Impact of natural ventilation in energy demand and thermal comfort of residential buildings in Catalonia

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ABSTRACT

The most representative typology of residential buildings of Catalonia has been simulated in TRNSYS to evaluate the impact of both infiltration and natural ventilation. The typology is a block of apartments constructed during 1950-1980.

In this paper the methods used to characterize the infiltration and the natural ventilation are described. The infiltration model (UNE-EN 15242, 2007) considers the tightness of the construction and allows the use of measurement data obtained from experimental studies, as blower door tests. The natural ventilation of the building is single sided ventilation with courtyard effect. The model used (Gids and Phaff, 1982) depends on the indoor temperature, courtyard temperature, outdoor temperature and wind velocity. The control strategy defined for the natural ventilation is based on the results obtained in surveys of the building characterization study done in the framework of the MARIE project (www.marie-medstrategic.eu). The control strategy follows the assumption that the occupants use the natural ventilation to cool the households, and when it is not enough to have comfortable conditions, they use the cooling system.

The results are presented in terms of energy demand and thermal comfort. The evaluation of the comfort is based on the adaptive ASHRAE model (ASHRAE 55, 2004), which is applied in buildings without mechanical cooling systems. The comfort indices evaluated are the Long-term Percentage of Dissatisfied (Carlucci, 2013) and the hours of overheating. The typology has been evaluated in different situations: current building and refurbished building; with natural ventilation and without natural ventilation. The objective is to show the effect of the natural ventilation in different building configurations.

KEYWORDS

Natural ventilation, infiltration, control strategy, thermal comfort, overheating

1 INTRODUCTION

European objectives 20-20-20, defined by the European Council (Energy Performance of Building Directive and Energy Efficiency Directive), are committed with the aim of reducing the greenhouse gas emissions by 20%, saving 20% of energy consumption through increased energy efficiency and promote renewable energy to 20%. In this context, it is needed to develop political guidelines to achieve these goals, establishing techno-economic criteria to make decisions at regional and local level.

Therefore, it is essential to use an approach that enhances the use of passive strategies, both in the design of new housing and in the refurbishment projects. The different constructive solutions, dimension, distribution of spaces, orientation, exposition to wind and the urban environment have an important role in the infiltration and in the natural ventilation, and in consequence in the energy demand and the thermal comfort of the buildings. In addition, the behaviour of the users plays an especially role in the use of the buildings and consequently in its consumption, such as the works done in the framework of the IEA-EBC Annex 66 demonstrate (www.annex66.org).

Within this context, the present paper describes a study where methods for improving the definition of the air leakage and the natural ventilation and how the users interacts with the building, have been implemented in a detailed building model through TRNSYS. The effects of both phenomena are evaluated in terms of thermal comfort and energy demand. In addition, four different scenarios have been compared, in order to analyse the behaviour of passive strategies applied in the refurbishment of buildings.

2 DESCRIPTION OF THE BUILDING'S MODEL

The paper is focused in the most representative typology of residential buildings of Catalonia, which represents the 45% of the dwellings (Garrido et al., 2012). This typology was built during 1951-1980, before the first building regulation (NBE-CT-79, 1979) and is characterized for having a low thermal performance. The building typology is a block of apartments with a commercial ground floor and five residential floors. There are two dwellings per floor with a 78.8 m^2 of surface each one. The typology has been simulated by (TRNSYS 17.1, 2012) in four climates of Catalonia, but in this paper only the results of the climate of Barcelona are presented.

