Design guidelines for direct ground cooling systems in different climates

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ABSTRACT: Direct ground cooling systems use water-to-ground heat exchangers connected to radiant panels in the building to provide summer comfort with a low energy consumption. In this paper the results of some dynamic simulations, carried out with TRNSYS, are presented. Model buildings, equipped with chilled floors connected to vertical U-pipes in the ground, are simulated. Different representative Italian climates, affecting both the cooling requirements and the ground temperature, are taken into account. A summer comfort index and a long term reliability criterion are applied to find out the proper ground heat exchanger size and configuration. The influence of some building envelope thermal properties on the ground cooling system performance and design is investigated. Then some design guidelines for different building cooling requirements are derived and discussed.

Keywords: ground, cooling, low-energy, design, comfort.

1. INTRODUCTION

The interest in ground source heating and cooling is rapidly growing in Europe and worldwide. The most popular technology consists of an electrically driven heat pump, extracting heat from the ground in winter by means of buried pipes and providing it to the building. The system operation can be reversed in summer, so that the heat pump removes heat from the building and injects it into the ground. Besides this, in favourable climate and ground conditions, cooling can also be achieved by circulating water directly between the ground heat exchanger and some radiant panels installed in the building [1-2]. An experimental study on a model direct ground cooling system was performed in Italy by the Department Best of Politecnico di Milano [3]. The direct ground cooling option is attractive because of its low energy consumption, due only to the circulation pump.

The ground heat exchanger design is a critical issue for all ground coupled systems. Undersizing can compromise the system performance, while oversizing has a strong impact on the first cost. Available design methods [4], guidelines [5] and softwares [6] address to heat pump systems and generally consider the heating operation mode. Their application to direct ground cooling systems is not straightforward, since direct systems performance essentially depends on the temperature difference between the water entering the buried pipes and the surrounding ground. The water inlet temperature is not set in a direct ground cooling system and it usually results different from that of a heat pump system. The surrounding ground temperature may rise year after year, since the ground is used only as a heat pond. Then a lack of design criteria for direct ground cooling systems is found.

In this research dynamic simulations are used to study the behaviour of a model direct ground cooling system and to derive some design criteria for the Italian climate. A sustainability perspective, taking into account long time operation of these systems, is adopted.

2. METHODOLOGY

In this study a small residential building is placed in three representative Italian climates. A direct ground cooling system is provided to the building. The system is assumed to operate only in summer, from June to September, for a period of 30 years. In order to size the ground heat exchanger, a long-term evaluation of the comfort conditions is performed. According to the the recently revised international standard [7], different categories of thermal environments may be specified. A “class B” thermal environment corresponds to the conditions $|PMV| \leq 0.5$ or $PPD \leq 10\%$. Then at every simulation time step the PMV is calculated for all the thermal zones of the building. From the PMV distribution, an average value <PMV> over the summer period and a standard deviation Δ are obtained. Then the ground heat exchanger size and configuration is adjusted so that for every thermal zone throughout the 30 years period:

$$\langle PMV \rangle + \Delta \leq 0.5 \qquad (1)$$

Since the climate affects both the building cooling requirement and the ground capability to match it, the procedure is repeated for each climatic condition. If necessary, some changes are made to the building envelope in order to lower its cooling energy demand.

Once the proper system size is found, a scale factor 10 and 100 is applied to the building. This way the single family house is replaced with a group of houses served by a district cooling system. From another perspective, the cooling load for the ground heat exchanger is set 10 and 100 times larger. The ground heat exchanger is then scaled accordingly and, if necessary, resized, in order to satisfy the new requirements.

3. SYSTEM LAYOUT

The model direct ground cooling system is made up of a water loop containing the ground heat exchanger and the building radiant panels, as shown in Figure 1.

