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BURIED PIPE SYSTEMS WITH SENSIBLE AND LATENT HEAT EXCHANGE : VALIDATION OF NUMERICAL SIMULATION AGAINST ANALYTICAL SOLUTION AND LONG-TERM MONITORING

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ABSTRACT

A finite differences numerical model for buried pipe systems is presented, accounting for sensible as well as for latent heat exchanges, so as for fully three dimensional heat diffusion in soil and flexible border conditions. After description of the algorithm, extensive validation against an analytical solution as well as against several long-term monitored real scale installations will be discussed.

INTRODUCTION

Lacking better tools, most authors (Athienitis et al. 2000; Bansal et al. 1983; Chen et al. 1983; Elmer and Schiller 1981; Levit et al. 1989; Rodriguez et al. 1988; Santamouris and Lefas 1986; Schiller 1982; Seroa da Motta and Young 1985; Serres et al. 1997; Tiwari et al. 1993; Tzaferis et al. 1992) are dimensioning air/soil heat exchangers by way of simple static exchange models, simple to handle but for which estimation of the fundamental parameters (air/soil heat exchange coefficient and effective soil temperature) isn't evident at all, especially in transient regime.

As an alternative, some analytical models explicitly treat heat diffusion in the soil. One of them (Claesson and Dunand 1983) concerns periodic heat diffusion from a cylindrical pipe embedded in a semi-infinite medium (with constant temperature at upper free surface). The induced effect on the longitudinal temperature of the airflow has been treated apart (Sawhney and Mahajan 1994), appropriate physical interpretation and operational presentation of the results unfortunately not being carried out. A similar problem includes the interference of neighboring pipes (Kabashnikov et al. 2002) but concerns deeply buried pipes, without interference of upper border conditions. As a last case, a cylindrical model (Hollmuller 2003) treats the case of a pipe subject to isothermal or adiabatic boundary condition at finite radial distance (limitation of available soil layer). Apart from yielding explicit understanding of the heat diffusion phenomenon (in terms of the natural temperature penetration depth) latter model also puts forward the theoretical possibility, under certain conditions, to completely phase-shift the periodic input while barely dampening its amplitude, a phenomenon apparently unexploited up to now.

Although they might give important insight in the physical heat exchange and storage phenomenon which are at work, preceding analytical models are obviously limited to constant airflow rates and rather simple geometries and border conditions. As an alternative, several numerical simulation models based on finite differences have also contributed to characterize diffusive heat exchangers. Some of them are limited to description of one only typical pipe (Bojic et al. 1997; Huber and Remund 1996; Mihalakakou et al. 1994). Other ones allow for the description of several parallel running pipes, with or without possibility to treat more complicated cases than steady flow rate, homogenous and laterally adiabatic soils, or sole sensible heat exchange (Boulard et al. 1989; De Paepe 2002; Gauthier et al. 1997; Gygli and Fort 1994). However, when validation against monitoring is ever carried out, latter in all cases remains limited to a few hours or days and does generally not concern real scale installations, thereby not providing necessary proof of robustness one would expect. Corroboration against an analytical solution is furthermore never given, except for the last one of these models and for the trivial case of one-dimensional heat diffusion without airflow.

As a response to preceding state of the art, we will present a flexible, finite differences numerical model, allowing for description of sensible as well as latent heat exchanges. After description of the algorithm, extensive validation against an analytical solution as well as against several long-term monitored real scale installations will be discussed.

NUMERICAL MODEL

The simulation tool developed here bases on a previously developed finite element model, which already accounted for simultaneous sensible and latent heat exchange between air and tubes, as well as fully tree dimensional heat diffusion in soil (Boulard et al. 1989). The original model has been completely revised, so as to allow for various geometries, soil properties and border conditions, as well as to include frictional losses, possible water infiltration and control of airflow direction. With particular care on flexible definition of in- and outputs, the model was adapted to TRNSYS, a modular environment for transient simulation of energy systems, allowing for links to other preexisting modules like buildings.

