HYGRO-THERMAL PERFORMANCE OF EARTH-TO-AIR HEAT EXCHANGER: LONG-TERM DATA EVALUATION AND SHORT-TERM SIMULATION

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ABSTRACT

The thermal comfort requirements and cooling energy demand have significantly increased during the last twenty years. Air heating and/or cooling in an earth-to-air heat exchanger (EAHX) is a possible approach for improvement of thermal comfort in a building and for reduction of ventilation heat loss. A passive family house using mechanical ventilation system equipped with heat recovery and simple EAHX is being monitored since the end of summer 2005. The paper deals with the evaluation of measured data collected during year 2006. Amongst others, the results show the tendencies in moisture performance of monitored EAHX. Besides pure data evaluation, the short-term hygro-thermal simulation of EAHX was performed with a numerical model specially developed for this purpose. The simulation is compared with the monitored data; the comparison serves as the basic experimental validation of the model.

INTRODUCTION

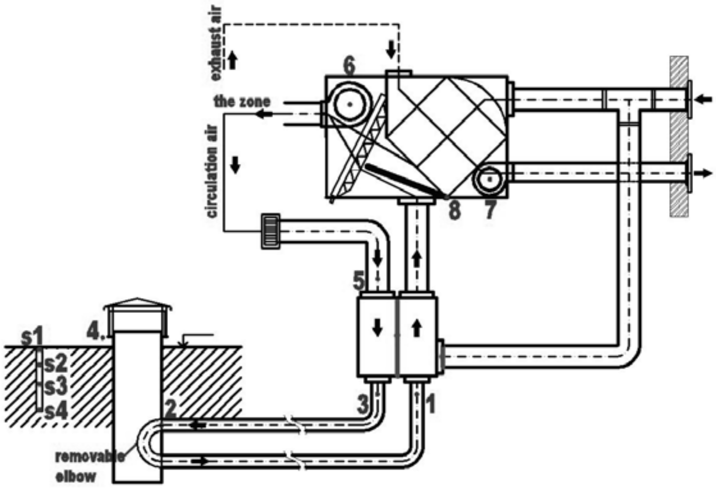
In general, EAHX has become quite popular in the Czech Republic. Small one-pipe systems are often used with mechanical ventilation systems for low-energy family houses. Even multi-pipe exchangers have been constructed, e. g. Education and Ecology Centre Sluňákov near Olomouc [1]. However, larger systems are still rather rare and perceived as partially experimental.

Either the computer simulation or monitoring of real size EAHXs is a way for studying hygro-thermal performance of EAHXs. The theoretical basis of the model which was used for simulation of EAHX was presented in [2]; a long-term simulation and the sensitivity analysis were presented in [3].

MEASUREMENTS ON VENTILATION SYSTEM OF PASSIVE FAMILY HOUSE IN RYCHNOV

The passive family house ventilated by mechanical ventilation equipped with heat recovery and a simple earth-to-air heat exchanger is being monitored since summer 2005. The scheme of the ventilation system is displayed in Figure 1. Table 1 provides a basic description of EAHX. The extensive monitoring is primarily aimed at operating the ventilation system linked with EAHX.

Measured data are collected in the main data logger (measuring step 1 min) and three other independent data loggers (measuring step 5 min). The first one is placed directly in the inlet shaft (position 2 in Figure 1); the second one is a living room data logger collecting parameters of indoor air (temperature, relative humidity, and CO_2 concentration). The third data logger collects undisturbed soil temperature from several depths under the surface (5, 30, 62, 105 cm).



1. Temperature + relative humidity [°C, %]
2. Temperature + relative humidity [°C, %]
3. Temperature + relative humidity [°C, %]
4. Ambient air temperature (sensor on the facade and outside of the inlet shaft) [°C]
5. Temperature (circulation air) [°C]
6. Air flow rate – suction fan [V, ac]
7. Air flow rate – exhaust fan [V, ac]
8. Flap position [V, dc]

Figure 1: The scheme of ventilation system with position of sensors; the closed loop mode of EAHX (circulation of internal air through the EAHX)

Number of pipes	Length of pipe [m]	Diameter [mm]	Depth [m]
2	23	200	1.0 and 2.0
Air flow rate [m^3/h]	Soil	Control strategy	Place
115 – 410, higher values for summer ventilation	Clay***** λ_s = 1,39 W/m.K ρc_p = 2,23 MJ/m^3.K	According to ambient air temperature and link with the actual ventilation mode	Rychnov near Jablonec nad Nisou, North Bohemia

