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HYBRID NATURAL VENTILATION & PERSONAL COMFORT SYSTEM APPROACH TO IMPROVE THE ENERGY EFFICIENCY OF COOLING-DOMINATED OFFICE BUILDINGS

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Keywords

Energy efficiency, Heat pump, Energy piles, Natural ventilation, Personal comfort systems, Thermal simulation

Abstract

Ground-source heat pump (GSHP) systems have been upheld as a possible alternative to the more conventional use of air-source heat pumps (ASHP) for the provision of renewable heating and cooling, due to the expected higher coefficient of performance (COP) that should result from lower variation in underground temperatures compared to air temperatures. Further, the use of building foundation piles as heat exchangers has been advanced to decrease capital costs by reducing or eliminating the cost of borehole heat exchangers. Unbalanced heating and cooling loads are a significant challenge to the use of shallow geothermal energy (SGE) systems however. In cooling-dominated scenarios, this imbalance can result in a build-up of heat in the ground, which decreases the heat pump's COP and increases energy consumption, and may result in failure through overheating of the system. Thus, low-energy and renewable solutions that reduce the unbalanced loads are required to improve overall efficiency. Natural ventilation (NV) is a possible solution, as previous studies have shown that the use of wind and temperature difference driven airflow can significantly reduce cooling energy needs. Another approach is the use of personal comfort systems (PCS), such as localized cooling devices (ceiling fans, in particular), which allow building occupants to tolerate higher indoor temperatures and have a twofold effect on cooling energy needs: the centralized cooling system can operate from a higher temperature threshold, and NV can be over a larger outdoor temperature range, which increases its availability and further decreases the need for mechanical cooling. In this study, a hybrid GSHP+NV+PCS solution is proposed to improve the heating and cooling energy efficiency of an office building in three cities in Portugal: Lisbon, Porto and Faro. Building energy simulations in these three cities revealed a significant imbalance in heating and cooling needs with the latter representing around 99% of the thermal load. In order to assess the energy performance of the proposed hybrid approach, four technology scenarios were used, in order to compare the effect of the use of GSHP and of the combined use of NV and PCS, relative to the more commonly used ASHP: (1) ASHP; (2) GSHP; (3) ASHP+NV+PCS hybrid; (4) GSHP+NV+PCS hybrid. A 50-year simulation showed the use of a GSHP system alone was not possible, as the unbalanced loads result in an excessive ground heating which limits the cooling load coverage and negatively impacts the GSHP system's COP, which increases electricity use by 7 to 8 %, relative to Scenario (1). The combined use of NV and PCS significantly decreases the building cooling load (96 to 97 %). With the ASHP (Scenario (3)), this results in an 86 to 89 % decrease in electricity use. In Scenario (4), energy use by the GSHP and ceiling fans is 92 % to 94 % lower than the sole use of the ASHP in Scenario (1). This scenario allows the GSHP to fully cover the cooling load and limits the temperature increase in the ground to 5.0 to 5.3 °C. These results show that a hybrid GSHP+NV+PCS solution can lead to significant savings in cooling-dominated scenarios and, therefore, should be considered as a possible approach for those cases.

1. INTRODUCTION

The ever-growing need for low-energy solutions within the building energy sector has encouraged the development of innovative solutions for heating and cooling that breakaway from the currently conventional use of air-source heat pumps (ASHP) [1]. Ground-source heat pumps (GSHP) have been recognized as a possible alternative as their coefficient of performance (COP) is expected to be higher, due to the lower variation in underground temperature in comparison with the variation found in the outdoor air used by ASHP. However, despite lifecycle analysis showing lower overall costs for GSHP systems, their widespread use has been hindered by high capital costs [2]. One possible solution to decrease these capital costs is the use of building foundation piles in place of purpose-drilled boreholes. In the first instance, the primary function of the foundation piles is to ensure the safe transfer of the building loads to the ground and this cannot be compromised, and it is usually not economic to adjust their design (e.g. increase length) to optimise heat exchange therefore there can be situations where the full thermal load cannot be managed through foundation heat exchangers alone, although this is readily managed through the introduction of supplemental technologies or by adding borehole heat exchangers, for example the development at One New Change, London, utilises a combination of thermally-activated piles and an open-loop well system to manage the heating & cooling loads [3]. Nonetheless, these are structural elements that are mainly designed for load bearing, potentially resulting in limited coverage of the thermal load [4, 5]. Unbalanced heating or cooling loads are a significant challenge, and in cooling-dominated scenarios, which will be addressed here, excessive cooling demand can result in a build-up of heat in the ground over time, which decreases the efficiency of the heat pump and, ultimately, increases energy consumption [6].

