A CONTROL MODEL TO OPTIMIZE THE PERFORMANCE OF A RADIANT FLOOR WITH A ZONED DUCTED FANCOIL

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ABSTRACT

Nowadays, aerothermal energy has been promoted as a low carbon solution in the residential sector as the main option for covering domestic hot water (DHW) and heating and air conditioning needs. Radiators, radiant floors (RF) and fancoils (FC) are the terminal units commonly used with heat pumps.

The heating RF is widely used because it guarantees thermal comfort and lower energy consumption. However, an important drawback is that due to the high thermal mass of the floor, delays and a high time response with thermal loads changes can occur, leading to higher energy consumption and dissatisfied occupants. On the other hand, in cooling mode, due to the limitation of the floor surface temperature to avoid condensation, in hot and humid climates, the sensible load that can be met is frequently lower than the peak load. Therefore, an auxiliary system must be available to meet the remaining thermal load and the latent load of the zone. In addition, it should be combined with a complementary ventilation system to provide fresh air to the zone and guarantee Indoor Air Quality (IAQ).

As a solution, the RF can be combined with FC, which works with less favourable water temperatures but shorter response times. Nevertheless, the management of these two terminal units is not easy and a control system is needed to ensure the correct performance of both. This paper presents several control strategies for HVAC systems combining an RF with a zoned ducted FC, and with just one water production unit. All of the above is supervised by a single control system. These control strategies optimize the operation of the system in the case of study of a residential dwelling with different climate conditions and compared with a similar HVAC system, configured by an RF for heating mode and individual FCs in each zone for cooling mode. In both cases, an air source heat pump is the thermal production unit. Both systems are modelled and simulated in Trnsys17.

In this way, it is important to make decisions regarding different aspects of the control, e.g., adjusting the water set-point temperature according to the terminal unit that is currently operating or selecting the performance model of the system between operating only with the FC, only with the RF or the combination of both, according to each zone control temperature of the building. The optimization criteria are the reduction of energy consumption, time response of the system and thermal comfort evaluated according to the PPD and PMV indices. Finally, an economic analysis is performed, and the payback period of the control system is calculated.

INTRODUCTION

Nowadays, the EU has admitted that there is an urgent need for a rapid transition to another energy model that would allow Europe to progressively eliminate its dependence on fossil fuels by 2030. To this end, the Commission proposes the REPowerEU plan [1], which will be based on diversifying gas supplies and reducing the dependence on fossil fuels, focusing on energy efficiency in buildings and promoting the heat pump for homes, among others. In European countries such as Spain [2], France [3] and Italy [4], aerothermal energy has been promoted in the decarbonization process of the residential sector as a solution to cover domestic hot water (DHW) and heating and air conditioning needs, replacing solar thermal collectors and conventional direct expansion air conditioning systems, respectively. The aerothermal can be combined with different terminal units: radiators, RF and FC.

Heating RF is widely used in very cold climates, because of its excellent performance for heating in terms of comfort and efficiency [5]. However, in cooling mode, the temperature of the floor is limited by the dew temperature of the room air to avoid condensation of air humidity, which reduces the cooling capacity to about 50 W/m^2 [6]. For this reason, in hot climates, an alternative is to combine it with FCs, which work with less favourable production temperatures, but have a higher cooling capacity and much faster response times to load changes in the zone. However, the combined operation of the two terminal units is not an easy task as it requires a control system to ensure the correct operation of both. In the literature, there are numerous articles on complex RF and FC control systems. Joe et al [7] presented a smart operation strategy based on model predictive control (MPC) to optimize the performance of hydronic radiant floor systems in office buildings, with energy savings from 29-50% when compared with a baseline air delivery system. Tianyi et al [8] applied the duty ratio fuzzy control method (DRFCM) on the electric valve control of a FC for cooling and dehumidifying and they obtained at least 30% energy savings over the conventional control method. Nevertheless, the literature review points out a research gap for the purpose of studying the control of both terminal units combined, particularly in the residential sector. Zarrella et al [9] analysed a cooling RF in an apartment in combination with five different dehumidification devices (being the FC is one of them). Recently, Liu et al. [10] proposed a convection-radiation (RF with FC) system in an office in China. Three operation strategies are compared and the system with an intermittent operation strategy obtained 39% of energy savings compared with a continuous operation strategy.