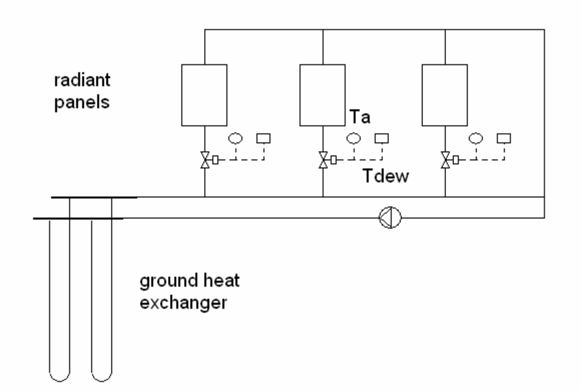

Figure 1: Direct ground cooling system layout.

The ground heat exchanger consists of some vertical polyethylene U pipes, with one U pipe per borehole backfilled with grout.

The ground temperature profile is influenced by the geothermal flux and, close to the surface, by the climate. A climatic wave with time period T is almost damped out at a depth equal to two-three times the penetration depth $\delta = \sqrt{k_g T / \pi C_g}$, where k_g and C_g are the ground thermal conductivity and volumetric capacity. The boundary condition at the ground surface should take into account the convective heat transfer with outside air, the solar radiation absorbed, the infrared exchange with the sky and the environment, the latent heat flux due to evaporation. A hypothesis has then to be made on the ground cover, its shading and water content [8]. For simplicity in this study the climatic influence is limited to the outside air temperature effect. The geothermal flux is taken into account through a constant gradient. Average thermal properties are assumed for the ground.

The number of boreholes N, their depth in the soil H and the pipe-to-pipe distance d are the parameters varied in the simulations to satisfy the building load. The main characteristics of the ground heat exchanger and the ground properties are summarized in Table 1.

Table 1: Main characteristics of the ground heat exchanger

Borehole diameter	12 cm
Pipe outside/inside diameter	3.2/2.6 cm
Grout thermal conductivity	1.47 W/(m K)
Ground thermal conductivity k_g	2 W/(m K)
Ground volumetric heat capacity C_g	2 MJ/(m^3 K)
Penetration depth (T=1y)	3.2 m
Geothermal gradient	0.02 K/m

The radiant panels in the building are chilled floors made of plastic pipes (outside diameter 1.7 cm, pipe-to-pipe spacing 10 cm) in a concrete slab, with backside insulation. Water circulation is controlled by a zone thermostat and a dew point sensor. The system is switched off whenever the air temperature in the zone is below T_{set}=24.5°C or a condensation risk on the chilled floor is detected.

4. REFERENCE BUILDING

The reference building is a two storey house with a square plan, a saddle roof and a total surface of about 100 m^2. Radiant floors are installed in the three main zones of the building, namely the living/kitchen room and the two bedrooms. The three zones have south facing windows. Typical residential internal gains due to occupants and equipments are considered. A ventilation rate of 0.8 vol/h is assumed, as a result of infiltrations and windows opening by the occupants. At the beginning, the envelope characteristics are chosen to simply follow the Italian building standards. The “A envelope” properties are reported in Table 2, together with the “B and C envelopes” characteristics that will be introduced in 7.1

Table 2: Reference building: envelopes A, B and C thermal properties

	Envelope A		Envelope B		Envelope C	
	U W/m^2K	g	U W/m^2K	g	U W/m^2K	g
External walls	0.46		0.46		0.24	
Roof	0.82		0.82		0.24	
Floor on ground	0.64		0.64		0.64	
Windows	3.28	0.76	1.74	0.39	1.74	0.39
Shading	Not present		Overhangs		Overhangs	

5. CLIMATES

A great climatic variety exists in Italy. Here Milano, Roma and Palermo are chosen as representative locations. Typical meteorological years are used as simulation inputs. By using these sets of hourly data, the yearly mean, minimum and maximum values of the air temperature for the three towns are calculated and shown in Table 3.

Table 3: Air temperature hourly data: yearly mean, minimum and maximum values for the reference climates.

	Tmean (°C)	Tmin (°C)	Tmax (°C)
Milano	11.8	-10.0	32.6
Roma	15.8	-4.0	31.8
Palermo	18.8	4.8	34.0

The sensible cooling energy requirements for the whole summer (June-September) for the A envelope reference building are shown in Figure 2. The graph refers also to envelopes B and C.