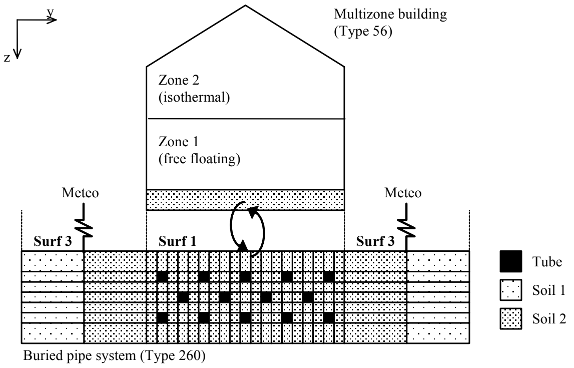

Figure 1 : Schematic example of model geometry and TRNSYS-link to multizone building.

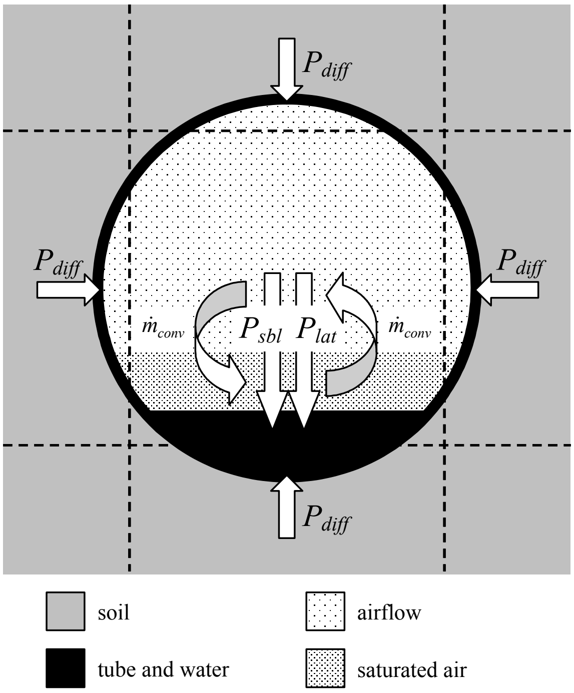

Figure 2 : Energy and mass transfer in a pipe node.

Hypothesis

Following hypothesis, options and constraints have been adopted (Fig. 1 and 2) :

- So as to be flexible, the orthogonal meshing allows for variable node widths in all three dimensions. Circular tubes are represented by way of equivalent square sections, lateral exchange surface being computed by way of an adequate corrective factor.
- Thermal heat diffusion is fully three dimensional. Soil characteristics may be inhomogeneous but are constant in time.
- Border conditions, which may be various on the same face, are either adiabatic or driven by a transient input. Latter can be defined in terms of temperature or heat load, with possibility to include an additional surface resistance.
- As for most other model and coherent with analytical approach developed in parallel (Hollmuller 2003), air temperature and velocity are considered to be uniform within a pipe section. Heat exchange with pipe is treated by means of an overall convective which depends on velocity, but not on temperature.
- The thermal effect of the charge losses, computed in function of a friction factor, the tube surface and the air velocity, is evenly distributed along the tubes. Eventual singular charge losses have to be treated apart.
- Transient water infiltration, if any, occurs on a predefined part of the tubes, where it adds to possible condensed water.

Algorithm

The model's kernel bases on the energy and mass exchanges between the airflow and the pipe (Fig. 2). They are computed iteratively for each pipe node, from air inlet to outlet, and comprise :

- The sensible heat lost by the airflow :

  $$P_{sbl} = S_{tub} \cdot h \cdot (T_{air} - T_{tub})$$

  computed for the lateral surface, with a convective exchange coefficient which depends on the air velocity :

  $$h = h_0 + h_v \cdot v_{air}$$

  as a simplified but quite accurate form of more refined formulations in terms of Reynolds and Prandtl numbers, with typical values of 3 W/K.m^2 for h_0 and 2.5 W/K.m^2 per m/s for h_v (Hollmuller 2002).
- The latent heat, determined by the Lewis analogy, which actually considers former sensible heat to result from a convective air exchange between the flow and a superficial layer at pipe's temperature, the analogy implying following convective air exchange rate :

  $$\dot{m}_{conv} = \frac{P_{sbl}}{c_{air} \cdot (T_{air} - T_{tub})}$$

  Considering the air layer to be saturated in humidity, this air exchange also induces a water vapor exchange, which is determined by the difference in humidity ratios of main flow and superficial layer :

$$\dot{m}_{lat} = (W_{air} - W_{tub}) \cdot \dot{m}_{conv}$$

where, according to perfect gases :

$$W_{air} = \frac{H \cdot \mathrm{Pr}_{sat}(T_{air}) \cdot M_{wat}}{\mathrm{Pr}_{air} \cdot M_{air}}$$

$$W_{tub} = \frac{100\% \cdot \mathrm{Pr}_{sat}(T_{tub}) \cdot M_{wat}}{\mathrm{Pr}_{air} \cdot M_{air}}$$

