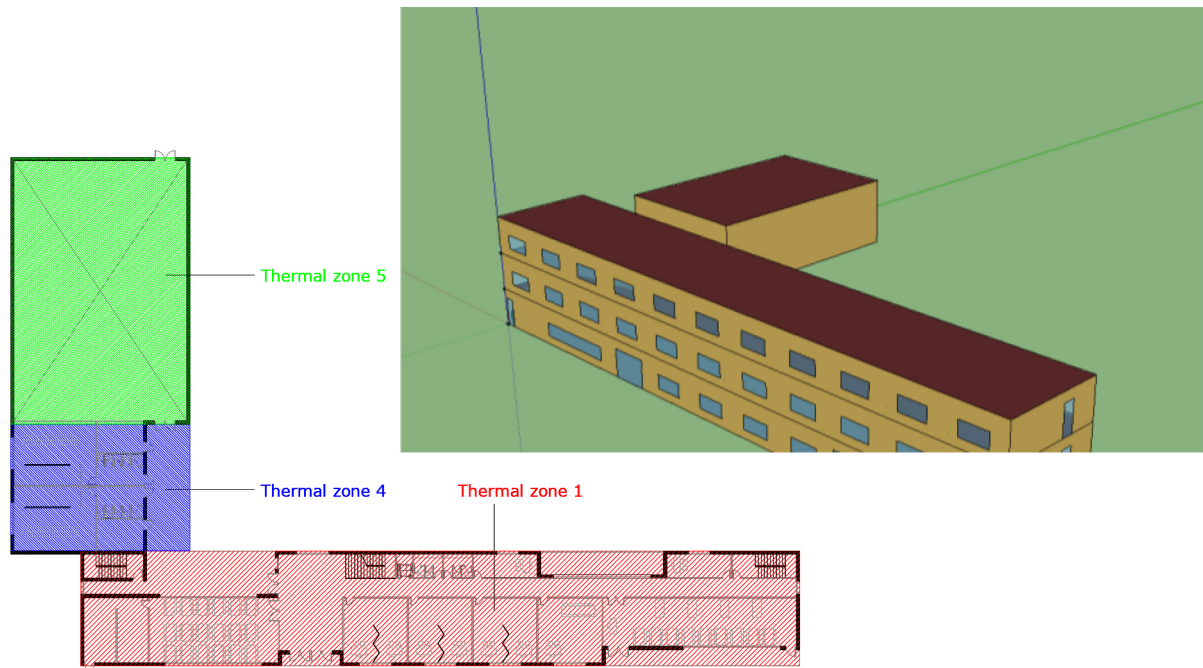


Figure 2. Perspective view of the civic building model and thermal zones considered on the ground floor.

The residential building consisted of a 7-storey block of dwellings (Figure 3), there being two dwellings on each floor. Three thermal zones were defined per floor: a common area and the two dwellings (the internal distribution of each dwelling was not considered). As the building consisted of 7 storeys, there were thus 21 thermal zones in all.

