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Experimental and modelling analysis of an office building HVAC system based in a ground-coupled heat pump and radiant floor

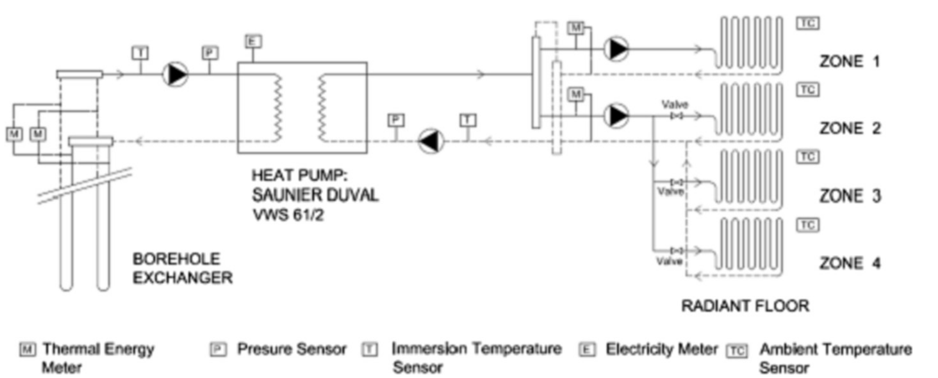
José Ignacio Villarino [a], Alberto Villarino [b,*], Francisco Ángel Fernández [c]

[a] Experimental Laboratory, Isbsol Company, C/Cerillo 7, 28490 Becerril de la Sierra, Madrid, Spain
[b] Department of Land and Cartographic Engineering, University of Salamanca, High Polytechnic School of Ávila, Hornos Caleros, 50, 05003 Avila, Spain
[c] Energetic Group. ETSII-University of Málaga, C/DoctorPedro Ortiz Ramos s/n, 29013 Málaga, Spain

HIGHLIGHTS

- A case study of a geothermal heat pump in an office building.
- A numerical model in EnergyPlus is validated by experimental results.
- An energy, economic and environmental analysis is presented.
- A comparison with other technologies demonstrates the potential of the system.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper shows the evaluation of the performance of a ground-coupled heat pump system monitored building providing heating, ventilating and air conditioning to an office building located in Madrid, in Spain. The system consists of one borehole exchanger, heat pump unit, radiant floor system, mechanical ventilation and data control system. A simulation model was performed with EnergyPlus software and validated. The analyzed period corresponds to the most unfavorable weather conditions in heating and cooling mode. The coefficient of performance obtained in heating and cooling mode was 3.86/5.29, considering all the energy consumption elements of the building and the thermal demand corresponding to an office operation. The CO_2 emissions obtained with a value of 34.68 kg corresponding to the period analyzed represents a low CO_2 emission system. The monitored temperatures reached set point values of 22 °C/25 °C, considered as acceptable comfort temperatures. The values obtained in the validated simulation model presented a deviation of 2% respected experimental results in heating and cooling mode. A comparative of COP_{sys} and CO_2 emissions with other technologies is performed in order to analyze GCHP compared to other available technologies. The GCHP system is presented as a technology that can fully supply the HVAC conditions for a building and environmentally friendly.

1. Introduction

Energy demand in buildings plays an important role in the European energy policy [1,2]. A sustainable development strategy has been implemented with the aim of promoting efficiency and

* Corresponding author.
E-mail addresses: jivillarino@unolab.es (J.I. Villarino), avillarino@usal.es (A. Villarino), franciscofh@uma.es (F.Ángel Fernández).

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Nomenclature

HVAC	heating, ventilating and air-conditioning
DHW	domestic hot water
CO_2	fossil carbon dioxide emissions (kg)
GCHP	ground-coupled heat pump
GHE	ground heat exchanger
RF	radiant floor
GWHP&GCHP	water source heat pump systems
AAHP&AWHP	air source heat pumps systems
B&S	boiler & split
COP_{sys}	system coefficient of performance
TRNSYS	transient systems simulation
GLHEPRO	ground heat exchanger software
MV	mechanical ventilation system
BHE	borehole heat exchanger
E_s	usable energy (kW h)
E_c	consumed electrical energy (kW h)
C_{ps}	factor for electricity ($kgCO_2$/kW h)
t_{ext}	outdoor air temperature (°C)
t_{int}	indoor air temperature (°C)
RH	relative humidity (%)
t_{hw}	hot-water temperature (°C)
t_{sr}	surface average temperature (°C)
P_r	dew temperature (°C)
R^2	coeff. of multiple determinations
LNTTS*i*	non-dimensional time ln(*T*/*Ts*)
GFNC*i*	G-function value
CTFs	conduction transfer functions