When positive, this vapor transfer corresponds to condensation, when negative to evaporation. In latter case it is further limited by the free water content in the considered node, as well as by the maximum humidity (saturation pressure) which can be absorbed by the airflow. With these definitions, the associated latent heat finally writes as :

$$P_{lat} = c_{lat} \cdot \dot{m}_{lat}$$

- The heat diffusion from the 4 lateral soil nodes and the 2 preceding and following pipe nodes :

$$P_{diff} = \sum_{soil} S_i k_i (T_{soil,i,t-1} - T_{tub}) + \sum_{tube} S_i k_i (T_{tub,i,t-1} - T_{tub})$$

The saturation pressure being non-linear in terms of temperature, the value of T_{tub} as well as preceding heat rates are being determined by iterative resolution of the energy balance :

$$P_{int} - (P_{sbl} + P_{lat} + P_{diff}) = 0$$

where the capacitive gains of the pipe and the free water are given by :

$$P_{int} = \frac{(c_{tub} \cdot m_{tub} + c_{wat} \cdot m_{wat,t-1}) \cdot (T_{tub} - T_{tub,t-1})}{\Delta t}$$

The associated hydric balance on its turn allows to determine the new water content of the node :

$$m_{wat} = m_{wat,t-1} + (\dot{m}_{inf} - \dot{m}_{lat}) \cdot \Delta t$$

Charge losses are taken in account by way of a friction coefficient f, for which typical values are to be found on a Moody diagram (ASHRAE, Ch.2, 1989) :

$$P_{fric} = \dot{m}_{air} \cdot f \cdot \frac{l}{d} \cdot \frac{v_{air}^2}{2}$$

Finally, preceding energy and mass balances yield the air input conditions of the next pipe node :

$$T_{air,i} = T_{air} + \frac{P_{fric} - P_{sbl}}{(c_{air} + c_{vap} \cdot W_{air}) \cdot \dot{m}_{air}}$$

$$W_{air,i} = W_{air} - \frac{\dot{m}_{lat}}{\dot{m}_{air}}$$

where computation repeats in the same manner.

After completing this calculation for all tube nodes, computation treats diffusion of heat into soil nodes, taking into account user-specified border conditions.

VALIDATION AGAINST AN ANALYTICAL MODEL

First validation of the model – as well as illustration of different configurations for preheating or cooling of buildings by way of such systems – concerns a unique pipe, embedded in a soil cylinder of finite radius and with perfectly adiabatic border conditions (corresponding to one out of a multi-layer array of parallel running pipes, each having a limited available soil layer, in absence of other border conditions), for which a complete analytical solution in periodic mode has been developed (Hollmuller 2003).

The simulated system is composed of a pipe of 25 cm diameter, a homogenous sandy and weakly saturated soil (conduction and capacity of 1.9 W/K.m and 1.9 MJ/K.m^3, yielding a 17 cm penetration depth around the pipe for the daily temperature oscillation, respectively a 3.2 m penetration depth for the annual oscillation, see Hollmuller 2003), and is subject to a constant 200 kg/h airflow, with an hourly input as given by the standard annual meteorological temperature for Geneva (Meteonorm 1995).

For the rest, simulation concerns a set of 3 different geometric configurations (Fig. 3) :

- A 50 m pipe length and a 2 m soil radius, enabling annual heat diffusion to expand almost fully over its natural penetration depth, and annual amplitude thus to be dampened down (as is necessary for winter preheating of fresh air);
- A 50 m pipe length and a 0.60 m soil radius, not enabling annual heat diffusion to expand over its natural penetration depth any more, so that only daily amplitude is being dampened down (as can be sufficient for summer cooling of buildings in Mid-European climates);
- A 400 m pipe length and a 0.60 m soil radius, which doesn't dampen the annual oscillation much more than in previous case, but allows its phase-shifting over some 6 months. Although such a configuration remains quite theoretical (in particular regarding the perfectly adiabatic border condition), it constitutes yet another good test case for cross validation of analytical and numerical model.

