ORIGINAL ARTICLE

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Energy analysis based on dynamic simulation of industrial heating by radiant modules with condensing unit

Analisi energetica basata sulla simulazione dinamica del riscaldamento industriale mediante moduli radianti con unità di condensazione

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Abstract

Industrial buildings are characterized by large dimension of the air-conditioned volume with respect to the occupied volume. This is mainly due to great heights and areas. Usually, industrial buildings are heated only. Radiant heating systems are particularly suitable for this kind of buildings, furthermore air systems are largely used as well. This paper reports on the dynamic simulation of a real industrial building coupled with an innovative condensing radiant heating system. A Trnsys type is modified in order to simulate the behavior of the high temperature condensing system. Energy performance is compared to that of two more traditional plants such as warm air heater and low temperature radiant floor coupled to condensing boiler. A comparison from the indoor thermal comfort point of view is reported as well.

Keywords:

- Radiant system
- Condensing unit
- Industrial heating
- Energy efficiency
- Air heater

Sommario

L'ambiente industriale è caratterizzato da grandi dimensioni del volume climatizzato rispetto al volume occupato, a causa delle elevate dimensioni in pianta e altezze. Si tratta di ambienti che di solito presentano il solo riscaldamento invernale. I sistemi di riscaldamento radianti sono particolarmente adatti a questo tipo di ambienti, ma sono molto utilizzati anche i sistemi di riscaldamento ad aria. Scopo di questo lavoro è, attraverso la simulazione dinamica di un edificio industriale reale e del relativo impianto, valutare le prestazioni energetiche in riscaldamento di un innovativo impianto a nastri radianti a condensazione, a confronto con due soluzioni basate su generatori di aria calda a basamento e pavimento radiante accoppiato con caldaia a condensazione. Viene svolto anche un confronto basato sulle condizioni di comfort interne.

Parole chiave:

- Sistema radiante
- Unità di condensazione
- Riscaldamento industriale
- Efficienza energetica
- Aerotermo

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Introduction

Traditional heating, ventilation and air conditioning (HVAC) plants are not commonly used in industrial buildings. These have different characteristics with respect to residential or commercial ones, such as higher heights (till more than 8 m), the presence of equipment on the walls or ceiling (bridge cranes, pipes and tubes, etc.), very big doors often opened, very large floor surfaces with different kind of occupation by workers, usually scarce thermal insulation, and different comfort condition requests (Lazzarin, 2002). For such reasons, two main types of heating systems are largely diffused for industrial heating: air heater systems and radiant systems. The former are installed in the form of ground or wall-mounted air heaters fueled by natural gas, wall-mounted air heaters supplied by hot water, and controlled mechanical ventilation plants (Lazzarin, 2002).

Radiant systems are characterized by the temperature of the radiant surface. Concerning the high temperature ones, many solutions are on the market since many years: modular systems equipped with small gas burners (radiant tubes), panels heated by steam or pressurized water, electrical radiant systems (Brunello et al., 2001) (De Carli and Polito, 2010). The advantages of high temperature radiant systems are related to their main heat transfer mode (i.e. radiation), so to the possibility of reducing the air temperature required for comfort conditions and addressing the heat flux towards the zone of interest. As a matter of fact, work is still needed on the design of these systems and on evaluating the energy performance and comfort conditions (Brunello et al., 2002) (D'Ambrosio Alfano, 2010).

Heating floor systems find some utilization also in industrial buildings, even if their application is not considered advisable (Lazzarin, 2002). The fact is that the heating floor is usually built up before the final plant lay out is known. Consequently, wide areas of the floor might result covered by machineries with modest heating ability. Another possibility is that warehouses are uselessly heated.

More recently, an innovative condensing radiant tubes (CRT) system is available on the market. In this system, the exhaust from the tubes is coupled to a condensing heat exchanger to produce hot water that feeds a wall-mounted air heater, thus enhancing the thermal efficiency of the radiant tubes. In this paper, energy performance and comfort conditions featured by such a system applied in a real industrial building located in the North-West of Italy are evaluated by means of dynamic simulations by using Trnsys rel. 17 software. The study is carried on firstly by simulating a typical industrial building in order to calculate the annual heating load. Successively, the innovative condensing radiant tubes system is modelled, and energy performance and indoor thermal comfort conditions are evaluated. Finally, two alternative heating systems are studied as benchmark: an air heater based system (Air), and a radiant floor coupled to a condensing boiler plant (condensing radiant floor, CRF). As a variety of real situations are present, the thermal efficiency of generators is considered varying in suitable ranges in order to take into account both modern and old plants for both Air and CRF system.

