OPTIMIZING THE OPERATION OF EARTH-TO-AIR HEAT EXCHANGERS IN HIGH-PERFORMANCE VENTILATION SYSTEMS FOR LOW-ENERGY BUILDINGS – A CASE STUDY

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ABSTRACT

Earth-to-air heat exchangers are energy-efficient systems that use the ground for cooling in summer and heating in winter. Design, simulation and planning tools are available in the market, and earth-to-air heat exchangers are well-accepted in the built environment. Furthermore, there is a wide knowledge on their performance in operation. Based on long experiences in the design and operation of earth-to-air heat exchangers, pre-defined operation strategies are applied in ventilation concepts. In ventilation concepts with highly efficient heat recovery systems, optimized operation strategy should optimized rather in a combined optimization of air-handling unit and earth-to-air heat exchanger than a single optimization of the earth-to-air heat exchanger.

The study is based on monitoring data from a sports hall which was built in Passivhaus style. The heating and cooling concept is based on thermo-active building systems which are supplied by a ground-coupled absorption heat pump. The supply air is heated in winter and cooled in summer by an earth-to-air heat exchanger. The air-handling unit is directly coupled to the earth-to-air heat exchanger without bypass option and doesn't contain any additional heating or cooling.

A coupled plant-and-building simulation model is set up for the design and development of an optimized operation strategy. The model is developed in the R program.

A monitoring campaign in summer is used for the model validation. The simulation models is based on the simple-hourly-method building model according to ISO 13790, a simplified heating and cooling system, a characteristic-line model for the heat recovery system, and a detailed earth-to-air heat exchanger model. The building is controlled by a building-energy-management-system (BEMS) which is modeled according to the current operation (for model validation) and is used for the optimization of the operation strategy.

The improved control strategy takes the indoor temperature and the outdoor temperature into account. The outlet temperature is not suitable as input for the control strategy since the monitoring value is only indirectly available in operation.

KEYWORDS

earth-to-air heat exchanger, passive house, model

1 INTRODUCTION

The atmospheric air thermal inertia is lower than that of the soil. The thermal energy accumulated in the soil can be used through an earth-to-air heat exchanger (EAHE) consisting in one or more tubes buried in the ground. The air entering the tube is heated in winter and cooled in summer, due to the temperature difference between the incoming outdoor air and soil. Using this type of renewable energy, the energy consumption required by a buiding can be reduced (Zhao, 2004). Several simple EAHE design solutions exist, such as single pipe EAHEs (Badescu, 2007) and two-pipe EAHEs (Bojic et al, 1997). More involved solutions consist of register type systems (Badescu and Isvoranu, 2011).

Earth-to-air heat exchangers may be used to save the energy in those buildings which are equipped with an active ventilation system (Badescu, 2007). This is particularly easy in case of passive houses (PH) where the active ventilation system makes part of the standard.

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Passive houses are buildings in which a high level of comfort is achieved in winter and in summer without a separate heating system or air-conditioning system - the house ‘heats’ and ‘cools’ itself purely ‘passively’ (Adamson, 1987), (Feist, 1988). The *Passivhaus concept* originated from a collaboration between Bo Adamson at Lund University in Sweden and Wolfgang Feist at the Institute for Housing and the Environment, Germany. The concept has been implemented by W. Feist in Germany in 1992, when the first passive house has been built. The two basic criteria for a passive house are: 15kWh/(m^2/year) for annual heating demand and 120 kWh/(m^2/year) for total primary energy consumption (Badescu et al, 2010), (Feist, 1993).

The present paper aims describes a passive building and its earth-to-air heat exchanger system and air-handling unit. A coupled plant-and-building simulation model is set up for the design and development of an optimized operation strategy. The model is developed in the R program and validated with monitoring data. The building is controlled by a building-energy-management-system (BEMS) which is modeled according to the current operation (for model validation) and is used for the optimization of the operation strategy. The improved control strategy takes the indoor temperature, the CO2 level (as an indicator for the actual use) and the outdoor temperature into account. In this example, the overall efficiency of the existing heating, cooling and ventilation system can be improved by an optimized operation strategy.

The Gerhard Grafe Sports Complex (Figure 1) is located in Germany, in the northern part of Dresden. The building was opened in June 2012 and has a total surface of 1360 square meters with a volume of 8935 cubic meters. Glazing area is 300 square meters and in figure 2 it can be seen a picture of the layout of the interior space and glazing. According to the heating and cooling required by the customer, this building passive requires only 32.65 kWh / m^2 as the main requirement and 24 kWh / m^2 as heating requirement, including photovoltaic system performance computing (Pfafferott, 2013).