Low-energy solutions that reduce the heat imbalance are crucial to increase the adoption of GSHP systems. One approach consists of distributing the cooling load between the GSHP and another cooling system, e.g. evaporative cooling systems, such as cooling towers [7] and dry-fluid coolers [8], which lower the heat rejected into the ground and, consequently, the overall imbalance. Another approach is nocturnal heat radiative cooling, which dissipates built-up heat in the ground through radiation during the night [9]. This study focused on reducing the thermal load imbalance by decreasing the overall cooling load, through two approaches: natural ventilation (NV) and personal comfort systems (PCS). Previous studies have shown that the use of wind and temperature difference-driven airflow can significantly reduce the cooling load [10, 11] and that localized cooling devices, such as ceiling fans, allow building occupants to tolerate higher indoor temperatures [12]. The use of ceiling fans as PCS results in a twofold effect on cooling energy needs: (i) the centralized cooling system can operate with a higher temperature threshold and (ii) NV can be used with higher outdoor temperatures, which increases its range of seasonal availability and further decreases the need for mechanical cooling [12]. In this article, a hybrid HVAC system that combines a GSHP system (with piles providing ground heat exchange) with both NV and PCS is proposed. Detailed thermal simulation of an office building is used to predict the thermal performance of the hybrid system in three Portuguese cities, and to compare these results with those of the more commonplace ASHP-based HVAC system. The following section describes the simulation model and the proposed HVAC solutions, while the subsequent sections present the results and analysis, and the conclusions of this study, respectively.

2. METHODOLOGY

This study used EnergyPlus [13], which is an open-source building thermal simulation software, to run a previously validated building simulation model [10-12]. This model is based on the Medium Office Model of the standard United States Department of Energy Commercial Reference Buildings dataset [14], which was modified order to improve its passive thermal behavior. Shading fins and low-emissivity double-glazing windows were added to reduce cooling needs. The floor plan was altered to allow ventilative cooling in the entirety of the office spaces [15], as shown in Figure 1. Occupation, lighting and other electric equipment were modeled according to typical or regulatory values [15-18]. Although the simulation model was based on a dataset of United States buildings, compliance with Portuguese regulations was nonetheless assured [19].