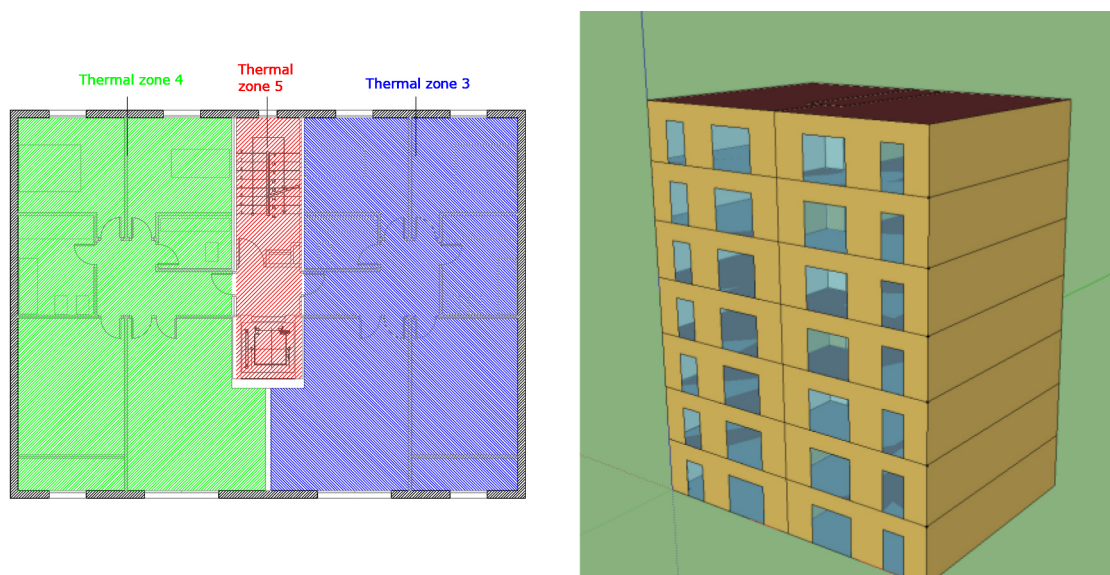


Figure 3. Perspective view of the residential building model and thermal zones considered on the first floor.

The internal loads (occupancy, lighting, apparatuses) were established based on the specifications of the document "Acceptance conditions of alternative procedures to LIDER and CALENER" published by the Ministry of Housing and the Institute for Energy Diversification and Saving (IDEA) [8]. Ventilation was established as one air renewal per hour. This value met the requirements set by the Technical Building Code (TBC) for a medium-sized dwelling [1] and by the Regulation on Thermal Installations in Buildings (RITE) with regard to offices [9].

Both buildings were equipped with ideal thermal conditioning systems with a total efficiency and an unlimited power. The thermal conditioning requirements to keep the temperature in the zones between 20 and 25°C were defined based on the TBC [1]:

- In the civic building, the heating and cooling systems were available all year round, from 7 h to 14 h every day and from 16 h to 20h on working days.
- In the residential building, the heating system was available all day from October to May. The cooling system worked from June to August, from 1 h to 7 h and from 16 h to 24 h.

The simulations were performed for two climate zones: a warm zone (B4/ Seville) and a cold zone (E1/Burgos). The building envelope materials were established such as to comply with the minimum thermal resistance required by the TBC for these climate zones [1]. As a block of dwellings was involved, the sides of the residential building were considered to abut adjacent buildings, so that it was assumed that these building envelopes were adiabatic.

On the other hand, it was verified that the effect of the ventilated façade depended on its orientation [3]. Indeed, the southern orientation was the most satisfactory, whereas the effect of the ventilated façade was practically nil in the northern orientation as it received no direct solar radiation. Consequently, the innovative construction systems based on the ventilated façade were installed in the south façades of both buildings and, in the case of the civic building, only in the block of classrooms. It was furthermore assumed that, just as in a real installation, the ventilated façade began on the first floor of the building instead of on the ground floor. Indeed, it is recommended that a panelled façade should be used on the ground floor to avoid breakage of the outer leaf by impacts.

Certain innovative construction systems were equipped with control systems to enhance their efficiency. In the case of the ventilated façade with evaporative cooling, a control system was used that deactivated the water film when there was a heating demand. For the ventilated façade with hot air recovery, two different systems were used, depending on the type of building. In the case of the civic building, when there was a cooling demand, the control system caused the ventilation to take place with outside air instead of with air preheated in the cavity. In the case of the residential building, where no heating system was available in summer, it was decided to deactivate air preheating in the cavity completely during this period.

4. RESULTS

Simulations of the energy demand in the buildings were performed by incorporating the following construction systems in the south façade: conventional building envelopes (STD), a conventional ventilated façade (FV), a ventilated façade with evaporative cooling (EE), and a ventilated façade with hot air recovery (AAC).

Figures 4 and 5 show the monthly evolution of the overall energy demand of the civic building in climate zones B4 (Seville) and E1 (Burgos). As was to be expected, in every case, there was a greater heating need in the coldest months of the year and a greater cooling consumption in summer. In the case of the buildings located in Seville, the heating demand was less than 6 kWh/m² every month. In contrast, the building located in Burgos exhibited considerably higher monthly heating demands. Moreover, the cooling consumption of the building in Burgos was not negligible, though it was much lower than that obtained in the calculations for Seville.