In the case of the numerical model, rectangular meshing was chosen so as to yield equivalent cylindrical sections as the analytical problem (at pipe as well as soil level). It was laterally submitted to adiabatic boundary condition and longitudinally segmented in 1 m pieces. In the case of the analytical model, Fourier analysis of the input temperature into a complete sum of harmonics (from yearly up to hourly frequency) allows for direct reconstruction of the corresponding output.

Despite the rectangular approximation of the numerical model, an excellent correspondence with the analytical approach is manifest (Fig. 3), with a mean bias in all cases below 0.5 K and a standard deviation below 0.2 K.

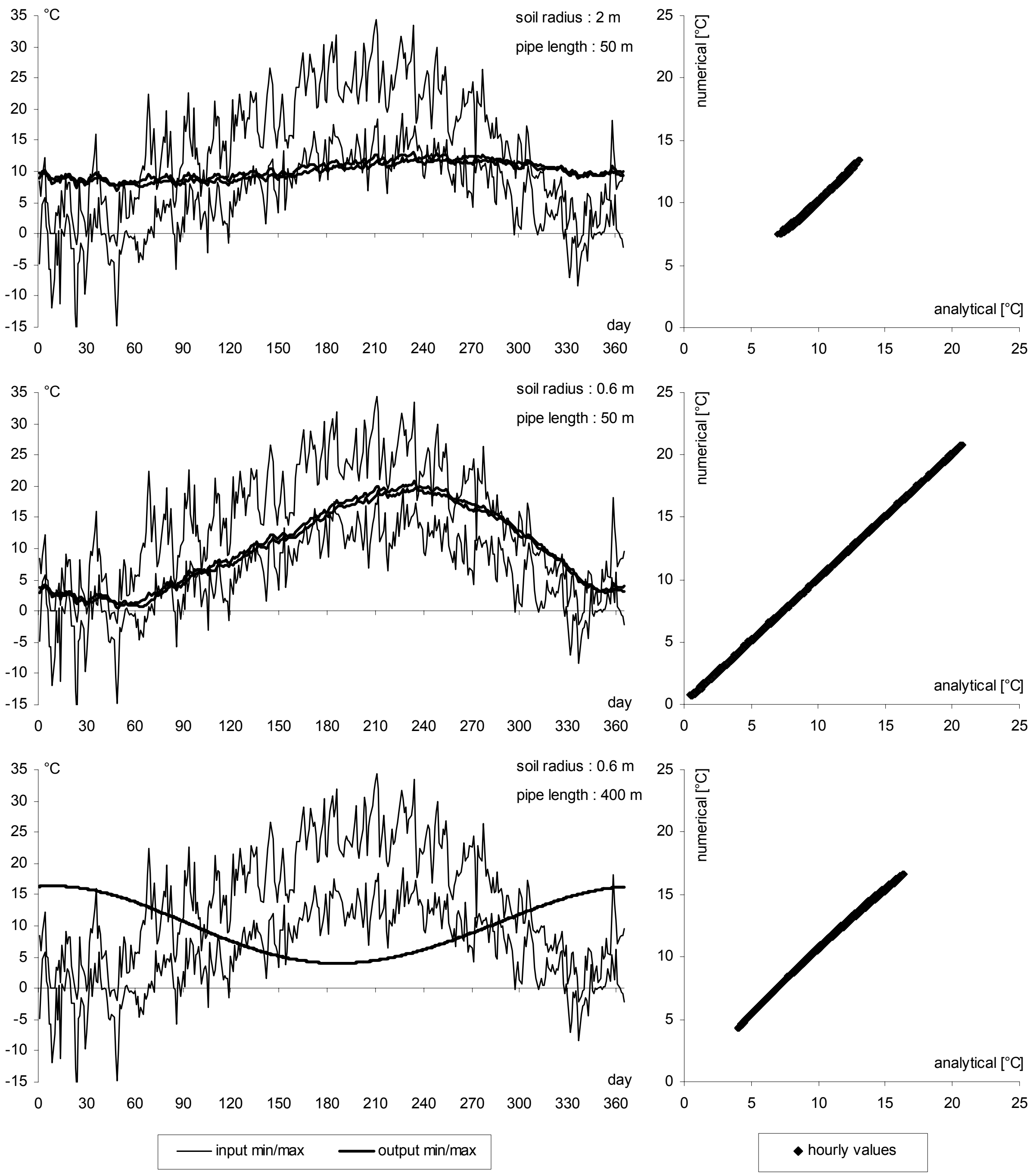

Figure 3 : Numerical simulation results for different configurations of single buried pipe with cylindrical heat diffusion and adiabatic border conditions : daily minimum and maximum input and output values (left) and hourly comparison with analytical model (right).