*Table 1: The description of EAHX; *Homogenous moist clay; the thermal properties are based on samples taken from a borehole drilled to depth of one meter.*

The mechanical ventilation system offers five ventilation modes divided into two air flow rate levels and three special modes switched on by external signals (e. g. by usage of W.C., bathroom, cooking in a kitchen). The more detailed description of the ventilation system is presented in [4]. EAHX may be operated in two principally different modes: a) the circulation of air between the ventilated zone and the EAHX (closed loop mode, experimentally used for cooling) and b) direct suction of air through the EAHX (open loop mode, usual option used for air pre-heating and cooling). The closed loop mode of the exchanger was experimentally installed by placing a removable elbow (from 11.7.2006 to 10.9.2006).

The short step of measurement allows the accurate determination of the ventilation mode. Therefore, it allows the precise determination of time intervals when EAHX was in operation and the determination of corresponding value of the air flow rate. The monitoring of air relative humidity also allows the determination whether air flowing through the pipe was moistened (the moisture deficit indicates that condensation within the pipe prevailed).

The example of time daily profiles measured on EAHX is depicted in Figure 2. The left column shows day 20.6.2006 with open loop mode of EAHX, the right column shows day 19.7.2006 with closed loop mode of EAHX.

The performance of the open loop mode (Figure 2, left column) shows a quite significant (and surprising) cooling effect of the inlet shaft itself; the response of the outlet air temperature on the change of air flow rate is also visible, but not so evident. Since the value of the convective heat transfer coefficient is only slightly non-linear function of the air velocity (in the expected range of air flow rates), the cooling effect in case of doubled value of air flow rate is, from the short-term perspective, only slightly reduced (see Figure 2, left column). The difference between the inlet air water vapour concentration and outlet air water vapour concentration indicates prevailing condensation within pipes. The amount of condensed water is in order of several kilograms per day. Because of the lower soil temperature and consequent higher temperature drop of outlet air, the pipe buried in depth of two meters tends to stronger condensation than the upper pipe.