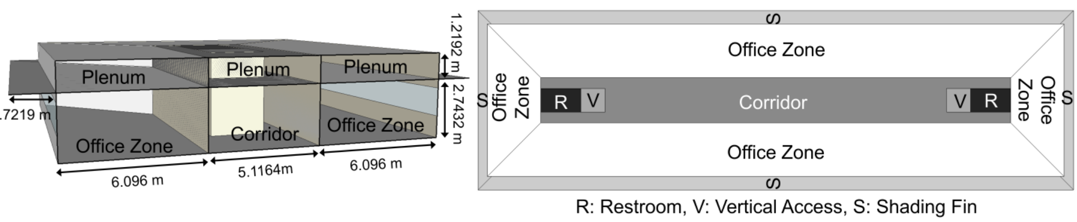

Figure 1. Building simulation model section cut (one floor) and simulation zones

A single building level was run in the simulation, with periodic boundary conditions created by connecting the floor and ceiling surfaces. This is a conservative approach (assuming a well-insulated top level), which simplifies the simulation by foregoing a more detailed analysis at both the lowest and uppermost floors [20]. The total energy demand can be obtained, in post-simulation analysis, by simple multiplication by the number of floors, which in this study was ten. The building energy simulations were run using typical mean year (TMY) weather data for the three Portuguese cities: Lisbon, Porto and Faro [21, 22]. The climate in all three cities was similar, with mild winters, and warm (in Porto) or hot summers (in Lisbon and Faro) [23]. With these climate profiles, low heating needs were anticipated with the cooling loads dominating thermal energy needs in all three cities, albeit not as high in Porto. The model's HVAC system is shown, schematically, in Figure 2. An air handling unit (AHU) with an integrated heat pump supplied both the outdoor fresh air and the heating and cooling load that was required to keep the indoor environment within standard comfort conditions, at each simulation time step [24]. Ceiling fans were used as PCS to supplement centralized cooling [25], while automatically-controlled openable windows allowed for naturally ventilated airflow into the building. The HVAC system was assumed to operate during weekdays only, between 08:00 and 18:00 [17]. At night, during weekends and holidays, the AHU and ceiling fans were shut off, while NV was available at all times.

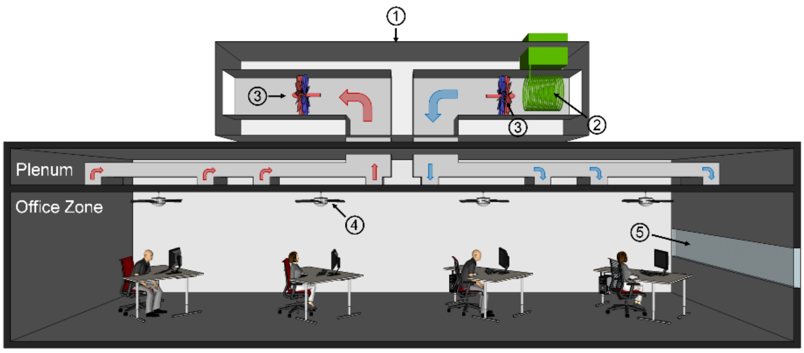

Figure 2. HVAC layout: (1) Rooftop air handling unit; (2) Heat pump and heat exchanger; (3) Fans; (4) Ceiling fan; (5) Window

This study used four heating and cooling scenarios: (1) ASHP, The heat pump exchanges heat with the outside air; (2) GSHP, The heat pump exchanges heat with the ground, through energy piles; (3) ASHP+NV+PCS, natural ventilation and personal comfort systems (ceiling fans) are used together, to decrease the load required of the ASHP; (4) GSHP+NV+PCS, natural ventilation and personal comfort systems (ceiling fans) are used together, to decrease the load required of the GSHP. For each scenario, a 10 % heat loss was considered in the heat distribution system. Final energy (electricity in this study) was calculated as the quotient between these increased thermal loads and the heat pump's COPs (calculated as described in the following subsections), which is increased by 10 %, to account for the power consumption of the fluid distribution pumps. Finally, in Scenarios (3) and (4), the power consumption of the ceiling fans was also added to obtain the total electricity needs [10-12].

2.1. SCENARIO (1): ASHP

A generic air-source heat pump was used to keep the building's indoor temperature between 20 and 26 °C, to ensure a predicted mean comfort vote (PMV) between –0.5 and +0.5 [24]. The ASHP's COP was calculated through post-simulation analysis as a function of its condenser and evaporator temperatures and of its efficiency (Equations (1) and (2)) [10-12]. This efficiency is defined as the ratio between the heat pump's actual COP and that of an ideal Carnot engine, and was considered to be 40 %, for both heating and cooling [26]. The condenser and evaporator temperatures were defined as a function of the heat distribution fluid and the outdoor air temperatures, as shown in Table 1 [10-12]. The calculated COPs are then applied to the respective heating and cooling loads in order to calculate the required electric energy.

