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Influence of different heating systems on thermal comfort perception: a dynamic and CFD analysis

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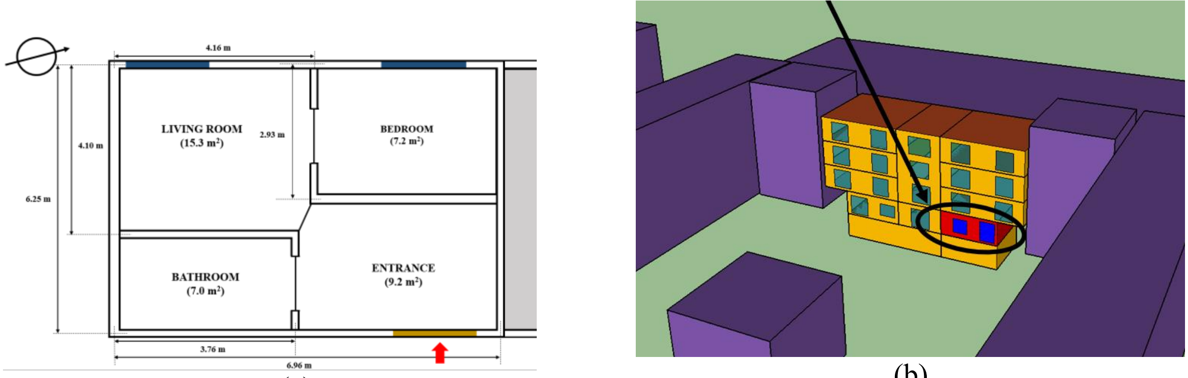
Abstract. In this paper, we investigate the influence of different heating systems on the thermal comfort indexes, Predicted Mean Vote (*PMV*) and Predicted Percentage of Dissatisfied (*PPD*), for a residential apartment located in Bologna (Italy). The apartment has an area of 40 m^2 and is located on the ground floor of 4 floors building. The envelop consists in horizontal perforated bricks with internal thermal insulation material and two windows. The analyses are performed employing Trnsys, a commercial dynamic simulation software and Simcenter STAR-CCM+, a multiphysics computational fluid dynamics (CFD) software. The CFD analysis regards a steady condition of a typical winter day in Bologna. Thermal comfort indexes and thermal energy demand are studied comparing two different heating generation systems existing in the considered apartment: a condensing gas boiler coupled with radiators as terminal emitters and an air-to-air heat pump. By crossing the results obtained by the dynamical approach and by the CFD simulations, a two-objective methodology where energy consumption is minimised while thermal comfort is obtained, is presented.

1. Introduction

Nowadays, an important part of greenhouse gas emissions comes from fossil fuels; in particular, in Europe natural gas is widely employed for residential heating [1]. In order to achieve the decarbonization goals [2], a possible solution is the use of electric heat pumps, instead of generators based on fossil fuels, for building heating. According to market data [3], in Europe the most widespread typology of heat pumps employed in residential sector for heating and cooling are air source heat pumps, ASHP. The prevalence of ASHP is related basically to the availability of the air as heat source and to the limited installation cost respect to other types of heat pumps as for example ground source heat pumps [4, 5]; air source heat pumps, on the other hand, are characterized by reduced performances with respect to ground source heat pumps, and their performance strongly depends on weather conditions and frost formation on the external evaporator, as suggested in many papers in the literature [6-8]. The transition towards more sustainable energy sources in building heating, however, should not overlook the importance of thermal comfort and indoor air quality. Ballerini et al. presented an economic analysis comparing gas boilers and heat pumps as generators for building heating [9]. The aim of the present paper is to complement the analysis presented in [9] by taking into account the comfort analysis. According to the ISO standard 7730 definition [10], thermal comfort is the "condition of mind which expresses satisfaction with the thermal environment". The predicted mean vote *PMV* and the associated predicted percentage of dissatisfied *PPD* indexes, developed by Fanger [11], are widely used to evaluate indoor thermal comfort in moderate environments. Aqilah N. et al. propose a review on thermal comfort in residential building [12]. Their findings show that an adaptive thermal comfort model, which will improve both the comfort requirements and the building energy performance, is still required. Several researchers focus their attention on the optimization of thermal comfort perception within residential environments and many of them uses CFD as a powerful tool to predict thermal comfort, as well as to simulate the behavior of screens on glass facades [13]. Concerning thermal comfort, Usman et al. [14], propose the CFD analysis of thermal comfort in a house under natural and mechanical ventilation. Results show how *PMV* values are improved when ceiling fan coil units are used. In the present paper the dynamic and CFD analyses concerning the comfort perception and building thermal energy demand are presented, employing an air-to-air heat pump and a gas boiler as heating generation system, considering a real residential apartment located in Bologna.