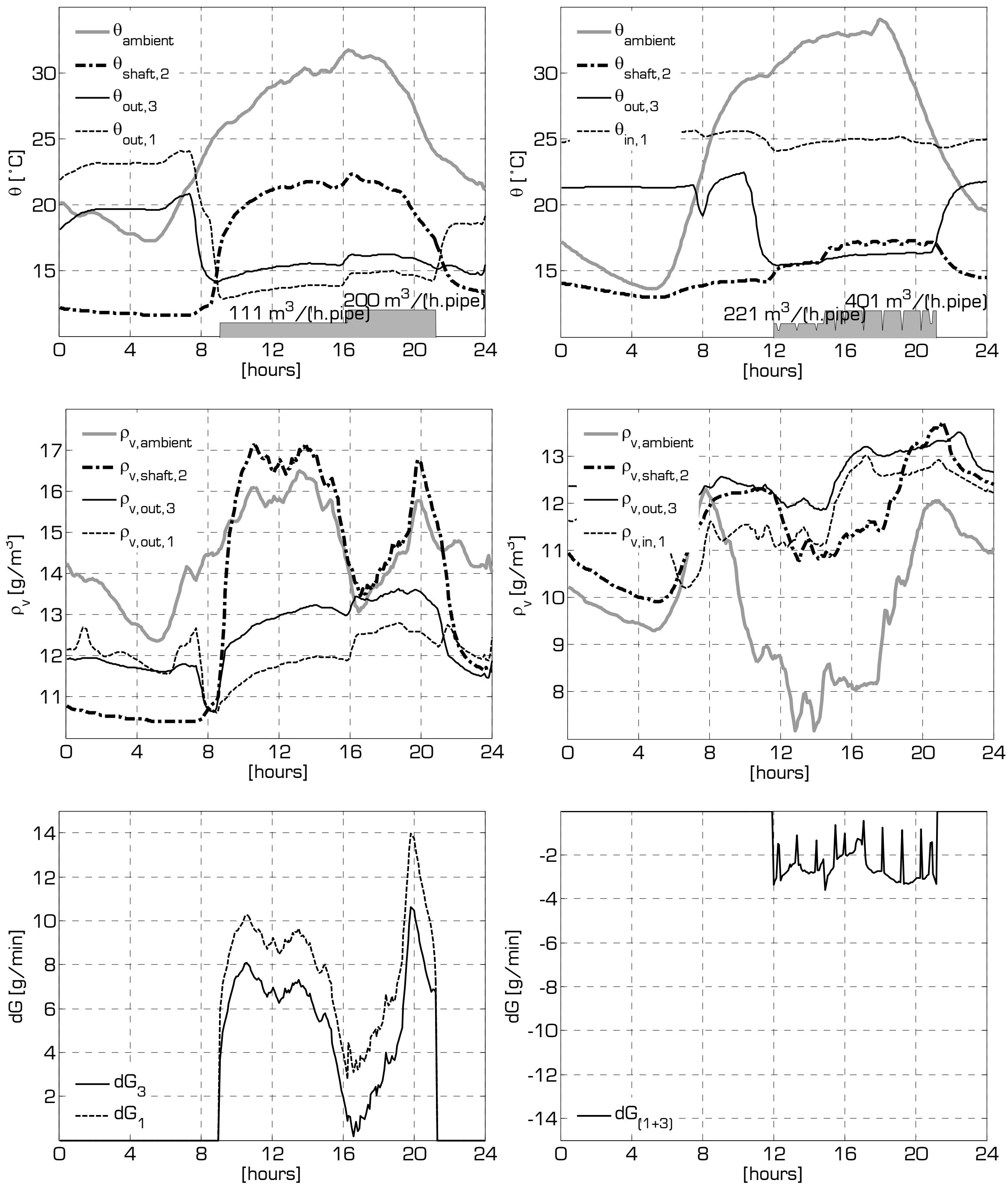


Figure 2: The measured temperature θ, water vapour concentration ρ_v and corresponding overall moisture rate ***dG*** *during two selected days; the overall moisture rate is the sum of condensation and evaporation rate within the whole pipe (positive value denotes prevailing condensation within the pipe); the left column represents day 20.6.2006 (open loop mode), the right column represents day 19.7.2006 (closed loop mode), the values measured by logger placed in the removable connection elbow (position 2) are influenced by unwanted air suction due to the leaky wall of elbow (e. g. see measured profile $\rho_{v,shaft,2}$).*

The case of closed loop mode (Figure 2, right column) may lead to totally different moisture performance than the open loop mode. Although the outlet air temperature is similar to the case of open loop mode, there is a negative moisture balance between inlet and outlet. The difference between inlet air (the air sucked from the building) and outlet air water vapour concentration indicates prevailing evaporation within pipes. The moisture present in the pipes is likely the result of previous open loop mode operation (prevailing condensation). The movement of water towards the inlet shaft is probably quite slow due to the surface tension so that some water stays inside the pipes and only a limited amount of water is drained into the inlet shaft. The rate of water uptake (evaporation) is lower in comparison to condensation rate. Probably, this may occurs due to the active area which is limited to thin stripe of water at the bottom of the pipe.

SHORT-TERM HYGRO-THERMAL SIMULATION OF EAHX

The simulation performed on the numerical model [2] focuses on hygro-thermal performance of the open loop mode during ten-day summer term from 13.6.2006 to 22.6.2006. The term is typical by very high ambient air temperature and intensive EAHX operation during daytime periods (see Figure 3).

One pipe of the exchanger only was simulated. The thermal influence of the neighbouring pipe and the thermal link with upper plane soil boundary was not included into the simulation. A calculation domain was a soil block 1.18 m (width) x 1.18 m (height) x 23 m (length of the pipe) with external adiabatic walls. The block was divided into 17 x 17 x 46 control volumes. The pipe was approximated by an equivalent square with perimeter which equals to perimeter of the pipe. The time step used for the simulation was 5 minutes. The initial soil temperature was assumed 8.5 °C in all control volumes of the block. This temperature was derived by means of linear regression from calculated heat flows injected to soil sorted by inlet air temperature. The inlet air temperature and relative humidity were equal to measured values in the inlet shaft (position 2, Figure 1). The influence of latent heat transfer due to condensation and/or evaporation within the pipe was neglected because the results were not closed to reality.