Table 1. Heat pump fluid temperatures

Temperature	Heating	Cooling
Distribution, T_{dist} [°C]	45	5
Condenser, T_{cond} [°C]	T_{dist} + 5	T_{out} + 5
Evaporator, T_{evap} [°C]	T_{out} – 5	T_{dist} – 5

$$COP_{heat} = \psi_{heat} \times \frac{T_{cond}+273.15}{T_{cond}-T_{evap}} \qquad (1)$$

$$COP_{cool} = \psi_{cool} \times \frac{T_{evap}+273.15}{T_{cond}-T_{evap}} \qquad (2)$$

2.2. SCENARIO (2): GSHP

In this scenario, the ASHP is replaced by a GSHP that also keeps the indoor temperature between 20 and 26 °C. The COP was calculated by using the EnergyPlus hourly thermal load results as inputs to a long-term (50 years) energy pile simulation in PILESIM2.1 [5, 27]. This often considered benchmark analysis tool uses a computationally efficient hybrid analytical-numerical modified version of the duct ground heat storage method (DST): local heat flow between the heat exchangers and the storage volume is modeled analytically, while finite differences are used for the global heat flow, i.e. the flow between the heat storage volume and the undisturbed ground [28]. The energy pile simulation model consisted of 27 foundation piles, which were 30 m long, had a diameter of 90 cm and were placed an average of 8.5 m apart from each other [29]. A 4-U tube pipe configuration was used to circulate the heat distribution fluid within the piles. The heat pump's efficiency and heating fluid distribution temperature were kept unaltered at 40 % and 45 °C, respectively. However, the cooling fluid distribution temperature was increased to 15 °C, a more common value for this type of system [30]. The aforementioned imbalance between the heating and cooling loads can lead to excessive heat buildup in the ground, which in turn results in the heat distribution fluid reaching excessively high temperatures. In order to avoid potential damage, such as high-pressure damage failure in the compressor, a fluid distribution temperature set point was set to 50 °C, above which the GSHP is shut down. Any remaining load was considered to be supplied by a supplementary ASHP, with the average COP obtained in Scenario (1) used to calculate its electricity consumption [29].

2.3. SCENARIOS (3) AND (4): NV+PCS

EnergyPlus was used to model hybrid natural-mechanical ventilation: within the simulation, for each office thermal zone and at each time step, the windows were automatically opened, allowing wind and buoyancy-driven airflow into the building [31]. This use of natural ventilation replaced the AHU and heat pump whenever the indoor temperature was between 10 °C (to avoid overcooling [32]) and the indoor air temperature. During unoccupied periods (at night and during weekends and holidays), when the AHU was already inactive, NV was still used, with the same temperature constraints. Ceiling fans were used as personal comfort systems, with one fan placed above each working station. The availability of PCS allowed an increase of the cooling set point to 30 °C [25], with all fans in operation whenever the indoor air temperature was between 26 and 30 °C, irrespective of the use of either the AHU or NV for cooling and mechanical ventilation. These operation parameters of the PCS were selected in order to maintain the PMV between –0.5 and +0.5 [25]. This hybrid system was expected to decrease the cooling load, without significantly affecting the heating load. The electricity consumption of Scenarios (3) and (4) were calculated through the methods of Scenarios (1) and (2), respectively.

3. RESULTS AND ANALYSIS

3.1. ENERGY PERFORMANCE

The annual heating and cooling loads for each scenario and city can be seen in Figure 3.

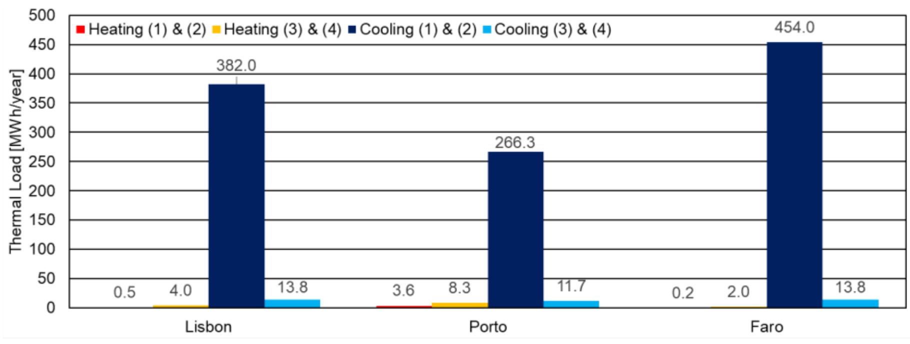

Figure 3. Annual heating and cooling loads without NV or PCS (Scenarios (1) & (2)) and with NV+PCS (Scenarios (3) & (4))

Table 2. COP for each scenario, fraction of thermal load covered by GSHP, and ground temperature increase after 50 years

