THE IMPACT OF A ZONING CONTROL SYSTEM IN THERMAL COMFORT AND ENERGY CONSUMPTION IN AN AIR-TO-WATER HEAT PUMP WITH A DUCTED FAN-COIL SYSTEM

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ABSTRACT

The analysis of a thermal zoning system integrated in a HVAC system based on an air-to-water heat pump with a ducted fan-coil is proposed in this paper. Zoned systems are based on independently controlling the temperature of each of the zones of a building. When a zone is not occupied or not in demand, the control board sends a control signal to the zone's motorised damper which interrupts the airflow supply to that room. Although this control system is gaining popularity in residential sector, the results obtained in terms of thermal comfort and energy consumptions are not evident and should be documented.

Besides, the control is based on an algorithm which allows acting over the heat pump, setting the set-point temperature and over the fan-coil, setting the fan speed. Based on this, it is possible to design an algorithm to optimize the performance of the installation ensuring thermal comfort and achieving energy savings, by increasing the number of hours during which the air conditioning unit works under part-load conditions.

The thermal zoning and the HVAC control system is programmed and simulated in Trnsys 17 for the case of study of a residential dwelling, comparing with the case of a non-zoned system. The comparison criteria of both cases are the evaluation of thermal comfort, based on the calculation of PPD and PMV values, and energy savings according to the energy consumption of the heat pump and fan-coils.

INTRODUCTION

Nowadays, in the residential sector, the use of ducted direct expansion inverter systems based on the on/off control of a single zone is very common [1]. This kind of system ensures the comfort level in the zone where the thermostat is placed but, with regard to the rest of the zones, even when the ductwork is well designed and the AC unit has the required maximum capacity, if the load profile is not similar to that of the control zone (use, orientation, thermal loads, etc.), their temperatures can fall outside the comfort range. As a solution, recent developments in sensors, electronics and communications have motivated a lot of research into designing and optimizing HVAC control systems for buildings, often referred to as smart buildings. The new Energy Performance of Buildings Directive 2018/844 of the European Parliament [2] promotes the use of HVAC control systems in buildings with the aim of optimizing the energy management and raising end-user's awareness about energy consumption. With this aim, several control strategies could be adopted: On/off, PID, model-based predictive, fuzzy logic, neural networks, etc. For example, Du et al [3] developed a control strategy based on the deep deterministic policy gradient (DDPG) method to generate an optimal control strategy for a multi-zone residential HVAC system. Huang et al. [4] evaluated the performance of a model predictive control for building energy management. In particular, according to the thermal zoning, in some European countries, the standard UNE 15232 [5] regulates the use of HVAC control systems in buildings with the thermal zoning as a fundamental condition to ensure the energy efficiency and thermal comfort. In this way, Stopps et al. [6] criticizes the use of occupant-centric smart HVAC control implementations in residential buildings.

Based on this, it should be noted that, as the complexity of the system increases (number of sensors, computational costs, etc.), the cost of the installation could become unjustified. For this reason, a simple and robust control system based on the concept of thermal zoning and the use of a communication gateway which allows the interoperability of different technologies is presented.

A zoned system is based on independently controlling the temperature of each of the zones of a building. To do this, a thermostat is installed in each room, allowing the thermal demand for each of the zones to be determined, and the selection of an independent set-point temperature depending on the preferences of the user. When the set-point temperature in a zone is reached, a control signal is sent to the zone's motorised damper which interrupts the air supply to that room. This concept will be applied in this study to a new HVAC system in the residential sector. Nowadays, the aerothermal energy has been promoted as a low carbon solution in the residential sector as the main option for covering the domestic hot water (DHW) and the heating and air conditioning needs, replacing solar collectors and conventional direct expansion HVAC systems, respectively [7,8,9]. The main reasons are the high thermal performance and the capacity of meeting the minimum renewable energy contribution established by the Directive 2009/28/EC of the European Parliament and of the Council [10].