2. Setting of the analysis

2.1. Dynamic simulations



(a) (b)

Figure 1 – Layout of the apartment (a); 3D view of the building modeled with Google SketchUp (b).

Table 1 – Transmittances *U* and dimensions (thickness/area) of apartment envelope components.

Component	Thickness (m)	Area (m^2)	U (W/(m^2K))
External walls	0.30	-	0.667
Dividing walls	0.10	-	2.047
Inter-floor	0.42	-	0.595
Entrance door	-	2.43	5.54
Window (bedroom)	-	1.89	1.69
Window (living room)	-	5.94	1.69

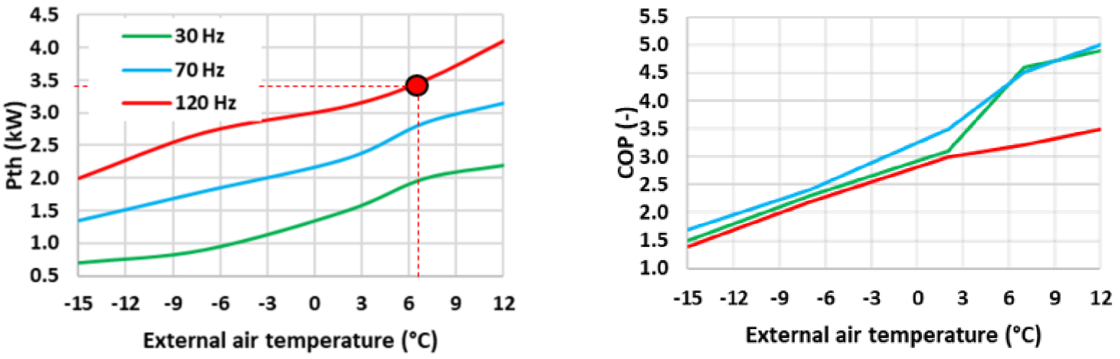
The apartment, modelled through Google Sketch-up [15] and imported in Trnsys [16, 17] employing Trnsys3d plugin [18], displays 4 thermal zones (Figure 1) rather than 3 zones as it really is: in particular the kitchen – living room has been split in two different thermal zones since all the thermal zones must be convex, in order to obtain a detailed calculation of the mean radiant temperature considering the view factors for each zone.

In Table 1 the dimensions and thermophysical characteristics of the main envelope elements are reported; the transmittance values of the main envelope elements (vertical walls and int-floor) are typical of the northern Italian buildings built in years 1970-1990, as reported in [9].

The building has been modelized employing type 56 (multizone building), while the generators have been modelized in two different ways: the gas boiler have been modelized employing type 122 coupled to radiators radiators (types 320 and 362 [19]), while the heat pump has modelized employing two interpolators, in order to determine step-by-step, the Coefficient of performance of the machine (*COP*) and the thermal power output (P_{th}), function of the external air temperature and of the inverter frequency. The performance maps of the *COP* and heat pump thermal power output are reported in Figure 2, for different inverter frequencies. The set-point temperature in the case of radiators is maintained employing thermostatic valves, while, when the heat pump is assumed as the heating generator system, the heat pump thermostat is modelized employing a *PID* (Proportional Integral Derivative) controller.

Four different dynamic simulations have been performed, as reported in Table 2, with the same boundary conditions. In detail, the air change rate of the thermal zones in the apartment is 0.6 h^{-1}, except for the bathroom, where it is 0.8 h^{-1}; in the garage the air change rate is 2 h^{-1}. The air change rate in the garages is higher than in all the other zones because they present large openings to the outside air, while the bathroom presents higher air change rate than other zones of the considered apartment since it is equipped with an extractor fan.

The temperature of the upper apartment, i.e., the only heated boundary zone, has been set to 20°C during the day (6:00 am – 11:00 pm) and 17°C during the night (11:00 pm – 6:00 am). The temperature of the garage and stairwells is determined by the dynamic simulation software: in fact, these two adjacent thermal zones are non-heated zones with respect to the considered apartment.



(a) **(b)**

Figure 2 – Thermal power output (a) and *COP* (b) of the heat pump considered, for three different inverter frequencies and for a fixed indoor air temperature of 20 °C. The red dot indicates the thermal power output at rated conditions (3.5 kW when the indoor air temperature is 20 °C, while the outdoor temperature is 7°C).