Comparison of the results obtained with the different construction solutions indicate that the ventilated façade reduced the cooling demand, both in Seville and in Burgos, in every month of summer. When an evaporative cooling system was incorporated in the ventilated cavity, the energy efficiency of the FV was enhanced, achieving lower cooling energy demands. It may be noted that EE was more effective in Seville than in Burgos, where the cooling demand was observed to change less when EE was incorporated. Both systems tended slightly to increase the heating demand.

With the hot air recovery system from the ventilated cavity, very significant energy savings were achieved in the overall building heating demand. However, despite the implemented control system, the civic buildings with AAC were observed notably to increase their cooling demand. This may be explained by the fact that in the hours in which the cooling system was not running, preheated air was introduced in order to ventilate the building, this being permitted by the established control criterion, which shows that this was not entirely appropriate.

With regard to the residential building, Figures 6 and 7 depict the monthly heating and cooling demands of this building in Seville and Burgos, respectively. The evolution was similar to that obtained for the civic building; however, in this case, heating and cooling consumption only occurred in the months in which the respective systems were available. In addition, comparison of the results obtained for this building with those corresponding to the civic building indicate that the heating and cooling consumptions of the residential building were much lower. This was due, on the one hand, to the smaller outer surface area exposed to the environment (the side building envelopes were adiabatic) and, on the other hand, to the smaller internal loads.

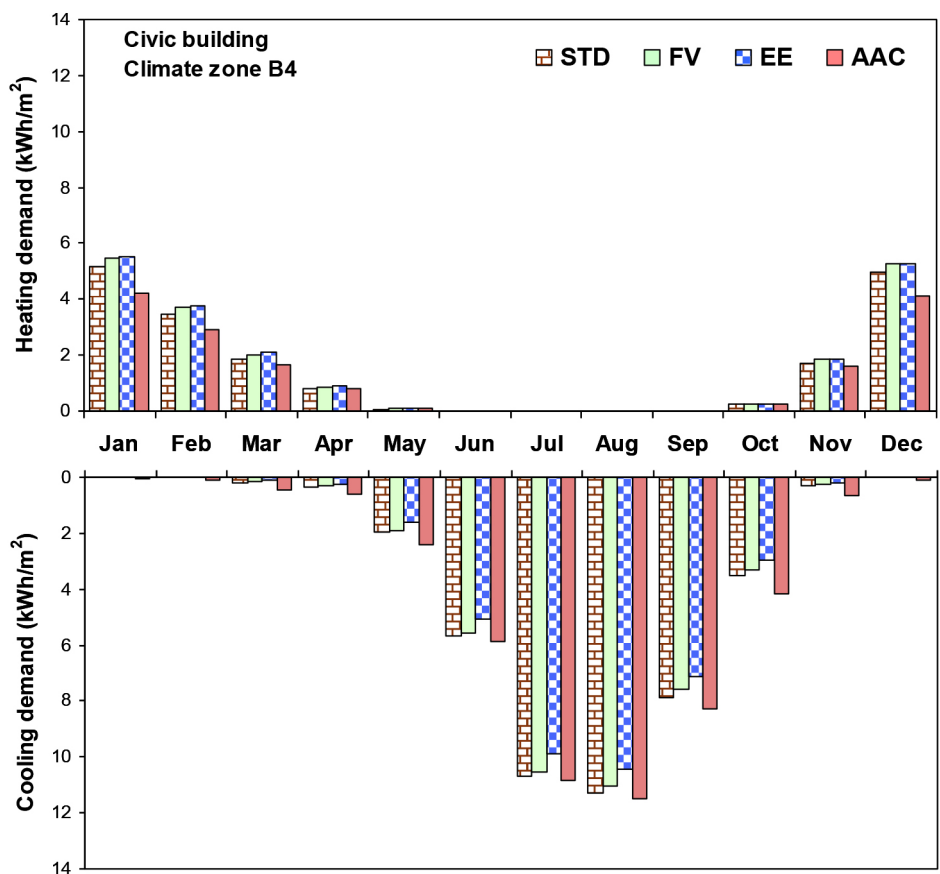


Figure 4. Heating and cooling demands for the civic building in climate zone B4.