Therefore, the control system presented is based on two fundamental elements: the thermal zoning and the communication gateway, a device that enables a two-way communication between the control board and the HVAC unit. This is only possible if the manufacturer shares the communication protocol and allows to read and set the operational parameters of the unit, such as: the operating mode, the fan-coil unit's fan speed or the water set-point temperature of the heat pump. From the information of the HVAC unit and the thermal situation of each zone, an algorithm is designed in order to optimize the performance of the installation, ensuring the thermal comfort and achieving energy savings, by increasing the number of hours in which the air conditioning unit works under part load conditions.

The thermal zoning and the HVAC control system are programmed and simulated in Trnsys 17, for the case of study of a residential dwelling, comparing with the case of a non-zoned system. The comparison criteria of both cases are the evaluation of the thermal comfort, based on the calculation of the PPD and PMV values, and the energy savings according to the energy consumption of the heat pump and the fan-coils.

NOMENCLATURE

COP	[-]	*Coefficient Operation Performance*
Cc	[-]	Degradation coefficient
Nzones	[-]	Number of zones
Nzones_dem	[-]	Number of zones in demand
Pvel	[-]	Thermal conductivity
Tz	[ºC]	Zone air temperature
Tset	[C]	Zone air set point temperature
Twset	[ºC]	Water set-point temperature

SYSTEM DESCRIPTION

Figure 1 shows the scheme of the system. The HVAC installation is composed by the air-water heat pump, the ducted fan-coil and the hydraulic circuit (pump and valves). The control system consists of the control board and the communication gateway. The first one receives the information of the rooms: the air temperature (T_{z1}, T_{z2}, ..T_{zN}) and the set point temperature (T_{set1}, T_{set2},..,T_{setN}) imposed by the users, from the thermostat placed in each zone (orange dashed lines). With this information, the algorithm imposes, thanks to the communication gateway, the control strategy with the configuration of the next elements (black lines):

- The fan speed of the fan-coil (F) is selected dynamically according to the airflow rate demanded by each zone, and the temperature difference between zone and the set point air temperature.
- The water set-point temperature of the heat pump (Tw_{set}) based on the temperature in each zone and the return air temperature to the fan-coil unit, taking into account the effect of thermal inertia in each zone.
- The position of the dampers of each room which control the amount of air supplied to the zones (D_1,D_2,..D_N),
- The operation signal of the circulating pump (P).
- The operation signal for the three-way mixing valve (V).

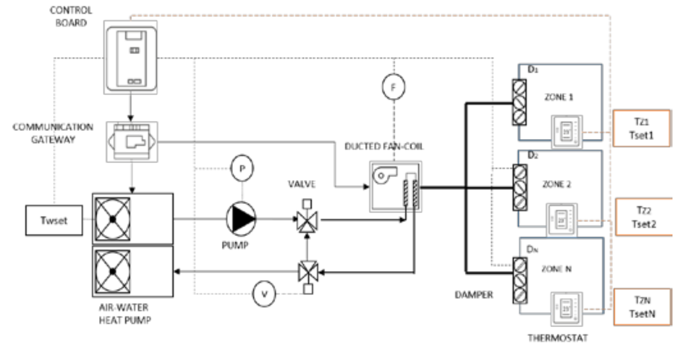

Figure 1 Scheme of the hydronic and zoned control system.

MATHEMATICAL MODELLING

New models of the heat pump, fan-coil and control system are created and implemented in Trnsys, for a better adaptation to the requirements of the simulation conditions.

Heat pump and ducted fan-coil models.

An air-water heat pump model is developed based on two sets of curves. Firstly, the typical set of curves of a manufacturer [11,12] which provides the heating and cooling capacity and electric consumption (COP at full load) as a function of the outside air temperature and the Tw_{set} required. Secondly, the COP should be modified as function of the part load ratio (PLR). The PLR is the ratio of the building's thermal demand to the current capacity of the heat pump, and, in addition, it is a function of the Part Load Fraction (PLF), which is defined as the relation between the current COP and the nominal COP of the equipment. According to European Standards for the calculation of seasonal energy efficiency EN 14825 [13], the PLF is calculated as a function of the PLR and the parameter Cc, that includes the impact of the decrease of the energy efficiency of the device due to the cyclic operation and power consumption in the stand-by mode, resulting as follows:

$$PLF = COP_{pl}/COP_{dec} = PLR/(PLR \cdot Cc + (1 - Cc)) \qquad (1)$$

The performed simulations adopted the curves of PLF from the standard EN 14825. This correction is very important because residential heat pumps predominately operate at part load and the influence of the thermal zoning in the part load operation is interesting with respect to a non-zoned system. As thermal zoning saves energy by turning off non-occupied zone's dampers, it makes efficient use of the system by increasing the number of hours that the heat pump works under part load conditions.