Table 2 – Dynamic simulations performed. In case DS1 the emitters are the radiators, while in case DS2, DS3 and DS4 the emitter is the internal unit of the air-to-air heat pump.

Case	Heating generation system	Daily set-point, 6:00 am – 11:00 pm (°C)	Night set-point, 6:00 am – 11:00 pm (°C)	Annual energy demand (kWh)
DS1	Gas boiler	20.5	17.5	3486
DS2	Heat pump	20.5	17.5	2669
DS3	Heat pump	21.5	17.5	2983
DS4	Heat pump	22.5	17.5	3303

In order to determine the ground temperature, typical thermophysical characteristics of the soil in Bologna (conductivity 1.8 W/(mK), density 2800 kg/m^3 and thermal capacity of 0.85 kJ/(kgK)) have been used [20].

The internal gains related to electric equipment and occupancy have been considered according to IAE Task 44 [21], considering a single occupant of the apartment. The latent internal gains (due to occupancy, cooking, equipment and wet surfaces) have been set to be 0.25 kg/h, as prescribed by UNI-TS 11300-1 standard for residential buildings [22]. The coupling air flow between the 4 zones (entrance, living – room, bedroom and bathroom) has been determined employing CONTAM [23], as function of the air density between the zones. The simulation time-step has been set to 15 s and, for all the considered cases, the analysis is restricted to the standard heating period for Bologna (15 October – 14 April).

2.2. CFD analysis

The commercial software STARCCM+ has been used to carry out a CFD analysis. The analysed governing equations consist of the mass (1), momentum (2), and energy (3) balance equations for steady state, incompressible, turbulent flows of an ideal gas, namely:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

$$\rho_0[(\vec{v} \cdot \nabla)\vec{v}] = -\nabla(\mathrm{p} + \rho_0 g z) + \rho_0 g \beta (T - T_0)\nabla \mathrm{z} + \nabla \cdot \tilde{\tau}_{eff} \tag{2}$$

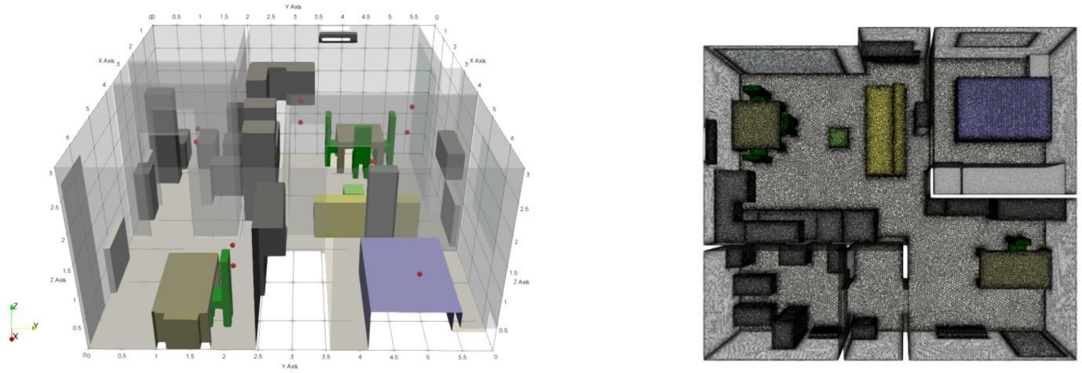
$$\nabla \cdot \left(\vec{v}(\rho e + p)\right) = \nabla \cdot [(k + k_t)\nabla \mathrm{T}] + \tilde{\tau}_{eff} \cdot \vec{v} \tag{3}$$

where $\vec{v}$ is the velocity vector, p is the pressure, β is the thermal expansion coefficient, $\tilde{\tau}_{eff}$ is the effective stress tensor, e is the specific enthalpy, k is the thermal conductivity and k_t the turbulent thermal conductivity.

To accurately account for turbulence anisotropy, the Reynolds Stress Transport (RST) turbulence model, along with the Elliptic Blending near-wall Reynolds-stress turbulence closure, was utilized. The governing equations were discretized into a set of algebraic equations using a second-order upwind scheme, and the pressure-velocity coupling problem was solved using the semi-implicit method for pressure-linked equations (SIMPLE algorithm). The simulation was monitored for convergence by measuring residuals, velocity, and temperature values at various randomly selected points in the room.