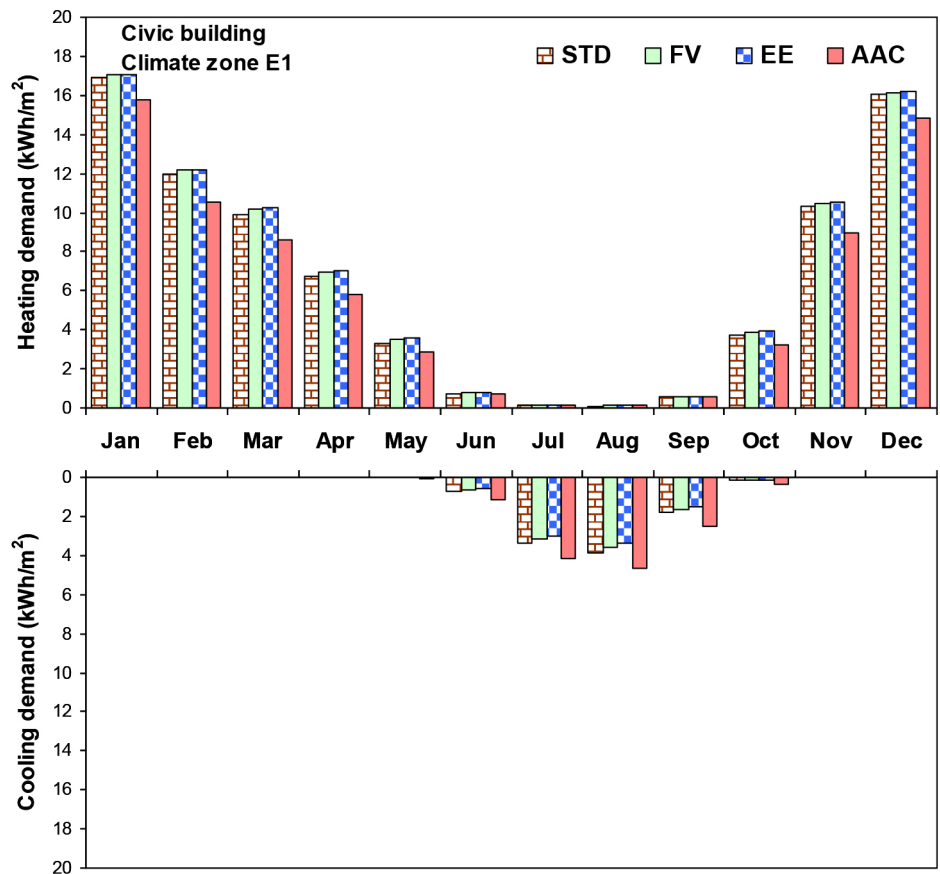


Figure 5. Heating and cooling demands for the civic building in climate zone E1.

The studied construction systems performed similarly in the residential building and in the civic building. The incorporation of the conventional ventilated façade decreased the cooling demand in comparison with that of the building with a conventional building envelope and, simultaneously, increased the heating demand. The ventilated façade with evaporative cooling heightened these effects, particularly in Seville.

The AAC system allowed the heating demand of the building located in Seville to be almost fully suppressed, and it considerably reduced that of the building in Burgos. In this case, in which it was decided to deactivate the system in summer, there was no significant increase in cooling consumption, which suggested that this simple control strategy could be sufficient. Similarly, the water curtain in the EE system could also be deactivated in winter. This would be more effective than the implemented control system, as several hours go by from the moment the heating demand is detected to the transmission of the thermal wave.

By way of summary, Table 1 details the annual energy demands of the buildings fitted with the studied construction systems in climate zones B4 and E1. The variation percentages that accompany these results are in relation to the corresponding STD system.

The evaporative cooling system is designed to enhance the energy performance of the ventilated façade in warm zones in summer. The simulations performed for Seville indicate a reduction in cooling demand of 8–10% with respect to the conventional building envelope and of 6–9% with respect to a conventional ventilated façade. It should be borne in mind that evaporative cooling led to an increase in heating demand, so that it would be advisable to stop the water film in winter.