The fan-coil model is based on the effectiveness-NTU method and it uses a constant value of effectiveness for every speed of the fan. The effectiveness can be calculated from the data given in the fan-coil catalogue [14]. The fan electricity consumption is a function of the speed and head loss in the ducts.

Zoned Control system algorithm.

As described in Figure 1, the control system acts at two levels: zones and system.

At zone level, the system has been modelled as an off/on control which is continuously turning on and off the HVAC unit depending on if the temperature of the zone is inside or outside the dead-band temperature range (typically 0.5ºC) with respect to the set point air temperature. As each zone has its own thermostat and motorized damper, when the zone air temperature is in the comfort dead-band, a control signal is sent to the zone's motorized damper which interrupts the air supply to the zone. Also, the dampers are closed in the zones that are not occupied. Dampers will be opened when the HVAC unit is on and closed when it is off (Figure 2).

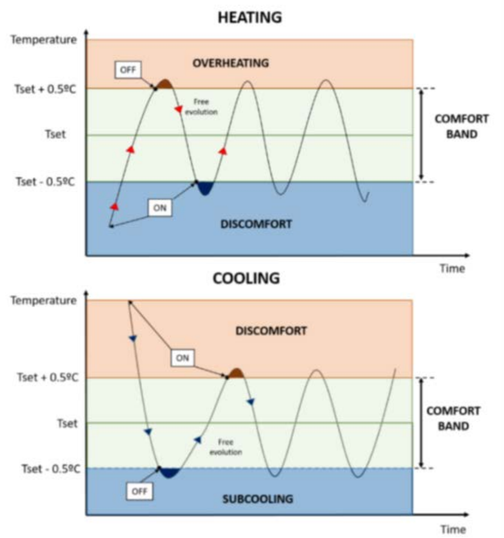

Figure 2. On/off control system in a zoned and non-zoned system**.**

With respect to the system level, the control algorithm sets the fan-coil's fan speed and the Tw_{set} as a function of the thermal behaviour and needs of each zone.

The fan speed control is based on the number of zones in thermal demand. The weight of each zone (P_{vel}) is proportional to the total number of zones.

$$P_{vel}=N_{zones\_dem}/N_{zones} \qquad (2)$$

Table 1 shows how the algorithm acts in the case of 3 velocities (low, medium and high) and 5 zones.

Table 2 Fan-coil fan speed selection

Nzones	Zones in demand	Pvel	Velocity
5	1	0.2	Low
	2	0.4	Medium
	3	0.6	Medium
	4	0.8	High
	5	1	High

Another advantage of changing the fan speed and then, adjusting the air mass flow rate to the zones as dampers are being sequentially closed, is avoiding an overpressure in the ductwork when only one or two zones are opened. In the case of a zoned control system but without the work of the communication gateway, which allows changing the speed of the fan, a by-pass should be needed. For that reason, in this study, the air distribution model in ductwork is not modelled.

When several zones have been conditioned at the same time, setting the Tw_{set} is not trivial. For this reason, two effects are checked. Firstly, the Tw_{set} depends on the difference between the zone air temperature and the set point temperature of each zone, and the biggest difference between all the zones in demand (ΔT_{max}) is considered. As shown in Figure 3, the ΔT_{max} sets a preselected Tw_{set} which may be or not modified by the second effect.