Methods

Building modelling

The industrial building (type of use E.8 by the Italian decree DPR 412/93) is located in the province of Cuneo (North-West of Italy), latitude 44°36' N, altitude 404 m a.s.l., 2814 degree days (climatic zone E). The heating period is from 15th September till 30th April. The thermal trasmittances expressed in $Wm^{-2}K^{-1}$ are: 0.389 for external wall, 0.128 for floor facing ground, 4.086 for ceiling, 0.208 for ceiling shed, 5.0 for windows.

The building is divided into two thermal zones whose main characteristics are reported in Table 1. The heating plant is supposed to be in operation from 6.00 am till 6.00 pm with an air infiltration of 0.5 vol h^{-1}, whereas the presence of people (degree of activity and clothing: 40 persons in zone 1, 8 persons in zone 2, 2 met, 1 clo) and lighting scheduling (heating gain fixed at 5 Wm^{-2}) are fixed from 8.00 am till 6.00 pm.

Table 1 – Thermal zones of the building

Tabella 1 – Zone termiche dell'edificio

	Thermal zone 1	Thermal zone 2
Floor area (m²)	7119	716.5
Net height (m)	8.24	8.22
Indoor air temp. (°C)	18	18
Net volume (m³)	58669	5886.2

The dynamic simulation of the building with a 0.25 h time step allows to calculate the heating loads (Figure 1). The thermal power of the heating generators is limited to 1500 kW and 100 kW for thermal zone 1 and 2 respectively, as to be consistent with the installed power in the real building by the condensing radiant tubes' manufacturer.

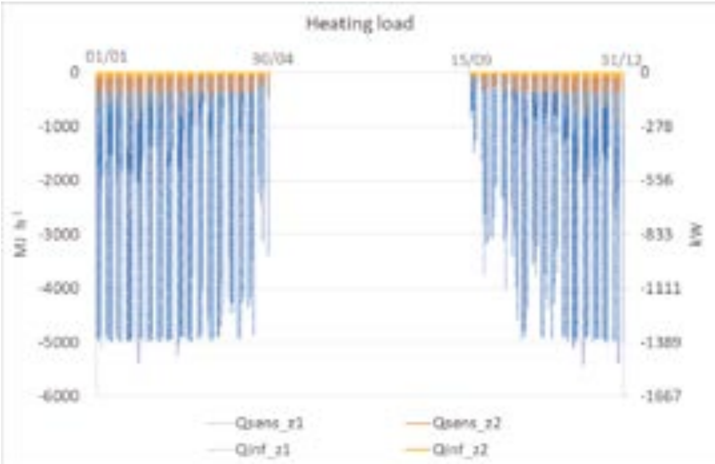

Figure 1 – Heating loads for the two thermal zones (sensible and due to infiltration of outdoor air)

Figura 1 – Carichi termici di riscaldamento (sensibile e dovuto alle infiltrazioni d'aria esterna) delle due zone termiche

Modelling of the CRT, Air and CRF systems

CRT are set up by a radiant tubes system coupled to a condensing heat exchanger that recovers the condensing heat of the exhaust to produce hot water (at around 50 °C) by means a wall-mounted air heater. An exhaust tab controls the combustion air flow rate by recirculating part of the exhaust (G_{rec}) to keep the air excess at the minimum value at part load operation (i.e. when natural gas fuel is regulated by a proportional valve, Figure 2).