City	Scenario	Heating COP	Cooling COP	Heating Load Covered	Cooling Load Covered	ΔT Ground [°C]
Lisbon	(1)	2.51	3.65	–	–	–
	(2)	4.34	3.32	100 %	72 %	23.4
	(3)	2.96	1.47	–	–	–
	(4)	4.35	5.75	100 %	100 %	5.0
Porto	(1)	2.45	4.15	–	–	–
	(2)	4.17	3.77	100 %	94 %	20.9
	(3)	2.61	3.40	–	–	–
	(4)	4.16	6.97	100 %	100 %	5.0
Faro	(1)	2.55	3.62	–	–	–
	(2)	4.15	3.20	100 %	60 %	23.6
	(3)	2.74	1.27	–	–	–
	(4)	4.24	5.11	100 %	100 %	5.3

In all three cities, without the use of either NV or PCS, the thermal load is nearly exclusively (above 99 %) for cooling: 382, 266 and 454 MW h/year in Lisbon, Porto and Faro, respectively, while heating is only 0.4, 3.6 and 0.2 MW h/year. With the use of NV and PCS, the cooling load decreases significantly (96 to 97 %). Although the NV+PCS approach was designed to decrease the cooling load without affecting the heating load, a minor increase occurred, nonetheless. This is due to the pre-cooling of the building thermal mass during the unoccupied period, which reduces the cooling load of the initial hours of each building operation day. Internal heat sources require a few simulation time steps to begin heating the thermal mass, during which the HVAC system is required to supply a small but non-zero heating load. For each scenario, the heat pump's heating and cooling COPs are shown in Table 2, which also presents the fraction of the thermal load and the increase in ground temperature over 50 years, for Scenarios (2) and (4). For these two scenarios, the presented COP does not account for any supplementary use of the ASHP, while for both hybrid scenarios, (3) and (4), the COP does not account for the electricity use of the PCS. As shown, the very low heating loads of these two scenarios are supplied without any limitations. Further, the build-up of heat in the ground that results from the imbalance between the heating and cooling loads leads to an increased heating COP for these GSHP scenarios, relative to those that use the ASHP.

The cooling COP decreases significantly between Scenarios (1) and (3). Despite the decrease due to the use of NV+PCS, the remaining load occurs when outdoor temperatures are highest (above 30 °C), which leads to lower cooling COPs. A decrease in cooling COP is also found between Scenarios (1) and (2). Although the cooling distribution fluid's temperature was increased, this is countered by the increase in ground temperature over the 50 years: 23.4 °C in Lisbon, 20.9 °C in Porto and 23.6 °C in Faro. In addition to the inefficient operation of the GSHP, these high temperatures result in shutdowns of the GSHP, to avoid carrier fluid overheating and subsequent equipment damage, which results in the GSHP only partly covering the required cooling load: 72 %, 94 % and 60 % in Lisbon, Porto and Faro, respectively. While the GSHP is turned off, some of the built-up heat is allowed to dissipate, but the correlation between heat build-up and COP becomes unpredictable. In Scenario (4), the lower cooling load and, consequently, the lower imbalance between heating and cooling decreases the build-up of heat in the ground to an additional 5.0 °C in Lisbon, 5.0 °C in Porto and 5.3 °C in Faro. These results fall within acceptable temperature changes (5 to 10 °C) that are required in some jurisdictions to maintain groundwater quality [33]. The lower heat build-up allows full coverage of the cooling load and also carries a lower penalty on the cooling COP. As can be seen in Table 2, cooling COPs are highest in Scenario (4).