Currently, in climates with hot summer and cold winter, the configuration composed of a heat pump with RF for heating and individual FC for cooling is widely used in the residential sector. For both systems, a thermostat is installed in each zone that allows handling the thermal needs of each of them individually. As an alternative, a RF with a ducted FC system is presented for both heating and cooling, taking advantage of the benefits of both terminal units by implementing a control system that allows combining their use, considering the thermal zoning in the building, the control of the water production setpoint temperature of the heat pump, the selection of the FC fan speed and the control of the hydraulic valves to optimize the operation of both systems. For this purpose, the system is modelled in Trnsys17 [11] and applied for a residential case study in three cities: Madrid, Paris, and Milan. The results are analysed in terms of thermal comfort and energy consumption. Finally, the economic analysis evaluates if the payback period of the control system proposed is acceptable.

SYSTEM DESCRIPTIONS

The configurations and control of both HVAC systems are described in this section.

RF and zoned ducted FC combined system (Combined mode)

Figure 1 shows the system schematic with the different control elements. The control system consists of two main elements: the zoning control board and the heat pump control board. Both have communication gateways, which, thanks to having the communication protocol with the heat pump and the FC, the FC fan speed or the heat pump water setpoint temperature (HPT) can be controlled.

Both control boards receive information from the thermostats of each zone: zone temperature (T_z), setpoint temperature (T_{setz}) and relative humidity (RH_z), and from this information, the control algorithm establishes the operation of the installation with the configuration of the following elements:

- At the zone level, the control system performs thermal zoning of the building. As each zone has its own thermostat and motorized damper (D), when the air temperature of the zone is in the comfort band, a control signal is sent to the motorized damper of the zone which interrupts the air supply to the zone. In addition, the dampers are closed in unoccupied zones.

- The fan speed (F) is selected based on the number of zones in demand and the number of total zones in the building. Based on this ratio, the fan speed is sequentially changed to meet the appropriate flow rates for each zone.

- The heat pump setpoint temperature (HPT) is determined according to the mandatory operation of the RF or the FC.

- The floor (VS) and/or fan coil (VF) valves can be opened or closed depending on the temperature evolution of the zone prioritizing the operation of each system. The presence of a mixing valve ensures that the water supplied to the RF in cooling mode is not as low as to cause surface condensation. In addition, each radiant floor is controlled by an individual valve which is used to ensure the thermal zoning.

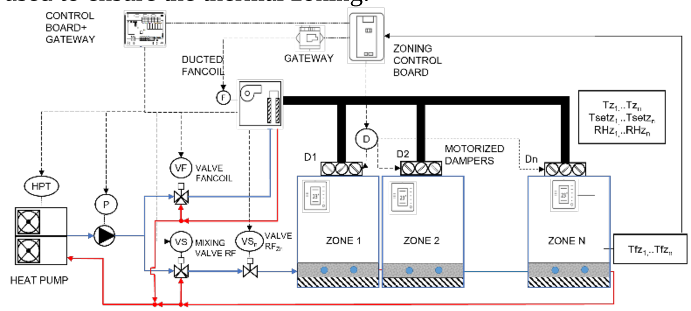

Figure 1 Combined mode system scheme

RF (for heating) and individual FC (for cooling) system

This combined system will be compared with a common configuration in the residential sector, where no control combines both units, but the RF is used for heating and an individual FC in each zone for cooling. In this case, there is no communication gateway to manage the HPT, so the hot/cold water production temperature is fixed. The fan speed of each FC is regulated according to the temperature difference between the zone and the setpoint. In addition, a thermostat is installed in each zone to allow thermal zoning of the building. This is an advanced control system but does not allow the simultaneous combination of both terminal units. Figure 2 shows the scheme of the configuration.