The Trnsys types 607 and 659 have been modified in order to simulate the behavior of the high temperature radiant tube system, considering both the radiative and the convective heat exchanges. Moreover, suitable baffles applied in the upper part are considered in order to reduce convection and consequent thermal stratification. The CRT burner turns on at maximum power in order to get the maximum exhaust temperature. As indoor air temperature approaches the set-point, thermal power by the CRT burner is modulated by controlling the natural gas proportional valve in order to have the

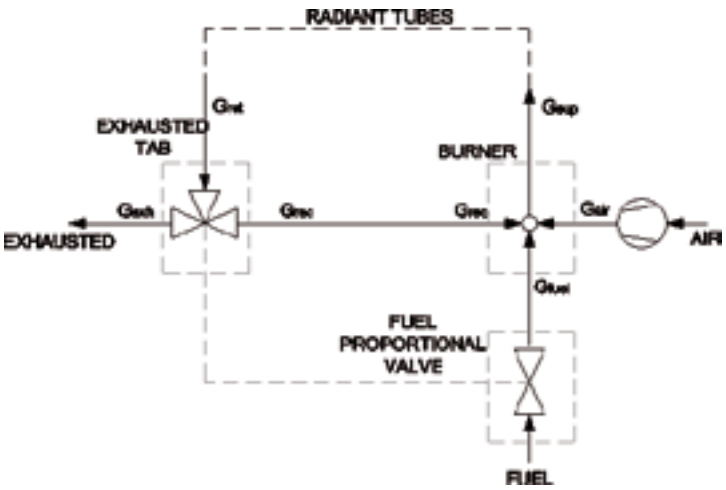

Figure 2 – Mass flow balance for the condensing radiant tube

Figura 2 – Bilancio di portata di massa per il nastro radiante a condensazione

suitable fuel mass flow rate (G_{fuel}) to produce the heating load requested at that time step (P_{heat_load}):

$$G_{fuel} = \frac{P_{heat\_load}}{\eta_{th,HHV} \cdot HHV_{NG}} \tag{1}$$

In Eq. 1, $\eta_{th,HHV}$ is the system's thermal efficiency based on the high heating value of natural gas (HHV = 39 MJ Sm^{-3}) (Figure 3). The fuel modulation decreases the exhaust temperature, and the exhaust tab is regulated in order to have the correct minimum air excess in the burner (Figure 3).

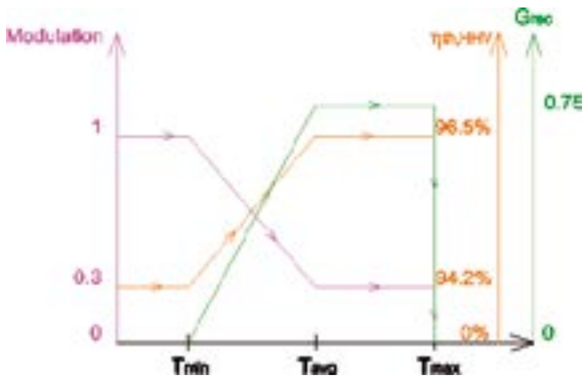

Figure 3 – Control logic of the natural gas proportional valve (purple) and the exhaust tab (green). G_{rec} is expressed in terms of fraction of the radiant tubes return flow (G_{ret} in Figure 2). Thermal efficiency (on HHV) vs modulation is reported as well (orange). In the simulations the hypotheses are T_{min} = 17 °C, T_{avg} = 17.5 °C, T_{max} = 18 °C

Figura 3 – Logica di controllo della valvola proporzionale gas (viola) e della serranda fumi (verde). G_{rec} è espressa come frazione della portata di ritorno del nastro radiante (G_{ret} di Figura 2). Viene riportato anche il valore dell'efficienza termica (rispetto il PCS) in funzione del grado di modulazione (arancione). Nelle simulazioni le ipotesi sono: T_{min} = 17 °C, T_{avg} = 17,5 °C, T_{max} = 18 °C

To evaluate the energy and thermal comfort performance of the CRT system, two alternative heating systems are considered as benchmark. A first solution is a radiant floor coupled to a condensing boiler plant (condensing radiant floor, CRF), the hypotheses considered are:

- distance between tubes 0.3 m, outer diameter and thickness of tubes 0.02 m and 0.002 m;
- radiant floor water flow rate 30 kg h^{-1} m^{-2};
- nominal thermal power of the condensing boiler 1600 kW (equal to the CRT case);
- supply water temperature variable as function of outdoor air temperature;
- thermal efficiency variable as function of the burner modulation (Figure 4a). As previously stated, thermal efficiency is considered varying in different ranges to take into account a more recent generator ($0.90 \le \eta_{th,HHV} \le 0.96$) or an older one ($0.87 \le \eta_{th,HHV} \le 0.93$);

The second benchmark system is a ground air heater system (Air), the hypotheses considered in this case are:

- total nominal thermal power of the ground air heater installed 1600 kW;
- supply air temperature variable as a function of outdoor air temperature;
- thermal efficiency and air flow rate variable as a function of the indoor air temperature as reported in Figure 4b (2 vol h^{-1} is considered the minimum value useful to keep suitable uniformity of indoor air temperature). Again, thermal efficiency is considered varying in different ranges: $0.80 \le \eta_{th,HHV} \le 0.84$ for a more recent generator case, and $0.70 \le \eta_{th,HHV} \le 0.72$ for an older one.