rational energy consumption in buildings [3,4]. Many renewable energy technologies have been developed to improve the efficiency of buildings and limit the use of fossil fuels in order to reduce emissions to the atmosphere [5,6]. For this reason it is necessary the encouraging of low energy consumption of heating, ventilating and air conditioning (HVAC) systems. In Spain, in 2010, the 51.5% of energy consumption in buildings was intended for HVAC, followed by 19.5% to domestic hot water (DHW), 19.4% equipment and 9.6% lighting. In the case of commercial buildings the percentage distribution is different, 58.4% HVAC, 3.6% DHW, lighting 21.1% and equipment 16.9%. The HVAC and DHW requirements are responsible of the 62% of the total energy consumption [7].

European directives dictate to Europe members states the laws, regulations and administrative necessary provisions to promote energy efficiency in buildings [8–10]. All buildings must have an energy performance certificate that evaluates the estimated fossil carbon dioxide emissions (CO_2) emitted by the final energy consumption of HVAC, DHW and lighting.

The HVAC system based in ground-coupled heat pump (GCHP) consists of a heat pump coupled with a ground heat exchanger (GHE) and radiant floor (RF) where the heat transfer fluid exchanges heat with the ground [11,12]. The GHE is a vertically drilled borehole with double U-tube and filled with cement, sand and bentonite. The GHE is drilled to a depth of 100 m. The ground is used like a heat source in heating mode and as a heat sink in cooling mode [13–15].

Many studies performed the operation of GHE from theoretical and simulation models [16–17] or in situ monitoring different variables [18–21]. Other researchers have investigated the experimental operation performance of HVAC systems based in GCHP. Dashamir Marini [22], using simulation results, demonstrates that water source heat pump systems (GWHP & GCHP) have higher performance than air source heat pumps systems (AAHP&AWHP) and boiler & split system (B&S). It was found that in Milan, AAHP&AWHP heat pump systems save 14.8% and 23.3% primary energy respectively compared to the B&S system, while GCHP and GWHP systems save 59.6% and 62.6% respectively. Sebarchievici et al. [23], in an experimental GCHP system, demonstrate the higher coefficient of performance (COP_{sys}) using an automatic control device for circulating pump speed versus a classical adjustment case (COP_{sys} 7–8% higher and 7.5–8% lower CO_2 emission level). When the circulating pump speed control system is operating, electricity savings and a reduction of CO_2 emissions of the 3% for building heating and 5% for building cooling were obtained at the same time with DHW production. In another research, Dan et al. [24], using transient systems simulation tool (TRNSYS) develop two numerical simulation models of useful thermal energy and COP_{sys} in heating mode, analyzing the results obtained and compared with the experimental data. The study shows that radiator system and radiant floor (RF) system have small differences (4.5%) in their COP_{sys} value, but the ON/OFF switching in the case of radiator system is almost three times higher than RF. In addition, there was 10% higher energy consumption and CO_2 emissions for the radiator system compared with the floor heating system under the same operating conditions.

Montagud et al. [25], make an evaluation of the performance of a GCHP system monitored plant since 2005, providing heating and cooling for an office building, using for the design GLHEPRO software and TRNSYS for the heat pump model built. The ground has a stronger recovery capability than expected when compared with GLHEPRO. The consumption of the heat pump was well predicted by the heat pump model developed in TRNSYS, presenting an average deviation of 2% respected experimental measurements. Cacabelos et al. [26], calibrate a simulation model following for a public library HVAC system with a GCHP and RF, using TRNSYS software. The system reduces the mean bias error and the coefficient of variation of the root men squared error below 5% and 12% respectively, by concentrating principally on the energy consumption of the system.

The present study focuses on the thermal analysis of an experimental building through the performance of a simulation model. The building is located in Madrid, Spain, and consists in a GCHP, RF and mechanical ventilation system (MV) to ensure the indoor air quality. Additionally, a numerical model simulation is developed using EnergyPlus software and validated. Finally the simulations obtained in EnergyPlus are analyzed and compared to experimental results. The main performance parameters (energy efficiency, CO_2 emissions) are calculated of the GCHP system and a comparative analysis with other technologies (Natural Gas, Diesel, Biomass) is performed to position the GCHP technology. The adverse periods for heating and cooling are analyzed in detail.

2. Description of the experimental system

2.1. Building

The experimental analysis was developed in a building of 189 m^2 floor area, and includes a reception, office room, meeting room, archive room, rest room, bathroom and test room (Fig. 1). The office is located in Madrid, Spain, latitude +40.7° and longitude −3.99° and altitude of 1.075 m above sea level in a continental