Radiant electrical plates for space heating and thermal comfort: an experimental study

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ABSTRACT

The use of electrical terminal devices for space heating is increasing in Europe, especially in low-energy or passive houses where the heating energy requirement reaches very low value. Some aspects are fundamental:

- low load in design condition
- low energy requirements during the winter season
- low inertial terminal devices
- due to the low operation time, the installation of low cost terminal devices is required.

According to these reasons, the use of radiant electrical plates may be successful, particularly when low energy requirements can be provided by site-production through photovoltaic modules. In this study, different types of radiant electrical plates are studied in a test chamber. After a description of the test room facilities and of the delivered experiments, the performances of the radiant plates are investigated from both energy and thermal comfort aspects. Moreover, the analysed equipments are applied to a low energy house in different sites in Italy to evaluate suitable combinations with photovoltaic modules.

KEYWORDS

Electrical radiant plates, heating, thermal comfort, low energy houses

INTRODUCTION

Radiant heating systems are widely diffused in Europe, mainly hydronic radiant systems because of the energy saving opportunities they may engender by using low temperature heat transfer carriers (Olesen, 2002; Babiak et al. 2007). Electrical systems are not as much common as hydronic systems, because, in typical dwellings, the use of electricity for heating purpose would cause an energy waste and, in many countries, it would also cause extremely high heating costs for the user. Nevertheless in new low-energy houses, heating is required few days or hours per year, and when it is required the system must react quickly to the thermal demand, to reinstate the proper thermal conditions (Feist et al. 2005 Isaksson et al. 2006, Thyholt et al. 2008, Nieminen 1994). Hydronic radiant systems have slightly low reactions to thermal demand: radiant ceiling are generally faster, because they have little inertia, but they are more expensive; radiant floor are generally cheaper, and more used in the houses, but slower. Due to the very little amount of heating energy required by low-energy houses, the use of cheap electrical systems could be suitable; furthermore the energy required by the heating system may be balanced, along the year, by the energy produced by a photovoltaic system, increasing the sustainability of the system. Electrical systems may be used for underheating floor or ceiling, and their comfort performance are the same of typical hydronic systems: they depends on the temperature level and on the surfaces area, related to the finishing material and to the control system as well (Watson et al. 2002). Nevertheless, radiant plates are much more typical, because they can be easily mounted on a wall when the building is already finished and can be shaped following many different styles. Radiant plates have nonetheless a reduced exchanged area and thus they must reach higher temperature compared with a floor or ceiling (Watson et al. 2002). Maximum radiant asymmetries due to warm walls are indeed fixed by thermal comfort standards; the thermal output of electrical radiant plates is therefore strictly limited by comfort reasons (Fanger et al. 1985).

Economical aspects, thermal comfort and thermal response of all the heating systems will not be faced in this paper because of the shortness of it, but it is important to not underestimate the importance of these three factors. In this paper, an experimental study about three different electrical radiant plates is reported. By means of dedicated facilities, their thermal output have been evaluated and compared to the thermal comfort conditions produced in the test chamber. Moreover, the possible use of the tested plates applied to low-energy houses at different latitudes in Italy was investigated and the combination with suitable photovoltaic system to provide electrical energy was discussed.

METHODS

The test facility The test facility arranged to experimentally characterize the radiant electrical plates is made up of an insulated chamber (3.57 m x 3.49 m x 2.55 m) and a data-acquisition system, placed in the basement of the "Politecnico di Torino" head office. The temperature of the environment around the test chamber can be controlled by means of an air-conditioning system, in order to simulate different heat loss conditions.