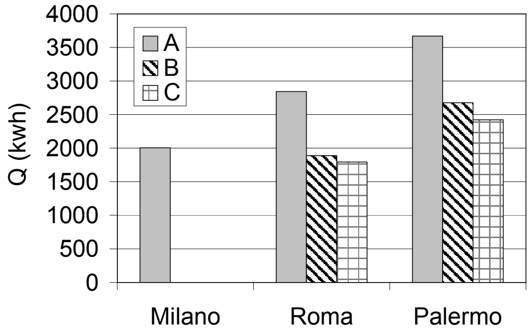

Figure 2: Summer sensible cooling energy requirement for the reference building (envelope A, B, C) in the three climates.

6. SIMULATION TOOL

The well known dynamic simulations software TRNSYS version 16 [9] was used for this study. The software comes with libraries of subroutines simulating different loads and systems. User-written subroutines may be added to the standard ones. The main components used to simulate the building and the ground cooling system are:

- the Multizone Building component Type 56, that includes an “active layer” model to describe radiant panels;
- the ground heat exchanger non standard component TRNVDSTP [10].

7. SIMULATIONS

7.1 The single building case

By varying the number of boreholes N, their depth in the soil H ($0<H\leq150$ m) and their distance d ($2\leq d\leq8$ m), the proper ground heat exchanger size for the single family building envelope A in the three locations is searched. Results for the first summer of operation are shown in Figure 3. Since d is found to have little influence on the system performance, the <PMV> can be plotted as a function of the total pipes length H_{tot}=N.H. The error bars represent the standard deviation Δ. <PMV> values at $H_{tot}=0$ correspond to free floating situations.

As the graph shows, the comfort condition is easily achieved in Milano with a single borehole 60 m long. By comparing the heat removed from the building by this system at the 1st and 30th year, a negligible decrease of 4% is found. The comfort criterion (1) is still satisfied at the 30th year.

On the contrary in Roma and Palermo a total borehole length of 360 m is not enough. At large values of H_{tot} the <PMV> decreasing is very slow. Then comfort condition is expected to be satisfied at very large H_{tot}.

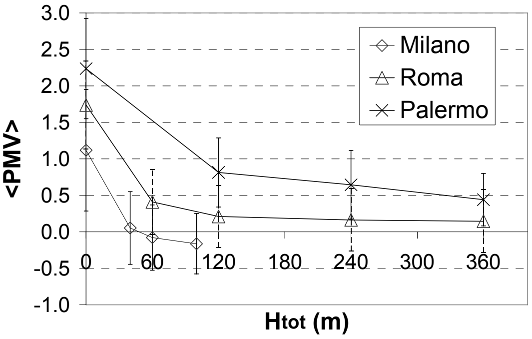

Figure 3: Single family building envelope A: <PMV> vs total boreholes length H_{tot} in Milano, Roma and Palermo.

In order to quantify the effects of the surface condensation control on the system performance, simulations for Roma and Palermo are repeated without any dew point control. In this case in Roma with H_{tot}=120 m it is possible to get within the comfort zone. In Palermo H_{tot}=360 m is still inadequate, proving that the high temperature of the ground source and the large cooling energy demand pay an important role as well.

In order to reduce the cooling energy demand in the critical cases of Roma and Palermo, some envelope changes are then applied to the reference bulding. In the “envelope B” configuration an example of solar gains control strategy is adopted for south facing windows. Double clear glazings (g=0.76) are replaced with selective ones (g=0.39; Light to Solar Gain LSG=1.7), and horizontal overhangs (depth=0.8 m) are provided. In the “envelope C” configuration, in addition to the solar control measures, the roof and external walls composition is changed reaching a thermal trasmittance U=0.24 W/(m^2 K), typical of a low-energy building. Summer sensible cooling energy requirements for envelope B and C are compared with envelope A requirements in Figure 2. The envelope B energy demand in Rome is almost equal to that of the envelope A in Milano, while the envelope C demand in Palermo is still 20% higher. The effects of coupling an increased thermal mass of the walls with night ventilation have also been investigated for Palermo. Since the daily air temperature swing in Palermo is very low, as shown in Figure 4 for August, only a negligible reduction in the cooling energy requirement is achieved.