In cold climate zones, ventilated façades are usually not installed because their use leads to increased heating demand. However, in this study, the possibility was examined of using the hot air from the ventilated cavity to support the building ventilation system, thus reducing the heating demand. The results obtained in the simulations indicate that the ventilated façade with AAC very effectively reduced the heating demand, for example producing a 24% decrease in the heating demand for the residential building in Burgos.

As in the previous case, a control system needs to be developed such that the hot air is only introduced into the building when it is needed, as hot air input into the building in summer would make the cooling demand shoot up.

Finally, even though for the calculations made, the construction systems were only incorporated in the south façade of the buildings, it may be noted that these systems would also be effective (albeit to a lesser extent) on the east and west sides.

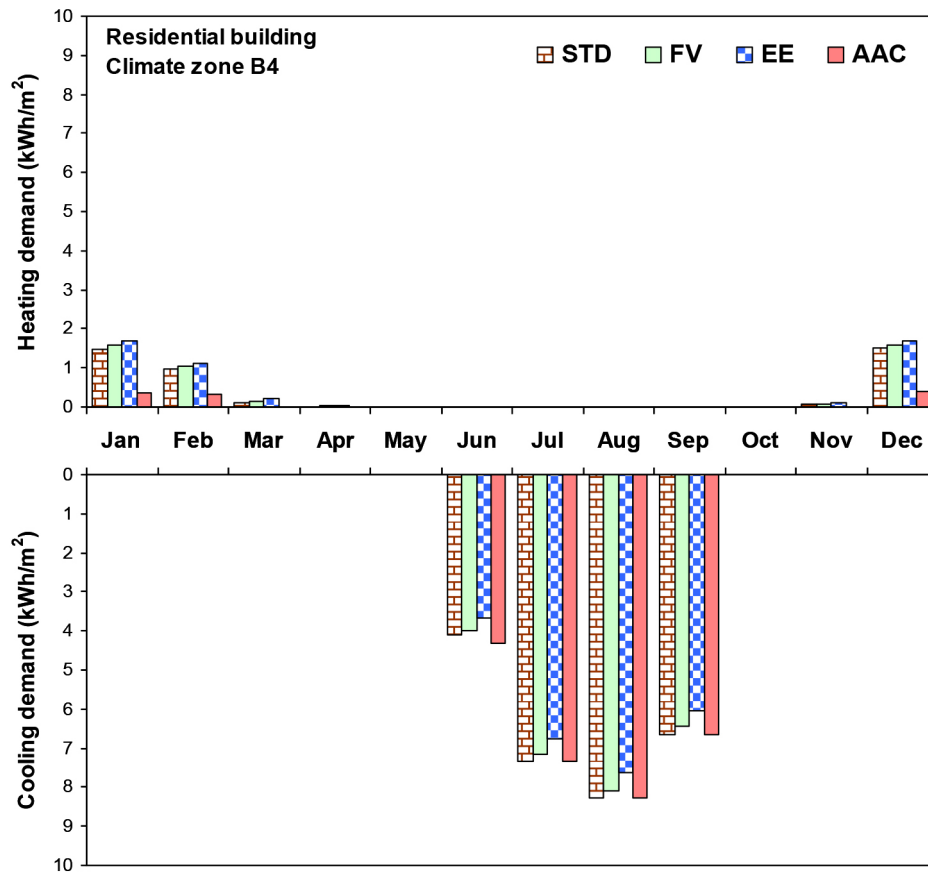


Figure 6. Heating and cooling demands for the residential building in climate zone B4.