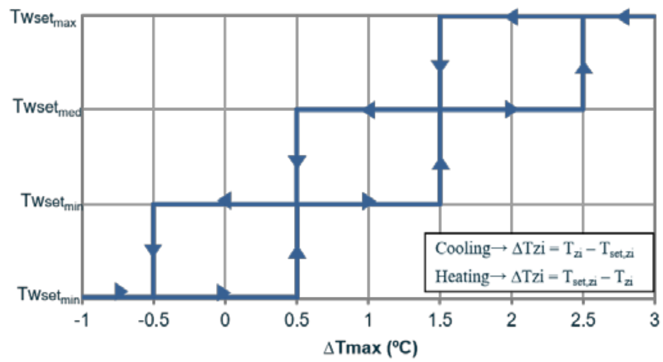

Figure 3. Tw_{set} control selection according to the zone $\Delta T_{max.}$

The second effect is related to the selected fan-coil speed. When there are a high number of zones in demand, the air supplied should be high, so the heat pump should be working in full load conditions. When the number of zones in demand decreases, the Tw_{set} is sequentially changing, and the heat pump works in better conditions. Considering the same case as Table 1, the Tw_{set} selection is indicated in table 2.

Table 2 Tw_{set} control selection according to the fan speed.

Number of zones	Zones in demand	Velocity	Tw_{set}
5	1	Low	Tw_{setmin}
	2	Medium	Tw_{setmed}
	3	Medium	Tw_{setmed}
	4	High	Tw_{setmax}
	5	High	Tw_{setmax}

The algorithm considers the possibility if, due to the fan-coil speed selected, it could be necessary to raise the preselected Tw_{set}, then the gateway would do so. The reason is that the final Tw_{set} selected should guarantee the strictest effect. Considering typical water temperatures in fan-coils, the range of temperatures are, in heating mode, Tw_{setmin}=42ºC, Tw_{setmed} =44ºC and Tw_{setmax} =45ºC, and in cooling mode, Tw_{setmin} =7ºC, Tw_{setmed} =8ºC and Tw_{setmax} =11ºC.

Non-Zoned Control system algorithm.

The non-zoned system only depends on the thermal demand of the master zone, and the remaining zones are conditioned without any control. Also, its thermal behaviour depends on the specific conditions (internal loads, solar gains, etc.) at that moment in time. The same on/off control as zoned system is applied in this case (Figure 2), but only for the master zone.

The fan-coil fan speed and Tw_{set} control in a typical installation with a heat pump and a ducted fan-coil is a traditional on/off control with hysteresis, as described in the zoned system (Figure 3). Thus, both systems have a similar performance with the aim to evaluate in detail the influence of the thermal zoning in the results.

CASE OF STUDY

The dwelling under study (Figure 4) has five heated/cooled zones (living room LR, kitchen K, office OF, parents' bedroom PR and children's bedroom CR), with a surface area of 121 m^2. The simulation is carried out in different European cities: Malaga, Paris and Milano. The EnergyPlus weather files are used in the simulation.

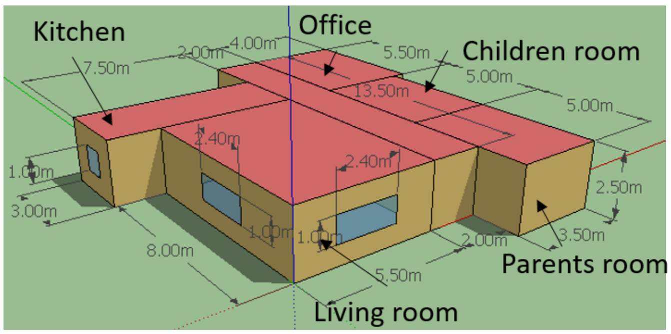

Figure 4. 3D representation of the home**.**

The enclosures are representative of the different regulations prevailing in each country. Table 3 shows the values considered for the overall heat transfer coefficient of the different enclosures of the dwelling.

Table 3 Threshold U-values.

City	Regulation	Wall	Ceiling	Floor	Window
Malaga	RITE 2019 [15]	0.65	1.1	1.1	2.2
Paris	RT 2012 [16]	0.24	0.66	0.66	1.14
Milano	D.Lgs.N.192 2005 [17]	0.34	0.33	0.3	2.2

A typical occupancy profile is applied in residential buildings to determine the operation of the HVAC system (Figure 5).