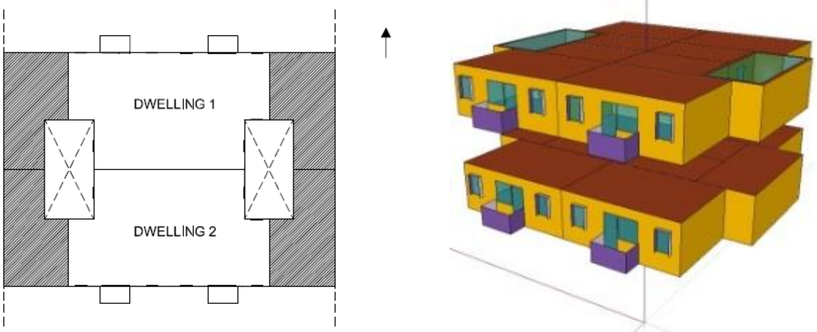

Figure 1: Building typology: block of apartments 1951-1980

The building's geometry (Figure 1) is introduced in the simulation by a multizone 3D model, using the plugin Trnsys3D for Google SketchUp. Only two floors are included, in order to simulate the building with more detail: the standard floor and the under roof floor. Each dwelling is divided following two zonification criteria: night and day use, and orientation. The building model includes the external environment and the corresponding shadings.

In the simulation, the occupancy has been defined as the main driver of the use of the building (heating, cooling, natural ventilation, solar protection and lighting use). For that reason, one of the main objectives is to use realistic profiles of the occupants. These profiles have to reproduce the variability of the actual occupant and, at the same time, their behaviour has to be representative of the average occupant. The stochastic profiles are created from the Time Use Data survey of Spain (INE, 2010). This survey allows knowing what people are doing at each moment of the day. Then, an annual profile was created applying a statistical analysis of the raw data, assigning a state of each occupant: outside of home, passive at home, and active at home. The family composition of the dwelling typology is made up of two adults and a kid.

The energy systems have been defined by a method based on the efficiency of the different parts of the system: generation, emission and control. The efficiency of generation is calculated using (IDAE, 2009) and the efficiency of the emitters and control following (EN 15316, 2008). The building model includes also the lighting and appliances consumptions, in order to take in consideration all the energy uses of the household. The details of the approach used in the simulations are explained in (Salom et al., 2014).

3 METHOD FOR INFILTRATION

3.1 Selection of the method

The infiltration or air leakage is the unintentional introduction of outside air into a building, typically through cracks in the building envelope and through the joint of doors and windows. In order to include a detailed model of infiltration in the building simulation, four different methods have been analysed:

1. K1, K2, K3 approach (ASHRAE, 1989): this method calculates the instantaneous air change rate, depending on outdoor temperature, indoor temperature, wind speed, and K1, K2, K3 coefficients. These coefficients have different values for tight, medium and loose construction. The method can be implemented in TRNSYS, using Type 571 (Thornton, 1998).
2. LBL infiltration model (ASHRAE, 2009): this method calculates the instantaneous air change rate, depending on the effective leakage area (ELA) and the superposition of wind and stack effects. The ELA depends on leakage coefficient and it can be calculated from experimental data of blower door test. The wind and stack effects depends on the outdoor temperature, indoor temperature, wind speed, the height of the building and its environment. The method can be implemented in TRNSYS, using Type 960 (McDowell, 2006).
3. Sherman Grimsrud approach (ASHRAE, 2005): this method is based on the LBL infiltration model too, with the difference that two coefficients are used to consider the superposition of the wind and stack effects. The method can be implemented in TRNSYS using Type 932 (Bradley, 2005).
4. EN15242 method (UNE-EN 15242, 2007): the direct method for exfiltration and infiltration calculates the instantaneous air change rate as a superposition of wind and stack effects. The result depends on outdoor temperature, indoor temperature, the height of the building, wind speed, and a coefficient that considers the pressure difference between windward and leeward sides. In addition, the method takes into consideration the building conditions, using the results of the blower door test (air changes per hour at 50 Pa, n_{50}) to calculate both the wind and stack air change rate. The blower door test is a common test to identify the air leakage of buildings. The method has been implemented in TRNSYS using equations.

In order to choose the infiltration method, the results of these four methods have been compared with the reference values of the PassivHaus design, which is based on (EN-ISO 13790, 2004). It permits to calculate a constant annual air renovation rate, as a superposition of wind and stack effect. It depends on the n_{50} parameter and two tabulated exposure coefficients: the number of façades exposed to wind and the environmental exposure.