Figure 1: Gerhard Grafe Building

To protect the building from outside influences, the building is embedded halfway down in the ground. This causes the building to be more resistant to changes in outside air temperature. For this reason even built-in heating system, heating the wall and the floor heating, are heat really slowly the building. A number of systems are installed in the gym, which must be coordinated: solar panels on the roof that can be used to supply hot water, power to the primary circuit of the heat pump, air is sucked and circulated through the earth-to-air heat exchanger.

Figure 2: Opening day

The energy used for air conditioning inside the building can be significantly reduced by using an earth-to-air heat exchanger system. Using the ground as a seasonal energy buffer allows here in winter pre-heating the incoming air and improves the reliability of the heat exchanger of the ventilation system. In summer the low temperature level of the earth can be used to cool the outside air entering the building. Active cooling of the areas of use is not necessary.
In the ventilation system of Gerhard Grafe sports hall in Weixdorf the earth-to-air heat exchanger is therefore upstream of an air handling unit.

The ground heat exchanger consisting of two pipe registers with eight parallel polyethylene pipe is laid along the east and west side of the hall at a depth of 2 m to 3 m. The tube length is 40 m with a nominal diameter of 250 mm. The outside air is filtered before entering the earth-to-air heat exchanger. There are two intake towers and after emerging from the EAHE reach in a suction building in the basement together, from which the ventilation device gets the air.

For indoor climate monitoring, mobile measurement technology is used to temperature and microclimate. The system consists of a station located inside the sports hall and two remote stations, weather station and the facade. The two outer stations can transmit recorded data archiving by Wirelles (W-LAN) station inside. A datalogger records ambient temperature and humidity in the gym and the operating temperature of the ventilation system [Pfafferott, 2013].

In the first data measurement campaign were collected data between June 9, 2012 (Sunday) 00:00 until July 11, 2012 (Tuesday) at 24:00. The measurements were made at a time interval of 3 to 6 minutes. After the test of plausibility, the measured values were converted into average for every 60 minutes.

2 MODEL VALIDATION

In this chapter, the simulation model of the building was implemented in the "R" programming language. It follows two main purposes:

- the possibility of a standardized comparison between measurement and simulation;
- in the future, this model can be used / developed on a large scale, as the model based on data analysis;

Measurement data can be stored and updated in R. The model can run at the same time a simulation and produce results and graphics with simulation and measurement data. Thus, a direct comparison between real and simulated operation may be possible without the need for additional interfaces.

For modelling the earth–to-air heat exchanger system and especially for a realistic view of the behaviour of the earth, it has been taken into account a number of complex relationships. First, knowledge of soil structure is necessary to determine the thermal conductivity and temperature. Individual parameters are taken from [VDI, 2006] or experience.

Regarding the time of using the building, a comparison between measurements made and the occupancy data given by the user did not provide a useful correlation. The use of the building was considered to be 12 hours per day from Monday to Friday. In the following we will present some computational relations and some parameters used in the model:

The building requires as input a number of parameters such as inlet temperature, air temperature at the output from earth-to-air heat exchanger, the temperature inside the building, the air velocity measured at the outlet of air handling unit, global solar radiation, diffuse solar radiation. Direct radiation is calculated as the difference between global solar radiation and diffuse solar radiation. The model includes some of the differential equations from ISO 13790 and the method is described in the standard. The time plan is set between 10:00 and 22:00, and the information is taken from the owner of the building.

In Figure 3 it can be seen simulate the operation of the building in the measurement campaign (33 days) and the comparison between the calculated temperature (model) and the measured temperature.

