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Solar Assisted Ground Source Heat Pump in Cold Climates

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Abstract

The geothermal heat pump(or ground source heat pump) uses the ground as heat source or sink for heating and cooling respectively. The design of the borehole field is the key element of these systems since the wrong evaluation of the boreholes' length affects the initial costs and/or the energy performance of the heat pump. The geothermal heat pumps are considered as renewable energy technologies, consequently can help the community to reduce the primary energy uses and also the CO_2 emissions. However the sustainability and efficiency are ensured in the long period only when the heat balance through the ground is guaranteed.

This work evaluates the thermal behavior of ground source heat pumps in cold climates, where the thermal load profile of buildings is not balanced between heating and cooling, especially in residential sector characterized by low internal loads. In these contexts, the heat pump mainly works in heating mode, extracting continuously heat from the ground. As a result, the ground temperature decreases gradually during the years affecting the energy performance of the heat pump. A possible solution to this problem is to use solar thermal collectors to stabilize or gradually increase the mean ground temperature(these systems are called Solar Assisted Ground Source Heat Pump – SAGSHP).

In this work a multi floors residential building with 12 flats (88 m^2 each)is analyzed in three climate zones, making use of the simulation tool TRNSYS. Different configurations of the plant system have been investigated and the case without the solar thermal collectors has been considered as reference.

*Keywords:*borehole heat exchangers, heat pump, solar thermal systems, cold climates, SAGSHP

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1. Introduction

The massive use of fossil fuels during the last decades has pushed to the exploitation of renewable energy sources also to reduce the CO_2 emissions at the same time. The recently concept of nearly Zero-Energy Building (nZEB) introduced by the recast of the Energy Performance Building Directive (EPBD) [1] combined with the 20-20-20 objective [2] represent an important challenge for the reduction of energy consumption, particularly for construction sector that covers about 40% of the total energy use. Nowadays one of the toughest issues is the improvement of storage efficiency in long time period, especially when renewable energy sources have to be preserved. In this field the most widespread renewable technologies from small to large scale are in the solar field. Ground Source Heat Pump (GSHP) technology has been long discussed in the last years due to its higher performance in Heating, Ventilation and Air Conditioning(HVAC) applications, compared to Air Source Heat Pump systems (ASHPs) [3]. GSHP system is a promising technology able to use the ground as a free heat source and sink for energy storage [4]. The temperature of the heat source-sink affects the efficiency of the heat pump. In ASHPs, the ambient temperature is very variable throughout the year depending on the location's weather and consequently the energy efficiency is also variable over time [5]; furthermore, the defrosting process has to be considered [6]. The use of the ground allows to obtain a more stable performance of the heat pump because the temperature of the ground is affected by the air temperature fluctuation only in the first meters below the surface [7]. Borehole Heat Exchanger (BHE) is the core of the system; it consists of a closed pipe loop buried in the ground and it may be horizontally or vertically oriented[8]. GSHPs work properly when the heating and cooling demand of the building is similar. When the building load profile is not balanced, the mean ground temperature changes during the years of operation. This phenomenon is known as "thermal drift" and its main consequence is the reduction of heat pump's performance. The possibility to use solar energy to recharge the ground in cold climates is one opportunity to use GSHP in heating dominated buildings. GSHPs that use solar thermal energy are commonly defined and known as Solar Assisted Ground Source Heat Pump systems (SAGSHPs) [9] [10].

2. Methodology

Energy analysis of HVAC systems using simulation tools requires consistent information regarding the characteristics of the building, the thermal plant system, and its equipment. In this work the simulation tool TRNSYS has been used. Simulations have been carried out in three locations using the Test Reference Year (TRY) data files [11]: Bolzano (Italy), Stockholm (Sweden) and Montreal (Canada). In the first step the thermal load profiles of the building have been calculated. Afterwards, the heating plant system has been designed and the properties of components of the system have been defined. The conceptual scheme of the system is shown in Figure 1. The main components are: BHEs field, solar thermal collectors field, tank, heat exchanger and heat pump.

In the last part of the study the performance of different layouts of the BHEs field is analyzed. The "baseline" reference case is the configuration without solar thermal collectors field. The design of thethermal plant system has been carried out by choosing the solar collector area, the tank volume and the properties of the BHEs field. The borehole field has been designed according to the ASHRAE method [12]. The maximum solar collectors area is supposed to be installed on south-facing roof side, and the configuration is the same for all the simulations of the location. The tank has a dimension to ensure an easy installation. The BHE characteristics are equal in all the case studies.