VALIDATION AGAINST IN-SITU MONITORED SYSTEMS

Preheating and cooling of air in controlled ventilation : Schwerzenbacherhof building

Located near Zürich (CH), this buried pipe system is part of the "Schwerzenbacherhof" commercial and administrative building (144 MJ/m^2 heating demand for 8'500 m2 heated surface), selected for the IEA "Low Energy Cooling Subtask" (Zimmermann and Andersson 1998). The system consists of 43 pipes (25 cm external diameter, 23 m length, 116 cm mean axial distance, 900 m^2 total exchange surface, including distribution and collector pipes) running at 75 cm beneath the second basement of the building (~ 6 m beneath ground surface). The system is used as well for winter preheating of fresh air (12'000 m^3/hr, 0.6 ach), in conjunction with heat recovery on exhaust air, as for summer cooling of building with slightly enhanced airflow (18'000 m^3/hr, 0.75 ach), in conjunction with direct night ventilation.

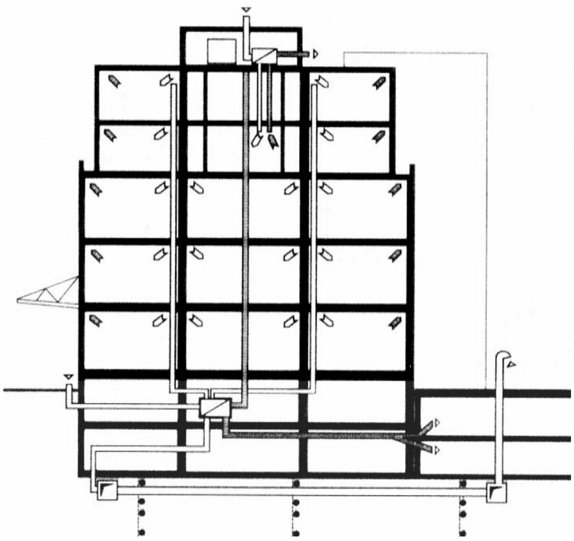

Figure 4 : Schwerzenbacherhof building and buried pipe system.

Extensive monitoring over a one year period, handed out by the Federal office of energy, indicates evaporation all year around without any condensation ever. Possibly due to some monitoring problem, latter evaporation could also result from water infiltration into the pipes, as already observed on similar systems. In this context, comparison with two different simulation runs, with and without water infiltration (defined by the daily quantity of water apparently evaporated, evenly distributed over 24 hours), allows for some insight in the importance such a phenomenon can have, as well as for further validation of the numerical model (Fig. 6) :

- Sensible heat exchanges are very well reproduced as well in hourly as in weekly dynamic and are almost independent of water infiltration being turned on or off, although later case best fits the annual balance (4% over-estimate on summer charge, 10% under-estimate on winter discharge).
- Latent heat exchanges, completely absent without water infiltration (no spontaneous condensation and evaporation), are relatively well reproduced when later is turned on (14% under-estimate on summer evaporation, 22% over-estimate on winter evaporation).
- Note presented here, heat diffusion from the basement of the building (as roughly estimated by three local temperature couples 50 and 75 cm above the pipe array) is quite well reproduced when water infiltration is set to zero, but rises when later is turned on, so as to compensate additional evaporation energy. Not so for heat diffusion to the deep ground, which is quite independent of water infiltration and subsequent evaporation to be at work or not.

Short term heat storage of excess solar gains in agricultural greenhouses : Geoser project

Realized in Sion (CH), the "Geoser" project aimed at comparing three identical agricultural greenhouses submitted to a common agronomical program, of which two were equipped with storage systems of the diurnal solar excesses : the first one in the soil, via a set of buried pipes, the second one in a water tank, via aero-convectors (Hollmuller et al. 2002). With some hundred sensors, a very complete monitoring campaign over 17 months in 5 minute steps (very nervous dynamic of the greenhouses, due to small thermal capacity) allowed to characterize the systems very precisely and to furnish complete comparative energy balances.