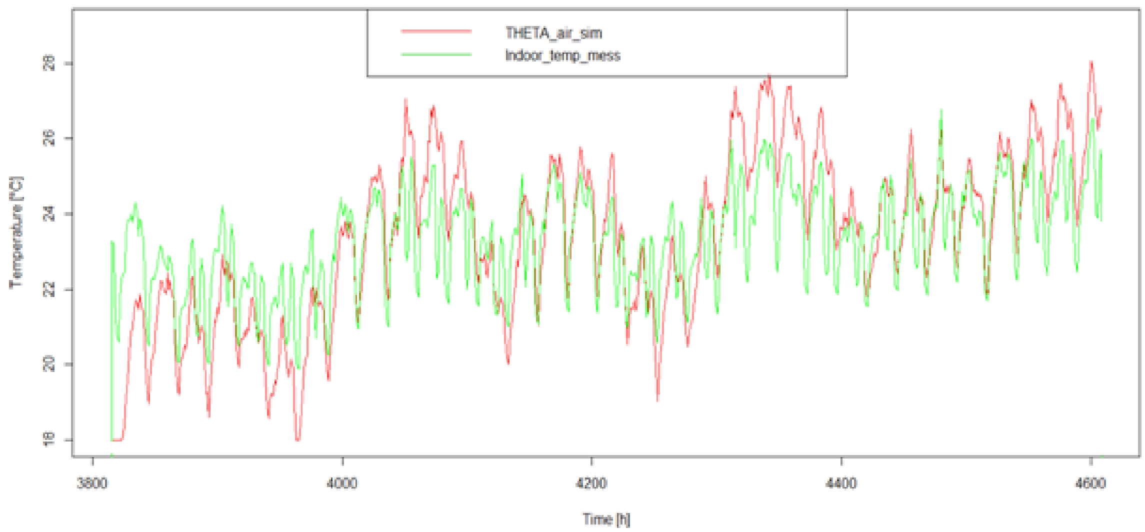

Figure 3: Comparison between the measured outlet temperature (Indoor_temp_mess) and the calculated outlet temperature (THETA_air_sim)

The average difference between the calculated temperature (model) and the measured temperature is 0.09 °C. The maximum temperature difference between the same values was 5.15 °C recorded on June 9, 2012 at 1:00, and the minimum temperature difference was 0.009 °C recorded on 4 July 2012 at 14:00.

Usual statistical indicators of accuracy are the mean bias error (MBE) and the root mean square error (RMSE) [Badescu, 1988], [Badescu and Isvoranu, 2011] defined by:

$$MBE = \frac{1}{n}\sum_1^n (T_{out,c,i} - T_{out,m,i}) \qquad (1)$$

and

$$RMSE = \sqrt{\frac{1}{n}\sum_1^n (T_{out,c,i} - T_{out,m,i})^2} \qquad (2),$$

where

$T_{out,c,i}$ is the computed outlet temperature, $T_{out,m,i}$ is the measured outlet temperature, while n is the number of values. MBE value for the indicated period was 0.09 °C and the RMSE value was 1.37 °C.

3 AIR COOLING AND HEATING

After achieving validation of the model, we simulated the functioning of the building for a period of one year. Since there were recorded data only for 33 days, we used annual reference test TRY [Deutscher Wetterdienst 2013 - http://www.dwd.de] to have hourly temperature values for a year (8760 hours). TRY appeared in 1985 and is updated annually. It contains hourly weather data that is based on records from previous years. It has been used for the same purpose in works such as [Janssens et al, 2005], [Breesch et al, 2005], [Pfafferott, 2004]. Annual reference test provides data for 15 different areas of Germany, of which obviously was chosen Dresden region. The system is simulated for a constant flow rate of 3000 m3 / h.

The building is controlled by a building-energy-management-system (BEMS) which is modeled according to the current operation (for model validation) and is used for the optimization of the operation strategy.

The improved control strategy takes the indoor temperature and the outdoor temperature into account. The outlet temperature is not suitable as input for the control strategy since the monitoring value is only indirectly available in operation.

Using the simulation model, it can be calculated the amount of energy provided by the efficient systems installed in the building. As it can be seen in figure 4, the yearly total amount of energy for the building is 68.59 MWh. The figure shows that in the winter period the amount is bigger than the rest of the year.

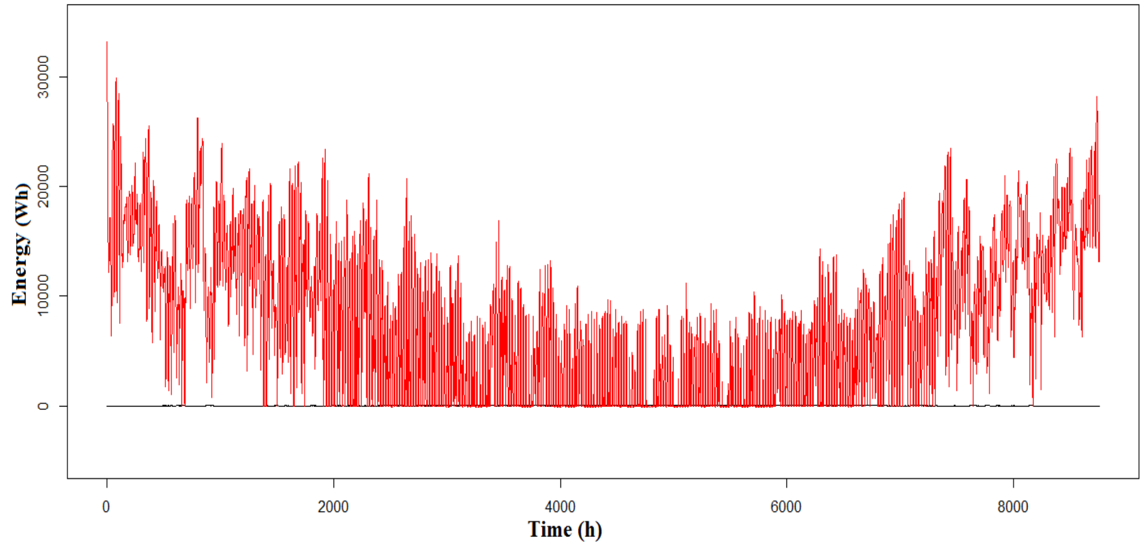

Figure 4: The yearly (8760h) amount of energy of the building

The distribution per season of the amount of energy is: 15.49 MWh in the spring, 4.99 MWh in the summer, 16.51 MWh in the autumn, and 31.59 MWh in the winter.