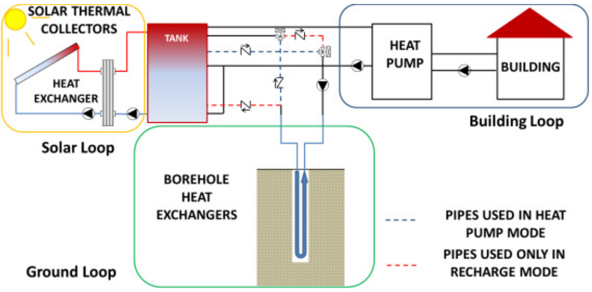

Fig. 1. Scheme of the system

3. Simulations of the case studies

The case study regards a block of flats located in three different climate zones, outlined in Table 1. The building consists of 12 flats of about 88 m^2 each. It is developed on three floors with a total useful area of about 1056m^2. Table 2 outlines information about the building. A radiant floor heating system is considered; its supply temperature varies as function of the external air temperature (i.e., it has been set between 30°C and 45°C when the external temperature moves from 15°C to 0°C).

Table 1. General Data

	Code	Latitude (°)	Longitude (°)	Metersa.s.l. (m)	T_{mean} (°C)	Degree Days (DD)	Climate Type (Köppen/ ASHRAE)	T_{min} (°C)	T_{max} (°C)	Tot. Hor. Radiation (MJ/m^2y)
Bolzano (Italy)	A	46.47N	11.33E	241	10.72	2913	Dfb/4A	-11.6	34.6	3831
Stockholm (Sweden)	B	59.45N	17.95E	61	6.49	4239	Dfb/6A	-17.0	27.1	3319
Montreal (Canada)	C	45.68N	73.03E	82	4.96	4862	Dfb/6A	-31.5	28.8	4884

Table 2. Thermal properties of the building and boundary conditions

	Building – U-value			Boundary Conditions		
	External Walls	0.17	($W/(m^2K)$)	Air Change Rate	0.5	(1/h)
	External Floors	0.23	($W/(m^2K)$)	Internal Loads	4.9	(W/m^2)
	Roof	0.24	($W/(m^2K)$)	g-value of Windows	0.59	(-)
	Walls to Stairs	0.17	($W/(m^2K)$)	Internal Set Point Temperature	20	(°C)
	Windows	1.27	($W/(m^2K)$)	Hours of Working	24h/24h	(-)

The BHE is a double U-tube in PEXa, coupled in parallel. The properties of BHEs and ground are outlined in Table 3. In each simulation of the case study(A,B and C),the building load profile and plant system characteristics are maintained constant. BHE field is modified by varying the number of boreholes, the mass flow rate and also the undisturbed ground temperature for each location, as reported in Table 4. The first one shows the design data obtained with the ASHRAE method [12] but without the solar loop (Cases A1, B1 and C1), the second one adds the solar system (Cases A2, B2 and C2) and the third, fourth and fifth have the solar and BHEs field reduced (Cases A3/4/5, B3/4/5 and C3/4/5). The BHEs are simulated in TRNSYS (Type 557).The solar radiation is transferred to the heat-carrier fluid through flat plate solar collectors installed on the roof and facing south with a slope of 30°. The properties of this system and its components are summarized in Table 5.

The tank has a volume of 4 m^3 with a mixture of 30%Antifreeze/70%Water as heat-carrier fluid. It is simulated by means of the Type 534 in TRNSYS considering the effect of the temperature stratification.

The heat pump is switched on when the building requires heat. It is connected to the tank on the evaporator side and to the building on the condenser side. The solar and ground loops increase the temperature of the heat-carrier fluid inside the tank and sometimes it can reach high temperatures so that the heat pump can be bypassed (free-heating). The heat pump is simulated with a three-dimensional matrix and the calculation code is implemented with an excel spreadsheet integrated in TRNSYS using data reported in Table 6.The simulations of the system were performed with time step of 15 minutes.