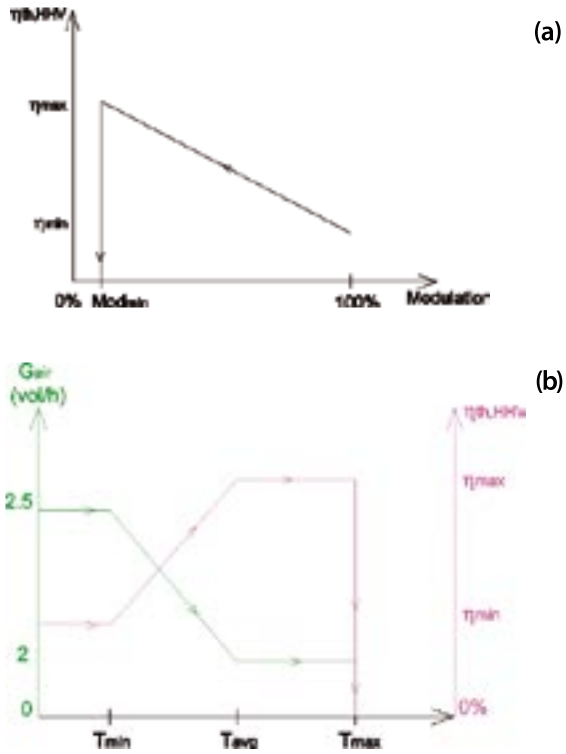

Figure 4 – (a) Condensing radiant floor system: thermal efficiency of the condensing boiler (on HHV) (η_{max} is equal to 0.96 or 0.93, η_{min} is equal to 0.90 or 0.87, Mod_{min} is equal to 0.10 or 0.30 for modern and old generator respectively); (b) Air heater system: thermal efficiency (on HHV, purple) and supply air flow rate (green, in vol h^{-1}) (η_{max} is equal to 0.84 or 0.72, η_{min} is equal to 0.80 or 0.70 for modern and old generator respectively). In the simulations the hypotheses are T_{min} = 17 °C, T_{avg} = 17.5 °C, T_{max} = 18 °C

Figura 4 – (a) Sistema con pavimento radiante e caldaia a condensazione: efficienza termica della caldaia (rispetto il PCS) (η_{max} è uguale a 0,96 o 0,93, η_{min} è uguale a 0,90 o 0,87, Mod_{min} è uguale a 0,10 o 0,30 per un generatore rispettivamente di moderna o vecchia tecnologia); (b) Sistema con generatore di aria calda a basamento: efficienza termica della generatore (rispetto il PCS, viola) e portata di immissione (verde, in vol h^{-1}) (η_{max} è uguale a 0,84 o 0,72, η_{min} è uguale a 0,80 o 0,70 per un generatore rispettivamente di moderna o vecchia tecnologia). Nelle simulazioni le ipotesi sono: T_{min} = 17 °C, T_{avg} = 17,5 °C, T_{max} = 18 °C

Results and discussion

Energy performance analysis

The monthly energy performance of the three heating systems are reported in Figure 5 as primary energy consumption in specific terms

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(per square meter of floor area), and as mean monthly thermal efficiency based on HHV of natural gas. As a matter of fact, the Air system features the worst performance in terms of primary energy consumed, even if considering the modern generator case. The savings allowed by the "condensing solutions" (CRT and CRF) are greater during mild months (from April to October) in relative terms, as the greater distances between their efficiencies and the Air systems efficiencies occur during the period with the lowest heating demand. This is due to the positive characteristic of the condensing heaters to increase their efficiency when operating at partial conditions.