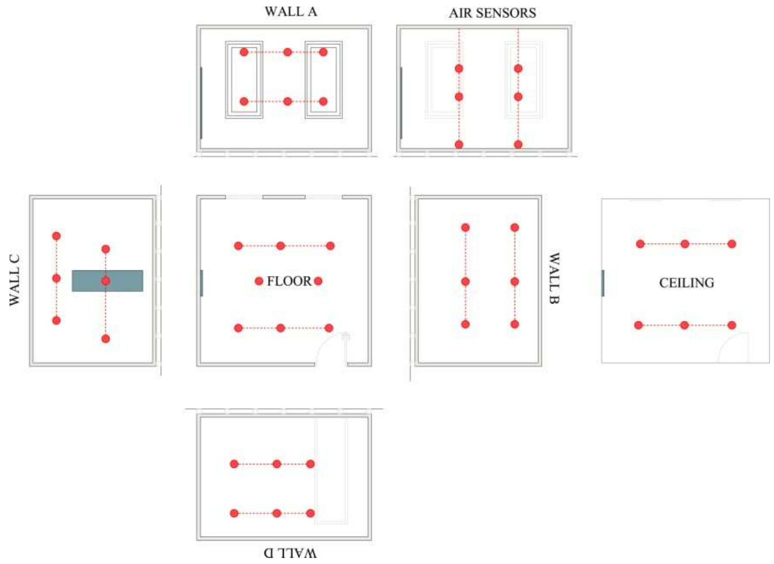

Figure 1. Position of the probes on the floor, on the ceiling and on the walls of the chamber.

The walls and the ceiling of the chamber are built with a dry structure, made by a rook wool insulating layer (80 mm) placed between two plasterboard layers (12.5 mm). The floor, raised and separated from the floor of the basement by some wooden boards, is constructed with four layers: a plywood panel (35 mm), an insulating extruded polyethylene layer (25 mm), an electric radiant carpet and a MDF (Medium Density Fibreboard) floor tile layer (5 mm). Two sealed windows and a door were respectively placed on the walls A and D, for visual control and inspection during the tests, while the electrical plate was placed on the wall C (Fig.1).

Three different kinds of electrical plates have been analyzed:

1- dimensions: 1.55 m x 0.44 m, surface colour: white
2- dimensions: 1.50 m x 0.53 m, surface colour: white, presence of a fan
3- dimensions: 0.82 m x 0.54 m, surface colour: white

Experimental apparatus

The characterization of the radiant plates under test require several quantities to be measured, which are summarized below:

- air and wall temperatures inside the chamber;
- plate surface temperature and corresponding heat flux;
- temperature and relative humidity outside the chamber;
- electric energy consumption (of the plates).

For this purpose, a data-acquisition system has been arranged that embeds a set of sensors and a Personal Computer (PC) that collects the measured quantities. With the aim to minimize the cables, a wireless system has been employed for temperature measurements. Such a system includes a base station, which is connected to the PC through an USB interface, and 14 measuring nodes. Each node, is powered by means of a CR2477 button lithium battery and is equipped with a chip CC2510F32RSPR by *Texas Instruments*, which embeds both a microcontroller unit and a 2.4 GHz radio transmitter CC2510. A circular-shape antenna is directly printed on the circuit, thus allowing a wireless communication with the base station, which is equipped with the same radio device. The base station mainly acts as a data collector, but it has also the capability to configure the measuring nodes by setting different parameters, such as the measurement interval and the transmission trials for each measurement session. The measuring nodes embeds three T-type thermocouples, whose cold junctions are thermally coupled to a digital thermometer that acts as a reference junction. The thermocouple voltage-outputs are acquired by means of a 24 bit three-channel Analog-to-Digital Converter (AD7799 by *Analog Devices*), whose internal programmable-gain instrumentation amplifier has been configured in order to have an input range of 78 mV and a resolution of about 0.02 °C (17 bit). Thanks to the use of cheap temperature sensors and wide-spread electronic components, the cost of each measuring node could be about 10 Euros for a medium-scale production. Further details about the circuitry and the micro-controller firmware can be found in (Carullo et al. 2009). The thermocouple warm-junctions of 12 measuring nodes are employed to monitor the temperature of the chamber walls, while the other 2 nodes measure the air temperature inside the chamber at different heights (10 cm, 110 cm, 170 cm). The position of each thermocouple is shown in Fig. 1, where the thermocouple that records the temperature of the radiant plate under test is also shown. One should note that the solution adopted for temperature measurement offers several advantages besides those ones that are inherent to a wireless system. Above all, the number of measuring nodes can be dynamically managed by the system, thus offering the possibility to map the chamber temperature in the most suitable way. Furthermore, the nodes can be easily removed from the test chamber for maintenance or calibration purposes. Thanks to this feature, the calibration of the wireless system has been performed by inserting the measuring nodes inside a climatic chamber. Initially, the errors of the reference-junction thermometers have been estimated, then the thermocouples have been verified against a traceable standard thermometer. Once the errors of the reference-junction thermometers have been compensated, the nodes have shown measurement errors lower than 0.5 °C. Four heat-flux sensors (*Hukseflux* model HPF 01) were fixed to the surface of the radiant plate under test (two on the front and two on the back of the plate) for measuring the plate heat-flux output. The voltage signals of the four heat-flux sensors were acquired by means of a data-logger (*DataTaker* DT600), which was connected to the PC through an RS-232C interface. The relative uncertainty of the measured heat flux was about 5%, which takes into account the contribution of both the sensors and the data-logger, while the temperature of the external walls of the chamber were measured by wired thermocouple sensors with an uncertainty of 0.5 °C.

