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Improving the energy efficiency of ground-source heat pump systems in heating dominated school buildings: A case study in Belgium

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ABSTRACT

A ground-source heat pump system in combination with different low temperature heating systems was installed in a new school building in Belgium. During the first two years of operation, measurement data indicated that the difference between heating and cooling load could affect the long term thermal stability of the ground storage and thus may result in poor energy efficiency of the GSHP system. This paper describes two low-cost measures that can be taken in order to reduce or prevent such unfavourable conditions. The school building and HVAC system were modeled and on-site measurement data was used for validation. First, the HVAC system was optimized by integrating an additional cooling coil in the exhaust airflow of the air handling unit in order to recuperate waste heat from the exhaust ventilation air. Additionally, the effect of passive cooling during summer holidays on the annual energy balance was investigated. Results indicated that heat recuperation of the exhaust ventilation air and passive cooling of the school building during weekends and summer holidays are complementary and contribute to a more stable ground temperature, consequently significant energy savings can be achieved.

1. Introduction

The energy efficiency of new buildings has increased rapidly over the last decade. Measures to improve the thermal insulation have resulted in a reduced heating load of new or renovated buildings. As a result, the energy consumption of school buildings in Belgium decreased by more than 13% over the period 2009–2013 [2].

In this context, ground-source heat pump systems (GSHP) offer great advantages over traditional heating and cooling systems as they can contribute to significant energy savings and an improved indoor climate [1,3–5]. Moreover, thermal comfort and air quality in classrooms have a large impact on the teaching and learning process in schools [6–8].

In general, better energy performance can be achieved when GSHP systems are applied in moderate-climate regions since the heating and cooling loads of buildings are more balanced over a year period [9–13].

In school buildings however this can be different since there are many holiday periods, in particular during the summer, a period which typically has the highest cooling loads. During summer holidays most school buildings are unoccupied and the HVAC system is disabled, therefore a large part of the heat cannot be rejected to the ground. Moreover, if additional passive cooling techniques (e.g. sunscreens, building overhangs or night ventilation) are used, they can affect the annual energy balance and long term stability of the ground temperature.

In these circumstances hybrid ground source heat pump systems (HGSHP) can prove to be advantageous [4,14,15]. HGSHP systems use an additional thermal energy source (e.g. outdoor air) in addition to a regular GSHP system. These HGSHP systems can be used in heating and cooling systems with a significant thermal imbalance since they are able to reject or extract the necessary energy from the secondary energy source [11,14]. However, HGSHP systems often use a dedicated cooling tower which can be difficult to incorporate in the built environment or to retrofit in an existing GSHP system. In addition, it raises investment and maintenance costs and increases the complexity of the system. Although many researchers have addressed the energy efficiency of GSHP systems in residential and office buildings, only very little research has been done on the use of low temperature GSHP systems in school buildings illustrated with on-site measurements. These barriers, in combination with the lack of knowledge on low temperature heating systems in class rooms can prevent widespread implementation of GSHP systems and in particular HGSHP systems in school buildings.

Wang et al. [5] investigated the energy performance of a single classroom in a school that meets the passive standard in Germany

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Nomenclature

$\dot{Q}_{dry}$	dry coil heat transfer
ϵ_a	air-side heat transfer effectiveness
ω_s	humidity of saturated air
C	ratio of air to water capacitance rate for dry analysis
C_{pm}	constant pressure specific heat of moist air
C_{pw}	constant pressure specific heat of water
C_s	average slope of saturation air enthalpy versus temperature
h_a	enthalpy of moist air per mass of dry air
h_{fg}	heat of vaporization for water under reference conditions
h_s	enthalpy of saturated air per mass of dry air
m	ratio of air to water effective capacitance rate for wet analysis
m_a	mass flow rate of dry air
m_w	mass flow rate of water
Q	overall heat transfer rate
q_a	air humidity ratio
T_a	air temperature
T_{dp}	air dew point temperature
T_s	surface temperature
T_w	water temperature
x	point on coil where condensation begins