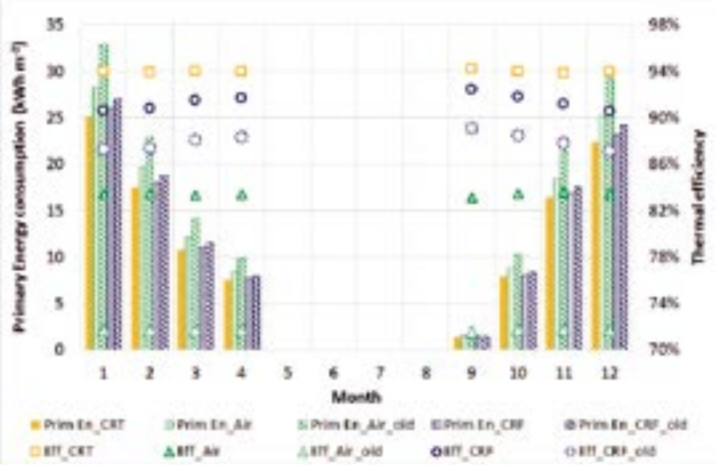

Figure 5 – Specific primary energy consumption and thermal efficiency for the different heating systems

Figura 5 – Consumo specifico di energia primaria ed efficienza termica per i diversi sistemi di riscaldamento

Figure 5 reveals also that the CRT features lower energy consumption with respect to CRF during the coldest months (from December to February, when the heating needs are the greatest), whereas energy performance of the two systems are quite similar during milder months. Obviously, the advantage of the CRT plant is greater when compared with CRF with older boiler.

Figure 6 reports the annual value of the specific primary energy consumption of the different solutions. The innovative condensing radiant tubes system features the best energy performance, allowing a very high primary energy saving (till more than 30%) with respect to the Air system, and a significantly higher energy saving (till more than 7%) with respect to the CRF one.

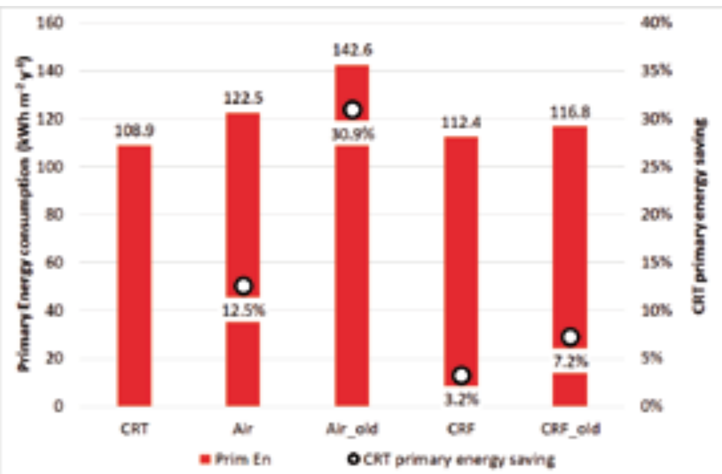

Figure 6 – Annual values of the specific primary energy consumption. Primary energy saving of CRT with respect to the benchmark technologies is reported as well

Figura 6 – Valori annuali del consumo specifico di energia primaria. Viene riportato anche il risparmio di energia primaria del CRT rispetto alle tecnologie di confronto

Indoor thermal comfort analysis

CRT allows view factors around one between the heating tubes and persons on the floor, whereas the presence of production equipment and appliances on the floor can reduce the useful area for the heat exchange in the case of CRF system. Therefore, it is worth to compare the heating systems from the indoor thermal comfort conditions point of view as well.

Such an analysis is carried out on two consecutive days of the heating period (e.g. 24th – 25th January), the former with a lower solar radiation and outdoor air temperature than the latter. Figure 7 reports the indoor air temperature and operative temperature for thermal zone 1 for the CRT and Air systems. For the CRF system, Figure 8 reports the same figures comparing the theoretical case (the whole floor area is available for the heat exchange) with a more realistic case (70% of the floor is available).