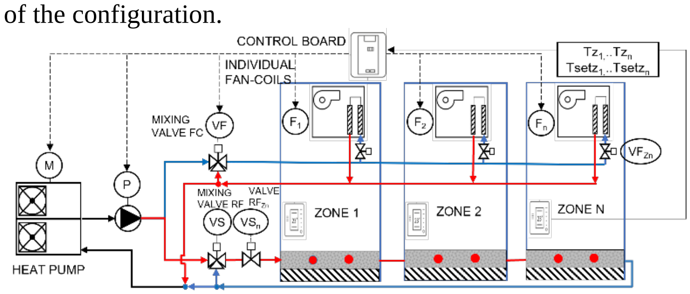

Figure 2 RF and individual FC system scheme.

CONTROL SYSTEM DESCRIPTION

Thermal zoning control 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 comfort band temperature range (typically ±0.5ºC) with respect to the setpoint air temperature. As each zone has its own thermostat and motorized damper, when the zone air temperature is in the comfort 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.

Description of the Combined Mode

The Combined Mode operates to ensure the thermal comfort in the zone, giving priority to the RF and activating the FC when the RF is not yet at the suitable temperature. Fig.2 shows the operation of the system in cooling mode depending on whether it operates as only RF, only FC, or both systems at the same time.

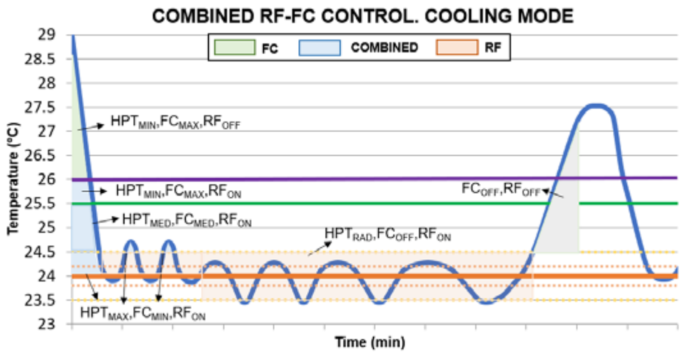

Figure 3 Combined Mode for cooling

Initially, the temperature difference between the ambient and the comfort setpoint is high and the FC is activated, at maximum speed and HPT_{min} (7 ºC). The objective is to bring the air temperature to the comfort zone as fast as possible. It is observed that depending on the temperature differential between the air and the setpoint, the production temperature is modified between 7 and 10 ºC and the fan speed is regulated from maximum to minimum. When the air is 2 ºC above the setpoint temperature, the RF is activated. When the air temperature is in the comfort band, the FC is switched off and only the RF is maintained, since priority is given to the floor to handle the sensible load of the zone, with a constant HPT of 18 ºC.

The same operation process can be applied to the heating mode, as shown in Fig. 3.

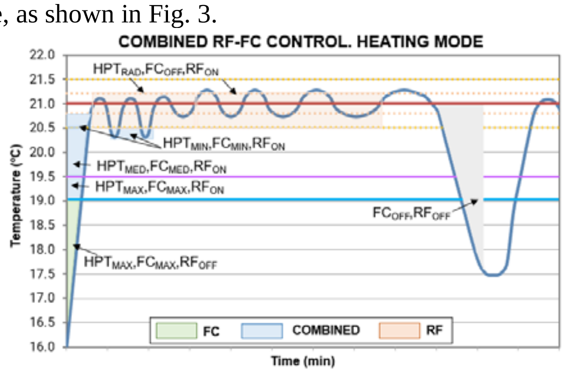

Figure 4 Combined mode for heating

When the zone air temperature is far from the setpoint, only the FC is activated to achieve a rapid increase in the air temperature, and the HPT is set to 45 ºC. As the air temperature rises, the RF is also activated to increase the floor surface temperature as quickly as possible. During this period, the combined system makes the air temperature closer to the set point by regulating the fan speed and decreasing the HPT. When the lower level of the comfort hysteresis is reached, only the RF remains active, and the HPT is fixed at 35 ºC. From this moment, the temperature is maintained with the thermal inertia of the floor and the FC is only turned on again when the temperature goes out of the comfort band.