In the figure 5 it can be seen the temperature distribution for a year. Generally, in the winter (or when there are low temperatures) the outlet air temperature is higher than the inlet air temperature. Similarly, in the summer the outlet temperature (or when there are high temperatures) is lower than the inlet temperature, like it is expected. Overall, the EAHE system fulfills the functions for which it was built.

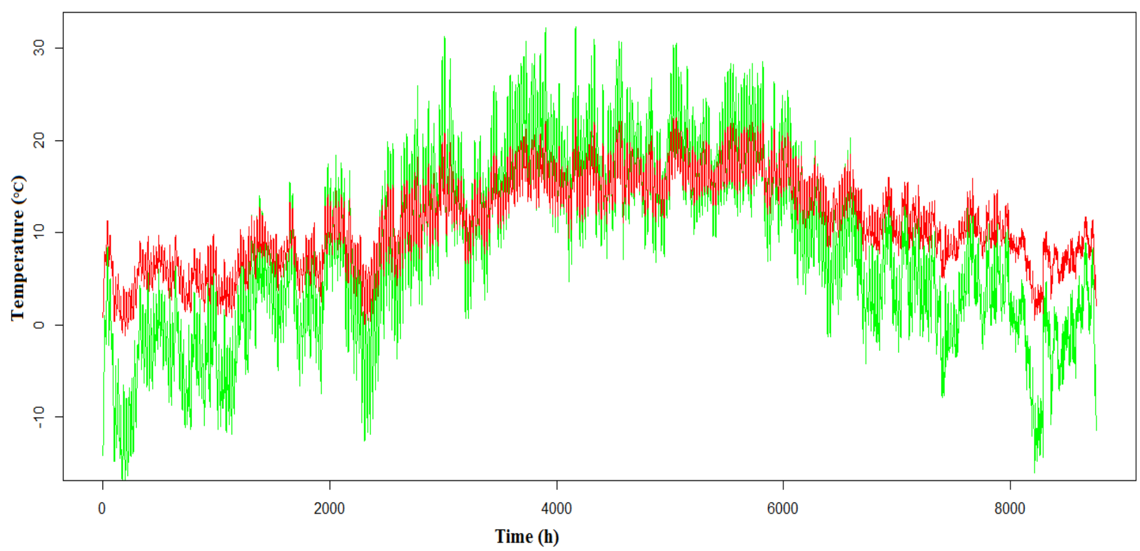

Figure 5: The yearly (8760h) temperature distribution; green – inlet air temperature (outside); red – outlet air temperature

However, analyzing the simulation data for a full year, not always the system provides useful energy. For example, in a day like March 25, at 9:00 the inlet air temperature is 10.7 °C and the outlet air temperature is 10.92 °C. All the night until that hour the EAHE was heating the air, providing useful energy. At 10:00 the inlet air temperature is 12.4 °C and the outlet air temperature is 12.18 °C. Similarly, at 11:00 the inlet air temperature is 14.7 °C and the outlet air temperature is 12.79 °C. It is clear that from 10:00 the system is not providing any more useful energy but is consuming electric energy and should be switched off. In this way, the BEMS can be set up for the heating the air if the inlet air is lower or equal with 10.7 °C.

Similarly, in the summer there is no need for cooling all the time. This aspect depends on the user and his preferences about the temperature in the building. It can be considered an ambient temperature of 22 °C. It is clear that, in the summer when the inlet air temperature is below this, value there is no need for cooling. The summer had 2208 hours and in 1539 hours the temperature was below 22 °C. In the same spirit the night ventilation concept can be used (Geros et al, 2005; Breesch, 2006; Pfafferott, 2004).

4 CONCLUSIONS

The Gerhard Grafe Sports Complex is briefly presented. The paper focuses on the earth-to-air heat exchanger system attached to this building. A new simulation model is proposed to predict the EAHE operation. The model was validated using experimental data recorded during 33 days in the summer period.

An improved control strategy is developed and takes the indoor temperature and the outdoor temperature into account. As a conclusion we can say that the bypass option can be used in several cases during a year. The recommendation is to use when the inlet air temperature is between 10.7 °C and 22 °C. The importance of this optimization is shown here and can improve the operation of those systems and electricity savings.

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