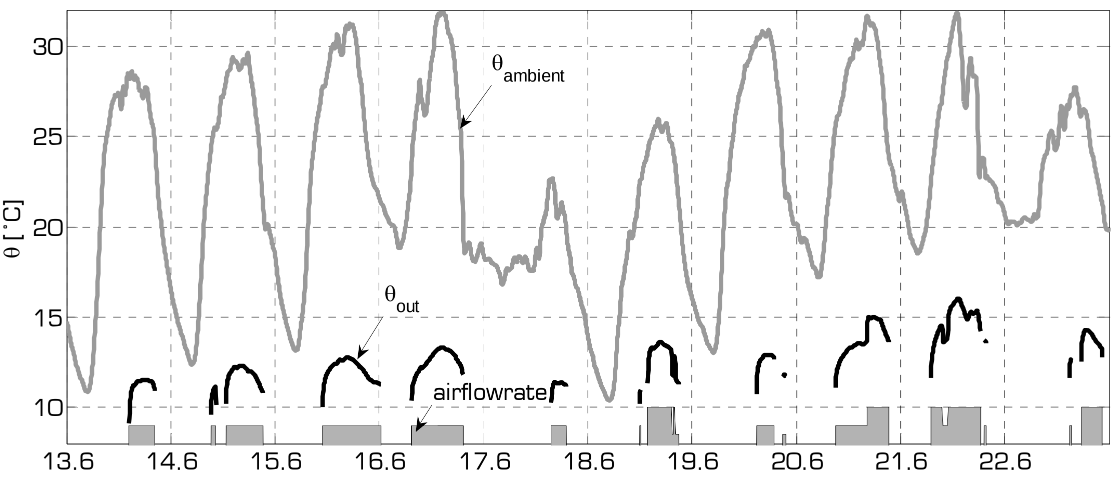


Figure 3: The measured ambient air temperature $\theta_{ambient}$, air flow rate (lower values – 111 m^3/h, upper – 200 m^3/h), and simulated outlet air temperature θ_{out}

The output parameters from the short-term simulation were compared with measured parameters. As shown in Figure 4, the correspondence of the model prediction with measurement is obvious, although the absolutely perfect agreement was not achieved. This comparison serves as a basic experimental validation of the developed algorithm.

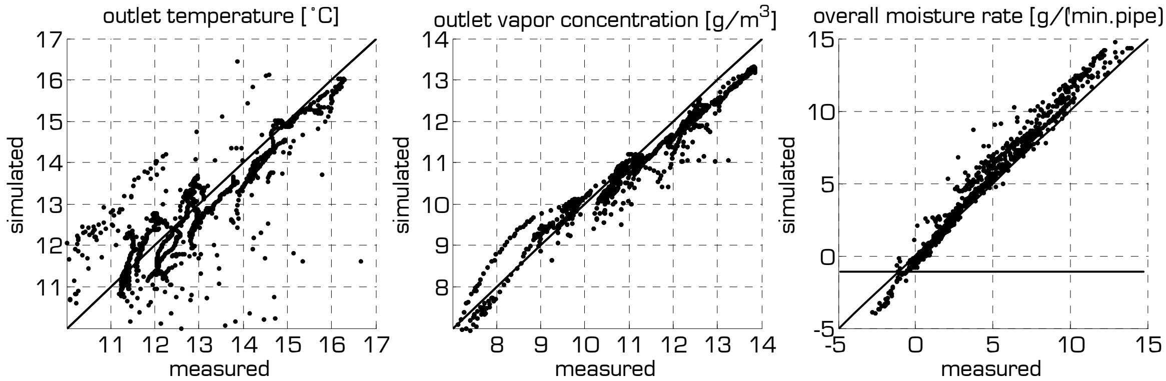


Figure 4: Scatter plot measured vs. simulated

LONG TERM DATA EVALUATION

The aim of this sub-chapter is the evaluation of some measured data collected during year 2006 and subsequent generalization. There arise many questions. Which input parameter has the most significant impact on the moisture performance of EAHX? In which values of inlet air humidity condensation occurs? Does the higher value of air flow rate reduce the amount of condensation rate?

The following simple consideration is rather illustrative. Assuming the likely range of the inlet air temperature and relative humidity during daytime in summer, the consequent range of water vapour concentrations in the inlet air will be 8 – 16 g/m^3. Assuming the likely range of the outlet air temperature between 12 °C – 18 °C (see Figure 5) and relative humidity closed to 100 %, the consequent range of water vapour concentrations in the outlet air will be 10 – 15 g/m^3. Thus, for instance, the deficit of 6 g/m^3 and the air flow rate 100 m^3/h would lead to the condensed rate 10 g/min which equals approximately 5 kg per day assuming 8 hours of EAHX operation.