A digital wattmeter (*LEM Norma* model D6000) was employed to measure the energy consumption of the plate under test, which was obtained with a relative uncertainty of 0.2%. Temperature and relative humidity of the air outside the test chamber were measured by means of a thermo-hygrometer probe (*Rotronic* HP101A-L5W1F), whose output signals were sent to a conditioning unit (*Rotronic* A2); the conditioned signals were measured by means of a digital multimeter (*Agilent* 34401A). Both the wattmeter and the multimeter were connected to the PC through an IEEE-488 standard interface, thus fully automating the measuring process.

RESULTS

Thermal power assessment

The object of the measurements was to evaluate the thermal power output of the radiant plates as function of the temperature difference between the plates surface and the room reference temperature. In fact a good performance of the heating equipment can be assumed only when the temperature of the plate surface is not too high, in order not to create local thermal discomfort to the occupants. In order to properly evaluate the performance of the plates, three different test conditions were carried out for each plates: high heat loss, moderate heat loss, low heat loss. All the test were preformed under steady state conditions, only the plate temperature was sometime fluctuating (depending on the control system installed). Only when stable periodic fluctuations were recognized the measurement was considered completed. The thermal power output was derived from the plate electrical energy consumptions during the test time and it was checked with values obtained by means of heat flux meters. The power output of the electrical plate was finally evaluated by mean of a characteristic equation, as in the case of common radiators, based on the experimental data:

$$\Phi = K_M \cdot \Delta T^n \quad [W] \tag{1}$$

Table 1. Thermal conditions during the tests and power output of the electrical plates.

		h	**E_{el}**	**T_{out}**	**T_p**	**$T_{a,110}$**	**T_{mr}**	**T_{op}**	**ΔT_{p-op}**	**Φ**	**Φ_1**
		[h]	[kWh]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[W]	[W/m^2_{pan}]
Plate 1	Test 1	8	2.13	16	55.0	20.6	21.1	20.9	34.1	266	403
	Test 2	24	3.95	18	41.8	20.9	21.2	21.0	20.8	165	250
	Test 3	20.3	1.34	20	31.1	21.2	21.4	21.3	9.8	66	100
Plate 2	Test 1	69	20.05	18.3	57.5	21.2	21.9	21.5	36.0	291	366
	Test 2	19.97	4.37	16.6	49.0	21.9	22.2	22.0	27.0	219	275
	Test 3	14.77	0.27	16	69.7	22.0	23.2	22.6	47.1	18	23
Plate 3	Test 1	6.87	1.26	13.9	60.8	18.7	19.5	19.1	41.7	183	413
	Test 2	5.18	0.75	16.9	51.0	20.1	20.8	20.4	30.6	146	329
	Test 3	8.75	0.40	19.5	32.4	21.0	21.3	10.5	21.9	46	103

where:

K_M = constant for the plate, n = constant for the plate [-]

In accordance with previous researches (Olesen et al. 2000; Causone et al. 2009; Causone 2009) the operative temperature in the centre of the chamber at 110 cm above the floor level was considered as the reference temperature.