3.2. ELECTRICITY CONSUMPTION

The average annual electricity consumption for heating and cooling is shown in Figure 4. In the case of Scenarios (2) and (4), this is a simple mean of the yearly consumption over the analyzed 50-year period. Expectedly, the lower COP of Scenario (2) results in a 7 to 8 % increase in electricity consumption, relative to Scenario (1). Nonetheless, this decrease is limited by the partial use of the ASHP, which replaced the GSHP when the ground became too hot. In Scenario (3), the total electricity consumption decreases by 86 % in Lisbon, 89 % in Porto and 87 % in Faro. This decrease is lower than that of the thermal cooling load due to both the decreased cooling COP as well as the consumption of the ceiling fans, which account for 29 %, 14 % and 30 %, respectively, of the total electricity used for heating and cooling. In Scenario (4), the higher COP further increases electricity savings for heating and cooling: 92 % in Lisbon, 93 % in Porto and 94 % in Faro, relative to Scenario (1). However, these savings are still limited by the electricity consumption of the ceiling fans, which are now a higher fraction of the total electricity used for heating and cooling: 56 %, 22 % and 61 % in Lisbon, Porto and Faro, respectively. When compared to Scenario (3), the energy savings are 48 % in Lisbon, 38 % in Porto and 51 % in Faro. These results show that the combined use of NV and PCS can help overcome the issues that result from built-up heat in the ground and which limit the efficiency of the GSHP.

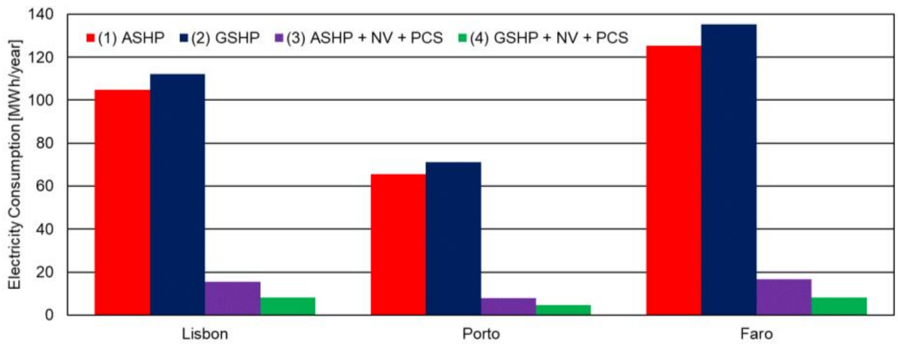

Figure 4. Average annual electricity loads

4. CONCLUSIONS

In this study, a hybrid GSHP+NV+PCS system was proposed to improve HVAC efficiency in a cooling-dominated office building in three Portuguese cities. Detailed building energy simulations were used to compare the energy performance of this proposed solution to three other approaches: the more commonly used ASHP, GSHP with energy piles without hybridization, and hybrid ASHP+NV+PCS. Without hybridization, the results show that GSHP with piles cannot fully supply the required cooling thermal load, due to excessive build-up of heat in the ground, which in turn is the result of the significant imbalance between the heating and cooling loads. Ground temperature increases by 20.9 to 23.6 °C over 50 years, which significantly hinders the GSHP's COP and increases electricity consumption. On the other hand, heating COP is increased, which decreases the electricity consumption of the already minute heating energy needs. Overall, direct replacement of the ASHP with a GSHP increased annual electricity consumption by 7 to 8 %.

The combined use of NV and PCS (ceiling fans) decreases the cooling load by 96 to 97 %. However, the remaining cooling load coincides with high outdoor temperatures, which, in the case of the ASHP, leads to low cooling COPs. These low COPs, together with the power consumption of the ceiling fans (14 to 30 % of the total electricity consumption), limit the electricity savings of this hybrid ASHP+NV+PCS approach to 86 to 89 % relative to the more commonplace ASHP solution. The GSHP+NV+PCS hybrid solution was the best of the analyzed approaches, as the lower imbalance between the heating and cooling loads decreases the build-up of ground temperature: 5.0 to 5.3 °C, over 50 years. This lower build-up of heat benefits the COP of the heat pump, which improves relative to the baseline ASHP approach. Despite the energy consumption of the ceiling fans, this scenario leads to a 92 % to 94 % decrease in annual electricity needs. Future work will focus on other approaches to avoid excessive build-up of heat in the ground, through other optimization approaches or additional hybrid HVAC technology, such as evaporative cooling or the use of earth-air heat exchangers. Nonetheless, the increase in efficiency and decrease in energy needs indicate that the hybrid GSHP+NV+PCS approach should be considered as a possible solution to cooling-dominated scenarios.

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