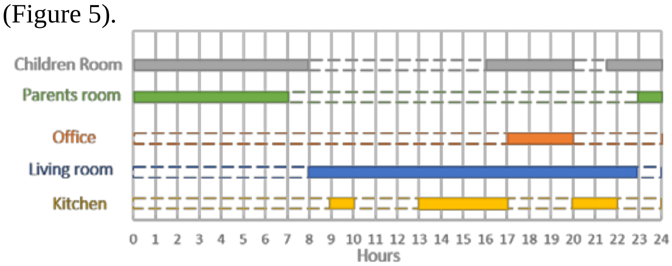

Figure 5 Occupational profile of the house.

A rate of 0.6 renewals/hour is set for outdoor ventilation airflow in all rooms except the kitchen, which is set at 2.9 renewals/hour.

RESULTS

The objective of this study is to evaluate the effects of a zoned control system with respect a typical non-zoned system. The criteria used for comparison are the electricity consumption and the comfort level provided by each of them. Thus, this section will be divided into different parts: the sizing of the heat pump, the evolution of the zone air temperatures in a typical winter day, the analysis of the comfort levels provided and finally, the comparison of the associated electricity consumption.

Influence of the thermal zoning in the sizing of the heat pump

The calculation of thermal loads in the house in each city is done with the user comfort range between 22°C and 24°C. In a non-zoned system, the distribution network has no element that allows the system to deal separately with the needs of each zone. Therefore, to guarantee the possibility of meeting peak loads in all zones, the performance rating of the unit must be greater than the sum of the peak sensible loads of the zones, even if they are not simultaneous. On the other hand, in a zoned system, the distribution network has motorized dampers that allows to adjust the thermal contribution of the system to the demand of each zone separately. This means that the unit is sized by considering the maximum simultaneous sensible load of the zones. In other words, for every time step, the loads of all zones are added together, and the unit is sized based on the annual maximum for cooling and heating. Table 4 shows the peak (NZon) and simultaneous (Zon) loads for the three cities, the percentage of thermal load saving in heating (%Heat) and cooling (%Cool) and the abbreviation of the model of the heat pump from a common manufacturer [11,12].

Table 4 Thermal loads of each city and heat pump model sized.

City	Malaga		Paris		Milan	
System	Zon	NZon	Zon	NZon	Zon	NZon
Qheat (kW)	3.5	4.5	7.3	8.0	8.1	8.8
Qcool(kW)	4.2	5.3	2.5	4.0	3.9	4.8
% Heat	22.2		9.3		8.0	
% Cool	20.8		37.0		18.8	
Heat Pump model	Q005	Q007	GA06	GA08	Q011	Q011

It should be noted that the sizing of the unit according to the simultaneous loads, allow to install a heat pump with a lower capacity than the typical peak load sizing procedure in Malaga and Paris, but not in Milan. From experience, as the weather is colder, the influence of thermal zoning in heating season is lower in this aspect. This is because, when a zone is not in demand or there are no people in it, the load of the zone increases and, when it is activated, the unit should meet a higher accumulated load. This effect has more influence in colder climates where the difference between the peak and simultaneous load is not very high.

Thermal Comfort Evaluation.

Firstly, the operation and performance of both control systems for the living room (LR), office (OF) and parents' room (PR) is analysed in a typical winter day, the 8th of February, in Paris (Figure 6). The simulation time step is one minute, the same as that of the operation of the control system.