Description of the Non-Combined system

The RF acts only in heating mode and two options have been evaluated.

- Zoned RF. The water is supplied to each zone only if the zone is in thermal demand. Thus, the energy consumption in the heat pump is conditioned to the amount of water that is heated according to the number of zones in demand, with a heat pump water set point fixed to 35 ºC. The valve of each RF (VS_n) is opened according to the change of the room temperature with respect to the setpoint, similarly to the radiant phase of Fig.3. A typical residential occupational profile is applied. This strategy avoids overheating in the zone and in the floor surface.
- RF always ON. The heat pump is always supplying heated water to each RF with HPT fixed to 35 ºC. All the zones are conditioned all day. This strategy is very favorable to avoid delays in zones, but energy consumption may be compromised with respect to Zoned RF.

The individual FCs are used in cooling mode. The control of each FC fan speed is a traditional on/off strategy with hysteresis and modifies both the fan speed and the HPT according to the difference between the zone air and the setpoint temperatures.

NUMERICAL MODELS

The air-water heat pump model is developed based on the typical set of curves of a manufacturer [12]. These curves provide information about heating and cooling capacity and electric consumption as a function of outside air temperature and the required HPT. The coefficient of performance and energy efficiency ratios are calculated from the capacity and the electric consumption. The fan-coil model is based on the effectiveness-NTU method, and it uses a constant value of efficiency for every speed of the fan. The efficiency can be calculated from the data given in the fan-coil catalogue [12]. The radiant floor was modelled using the component Type 705, available in TRNSYS library. This component uses the finite volume method to model a slab with tubes embedded in it. Trnsys' multizone building model Type 56 is used for the thermal modelling of the dwelling.

CASE OF STUDY

The dwelling under study (Figure 5) 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.

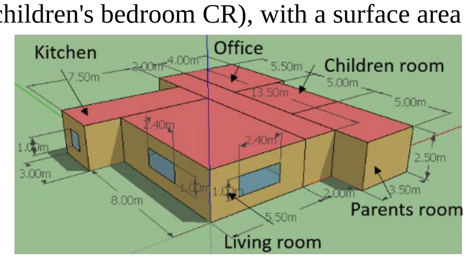

Figure 5. 3D representation of the home**.**

The simulation is carried out in Trnsys 17 for different European cities: Madrid, Paris, and Milano. These three cities have a continental climate, with hot summers and cold winters, with different severity levels. EnergyPlus weather files are used in the simulation.

Enclosures are representative of the different regulations prevailing in each country. Table 1 shows the values considered for the overall heat transfer coefficient of the different enclosures of the dwelling.

Table 1 Threshold U-values.

City	Regulation	Wall	Ceiling	Floor	Window
Madrid	RITE 2019 [13]	0.65	1.1	1.1	2.2
Paris	RT 2012 [14]	0.24	0.66	0.66	1.14
Milano	D.Lgs.192 [15]	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).

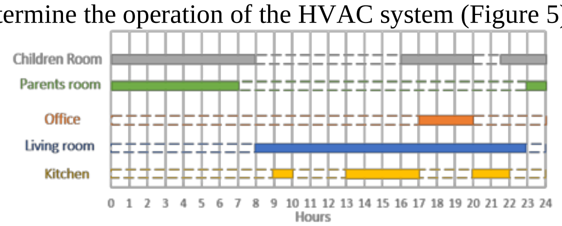

Figure 6 Occupational profile of the house.

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

RESULTS AND DISCUSSION

The objective of this study is to evaluate the benefits of the combined mode with respect to the proposed conventional control. This section will be divided into different parts: the sizing of the heat pump and terminal units, the performance of the systems on a typical winter day, the analysis of the comfort levels provided, and finally, the comparison of the related electricity consumption.