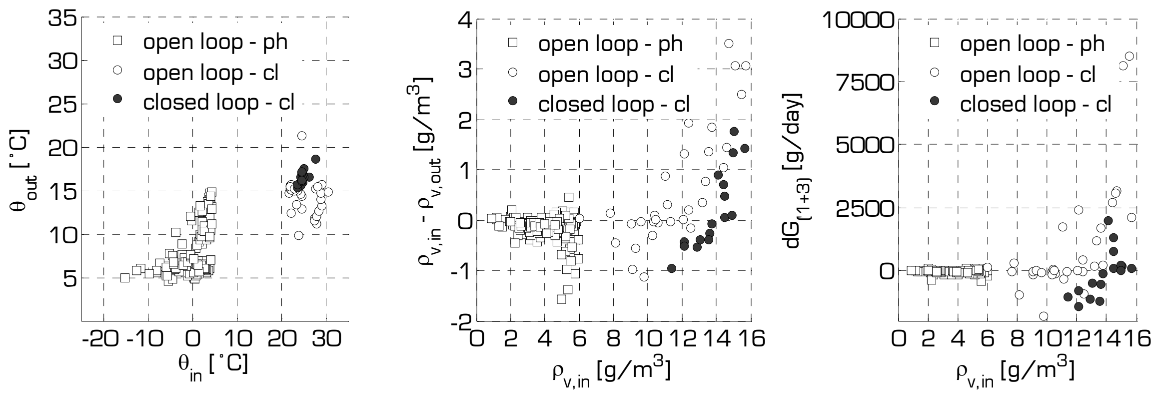


Figure 5: Left - scatter plot inlet air temperature θ_{in} vs. outlet air temperature θ_{out}; Central - water vapour concentration in the inlet air $\rho_{v,in}$ vs. the difference between inlet and outlet water vapour concentration ($\rho_{v,in}$ - $\rho_{v,out}$), the positive values denote prevailing condensation within the pipe; Right –water vapour concentration in the inlet *air $\rho_{v,in}$ vs. overall moisture rate* ***dG****. All depicted values are daily means over the EAHX operation,* ***ph*** *denotes pre-heating,* ***cl*** *denotes cooling.*

As seen in Figure 5, no condensation or evaporation takes place during winter period of air pre-heating; the pipe is perfectly dry. During summer term, the deficit of water vapour (Figure 5, central) could indicate the stronger tendency to condensation of the open loop mode than closed loop mode (Figure 5, right). However, the moisture performance is also dependent on the long-term temperature performance of EAHX which is governed by thermal link with the upper plane surface. Since the closed loop mode was used in the second half of summer, the outlet air temperatures were higher than during open loop mode operation as the outlet air temperature follows the undisturbed soil temperature profile. The tendency to condensation was the strongest at the beginning of summer when the soil is cold.

CONCLUSIONS

The extensive long-term monitoring introduced in this paper brings clear information about processes taking place during EAHX operation. The monitoring is detailed enough for a robust experimental validation of the developed EAHX model. Despite relatively good accuracy of the numerical simulation achieved here, the accurate simulation of EAHX should be considered as rather difficult because of low air-to-soil heat flow, the intermittent pattern of EAHX operation, and moisture flow in the pipes.

The examples presented above should not imply that the closed loop mode is an absolute cure for condensation within the pipes. Even with the closed loop mode, condensation may prevail within the pipes. The value of water vapour concentration in the inlet air, the temperature of surrounding soil (the temperature of the pipe surface), the air flow rate, and the length of EAHX should be considered as the input parameters influencing the moisture performance of EAHXs. The complete generalization of EAHX moisture performance met the problem of complexity. Therefore, as a logical progression, it should be beneficial to perform a numerical study in order to display the relationship between key input parameters governing the moisture performance of EAHXs.

The condensation inside the pipes can not be eliminated completely. Therefore, the question of mould growth inside pipes should remain open, although the several existing studies, e. g. [5], have not confirmed any hygienic problems.

ACKNOWLEDGEMENTS

This outcome has been achieved with the financial support of the Ministry of Education, Youth and Sports of the Czech Republic, project No. 1M0579, within activities of the CIDEAS research centre. The monitoring is research cooperation between CTU Prague and a company ATREA (http:/www.atrea.cz).

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