Figure 2 compares the four methods with the reference of PassivHaus considering three values of n_{50} (5, 7 and 10), obtained as typical values from experimental data in existing buildings. Analysing the results of the different methods, it is possible to observe that the K1, K2, K3 approach is not able to distinguish the building features with a high detail, in comparison with the other methods, due to the qualitative definition of the construction (tight, medium and loose). It means that this approach is not able to distinguish different levels of loose construction, and the same coefficients have been used in the three cases, with no changes in the result. If the analysis is focused on both ELA methods (LBL infiltration model and Sherman Grimsrud approach), the average air change rates have a direct relationship with the different n_{50} values; however, the air changes rates obtained are the lowest of all methods. If both methods are compared with the PassivHaus reference, the air change rate is 0.1-0.3 h^{-1} lower, being this difference higher as the value of n_{50} increases. Finally, the EN15242 is analysed: the air change rate is also lower than the reference value, with a difference between

0.05-0.1 h^{-1}. In this case, the difference is lower in comparison with the other methods, and the relationship with the n_{50} and the air change rate is similar to the PassivHaus reference.

After this analysis, the selected method is the EN15242, due to two main reasons: the method allows to relate the air leakage of the household with experimental data (blower door test), and the results of the method are consistent with the reference of PassivHaus Design.

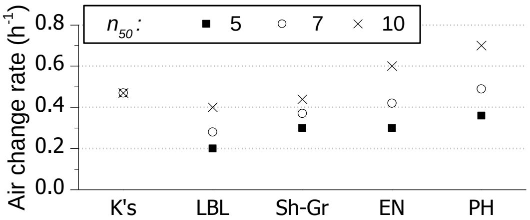

Figure 2: Comparison of the methods of air leakage's modelling (K's: K1, K2, K3; LBL: LBL infiltration; Sh-Gr: Sherman Grimsrud; EN: EN15242; PH: PassivHaus)

3.2 Implementation

The EN15242 method has been implemented in the building model to estimate the air change rate due to the air leakage of the building. In this study, the assumptions of n_{50} values are the following: 7.5 h^{-1} for existing building, and 5 h^{-1} for refurbished building. These values have been obtained from (Alfano et al., 2012; Jimenez et al., 2013), where they collected and analysed experimental data of air tightness from residential and Mediterranean buildings.

4 METHOD FOR VENTILATION

4.1 Selection of the method

The method for modelling the renovation rate due to natural ventilation depends on the building features and the type of ventilation. This can be: single sided ventilation, cross ventilation or stack effect due to courtyards. The references used to model each natural ventilation phenomenon and which are implemented in a dynamic simulation, are described in the paragraphs below.

1. Single sided ventilation, using (Gids and Phaff, 1982): this method calculates the air change rate in function of the opening dimensions, wind speed, indoor and outdoor temperature depending on wind and buoyancy effect.
2. Cross ventilation, using (British Standard, 1991): this method calculates the air change rate considering the thermal buoyancy effect and the wind effect, depending on the wind speed and the difference of indoor and outdoor temperature, in each moment. The method takes also into consideration the opening area, the height of the building and pressure coefficients.
3. Courtyard effect: in this case, the stack effect due to courtyard effect has been implemented in a simplified way, due to the complexity of the calculation. The courtyards are designed to extract the air from the households, due to the difference of temperatures between the outdoor and the courtyard. For that reason, the rule used to define the courtyard effect is mainly related to the outdoor temperature (T_{out}) and the courtyard temperature (T_c), because depending on that difference, the direction of the air flow changes (from household to outside, or from outside to household). If the $T_c > T_{out}$, the air flow goes from household to outside and the effect is the desirable. On the contrary, if the $T_c < T_{out}$ the air flow is opposite and does not comply with the design. Usually, the courtyard ventilation is a complementary phenomenon from the main ventilation strategy: single sided or cross ventilation. For that reason, the air change rate is related to the main ventilation method of the household, and the temperature comparison defines if the

courtyard ventilation is active or not. If the courtyard ventilation is active, then the rooms (zones) of the households that are influenced by the courtyard are ventilated.

4.2 Implementation

In the building typology that is analysed in this paper, the natural ventilation is single sided with the courtyard effect. For that reason, the Gids and Phaff method has been implemented.