Influence of the control system on the sizing of the HVAC systems

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 this case, a zoned system, the distribution network has motorized dampers that allow adjusting 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. Table 2 shows the simultaneous loads for each city, as well as the heat pump and ducted fan coil selected (based on a manufacturer's model [12]).

Table 2 Heat pump and FC sizing.

City	Madrid	Paris	Milano
Qheat (W)	6849	7248	8106
Qsens,cool (W)	4471	2523	3963
Qtot,cool (W)	5215	3249	4115
Heat pump	EBLQ07CV3	EBLQ07CV3	EBLQ07CV3
Ducted FC	FWM08D	FWM08D	FWM010D

On the other hand, the case study with which it will be compared is also a zoned system, so the sizing of the heat pump in both cases is the same (Table 1). However, in the case of cooling with individual FCs, the sizing should be performed according to the peak load of each zone. According to this, the FWT02 model is selected for all the zones in the three cities except for the kitchen where an FWT04 is needed [12].

Thermal Comfort Evaluation.

Firstly, the performance of the Combined mode (Figure 7) with respect to the Zoned RF (Figure 8) and RF always ON (Figure 9) is analysed on a typical winter day in Milan, for the living room (LR) and children room (CR). The simulation time step is one minute, adapted to the operation of the control system.

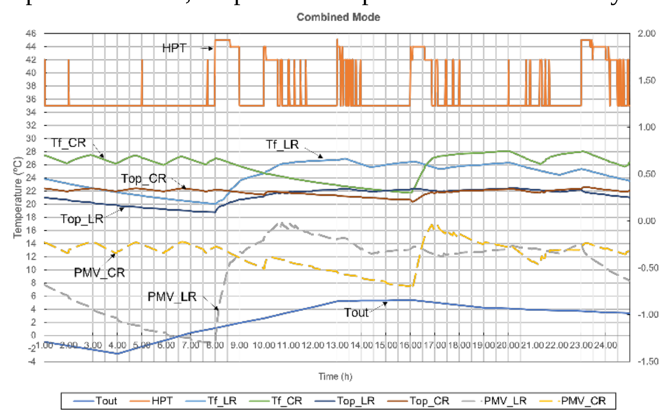

Figure 7 Combined Mode. Milan (Heating)

In the Combined Mode and Zoned RF, the influence of the thermal zoning on the thermal behaviour of the zones is presented. All zones are in thermal comfort in the time range of the occupational profile. Operative temperatures are about 21-23 ºC, and the Predicted Mean Vote (PMV), calculated according to the ISO 7730 standard [16], sets a comfort sensation between slightly warm and cool (PMV between -0.5 and 0.5). The rest of the time, the evolution of the temperature and the PMV is not maintained within the comfort band. However, in the Zoned RF mode, where the RF is activated when the zone is occupied and, due to its thermal inertia, comfort is not achieved until the floor temperature can handle the heating load. While the combined mode avoids this with the FC operation in each zone, which rapidly allows the increase of air temperature to the set point. As it can be seen, the HPT changes from 35 ºC (RF) to 42-45 ºC (FC) when a zone is activated or when a zone needs the FC actuation.

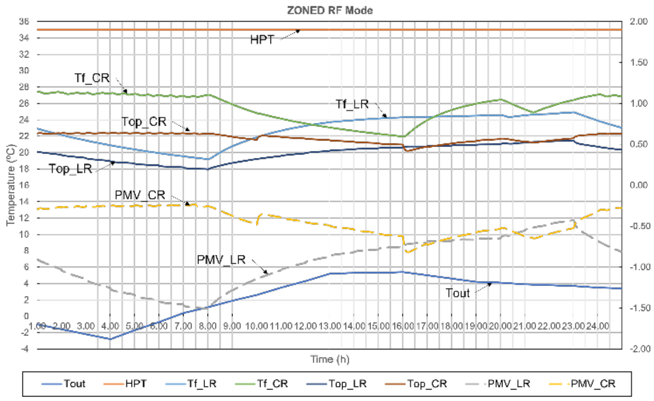

Figure 8 Zoned RF Mode. Milan (Heating)

With respect to the RF Always On mode, it should be noted that the occupational profile is not applied, so the operative temperatures and PMV are very stable around the comfort band. The control system only acts to supply hot water to the zones when the thermal inertia of each RF is not capable of maintaining comfort due to the increase of the heating load in the zone.