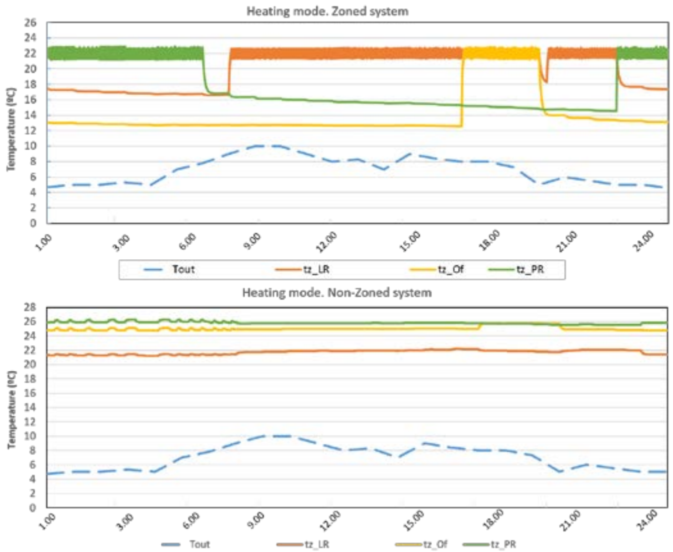

Figure 6 Zoned and non-zoned system performance during a typical winter day in Paris (8th February).

Figure 6 depicts the influence of the thermal zoning in the thermal behaviour of the zones. The zoned system (upper graph) shows how all the zones are in thermal comfort in the time range of the occupational profile, while the rest of time, the evolution of the temperature is not maintained within the comfort dead-band. For example, the parents' room is comfortable from 23:00 to 7:00, but the rest of the day the temperature decreases around 15-16ºC. The office is only in demand from 17:00 to 20:00, and the living room is occupied during daytime hours, both in thermal comfort during these periods.

On the other hand, the comparison with the non-zoned system is very interesting (lower graph). The evolution of the temperature in the living room is very stable, around the set point of 22ºC, but it can be seen how the temperatures of the office and parents' room are higher, from 24.5-26ºC during all the day. Therefore, overheating occurs in these zones with the consequent thermal discomfort of the users.

From this analysis, a more detailed comfort analysis is evaluated in each zone. As comfort indicators, the Predicted Percentage of Dissatisfied (PPD) and the Predicted Mean Vote (PMV) are used according to the ISO 7730 standard [18]. The design criteria for a standing or relaxed person wearing typical winter and summer indoor clothing is considered. According to this standard, the comfort categories are presented as follows:

- Category A: PPD <6% and PMV between -0.2 and 0.2.
- Category B: PPD<10% and PMV between -0.5 and 0.5.
- Category C: PPD<15% and PMV between -0.7 and 0.7.

Tables 5 and 6 show a summary of thermal comfort results using the percentage of hours that the corresponding zone obtains PPD and PMV values according to the categories presented. The cooling season for the warmest climate of Malaga, and the heating season for Paris have been chosen as representative sample, with the analysis of the living room, kitchen and children's room.

Table 5 Thermal comfort analysis in Málaga (cooling season).

Zone	Living Room		Kitchen		Children's Room	
System	Zon	NZon	Zon	NZon	Zon	NZon
Category A	48.1	27.6	72.7	17.0	40.3	28.1
Category B	38.5	24.5	26.6	43.0	46.2	17.2
Category C	3.6	5.4	0.6	25.5	3.7	12.1
Disconfort	9.8	42.5	0.1	14.5	9.8	42.7

Table 6 Thermal comfort analysis in Paris (heating season).

Zone	Living Room		Kitchen		Children Room	
System	Zon	NZon	Zon	NZon	Zon	NZon
Category A	0.0	31.8	0.0	9.6	0.0	1.6
Category B	68.4	28.9	40.4	25.5	80.7	3.0
Category C	26.8	16.6	37.5	28.6	17.7	5.8
Disconfort	4.8	22.6	22.1	36.3	1.5	89.6