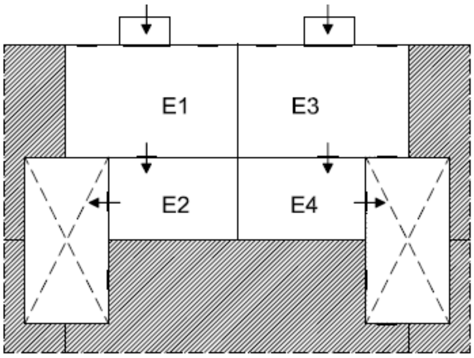

Figure 3: Natural ventilation strategy for a dwelling

Figure 3 represents how the natural ventilation has been implemented in the building model, depending on the zones' distribution. On the one hand, there are two external zones (E1 and E3), where the single sided ventilation method is implemented, assuming a windows' total area of 4 m^2 for each zone. On the other hand, the zones E2 and E4 are internal zones connected to the E1 and E3, respectively, and to the courtyard zones. In that case, the ventilation of both zones depends on the relation between the outdoor temperature and the courtyard temperature, as it has been introduced in the previous section. If the effect of the courtyard is positive ($T_c>T_{out}$, so that the air flow goes from household to outside), there is an air exchange between the external zone and the internal zone. In the other case, if the courtyard effect is negative ($T_c<T_{out}$), there is not air exchange between these zones. The air change rate between zones has been assumed to be the same than the single sided ventilation in each moment. Finally, the courtyard zone has been simulated as a ventilated zone and 4 air changes per hour have been assumed over all the year.

5 CONTROL STRATEGY

The natural ventilation is considered as the main strategy to reduce the temperature during the warm season, following vernacular behaviour in Mediterranean zones. The strategy is based on the following assumption: the users use the natural ventilation for cooling the household. In the case that the natural ventilation is not enough and overheating occurs, then, the windows are closed and the cooling system is switched on. This assumption is consistent with the results obtained in the surveys done in Catalonia during the MARIE project (www.marie-medstrategic.eu). The survey shows that 80% of the households use the natural ventilation for cooling and the 60% of households use the cooling system punctually, when the weather is very hot and consistent with adaptive comfort theory

In the building model, the infiltration is related mainly to the window perimeter. For that reason, although actually the infiltration is present all the time, in the building model the effect of the infiltration is active only when the natural ventilation (window opening) is not used.

The control of the natural ventilation depends on the following parameters: occupancy, operative temperature of the zone, courtyard temperature and outdoor temperature. Table 1 describes the control rules of the natural ventilation applied in the simulation model. In general terms and if there is occupancy in the household, the natural ventilation is *on* when the operative temperature is between 24ºC and 28ºC. This range of temperature is comfortable for ASHRAE adaptive comfort model (ASHRAE, 2004), especially when the outdoor temperature is higher than 20ºC (warm season). When the indoor temperature reaches the 28ºC, then the natural ventilation is off, and the cooling system turns on until the outdoor temperature is lower than the operative temperature, usually at night.

Table 1 Control strategy implemented in the building model

General rules of control	**Condition**	**Natural ventilation**
First condition:		
Occupancy	>0	YES
	0	NO
If the occupancy is >0		
Operative temperature (Top)	Top<24ºC	OFF
	24ºC>Top>28ºC	ON
	Top>28ºC	OFF
If the natural ventilation is OFF because Top>28ºC		
Outdoor temperature (Tout)	Tout>Top	OFF
	Tout<Top	ON
If there is a courtyard in the household and the natural ventilation is ON		
Courtyard temperature (Tc)	Tc>Tout	Courtyard effect ON
	Tc<Tout	Courtyard effect OFF

6 RESULTS

The results presented in this section are for the current building (base case) and of the building after a deep renovation with the implementation of passive measures (deep renovation). Table 2 shows the characteristics of the two building models.