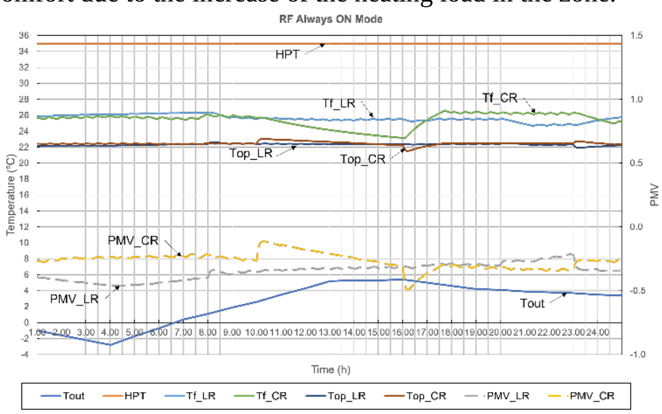

Figure 9 RF always ON Mode. Milan (Heating)

A more detailed comfort analysis is evaluated in each zone. Figure 10 shows a summary of thermal comfort results using the percentage of hours that each of the zones obtains PPD and PMV values according to the comfort categories [16].

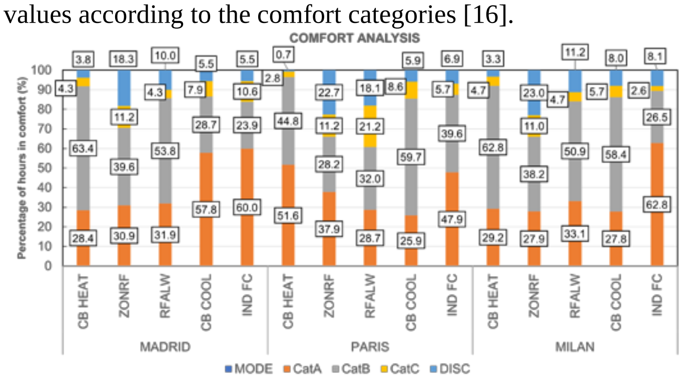

Figure 10 Thermal comfort analysis

Nowadays, comfort requirements in buildings are very demanding, and categories A (PPD<6%) or B (PPD<10%) are expected, especially in efficient and sustainable buildings that obtain BREEAM or LEED certifications [17]. Then, in a first general analysis, the results of Figure 10 confirm the conclusions previously presented. Zoned RF, due to its high characteristic time in the initial period of each zone, presents higher percentages of discomfort (category C and discomfort, from 29-44%). These results are even higher in colder climates, where the mean radiant temperature is lower, and the heat pump works in worse external conditions. In addition, in zones such as the OFF, that is only occupied from 17:00 to 20:00 hours, the accumulated heating load is very high and the characteristic time is increased. The RF always ON mode solves the problem of the ZonedRF at the expense of higher energy consumption and achieves good results of comfort. However, there are some periods of overheating on warmer winter days as it can be observed in the discomfort results from 10 to 18%. The combined mode achieves the best thermal comfort results. The RF is prioritized due to its high thermal inertia and its direct impact on the operating temperature of the zone, and the FC is initially activated to avoid the delay of the RF and to maintain, when it is necessary, the zone air temperature in the comfort band.

Energy consumption

To complete the evaluation, it is important to compare the control systems by analysing the energy consumption which includes the electrical consumption of the heat pump and the fans. Table 3 presents a comparison in terms of the total energy consumption of the building and the energy savings obtained in the combined system (CB) with respect to the Zoned RF (ZRF), RF Always on (RFA) and individual FCs (FCs) systems.