In table 1, it is shown the average air temperature in the basement (T_{out}), the plate average surface temperature (T_p) , the air temperature in the test chamber (T_a), the radiant mean temperature (T_{mr}), the operative temperature (T_{op}) and the delta between the plate surface and operative temperature (ΔT_{p-op}). T_{mr} and T_{op}, which characterize the room thermal conditions, have been calculated using the experimental data as input of the following algorithms:

$$T_{mr} = \frac{\sum_{j=1}^{n} S_j \cdot T_j}{\sum_{j=1}^{n} S_j} [°C] \tag{2}$$

$$T_{op} = \frac{T_{mr} + T_a}{2} [°C] \tag{3}$$

where:

S = area of the j^th surface, T = mean temperature of the j^th surface, n = number of surfaces.

Table 2. Air temperature inside and outside the chamber and thermal comfort indexes evaluated during the tests.

		T_{air} [°C] h.110cm	ΔT [°C] $\Delta T_{10\text{-}110}$	ΔT [°C] $\Delta T_{10\text{-}170}$	T_{out} [°C] Outdoor	ΔT_{prh} [°C]	PMV [-]	PPD [%]
Plate 1	Test 1	20.6	0.3	0.9	16	47.3	(-0.1)-(+1.5)	4.2-50.6
	Test 2	20.9	0.3	0.7	18	36	(+0.0)-(+1.2)	4.6-37.0
	Test 3	21.2	0.2	0.6	20	24.9	(+0.2)-(+1.1)	6.1-32.2
Plate 2	Test 1	21.2	0.8	1	18.3	53.6	(+0.0)-(+1.9)	4.1-70.0
	Test 2	21.9	0.6	0.8	16.6	28.2	(+0.1)-(+1.0)	4.9-25.2
	Test 3	22	1.2	1.4	16	58.9	(-0.1)-(+1.9)	3.9-72.9
Plate 3	Test 1	18.7	0.2	0.8	13.9	25.2	(-0.4)-(+0.4)	5.2-8.4
	Test 2	20.1	0.2	0.6	16.9	18	(-0.2)-(+0.3)	5.0-7.2
	Test 3	21	0.1	0.3	19.5	6.7	(-0.1)-(+0.1)	5.0-5.5

Thermal Comfort Evaluation/Assessment

Comfort simulations were conducted with the software Hypercomfort®, an hypertextual tool for the evaluation of the thermal, visual, acoustic and olfactory comfort, developed at the Department of Energetics of Politecnico di Torino. The quantities Top, PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), calculated on the basis of measurements during three tests, are compared in Table 2. The aim is to assess how the three different plates can alter the thermal environment in which they appear, having analogous average thermal power end energy consumptions and time intervals of monitoring. The air velocity was measured in the chamber, but it was always very low (<0,1 m/s), the relative humidity, not controlled by the heating plate, was always assumed to be 60% RH, while the metabolic rate of occupants was supposed to be 1.2 met (sedentary activity according to EN ISO 7730/2005) and the clothing insulation 1 clo (typical value of the winter insulation according to EN ISO 7730/2005).

Analyses were performed evaluating T_{op} at the distances of 0.5 m and 1.5 m from the plate and at height of 0.6 m above the floor.

Results are shown in the charts of fig. 2 and 3 according to the comfort categories expressed in terms of operative temperature as described in the UNI EN 15251 Standard:

- Category I - High level of expectation
- Category II - Normal level of expectation
- Category III - An acceptable, moderate level of expectation
- Category IV - Values outside the criteria for the above categories

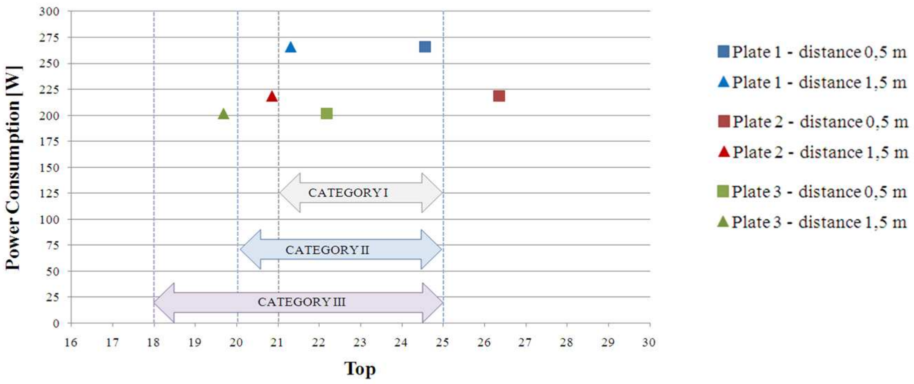

Figure 2. Operative Temperature calculated at 0.5 m and at 1.5 m far from the plates.