Table 3. Thermal properties of the BHE and Ground

BHE Properties			Ground Properties (clayey marne)		
Thermal conductivity of pipeλ_{pipe}	0.4	(W/(mK))	Undisturbed T_{ground} – Case A-1/2/3/4/5	10.72	(°C)
$D_{internal,pipe}$/ $D_{outer,pipe}$	26 / 32	(mm / mm)	Undisturbed T_{ground} – Case B-1/2/3/4/5	6.49	(°C)
Distance between pipes	50	(mm)	Undisturbed T_{ground} – Case C-1/2/3/4/5	4.96	(°C)
Radius of the Borehole	70	(mm)	Geothermal gradient	0.03	(°C/m)
Thermal conductivity of groutλ_{grout}	2	(W/(mK))	Thermal conductivity $\lambda_{equivalent,\ ground}$	2.1	(W/(mK))
Mass flow rate for BHE	0.26 – 0.31	(kg/s)	Ground volumetric heat capacity	2.25	(MJ/(m^3K))
Specific heat capacity (30%Antifreeze/70%Water)	3.68	(kJ/(kgK))			

Table 4. Properties of the case studies

	Building	BHEs Field						
	Peak Power (kW)	Distance (m)	Depth (m)	Number (# Series) A/B/C + #				Total Length (m)
				1/2	3	4	5	1/2-3-4-5
Bolzano (Italy) → A	33	7	92	20 (2)	10 (2)	6 (2)	4 (2)	1840-920-552-368
Stockholm (Sweden) → B	40	7	107	20 (2)	10 (2)	6 (2)	4 (2)	2140-1070-642-428
Montreal (Canada) → C	48	7	115	20 (2)	10 (2)	6 (2)	4 (2)	2300-1150-690-460

Table 5. Solar Collectors Field Properties

Solar Collectors field			Heat Carrier Fluid – Solar Collectors Side (50%Antifreeze/50%Water)		
Total solar collectors area	176.2	(m^2)	Total mass flow rate	5940	(kg/h)
Gross area of the collector	2.5	(m^2)	Specific heat capacity	3.35	(kJ/(kgK))
Absorber area of the collector	2.2	(m^2)	Heat Carrier Fluid – Tank Side (30%Antifreeze/70%Water)		
Number of collectors (# series)	78 (6)	(-)	Total mass flow rate	5404	(kg/h)
η_0 (EN 12975)	0.768	(-)	Specific heat capacity	3.68	(kJ/(kgK))
a_1 (EN 12975)	3.4	(W/(m^2K))	Heat Exchanger		
a_2 (EN 12975)	0.0089	(W/(m^2K^2))	Efficiency	90	(%)

Table 6. COP and ratio (R) between maximum and nominal thermal capacity of the heat pumps

$T_{Evaporator}$→	0 °C		5 °C		10 °C		15 °C	
$T_{Condenser}$	COP	R	COP	R	COP	R	COP	R
30 °C	4.6	0.89	5.5	1.06	6.5	1.23	7.7	1.41
35 °C	4.0	0.86	4.8	1.03	5.5	1.19	6.6	1.38
40 °C	3.6	0.84	4.2	1.00	4.8	1.16	5.6	1.33
45 °C	3.2	0.83	3.70	0.98	4.19	1.13	4.8	1.30
Nominal Thermal Power:Case A – 36kW, Case B and C – 48kW								

4. Results

The main objective of this work is to understand how it is possible to reduce the BHEs field in heating dominant building by the use of solar thermal collectors system. Table 7 outlines the main simulation results. As can be seen, the integration of solar energy is useful both to improve the performance of the heat pump and to inject the excess of heat into the ground when it is not needed. This allows to rechargethe ground in the long term, so the heat pump efficiency reaching up to a 30% increase in Montreal, where the seasonal COP ranges from 3.59 (for C1) to 4.70 (for C2). Looking at the results, it is evident that the most important consequence of using a SAGSHP system is the possibility to undersize the BHEs guaranteeing the same results in terms of seasonal COP of the heat pump. In detail, the BHE field can be reduced of 80% in Bolzano and Montreal and 70% in Stockholm. One negative point of this reduction is the increase and decrease of the maximum and minimum temperature of the heat carrier fluid during the years.The electrical costs due to the pumps were not evaluated in this work; however the results summarized also the hours of operation of the BHEs field and of the solar collector field.As it can be seen, the costs due to the pumps on the solar loop are balanced with a reduction of the time for the ground loop. The free-heating conditions occurred but their impact is not meaningful in all cases and it is less than 3% of the total heating demand of the building (see case C5).Figure 2 shows the profiles of the inlet temperatures of the heat-carrier fluid at the BHEs over the ten year period in Montreal for the common GSHP (the reference case C1) and the SAGSHP (Case C2); as expected, the inlet temperature at the BHEs decreased over the time when no heat was injected into the ground (Case C1).