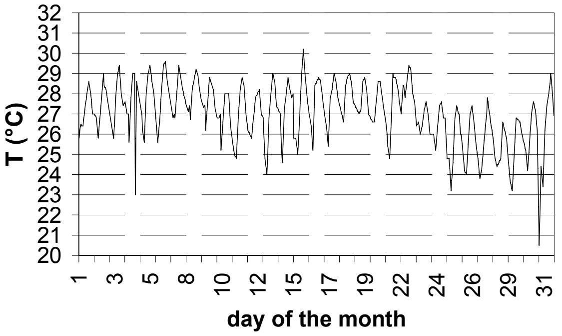

Figure 4: Air temperature in August in Palermo (data from a typical meteorological year).

Figure 5 shows that the comfort condition (1) is achieved for the envelope B in Roma, throughout the 30 years, with a single borehole 70 m long.

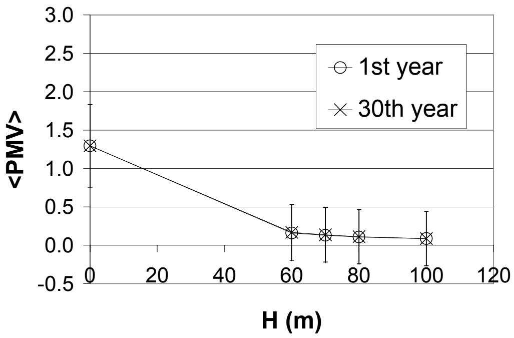

Figure 5: Single family building: <PMV> vs borehole length H in Roma for envelope B at the 1st and 30th year of operation.

The envelope B case is still critical for Palermo, where the comfort condition (1) is not achieved even with H_{tot}=450 m. However if a less severe comfort level could be accepted, such as:

$$\langle PMV \rangle + \Delta \leq 0.8 \qquad (2)$$

for the envelope C case a total boreholes length H_{tot} =180 m would be enough (see Figure 6). In this case the summer average operative temperature would be $\langle T_{op} \rangle$=25.3 °C with a standard deviation Δ=1.2 °C. The system performance reduction after 30 years would be only 3%. Design criteria for the single family building are summarized in Table 4.

Table 4: Single family building: ground heat exchanger design criteria depending on the climate and on the envelope.

Climate	envelope	comfort level	H_{tot}(m)	Configuration
Mi	A	(1)	60	N=1 H=60m
Ro	B	(1)	70	N=1 H=70m
Pa	C	(2)	180	N=2 H=90m d≥2 m

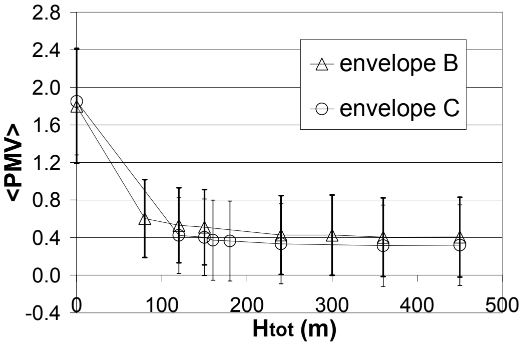

Figure 6: Single family building: <PMV> vs total boreholes length H_{tot} in Palermo for envelopes B and C.

7.2 The 10 buildings case

The results found for the single building in Table 4 are used as a starting point for the 10 buildings case. Envelope A and comfort level (1) are chosen for Milano, envelope B and comfort level (1) for Roma and envelope C and comfort level (2) for Palermo. The methodology consists in scaling the total boreholes length by a factor 10 and checking the long term behaviour of the ground heat exchanger.

As shown in Table 5, in Milano H_{tot}=60 m x10=600 m is enough. However now the pipe-to-pipe distance d is a relevant parameter.