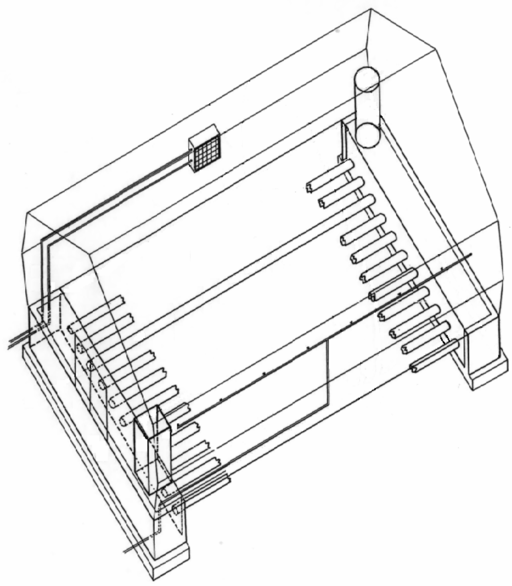

Figure 5 : Geoser greenhouse with buried pipe system.

The buried pipe system consists of 24 PVC pipes (16 cm diameter, 11 m length, 33 cm axial distance, 132 m^2 exchange surface) running at 80 cm below the greenhouse. A variable and reversible fan (0 – 6'000 m^3/h) provides for diurnal storage as well as nightly discharge, in closed loop with the greenhouse.

Again important latent exchanges are being observed, in this case as well in the form of condensation (during first hour of diurnal storage, when the airflow is quite humid) as in the form of evaporation (during following diurnal hours or during nightly discharge).

However, an important mass deficit again indicates that some kind of water infiltration has been at work (evaporation and water drainage at pipe being much more important than associated condensation). Latter clearly seems to result from the automatic fog system in the greenhouse, the fine water droplets possibly being swept into the pipes by the airflow, hypothesis which is compatible with calculation on the time needed for such droplets to evaporate (Hollmuller et al. 2002).

Comparison with numerical simulation, again with and without water infiltration (defined by the apparent monitored daily water deficit, evenly distributed over 24 hours), yields similar results as before (Fig. 7) :

- Sensible heat exchanges are very well reproduced, as well in hourly as in weekly dynamic, and are almost independent of water infiltration being turned on or off. Later case however fits the annual balance best (1% under-estimate on annual charge, 3% under-estimate on annual discharge).
- Evaporation, almost inexistent without water infiltration, is very well reproduced when later is turned on (1% under-estimate on annual integral). Not so for condensation however, which remains way too low (91% under-estimate on annual integral).
- Heat diffusion to and from the greenhouse also is more important with than without water infiltration (compensating for evaporation and condensation energy), with annual integrals closer to the monitored data (corroborating the hypothesis of such an infiltration actually to have been at work).

CONCLUSION

We developed a finite differences numerical model for buried pipe systems, accounting for sensible as well as for latent heat exchanges, so as for fully three dimensional heat diffusion in soil and flexible border conditions. An extensive validation campaign yields following results :

- Comparison with a complete analytical solution in cylindrical symmetry, without latent exchanges, yields perfect reproduction of temperature outputs, for a variety of analyzed configurations.
- Comparison with two long-term in-situ monitored systems, both with important latent exchanges, yields very good reproduction of sensible as well as latent heat exchanges, provided the monitored water deficit is given as water infiltration.

NOMENCLATURE

Symbols correspond to node and time step under consideration, unless marked with *i* (neighbor node) or *t-1* (preceding time step).

c_{lat}	J/kg	latent heat of water
c_{air}	J/K.kg	specific heat of air
c_{vap}	J/K.kg	specific heat of vapor
c_{wat}	J/K.kg	specific heat of water
c_{tub}	J/K.kg	specific heat of tube
d	m	tube diameter
f		friction factor
h	$W/K.m^2$	convective heat coefficient
H	%	relative humidity
k	$W/K.m^2$	conductive heat coefficient
l	m	tube length
M_{air}	kg/mol	molar mass of air
M_{wat}	kg/mol	molar mass of water
m_{tub}	kg	mass of tube
m_{wat}	kg	mass of free water
$\dot{m}_{air}$	kg/s	airflow
$\dot{m}_{conv}$	kg/s	air/tube convective exchange
$\dot{m}_{inf}$	kg/s	water infiltration
$\dot{m}_{lat}$	kg/s	condensation/evaporation
P_{diff}	W	heat diffusion
P_{fric}	W	frictional losses
P_{int}	W	internal heat gain
P_{lat}	W	latent heat exchange
P_{sbl}	W	sensible heat exchange
Pr_{air}	Pa	pressure of air
Pr_{sat}	Pa	pressure of saturated air
S	m^2	lateral node surface
S_{tub}	m^2	tube surface
Δt	s	time step
T_{air}	°C	temperature of air
T_{soil}	°C	temperature of soil
T_{tub}	°C	temperature of tube
v_{air}	m/s	velocity of air
W_{air}	kg_{water} / kg_{air}	humidity ratio of air
W_{tub}	kg_{water} / kg_{air}	humidity ratio at tube surface