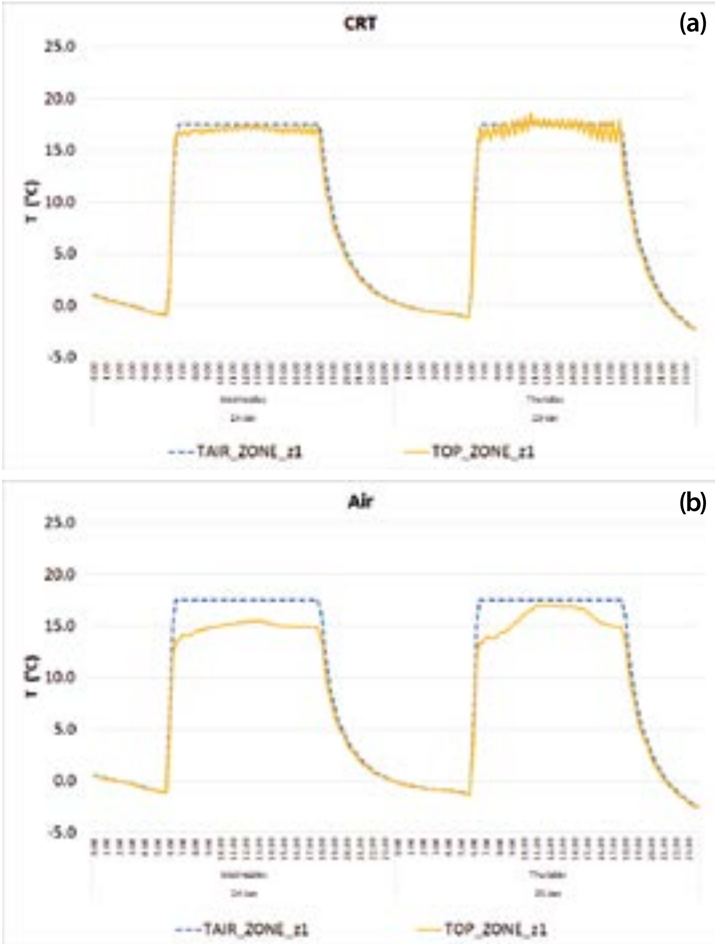

Figure 7 – Indoor air temperature (T_{AIR}) and operative temperature (T_{OP}) for thermal zone 1: (a) CRT system; (b) air heater system

Figura 7 – Temperatura dell'aria interna (T_{AIR}) e temperatura operativa (T_{OP}) per la zona termica 1: (a) Sistema CRT; (b) Sistema con generatore di aria calda a basamento

Even if all the heating systems allow a predicted mean vote between 0 and 0.4 during the occupation time (that is satisfactory thermal comfort conditions useful to classify the indoor environment in class B based on ISO 7730 standard), the operative temperature (continuous orange line) for the CRT plant remains more constant and more similar to the air temperature (blue dotted lines) during the day with respect to the CRF and, above all, to the Air system.

Moreover, the CRT plant allows a greater swiftness of reaching the set-point value at the start of operation (at 6.00 am). As a matter of fact, the CRF system features a lower control capacity of the operative temperature with respect to CRT solution (above all during the second day when the greater solar radiation thermal gains can disturb the control), and a lower decay of air temperature during the night.