A mesh sensitivity analysis was conducted to optimize the computational demand and quality of the results. The final mesh consisted of 9 x 10^6 elements with a base size of 4 cm. A boundary layer was modelled with 5 layers and a total thickness of 5% of the base size. Additionally, surface refinements were necessary for the heat pump internal unit, radiators, and internal furniture. The distribution of furniture within the apartment is shown in Figure 3(a), while Figure 3(b) illustrates the top view of the final mesh on the internal surfaces.

Two different steady state simulations have been performed to compare the two different heating systems equipped in the apartment during a typical winter day in Bologna. An external temperature of 6.9 °C has been prescribed. The ceiling, floor and internal wall (adjacent to the stairs hall) display a temperature of 20 °C, 10 °C and 12 °C respectively. The heat pump internal unit is composed by an inlet section where a fixed velocity inlet boundary condition is imposed of 2.4 m/s, according to experimental data, with a discharging angle of 45° with respect to the ceiling and an outlet section where a pressure outlet boundary condition is applied. Radiators, instead, are modelled as heat sources, obtaining a surface temperature of 60 °C. The parameters obtained by the simulations have been used to evaluate the global thermal comfort indexes *PMV* and associated *PPD* within the apartment.



(a) (b)

Figure 3 – Furniture layout (a) and top view of the internal mesh (b).

3. Results

3.1 Dynamic analysis results

In the last column of Table 2 the results of the dynamic simulations for cases DS1 – DS4 are reported. The results clearly show the difference in thermal energy demand of the building in the case of radiators and heat pump. In Figure 4, the PMV and PPD are shown for a representative day of the heating season that presents a mean outdoor temperature is 6.9 °C. The comfort indexes have been calculated considering a fixed air velocity of 0.1 m/s, a clothing factor of 1.1 clo and a metabolic rate of 1.1 Met. In particular, in Figure 4 the red line refers to the case when the gas boiler coupled to radiators as heating system are considered, while the other three lines refers to the cases when the air-to-air heat pump is considered, with three different air set-points.

