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Research Paper

Ground source heat pumps in high humidity soils: An experimental analysis

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HIGHLIGHTS

- A ground source heat pump (GSHP) was installed in Venice.
- A monitoring campaign of the building-plant system was carried on.
- High humidity and ground water favor the thermal rebalancing of the borehole field.
- The air source heat pump performances were investigated in the same operating mode.
- The study shows a clear superiority of the ground source vs the air source.

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ABSTRACT

This paper shows the results of a monitoring campaign on an invertible ground source heat pump (GSHP) with borehole heat exchangers installed in the historical center of Venice in the frame of the renovation of an ancient building where other renewable energy systems, such as solar energy systems, are not admitted because of historical preservation regulations. Despite the coastal position, the use of surface or ground water was not achievable in this case. In fact, the withdrawal from wells is absolutely forbidden in Venice, due to the risk of subsidence of the soil. In addition, as often happens in Venice, the internal channels next to the building have insufficient water flow rate. The experimental analysis highlights very satisfactory performance especially in comparison with the alternative use of air source heat pumps. The high humidity of the soil and the underground water flow present even in the surface layers of the soil promote the quick thermal rebalancing in the borehole field. For the same reason, although there is unbalance between the heat rejected in summer and the one extracted during winter, no consequent thermal degradation of the ground heat exchange is encountered.

1. Introduction

The present paper is aimed at the assessment of the actual performance of a GSHP system installed in Venice, hence coupled with a humid soil. Such an assessment originates from the results of an extensive and detailed monitoring campaign performed in a large historical building, recently refurbished and object of a previous simulation study by Schibuola et al. [1], and will include a detailed analysis about the beneficial influence due to the soil saturation and presence of underground water.

Many papers, such as [2–5], identify ground source heat pump (GSHP) systems among the most energy efficient technologies for HVAC (Heating, Ventilation and Air Conditioning). However, in everyday design, such systems still suffer from relevant differences between forecast simulations and actual performance monitoring. One important factor of uncertainty consists in the assessment of the actual soil conditions. One especial case regards GSHPs installed in humid soils, such as in the case of coastal cities in the Mediterranean basin. On this regard, Leong et al. [6] showed the major influence of the high humidity of the soil in the assessment of the performance of GSHPs. Leong et al. considered three different types of soil (sand, silty loam and silty clay) and five degrees of saturation (0, 12.5, 25, 50 and 100%) and computed the consequent performance of a GSHP system via detailed computer simulations. The results of the study by Leong et al. show that the performance of GSHP systems strongly depends on the moisture content, especially for degrees of saturation below 50%.

The importance of groundwater is confirmed by other studies, such as [7–9]. Sutton et al. [7] define a new ground resistance for use in existing vertical bore heat exchanger design algorithms, able to account for the added heat transfer mode of convection due to groundwater flow. The study shows that the resulting convection ground resistance differs relevantly from the usual conduction-only ground resistance. Gehlin and Hellström [8] compared three

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different models for the estimation of the heat transfer effect consequent to groundwater presence, showing large effects on the effective thermal conductivity calculated with each approach, in presence of groundwater. In [9], Diao et al. show the prominent impact of moderate groundwater flow on the heat transfer, however depending on the ratio between the groundwater velocity and the thermal diffusivity of the dry soil.

Moreover, the identification of accurate heating/cooling load profiles at the design stage would imply higher accuracy in energy assessments, through the definition of a reliable distribution of part load conditions throughout the year. Unfortunately, mere assumptions about actual occupation profiles and occupants' behavior are usually possible, and more accurate energy analyses are possible only when buildings are monitored. The importance of the distribution of part load conditions over a year in the assessment of GSHP performance is clearly shown by Magraner et al. [10]. Their study, performed by means of software TRNSYS [11], shows that simulation results solely based on nominal heat pump capacities and performance imply overestimations of the overall energy performance between 15% and 20%, whereas the accurate knowledge of heating/cooling load profiles and the consequent accurate simulation of part load conditions may decrease uncertainty down to around 5%. The amount of energy losses consequent to part load conditions depends by the kind of heat pump control: on–off, multi-stage or by inverter-driven compressor. In this regard, several studies have been carried out, such as [12–15], with contrasting results. While Zhao et al., in [12], show increased COP for GSHP provided with variable speed compressors and working under part load conditions, Karlsson et al., in [13] and [14], state that additional inefficiencies brought by the inverter hamper the actual achievement of high COP. On the other side, Cuevas et al. [15] declare that typical energy losses at the inverter, usually lower than 5%, are not able to damage the efficiency of inverter-driven compressors. The results of Zhao et al. and Cuevas et al. are indeed confirmed by studies behind Standard EN 14825 [16].