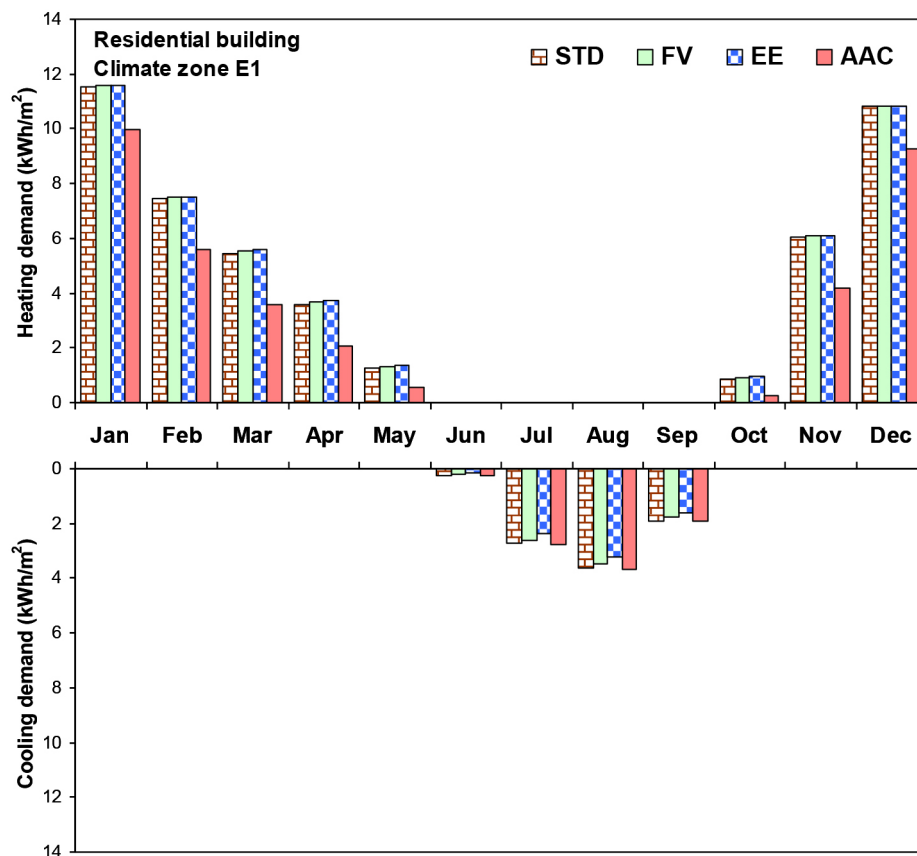


Figure 7. Heating and cooling demands for the residential building in climate zone E1.

Building	Location	Construction system	Heating (kWh/m ²)	Cooling (kWh/m ²)
Civic	B4	STD	18.3	41.8
		FV	19.5 (+6.5%)	40.8 (-2.5%)
		EE	19.8 (+8.2%)	37.7 (-9.9%)
		AAC	15.7 (-14%)	45.0 (+7.7%)
	E1	STD	80.5	10.0
		FV	81.9 (+1.8%)	9.2 (-7.6%)
		EE	82.4 (+2.4%)	8.6 (-14%)
		AAC	72.2 (-10%)	12.9 (+30%)
Residential	B4	STD	4.2	26.4
		FV	4.4 (+6.0%)	25.7 (-2.5%)
		EE	4.8 (+16%)	24.1 (-8.5%)
		AAC	1.1 (-74%)	26.5 (+0.7%)
	E1	STD	47.0	8.5
		FV	47.4 (+0.9%)	8.0 (-5.3%)
		EE	47.6 (+1.4%)	7.3 (-14%)
		AAC	35.5 (-24%)	8.6 (+1.2%)

Table 1. Annual energy demands of the studied buildings.

5. CONCLUSIONS

This study presents two innovative systems to enhance ventilated façade energy efficiency: an evaporative cooling system to reduce the cooling demand and air recovery from the ventilated channel to reduce the heating demand.

To quantify the degree of improvement of the innovative systems, mathematical models were developed that describe their thermal performance. These models were integrated into the EnergyPlus program for calculating building energy consumption. The integration was performed such as to enable future models of non-conventional building envelopes to be simply incorporated.

The results obtained in the simulation of realistic buildings that incorporated the innovative construction solutions confirmed their effectiveness. However, the simulations also showed that these systems require appropriate control systems to prevent negative effects (increased heating demand by evaporative cooling and increased cooling demand by air recovery from the channel).

In particular, air recovery from the channel was shown to be quite effective in reducing the heating demand. This finding calls into question the usual understanding that ventilated façades are inappropriate for cold regions.

6. ACKNOWLEDGEMENTS

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