Table 7. Results of the simulations for the three climate conditions

	Solar Field Loop				Ground Loop					Heat Pump + Building Loop				
	Tot. Sol. Radiation	Total Useful Heat	Efficiency	T_{max} heat carrier fluid	Heat Extraction	Hours of Operation	Heat Injection	Hours of Operation	T_{min} heat carrier fluid	Building Load	Heat Pump Load	Electrical Consumption	Seasonal COP*	Free-heating
	(MWh)	(MWh)	(-)	(°C)	(MWh)	(h/year)	(MWh)	(h/year)	(°C)	(MWh)	(MWh)	(MWh)	(-)	(MWh)
A1	-	-	-	-	51.69	1386	-	-	1	60.89	60.89	14.12	4.31	-
A2	200.13	120.41	0.60	60	27.78	356	112.87	1854	4		60.10	12.29	4.89	0.79
A3		112.20	0.56	73	27.08	616	102.92	2007	3		59.88	12.43	4.82	1.01
A4		103.25	0.52	86	26.62	1041	92.07	2142	-2		59.63	12.55	4.75	1.26
A5		95.51	0.48	96	25.24	1422	82.83	2543	-6		59.45	13.32	4.47	1.44
B1	-	-	-	-	70.81	5071	-	-	-1	85.11	85.11	21.61	3.94	-
B2	192.05	115.36	0.60	60	50.94	1277	109.22	1696	3		84.90	18.99	4.47	0.21
B3		107.86	0.56	64	48.99	2213	100.23	1778	-1		84.89	19.44	4.37	0.22
B4		100.41	0.52	77	45.67	2611	91.00	1884	-6		84.65	21.49	3.94	0.46
B5		93.54	0.49	88	41.08	2800	81.50	1981	-9		84.19	24.21	3.48	0.92
C1	-	-	-	-	72.24	6091	-	-	-2	89.87	89.87	25.08	3.59	-
C2	284.52	168.97	0.59	66	39.98	848	155.72	1574	2		89.05	18.95	4.70	0.82
C3		161.23	0.57	71	38.28	1147	146.02	1870	-2		88.89	19.14	4.65	0.97
C4		151.44	0.53	84	36.23	1448	133.70	2113	-6		87.83	19.90	4.42	2.04
C5		141.25	0.50	96	33.22	1642	120.43	2376	-9		86.51	21.41	4.05	3.36

* COP (Coefficient Of Performance) is the ratio between the heat provided by the heat pump (Heat Pump Load) and the Electrical Consumption over 10 years of operation. All the results are shown as mean values over 10 years of operation except for T_{min} and T_{max}.

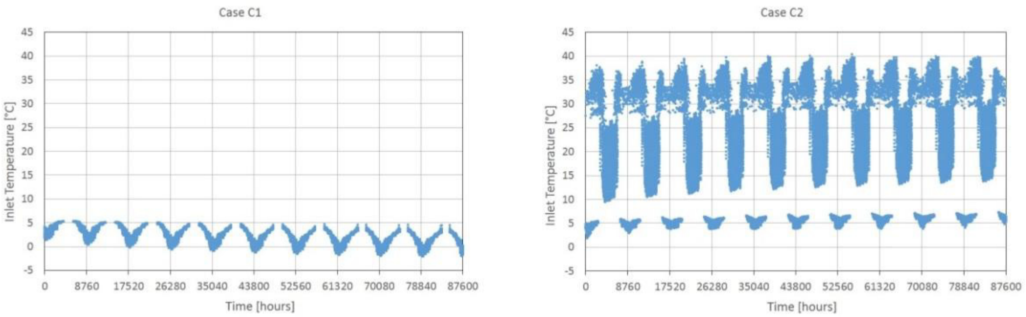

Fig. 2. The inlet temperatures of the heat-carrier fluid at the BHEs over the ten years period in Montreal.

5. Conclusions

The aim of this work is to analyze a ground source heat pump and solar thermal collector coupling in cold climates. The building load profile is usually heating dominated in these climates since the cooling demand is negligible in view of the low temperatures characterizing the summer season. In this scenario the ground is subject only to the extraction of heat for heating and the mean ground temperature therefore decreases during the years. Consequently, the heat pump performance also decreases.When solar thermal collectors are integrated, the total borehole length can be reduced, making the initial cost of installing the borehole more economic.

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Biography

Dr. Eng. Angelo Zarrella (PhD) works as Research Fellow at the Department of Industrial Engineering of Padua. He graduated in Mechanical Engineering and he achieved the Ph.D. in Applied Physics. He develops research activity basically in the sectors of energy efficiency of the built environment. He is author of several publications.