Table 5: 10 buildings: ground heat exchanger design criteria depending on the climate and on the envelope.

climate	env.	comf. level	H_{tot} (m)	configurations	
				d	H, N
Mi	A	(1)	600	≥8 m	H=15÷150m N=40÷4
				4 m	H=15m N=40; H=100m N=6; H=150m N=4;
Ro	B	(1)	1000	≥8 m	H=20÷150m N=50÷7
Pa	C	(2)	1800	≥8 m	H=20m N=90
				≥16 m	H=90m N=20
			3000	≥8 m	H=120m N=25
				≥8 m	H=90m N=33

A comparison among d=2, 4 and 8 m is shown in Figure 7, where the total heat removed in a summer from the building Q is plotted against H, setting H_{tot}=600 m. If d=2 m the performance decreases significantly at the 30th year. The decreasing is less severe for d=8 m and for those configurations with d=4 m with very short or very long pipes length H. The adequate configurations are again summarized in Table 5.

In Roma H_{tot}=70 m x10=700 m is found to be insufficient, even at large pipe-to-pipe distances such as d=20 m. By increasing the total boreholes length until H_{tot}=1000 m, and by setting d≥8 m, the comfort level (1) is assured throughout the 30 years.

Finally in Palermo H_{tot}=180 m x10=1800 m is found to be satisfactory at d≥8 m only for very superficial boreholes, or for deep boreholes far apart (d≥16 m). By increasing H_{tot} to 3000 m, distance can be lowered to 8 m even for deep boreholes.

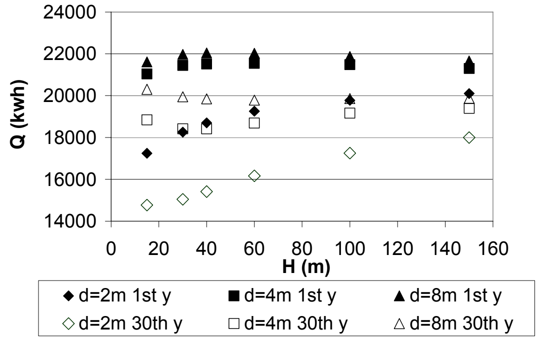

Figure 7: 10 buildings in Milano, ground heat exchanger with H_{tot}=600 m: Q (heat injected into the ground in a summer) vs H and d at 1st and 30th year.

7.3 The 100 buildings case

The scaling factor methodology used in 2.2 is applied again, starting with results reported in Table 5. Adequate configurations found for the 100 buildings district cooling are listed in Table 6.

8. CONCLUSIONS

Simulations performed allow us to point out some important characteristics of direct ground cooling systems:

- in warm humid climates a control preventing condensation on chilled surfaces is needed; at the same time the necessity to switch off the system in case of condensation risk may limit the capability of the ground cooling system to satisfy the building load;
- the ground cooling system performance and the heat exchanger size are strongly related to the envelope thermal properties; lowering the building cooling energy requirements, for example through a solar control strategy, means a smaller heat exchanger and a better comfort;
- the ground heat exchanger design is very sensitive to the ground source temperature level, so that attention should be paid when dealing with different locations;
- small scale direct ground cooling systems with few boreholes can operate on a long time scale without any significant reduction of their performance;
- in medium and large scale direct ground cooling systems thermal interactions between neighbour boreholes and heat injection into the ground summer after summer may compromise the system performance on a long term. A larger pipe-to-pipe distance is required as the system scale grows. Total boreholes length being equal, best long term behaviour is found for configurations with short boreholes, since their aspect ratio permits natural ground recharge in winter by heat transfer with outside air.

The influence of ground thermal properties (conductivity and volumetric capacity) on the ground heat exchanger performance and size is investigated in another paper to be published.

Table 6: 100 buildings: ground heat exchanger design criteria depending on the climate and on the envelope.

climate	env.	comf. level	H_{tot} (m)	Configurations	
				d	H, N
Mi	A	(1)	6000	≥8 m	H=15m N=400
				≥16m	H=100m N=60
			9000	≥8 m	H=30m N=300 H=60m N=150
Ro	B	(1)	10.000	≥8 m	H=20m N=500
				≥20m	H=100m N=100
			15.000	≥12 m	H=100m N=150
Pa	C	(2)	18.000	≥12 m	H=20m N=900
				≥20 m	H=90m N=200
			30.000	≥16 m	H=120m N=250
				≥ 8 m	H=30m N=1000

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