Furthermore, when referring to Mediterranean cities, the relevant cooling needs must be taken into account. As a matter of fact, the heat rejected into the ground, especially in the case of highly insulated buildings, might imply, on the long term, temperature drifts of the soil, thus resulting in reduced cooling efficiencies. In this field, Urchueguía et al., in [17], report an experimental assessment of GSHP performance in typical Mediterranean coastal climate. In particular the analysis in [17] contains a comparison between GSHP systems and air-water heat pumps involving the presence of a specially optimized water–water heat pump using propane (R290) as a refrigerant fluid. The same project produced also relevant results consequent to a robust monitoring campaign, 5 year long, presented in [18] by Montagud et al. The results contained in [18] focus on the evolution of the return water temperature from the ground and show that the system energy performance is maintained through the years with no appreciable impact on ground thermal response.

Moreover, the presence of groundwater and consequent advection and thermal dispersion phenomena imply relevant uncertainty in the assessment of GSHPs performance, as Casasso and Sethi showed in [19].

The assessment of the GSHP performance boost induced by high humidity soils may be useful in order to limit system oversizing and hence to increase the ratio performance/costs, thus allowing a larger spread of this technology. In this context, the optimum performance monitored in the GSHP system presented in this paper confirm the chance to avoid oversizing and increase the compactness of GSHP systems when installed in coastal cities, because of the fast thermal recovery of the soil.

The general building-plant system analyzed in this paper is introduced in Section 2, and Section 3 shows the details of the monitored GSHP system. Section 4 shows and discusses the results of the extensive monitoring campaign, then summarized in Section 5.

Fig. 1. Aerial photo of the Tolentini structure. (a) Longitudinal section. (b) Cross sections.

2. The building-plant system

Fig. 1 shows the South wing of the building. It was originally founded as a monastery, at the end of the 16th century, then, Napoleon, in 1806, converted it into barrack, military district and deposit. Since the 50s of the last century, the property is available to the University IUAV of Venice to become its main building. Fig. 2 shows longitudinal and transversal cross-sections of the building. The total heated volume is 9980 m^3, with a useful floor area equal to 1840 m^2. The relocation of the educational activity into other buildings has allowed an intervention to transform the second and third floors, previously used as classrooms, into library reading rooms. A very relevant operation, however, was the adaptation of new HVAC systems inside this historic building subject to heavy monumental protection restrictions. The new plant equipment replaced the previous heating system based on mere radiators.

In the reading rooms, the HVAC system consists of a primary air system from a dedicated air handling unit (AHU) and fan-coils appropriately masked in the furnishing and fed by hot or chilled water. In the main hall of the first floor, used as an Aula Magna (250 seats), the HVAC plant refurbishment provided a constant air volume (CAV) system with two AHUs. The HVAC systems are fully supervised by the building management system (BMS) which allows an easy interface with the user for controls and adjustments. In addition, the BMS measures and records all the data required to assess plant performance. This registration has allowed the authors to monitor the behavior of the geothermal system here reported.

3. The GSHP system

Fig. 3 shows the scheme of the plant, derived from a screenshot of the BMS. The thermal energy production is based on two invertible heat pumps operating in parallel:

- One water-to-water heat pump with a nominal capacity of 50 kW (41 kW in cooling), coupled with a ground heat exchanger with vertical borehole heat exchangers, and used as the main heat pump.
- One air-to-water heat pump with a nominal capacity of 183 kW (174 kW in cooling), used for back-up purposes.

Both the heat pumps are provided with multiple scroll compressors and R410A brine. In summer, partial recovery from the condensers of the machines takes place: in detail, the refrigerant gas at the compressor outlet is desuperheated in a heat exchanger (desuperheater) to feed the post-heating of the air handling units, thereby limiting the operation of existing boilers. Therefore, from the two heat pumps, two pairs of pipes originate, namely the primary circuit of the heating/cooling for the winter/summer period and the