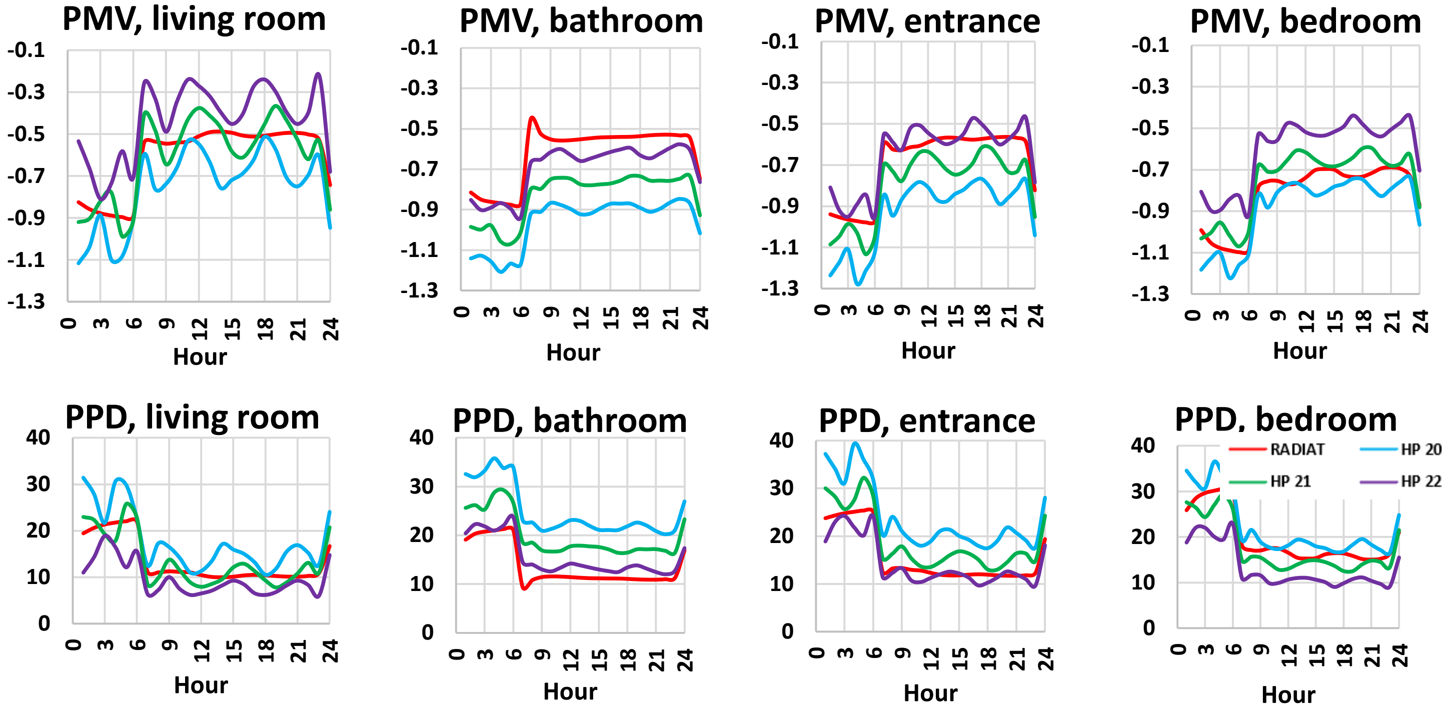


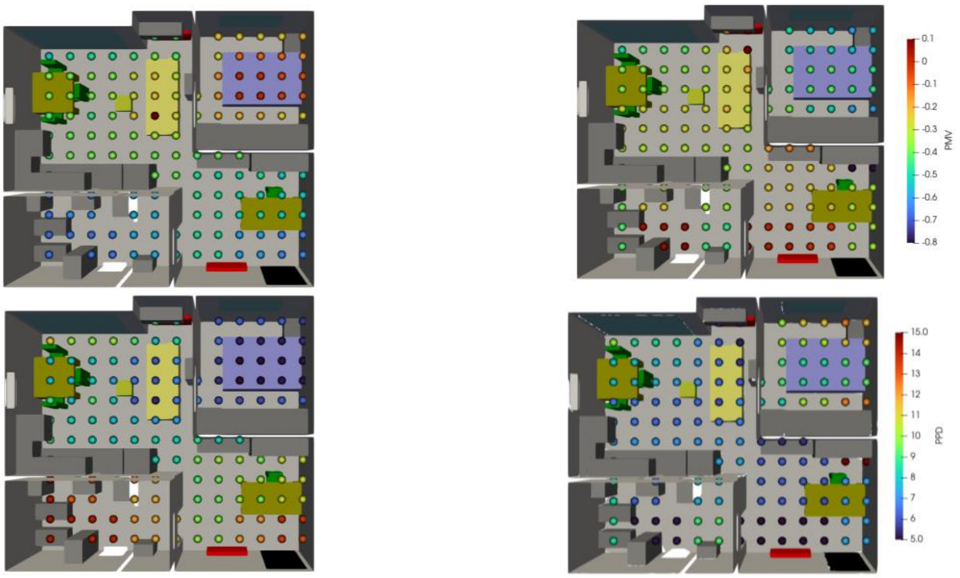
Figure 4 – *PMV* and *PPD* for a day of the heating season, with mean outdoor temperature 6.9 °C.

3.2 CFD analysis results

Figure 5 shows the *PMV* and *PPD* distribution obtained within the apartment through the numerical simulation for both heating systems. It can be noted how the choice of the system lead to different distribution of the thermal comfort parameters. As the matter of facts, the distribution of the relevant parameters for the evaluation of the PMV index significantly differs among the two configurations. As shown in Figure 6, the streamlines associated to the heat pump follows the discharging angle of 45° reaching the sofa zone, and then, under the buoyancy effect, tends to go upwards and enters the bedroom. As a result, less hot air is delivered to the bathroom and entrance, leading to lower degrees of comfort in these areas. The situation changes when using the radiators as emitters since they improve the mean radiant temperature distribution throughout the apartment, resulting in a different comfort situation.