Table 2 Characteristics of the buildings: base case and deep renovation

Characteristics	**Base case (BC)**	**Deep renovation (DR)**
Façade (U-value, W/m^{2}K)	With air chamber (1.22)	External insulation EPS 12cm (0.24)
Roof (U-value, W/m^{2}K)	With air chamber (1.17)	Internal insulation mineral wool 8cm (0.32)
Window (U-value, W/m^{2}K – g, -)	Aluminium without thermal break with clear double glazing 4/12/4 (5.68 – 0.85)	PVC with clear double glazing 4/16/4 (2.83 – 0.75)
Air leakage (h^{-1})	7.5	5
Solar protection	Internal blinds	Internal blinds
Heating system	Conventional NG boiler	Conventional NG boiler
Cooling system	Conventional AC Split (E1 & E3 zones)	Conventional AC Split (E1 & E3 zones)

The building model has been configured with the option to simulate the building with natural ventilation (NV) and without natural ventilation (nNV). The objective of this configuration is to be able to distinguish the buildings that have the possibility to do natural ventilation or not, due to its surrounding conditions and location (the possibility of ventilation is not the same in a spacious village than in a compact city).

6.1 Building behaviour and control strategy

The results presented in the Figure 4 show the results of the base case simulation with natural ventilation and without natural ventilation for a representative summer week (left and right side, respectively). The objective of these figures is to show the behaviour of the building model with the implementation of the infiltration and natural ventilation strategy described in the previous chapters.

The first row of figures shows the occupancy profile, which is the main driver of the use of the building. If there is occupancy, then the cooling systems or the natural ventilation are used. The second row of figures represents the outdoor temperature, the indoor temperature and the operative temperature. The behaviour of the indoor and operative temperatures follows the use of the building, reaching comfort conditions when the occupancy is in the household, thanks to the cooling strategies. The third row of figures shows the air change rate due to infiltration and natural ventilation, and the wind speed. In that case it is possible to see that in the simulation without natural ventilation, the infiltration is always active. For the simulation with natural ventilation, the natural ventilation is switched on, depending on the occupancy and the operative temperature, and following the control strategy presented before. Finally, the last row of graphs represents the cooling consumption, reflecting an important difference on the use of the cooling system between the simulation with natural ventilation and without natural ventilation.