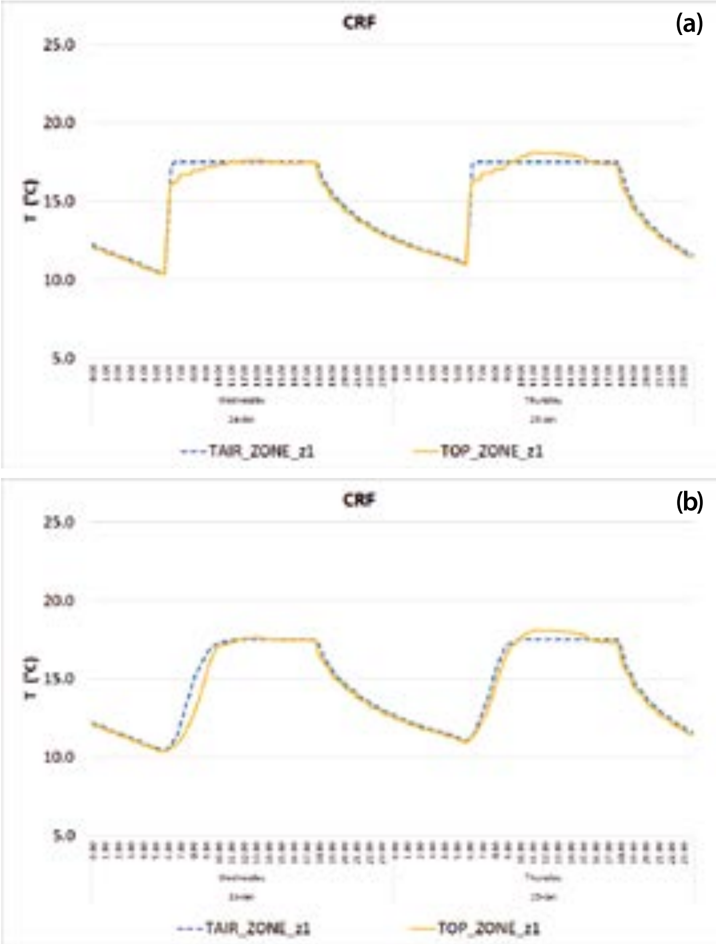

Figure 8 – Indoor air temperature (T_{AIR}) and operative temperature (T_{OP}) for thermal zone 1: (a) CRF system with radiant area equal to the available floor area; (b) with 70% radiant area

Figura 8 – Temperatura dell'aria interna (T_{AIR}) e temperatura operativa (T_{OP}) per la zona termica 1: (a) Sistema CRF con area radiante pari alla superficie del pavimento disponibile; (b) area radiante pari al 70% della superficie del pavimento disponibile

NOMENCLATURE

Symbol	Meaning	Unit
G	Mass flow rate	kg s^{-1}
P	Power	kW
T	Temperature	°C
η	Efficiency	-

Subscripts	Meaning
air	combustion air
avg	average
exh	exhaust
fuel	combustion fuel
heat_load	heating load
HHV	high heating value
min	minimum
max	maximum
NG	natural gas
rec	recirculated
ret	return
sup	supply
th	thermal

This is due to the greater thermal inertia of the condensing radiant floor system. Such a characteristic is even more stressed in case of partial unavailability of the floor area due to occupation by production equipment and when warehouse areas are uselessly heated: in Figure 8b there is an increasing difficulty to guarantee the indoor thermal comfort condition during the start-up of the plant, and the set-point values are reached with a delay of about two hours with respect to Figure 8a. This is also the main cause of the greater primary energy consumption of the CRF plant as previously described, as the condensing boiler has to operate at nominal power for longer.

Conclusions

The comparison of energy performance of three heating systems for an industrial building located in a severe climatic conditions resort allows to find a very interesting primary energy saving of the innovative condensing radiant tubes system up to 30% with respect to a traditional air heater system. Compared to a radiant floor coupled to a condensing boiler, the energy saving is lower but not negligible. Moreover, radiant floor performance in an industrial arrangement is strongly bound on the effective available radiant area, as large fraction of the floor could be occupied by production machinery. In terms of thermal comfort conditions, the condensing radiant tubes allow a better performance as the operative temperature remains more constant and more similar to the air temperature during the day with respect to the CRF and, above all, to the Air system. Furthermore, a quicker reaching of the set-point temperature is allowed by the CRT system at the morning start-up of the plant. This make the radiant tubes system a competitive solution for the heating of industrial buildings both from energy performance and indoor thermal comfort conditions.

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REFERENCES

Brunello P., De Carli M., Magagnin P., Polito A., Zecchin R., Riscaldamento radiante a gas in ambienti industriali: fenomenologia, progettazione, verifica (Gas radiant heating in industrial ambients: phenomenology, design, control), Proceedings AiCARR Congress Progettare l'involucro edilizio: correlazioni tra il sistema edificio e i sistemi impiantistici, Bologna, 2001.

Brunello P., De Carli M., Polito A., Zecchin R., Comfort criteria and design aspects in high temperature radiant heating, Proceedings Indoor Air 2002, Monterey, California, 2002.

D'Ambrosio Alfano F. R., L'ambiente termico nell'industria (Industry thermal ambient), Proceedings AiCARR Congress Riduzione dei fabbisogni, recupero di efficienza e fonti rinnovabili per il risparmio energetico nel settore industriale, Padova, 2010.

De Carli M. and Polito A., Sistemi di climatizzazione per irraggiamento (Radiant climatization systems), Proceedings AiCARR Congress Riduzione dei fabbisogni, recupero di efficienza e fonti rinnovabili per il risparmio energetico nel settore industriale, Padova, 2010.

Lazzarin R., Intervista sul riscaldamento degli ambienti nell'industria (Heating of industrial ambients: an interview), SGE, Padova, 2002.