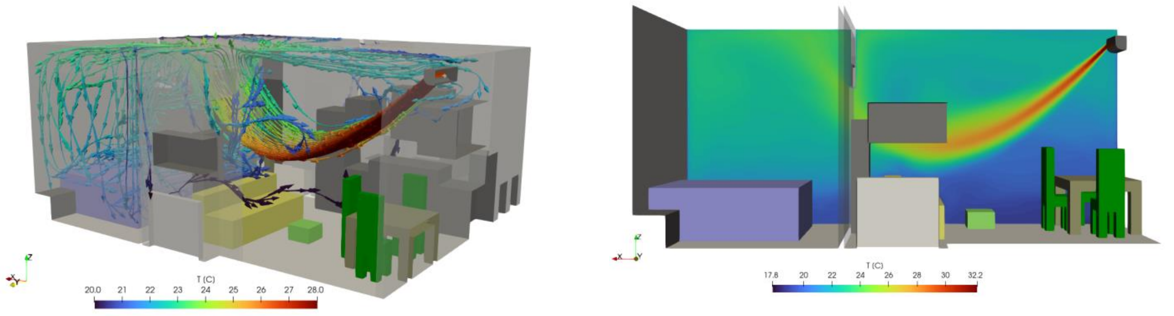
4. Discussion

Table 2 presents an important reduction of thermal energy demand in the case of a heat pump as a generator, instead of a gas boiler: the reduction for case DS2 with respect to case DS1 is 23 %, while there is a similar energy demand in cases DS1 and DS4, but in this latter case the heat pump has a set-point temperature of 22 °C during the day. The different thermal energy demand between the two different heating systems is primarily due to the fact that the heat given by the heat pump is purely convective, while the heat coming from radiators is partly convective and party radiative.



(**a**) (**b**)

Figure 5 – Top view of *PMV* (upper figures) and *PPD* (lower figures) distribution for heat pump (a) and radiators (b).



(**a**) (**b**)

Figure 6 – Streamlines of the heat pump discharged air (**a**) and temperature profile (**b**) along a section in correspondence of the heat pump internal unit.

The use of the heat pump instead of the gas boiler results advantageous in terms of energy savings, but affects the comfort in the apartment, as shown in Figure 4: in particular, it can be noticed that the *PPD* is higher for the case DS2 (heat pump with a set-point of 20 °C during the day) in all the zones except the bedroom that has no radiators. It can also be observed that *PPD* are comparable only in cases DS1 and DS4 in almost all the thermal zones: therefore, the heat pump can guarantee the comfort given by the gas boiler coupled with radiators only with a set-point of 22 °C. Moreover, the analysis on comfort indexed referring to the coldest day of the heating season, with mean outdoor temperature –4 °C, highlights an important reduction of comfort indexes, especially for the heat pump cases: for example, the *PPD* is up to 50 % in bedroom, entrance and bathroom for case DS1; in case DS4 the *PPD* results slightly lower (5-10 %) with respect to case DS1 only for bedroom and living room. In terms of comfort index, the most important difference between case DS1 and the other cases is the mean radiant temperature: in the representative day of the heating season characterized by a mean outdoor temperature of 6.9 °C, the difference in mean radiant temperature calculated in the thermal zones is about 1-2 K, i.e., in the case DS1 the mean radiant temperature is always higher than in the heat pump cases. This aspect become more relevant considering the coldest day of the heating season, when the mean radiant temperature for all the zones referring to case DS1 is higher up to 3 °C. The CFD analysis reveals differences in the levels of comfort achievable with the two heating systems. For instance, the use of the heat pump results in nearly zero *PMV* values in the bedroom, whereas low *PMV* values are observed in both the bathroom and the entrance (Figure 5(a)). Furthermore, the high velocity and temperature of the discharged air from the heat pump can create discomfort zones, with hot thermal plumes reaching the sofa, placed in the living room. In contrast, the use of radiators leads to a more uniform distribution of *PMV* throughout the apartment. This is due to the positioning of the terminals, which results in higher *PMV* values in both the bathroom and the entrance compared to the heat pump heating mode. However, this improvement comes at the expense of thermal comfort in the bedroom, where *PMV* values are significantly lower due to the absence of a radiator and the presence of a huge window.

5. Conclusion

In conclusion, the main results of the present analysis are the following:

- The air-to-air heat pump as alternative to gas boiler leads to important savings in terms of thermal energy demand of the building (up to 23 %)
- As determined by dynamic simulation, the comfort perception inside the considered apartment is worse in case of heat pump instead of gas boiler coupled with radiators, especially during the colder days of the heating season

- The poorer comfort indexes, particularly on colder days, are due principally to the reduced mean radiant temperature determined using the heat pump instead of the radiators.
- As shown by the CFD analysis, while the air-to-air heat pump system can provide satisfactory *PMV* values in the living room and the bedroom, it cannot meet the thermal requirements of the bathroom and entrance areas. Additionally, due to the high velocity and temperature of the discharged air, local discomfort may be experienced by occupants. To improve the overall thermal comfort throughout the apartment, the internal unit's position could be changed, or a supporting unit could be added to address the areas with lower *PMV* values.
- The CFD simulation shows radiators can provide a more comfortable experience for occupants due to the uniform distribution of internal thermal parameters within the apartment.

Further analyses will focus on the integration of the dynamic and CFD results with experimental measurements to evidence the influence of certain dynamic parameters on the simulation results.

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