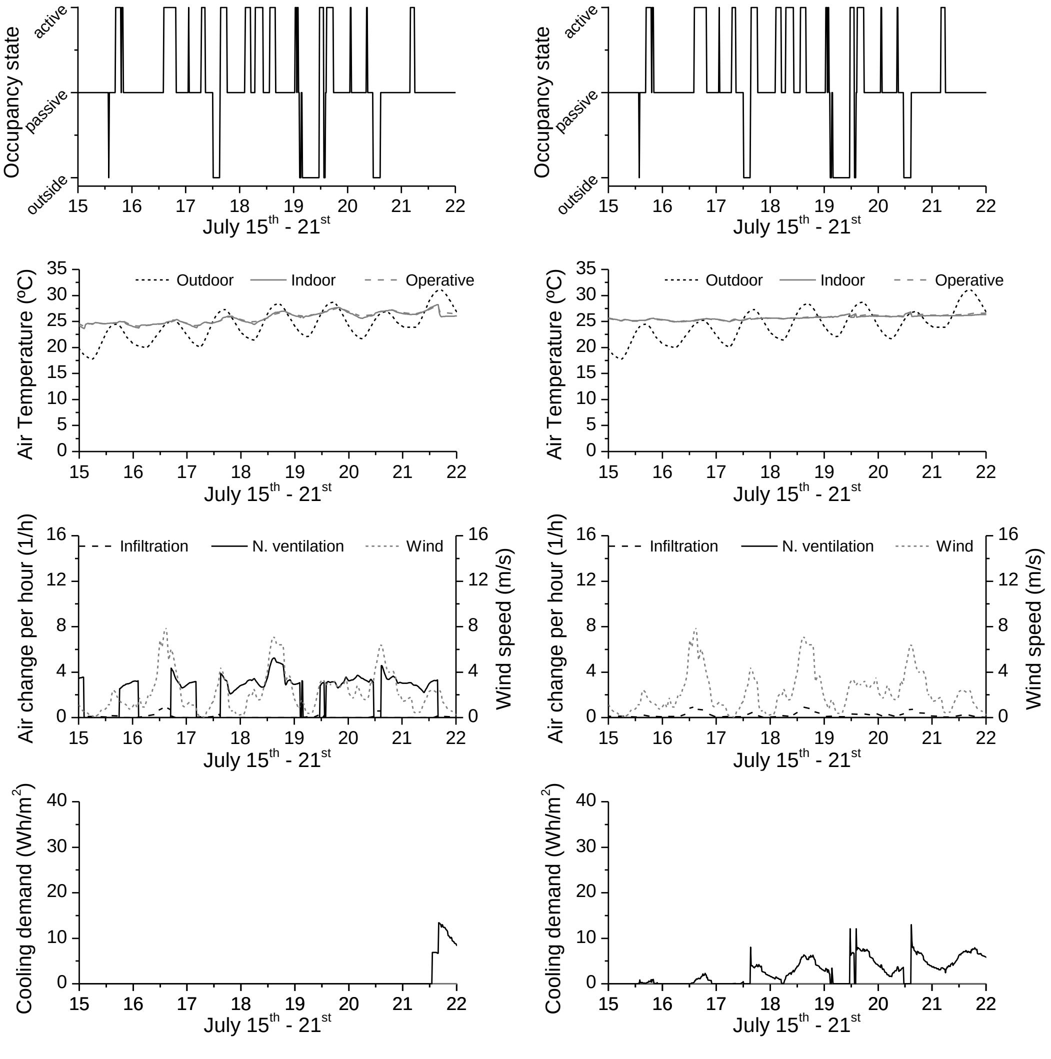

Figure 4: Results of the simulation for a summer with natural ventilation (left) and without natural ventilation (right).

6.2 Thermal comfort

For the comfort evaluation, the building has been simulated without the use of the heating and cooling system (free running mode) and the comfort model used is the ASHRAE adaptive model (ASHARE 55, 2004). The purpose is to explore to what extend the passive measures are able to improve the comfort conditions without the use of the mechanical systems. The comfort parameters used for the evaluation are the Long-term Percentage of Dissatisfied (LDP) developed by Carlucci (Carlucci, 2013) and the hours of overheating (OH).

The LDP is a long-term index that evaluates the comfort along a period. The index has been calculated for three periods (annual, cold season and warm season), in order to have information about the behaviour of the building under different weather conditions. The comfort requirement for a residential building is LDP < 20% (ASHARE 55, 2004). It means that the occupants have a comfortable condition at least during the 80% of the time. The calculation details of the LDP are explained in (Carlucci, 2013).

The hours of overheating (OH) are included in order to complement the LDP for the warm period. One of the main problems of the Mediterranean regions is the increase of the overheating hours due to a not appropriate design of the building. The analysis of this parameter can help to detect overheating problems and then, evaluate the possibility to avoid an active cooling system. The criterion used is that the percentage of OH has to be lower than the 1% of the warm season period in order to have a comfortable building. If the hours of OH are lower than 1%, it means that the building achieves comfortable conditions without the use of mechanical cooling system, and then it could be removed. The criterion was proposed by CIBSE (CIBSE, 2006), however, an adaptation in the calculation of the index has been done: the upper threshold is not a constant value and it depends on the ASHRAE adaptive comfort model.

$$P_{OH} = \frac{\sum_{t=1}^{T} p_t \cdot OH_t}{\sum_{t=1}^{T} p_t \cdot h_t} \qquad \left\{ \begin{array}{l} OH_t = 1 \Rightarrow T_{op,t} > T_{upperASH,t} \\ \\ OH_t = 0 \Rightarrow T_{op,t} \leq T_{upperASH,t} \end{array} \right. \tag{1}$$

Where P_{OH} is the Percentage of hour of overheating, $T_{op,t}$ is the operative temperature and $T_{upperASH,t}$ is the upper comfort temperature of the ASHRAE adaptive comfort model at time t. For the climate of Barcelona the 1% of the warm season hours corresponds to 41 hours.