The chart in fig. 2 shows the relation between monitored power consumptions and T_{op}. Plate 1 is able to hold the T_{op} value inside the Category I both for the distance of 0.5 m and for the 1.5 m. Plate 2, instead, gives good results at the distance of 1.5 m, but at the distance of 0.5 m the Top value exceed the category I limit of 25 °C. This is because the surface temperature is slightly higher for the second plate than for the first. Plate 3 gives a satisfactory T_{op} at the distance of 0.5 m, while shows a limit value (Category II) at 1.5 m of distance. Nevertheless, the emitted power of the third plate is slightly smaller than the previously tested plates 1 and 2, it is possible to assume that raising the power output of Plate 3, both the T_{op} values (at 0.5 m and 1.5 m) would fall inside the Category I.

In figures 3a and 3b, PMV and PPD values are shown. According with the previous analyses, Plate 1 is able to maintain an environment in category I at the distance of 1.5 m, also using the PMV as indicator, while it is able only to reach Category II at the distance of 0.5 m. The PMV value calculated for Plate 2 is close to the acceptable limit of the category I at the distance of 1.5 m, while it is close to the acceptable limit of the Category II at the distance of 0.5 m.

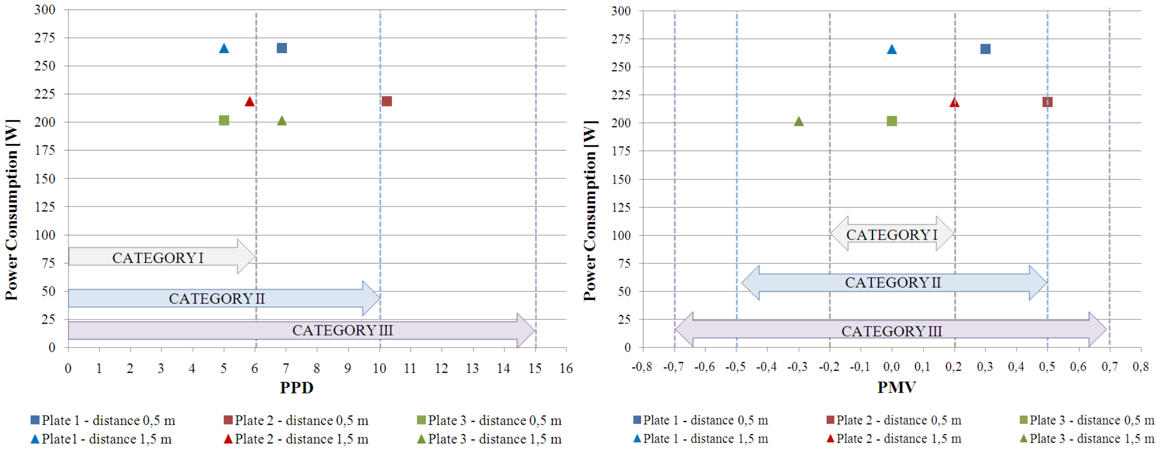

Figure 3 (a-b). PMV and PPD indexes calculated at 0.5 m and at 1.5 m far from the plates.

The higher temperature of Plate 2, compared with Plate 1, is probably the cause of the difference reported above. Plate 3 shows a PMV in Category I at the distance of 0.5 m and in category II at the distance of 1.5 m. As previously highlighted this is due to the power output emitted by the plate 3, which is slightly lower than the power emitted by Plates 1 and 2. The PPD, being directly related to the PMV, shows relatively low values. Plates 1 and 3 show values in Category I and II, while only Plate 2, at the distance of 1.5 m, shows a percentage of dissatisfied next to the upper limit of Category II. Also the vertical air temperature difference between head and ankles was calculated but no values out of the limits suggested by the local discomfort due to EN ISO 7730:2005 Standard were reported. Some improper values were instead noted for the radiant asymmetry between vertical surfaces (ΔT_{prh} - Plane Radiant Asymmetry), which the standard EN ISO 7730:2005 suggests should not be higher than 35 °C in order not to generated a percentage of dissatisfied higher than 10%. Plate 1 shows a value over the limits suggested by the standard, while Plates 2 shows two values over the limits. In general it can be observed that, under the conditions simulated in the chamber, when the radiant plate assume temperature higher than 55 °C it can cause local thermal discomfort to the user.