Table 3 Comparison of energy consumption

Mode	System	Madrid	Paris	Milan
Heating	CB	4229	4836	5428
	ZRF	2945	3487	3876
	RFA	3968	4544	5258
Cooling	CB	2797	1146	2289
	FCs	5275	4148	4721
Total savings (%)	%CB-ZRF	14.5	21.6	10.2
	%CB-RFA	24.0	31.2	22.7

As it can be seen, in heating mode, the RFZoned is the most efficient, but the high values of thermal discomfort make that the RFAlways ON mode more convenient because it consumes less than the combined mode, although the differences are only about 6 %. The combined mode can be justified due to the total electric consumption because the energy savings concerning the individual FCs are about 40-45%. The combination of RF and FC improves the performance of the heat pump, and the fan energy consumption of the ducted FC is lower than the sum of the individual FCs case. Therefore, the total energy savings are from 10-31%, which are more favourable in cities with less severe winters.

Economic analysis. Life cycle and payback period

The economic feasibility of the different HVAC configurations considered is evaluated through the calculation of the payback period (PB) of the combined system with respect to the others, which depends on the initial cost (IC) and the operating cost (OC). The initial costs of the heat pump, terminal units (ducted and individual fan coils), air diffusion equipment (dampers and motorization) and zoned control system (control boards, communication gateways) have been obtained from manufacturers catalogues [12,18]. The OC is calculated from energy consumption results (Table 3) and the electricity cost. A conservative value of 0.24 €/kWh is assumed which is recently updated [19]. Table 7 resumes the PB period calculation.

Table 7 Payback period calculation

	System	Madrid	Paris	Milan
IC (€)	CB	9628	8048	9628
	IndFC+RF	8953	7877	9272
OC (€)	CB	1405	1196	1543
	ZRF	1644	1527	1719
	RFA	1849	1738	1996
PB (years)	CB-ZRF	2.8	1.0	1.1
	CB-RFA	1.5	0.3	0.7

Although the initial cost of the combined system is higher in all cases due to the cost of the control system, the reduction of the energy consumption results in a lower operating cost. The payback periods in each city are from 1- 2.8 years with respect to the Zoned RF and from 0.3-1.5 years with respect to the RF always ON. Considering that the lifespan of the different elements of an HVAC installation is around 15 years, thus payback periods obtained are acceptable.

CONCLUSION

This study analyzes the performance of a control system applied to a combined system of zoned ducted FC with RF and it is compared with a system based on an RF for heating and individual FCs for cooling. The case of study is a residential dwelling, and it is evaluated in three different cities with a continental climate, which is very favorable for this HVAC configuration. The combined mode prioritizes the use of the RF as the main unit, taking advantage of the thermal inertia and its capacity of influence in the operative temperature of each zone, and the ducted FC, applying the thermal zoning control, and acting only when the RF is not capable of handling the heating or cooling load or in the initial periods when the temperature of the floor has not reached the stationary regime yet. The main conclusions are:

1. In heating mode, the combined mode is the best in terms of thermal comfort. The Zoned RF mode presents an important percentage of hours of discomfort due to the high characteristic time of the system. The RF always ON mode solves this problem but on winter days with low heating load, overheating in some zones can occur in a climate with less severe winter. In the combined mode, the FC acts when a zone is activated to rapidly increase the air temperature and when the RF is not capable of handling the heating load. In cooling mode, the combined mode is compared with the individual FCs. Both control systems achieve high percentages of thermal comfort.
2. With respect to energy consumption, the combined mode obtains total energy savings from 14 to 31%. The differences are more important in cooling, where the heat pump has a better performance with a high number of hours operating with a HPT of 18 ºC, with respect to 7 ºC of the individual FCs.
3. The payback period in each city is calculated and the combined mode obtains a PB of 1-2.8 years compared to the Zoned RF and from 0.3-1.5 years with respect to the RF always ON.

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