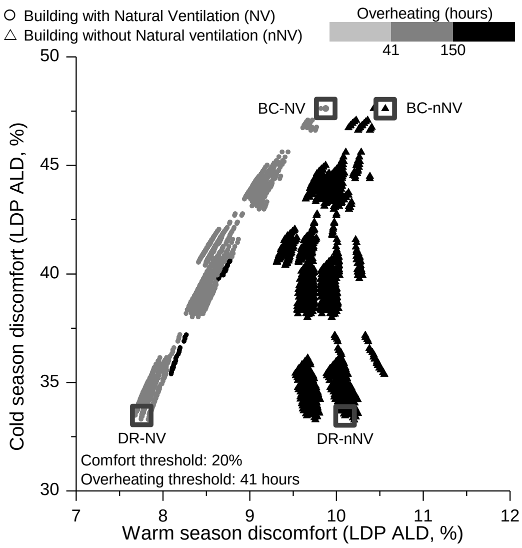

Figure 5: Comparison of the simulation with natural ventilation (circles) and without natural ventilation (triangles). Cold season comfort vs. warm season comfort. Colour scale: hours of overheating.

Figure 5 shows the results of the simulation in terms of thermal comfort. Each dot on the graph reflects a result of a simulation, where the building typology has been simulated with different combination of passive measures. The highlight simulations (square) are the base case with natural ventilation (BC-NV), the base case without natural ventilation (BC-nNV), the deep renovation with natural ventilation (DR-NV) and the deep renovation without natural ventilation (DR-nNV), which are analysed in the present paper. The x-axis represents the thermal discomfort during the warm period, and the y-axis the thermal discomfort during the cold period. The colour scale is the hours of overheating, revealing that for this building typology, all the simulations are suffering overheating (>41 hours).

An important difference between the set of simulation with natural ventilation (circle) and the set of simulation without natural ventilation (triangle) is observed. The first group of simulations follows a linear trend: when the thermal comfort of the cold period is improved, the comfort of the warm period is also improved. However, for the simulations without natural ventilation, this situation is opposite, especially when the thermal comfort of the cold period is better (deep renovation).

6.3 Energy demand

Table 3 shows the results of energy demand for heating and cooling, for the base case and for the deep renovation. As explained before, each case has been simulated with and without the possibility to use natural ventilation as a cooling strategy. A deep renovation of the building permits to reduce the heating demand around 65%. In the case of cooling demand, the deep renovation allows to reduce the cooling demand around 26%, in the case with natural ventilation. No significant changes are shown in the case without natural ventilation; however a slight tendency to increase the cooling demand can be sensed, as shown in the comfort results. Finally, comparing the same building with or without natural ventilation, the cooling demand can be reduce around 70-80%.

Table 3: Results of energy demand

Energy demand	**Base case (BC)**		**Deep renovation (DR)**	
(kWh/m^{2}yr)	**Heating**	**Cooling**	**Heating**	**Cooling**
With Natural Ventilation (NV)	60.9	1.1	21.5	0.8
Without Natural Ventilation (nNV)	60.9	3.9	21.5	4.0
Comparison (NV vs. nNV)	-	-72%	-	-80%

7 CONCLUSIONS

The paper presents a dwelling simulation developed with TRNSYS, where the estimation of the air thickness effect and the natural ventilation has been implemented through two detailed methods: EN15242 and Gids and Phaff, respectively. In addition, a control strategy of the natural ventilation has been developed in order to reproduce the actual behaviour of the occupants (based on surveys): the users use the natural ventilation as a main strategy for cooling the household. The occupancy profile used in the simulation has been obtained from the TUD analysis. Four different scenarios have been analysed and compared (with or without natural ventilation, existing building and renovated), in order to evaluate the effect of the natural ventilation, in terms of thermal comfort and energy demand.

The results show that the methods implemented in the dwelling simulations reproduce properly the effect of the natural ventilation and air infiltration. The analysis of the thermal comfort indices, LDP and OH, is consistent with the energy results, being useful and complementary information to evaluate the adaptation of different energy efficiency measures in each building typology.

Regarding to the building typology analysed, the results show that the natural ventilation allows to reduce the cooling demand around the 70-80% in comparison with the same building without natural ventilation. Despite of the positive effect of the natural ventilation, in that case, it is not possible to avoid the cooling system due to the dwelling reflects some overheating problems based on the current comfort models.

8 ACKNOWLEDGEMENTS

The research was supported by the MED Programme of the European Union under the MARIE strategic project (Agreement Nº 1S-MED10-002) and has been done with the collaboration of Universitat Politècnica de Catalunya (UPC).

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