Nowadays, the comfort requirements in buildings are very demanding. In the non-residential sector, a minimum of category B is usually expected, but in residential sector category C is accepted. Then, in a first general analysis, the results of tables 5 and 6 confirm the conclusions presented in figure 6, where the master zone, the living room, is in comfort, but the not controlled areas are overheated 2-3ºC over the upper limit of the comfort dead-band. From this more detailed analysis, high percentages of hours in thermal discomfort can be observed in Paris when using a non-zoned system up to 36.3% in the kitchen and 89.6% in the children's room. While in the living room, the hours in thermal discomfort are about 22%. In contrast, the zoned system ensures a high percentage in thermal comfort higher than 80% in all the zones for categories A and B. With respect to the cooling season, the conclusions are similar, but it is interesting to discuss the 42.5% of discomfort hours caused by undercooling in the living room, being the master zone for the non-zoned system. The summer in Malaga is not very hot. In a typical summer day, the temperature is around 28-30ºC with a high humidity content, but this only occurs during the months of July and August. If the temporal evolution of the PPD and PMV values are analysed, it should be noted that the deviation from the comfort zone is carried out in the months of May, June or September, when the heat pump operates in part load performance. This situation confirms the advantages of the sizing procedure with simultaneous loads in the zoned system, which can adapt the power of the unit to the needs of the zones.

Energy consumption

To complete the evaluation, it is important to compare both control systems by analysing the energy consumption which includes the electrical consumption of the heat pump and the motor of the fans. Figure 7 presents a comparison in terms of the total energy consumption of the building and the energy savings obtained with the zoned system.

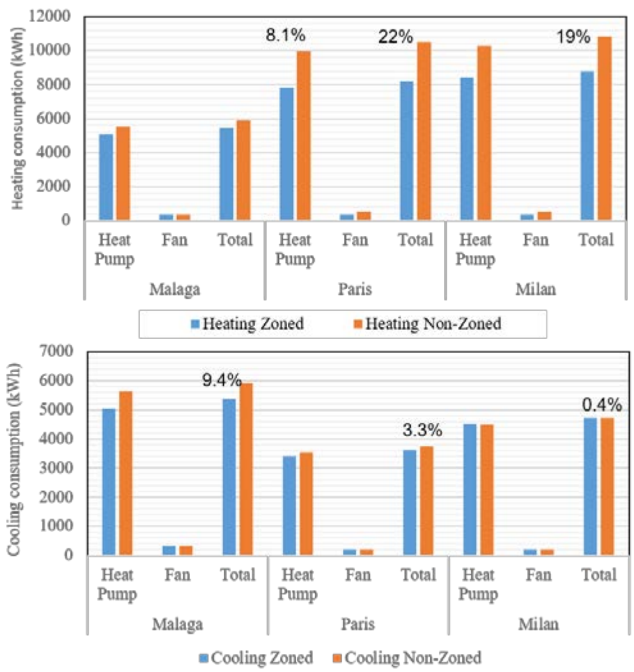

Figure 7 Comparison of energy consumption in each city for heating and cooling seasons.

In all cases the heat pump consumption, which is the most important, is reduced when a zoned system is installed. Thus, energy savings are achieved in the three cities under study. In heating mode, remarkable energy savings between 19-22% in Milan and Paris are obtained., where the total energy consumption is important. Regarding the cooling zone, a 9.4% of energy savings in Malaga is achieved but it is not so significant in Paris and Milan, although the energy consumption in this season is lower.

CONCLUSION

In this study, a new model of an air to water heat pump with a ducted fan-coil with a zoned control system is developed using available energy analysis software. The advantages and benefits of the zoned control system have been presented in terms of energy consumption and thermal comfort when compared to a non-zoned system, in a residential building, and under different climatic conditions. The main conclusions are:

1. When the heat pump is sized, it can be observed that the zoned control system reduces the thermal energy the unit must provide to meet the thermal load of the zones. In warmer climates the thermal savings are more significant and then, a heat pump with a lower capacity can be installed.
2. The zoned system improves the thermal comfort of the building compared with a non-zoned system. The zoned system adjusts the supply airflow rate to the zones according to their thermal requirements avoiding overheating/overcooling in the zones that can occur when the non-zoned system is operating. Then, using a zoned control system guarantees to achieve the best comfort categories most of the time in all zones, while a non-zoned control system can only assure to reach comfort conditions in the master zone.
3. High energy savings are achieved in all the cities because of the regulation of the fan-coil fan speed and the Tw_{set} of the heat pump according to the thermal requirements of the building, thanks to the communication gateway. It is highlighted a 19-22% of savings in energy consumption for heating application in Paris and Milan.

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