Abbreviations

AHU	air handling unit
BAU	business as usual
BMS	building management system
BTES	borehole thermal energy storage
COP	coefficient of performance
EAHE	exhaust air heat exchanger
GSHP	ground-source heat pump
HGSHP	hybrid ground source heat pump systems
NTU	overall number of transfer units
PCSH	passive cooling during summer holidays
RMS	root mean squared
TLC	thermal load coverage
TRT	thermal response test
UA	overall heat conductance

Subscript

a	air stream conditions
dry	dry surface
e	effective
o	outlet or outside conditions
s	surface conditions
w	water stream conditions
wet	wet surface

and found that the heat recovery rate of the ventilation unit accounts for the major part of the work for heating. Also night ventilation can greatly reduce the need for active cooling during the day taking into account the local climate conditions. Pre-ventilation in the morning before classes begin can have a positive impact on the indoor air quality but can also reduce energy demand for heating or cooling. Furthermore the thermal comfort in the passive school with optimized HVAC control system improved. Nearly all measurement data was within the comfort zone in winter heating or summer cooling periods.

The energy consumption of similar schools with and without GSHP systems in the Lincoln, Nebraska, Public School District was investigated by Shonder et al. [16]. They compared a dataset of seven schools with comparable ventilation delivery and percentage of floor space cooled and found that the school using a GSHP system consumed 26% less energy per square foot per year than the schools without GSHP system. Although 12% of the schools in the district use less energy per square foot than the GSHP schools, most of these schools cool less than 15% of their floor area and deliver less ventilation air in contrast to the GSHP schools where the total floor area is cooled.

Thewes et al. [17] reported on the energy consumption of school buildings in Luxembourg and found that there is still potential to decrease their heating demand. This was established by the large variation on the specific heat demand which was on average 93 kWh/m^2 compared to the best practice of 50 kWh/m^2. In contrast, the mean electricity consumption increased in the new school buildings, probably as a result of the presence of kitchen canteens, PC's, video projectors or the use of mechanical ventilation systems in new low-energy and passive schools.

A review on the current building energy assessment methods used in a regulatory context in Flanders was presented by Wauman et al. [18]. They found that certain preset values used in this context (e.g. use of artificial lighting and equipment, ventilation characteristics, internal heat gains) were sometimes inaccurate or unrealistic. They redefined boundary conditions that approach real conditions more accurately and are adapted to the use and typology of the building based on collected field data and monitoring results from school buildings in Flanders. The users' and load profiles, comfort settings and the occupant density rate of the classrooms were found to be the most dominant parameters.

Dallo et al. [19] investigated the energy performance of 49 school buildings in Italy. They performed a simplified energy audit in order to verify the energy quality of the buildings and to define strategies for improving energy efficiency. The study demonstrated that it is difficult to reach a high level of energy efficiency according to the EPBD directive and that it was not cost-effective in many cases.

Capozzoli et al. [20] designed two types of estimation models that allow to estimate the energy consumption of school buildings in the North of Italy.

A sample of 60 schools in Italy was studied and used to validate cluster analysis in order to develop strategies for an extensive refurbishment according to a cost optimal approach [21].

A method for allowing a quick assessment of cost-optimal decisions for renovations of school buildings was presented by Stocker et al. [22]. The study was based on existing school buildings in the Alps and showed a cost optimal annual energy consumption between 50 and 60 kWh/m^2. The building age and compactness have a high impact on the results.

In this paper the performance of a GSHP system in combination with low temperature heating in a school building in Belgium is described. Two low-cost measures for improving the energy efficiency of GSHP systems in heating dominated school buildings are investigated. On-site measurement data is used for model validation.

2. School building and HVAC operation strategy

2.1. Building description

The school building is located in Veurne, in the northwest of Belgium, at a distance of 7 km from the North Sea. The construction works started in 2010 and were completed in 2013. The new building consists of 2 floors with 16 class rooms, a teachers room, storage rooms and several other rooms. An overview of the room surfaces, set point temperatures and air flow rates is given in Table 1. These air flow rates are based on the design flow rates and the extraction and pulsation flow rates at each valve were calibrated when