Radiant plates in low-energy houses

As clearly stated in the introduction of the paper, the use of electrical radiant plates can be considered suitable only in houses with low-energy demand (low energy demand for heating).

In order to evaluate the number of radiant plates required by such a residential building (and consequently the initial costs), a case study was developed: a typical single family house with a floor area of 122 m^2 and a net internal height of 3 m (single floor). The ratio between transparent and opaque envelope was considered to be constant (Tab. 3), while the thermo-physic characteristic of the envelope have been changed in order to satisfy the building energy performance requirements of the Italian legislation for heating and domestic hot water, at different climatic areas in the North of Italy (Bolzano, Torino, Firenze). The hot water production has been considered constant and calculated on the basis of the Italian Standard UNI-TS 11300-2 (15 kWh/m^2y). Simulations have been developed with a semi-stationary method, according to Standard UNI EN 11300-2, considering an air change per hour of 0.5 vol/h. It was furthermore calculated the amount of square meters needed to balance the heating requirement, by producing photovoltaic electricity on site. The heating requirements to fit a level vary from city to city, depending on the climatic area thus mainly on the HDD (Heating Degree Days) and on the solar radiation at the ground in the city analyzed. The climatic data used in the simulations derived from the weather data archive of the Italian Energy Agency (ENEA). An assumption of an efficiency of 13.7% of the photovoltaic modules have been made, which corresponds to polycrystalline silicon commercial modules.

Table 3. Ratio between the transparent and the opaque envelope at different orientations.

	Nord	Sud	Est	Ovest
S_t/S_o	0.1	0.2	0.15	0.15

As confirmed by the results, the use of the tested electrical radiant plates can be considered suitable only in houses with low heating demand, where the number of elements is low and the area required for photovoltaic modules too.

Table 4. Number of radiant plates (type: P1, P2, P3) required to heat the house, heating demand calculated for the standard house in order to fit the different energy levels and photovoltaic area required to balance the heating energy consumptions for the three Italian cities considered.

	Heating demand	Required number of radiant plates (type: P1, P2,			Required delivered energy for heating	Required photovoltaic area to balance heating	
		P1	P2	P3	kWh/m^{2}y	m^2	kWp
	Very low	8	4	4	10	9.3	1.3
	Low	12	6	6	24	23.1	3.3
	Standard	17	9	8	49	46.8	6.7
	Slightly high	26	14	13	82	78.1	11.2
	Very low	7	4	3	12	10.7	1.7
	Low	9	5	4	24	21.5	3.1
	Standard	14	8	7	59	52.3	7.5
	Slightly high	19	11	9	77	68.9	9.8
	Very low	5	3	3	8	6.5	0.9
	Low	7	4	3	17	14.9	2.1
	Standard	11	6	6	48	41.3	5.9
	Slightly high	15	8	7	62	53.1	7.6

CONCLUSIONS

The measurements and calculations reported in the paper showed that electrical radiant plates may be a suitable heating system, equipped by control system. The main problem of a radiant plate can be a too high surface temperature, able to engender radiant asymmetries in the room.

Due to these reasons electrical radiant plates are particularly proper in houses with low thermal loss. This kind of buildings are highly insulated and fit properly a heating system with a quick reaction to eventual thermal stresses.

Due to the high quality and value of electrical energy, the use of it for heating is furthermore acceptable only in low-energy building, where the yearly heating consumption can be balanced by the production of photovoltaic energy on site. Low cost equipments can, under these conditions, be competitive with other systems: in fact, for economical sustainability, low energy requirements have to be faced by low cost technologies in order to give suitable payback time.

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