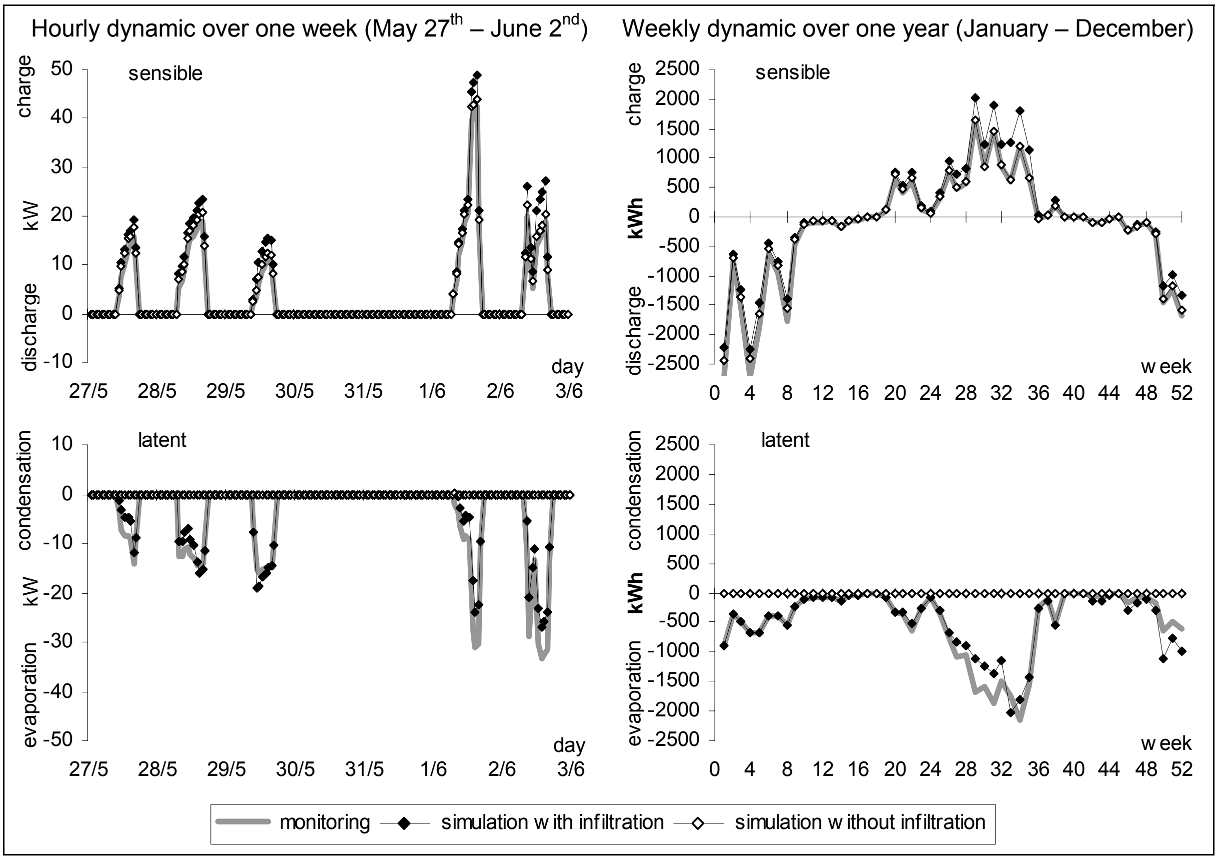

Figure 6 : Schwerzenbacherhof , comparison of monitoring and numerical simulation.

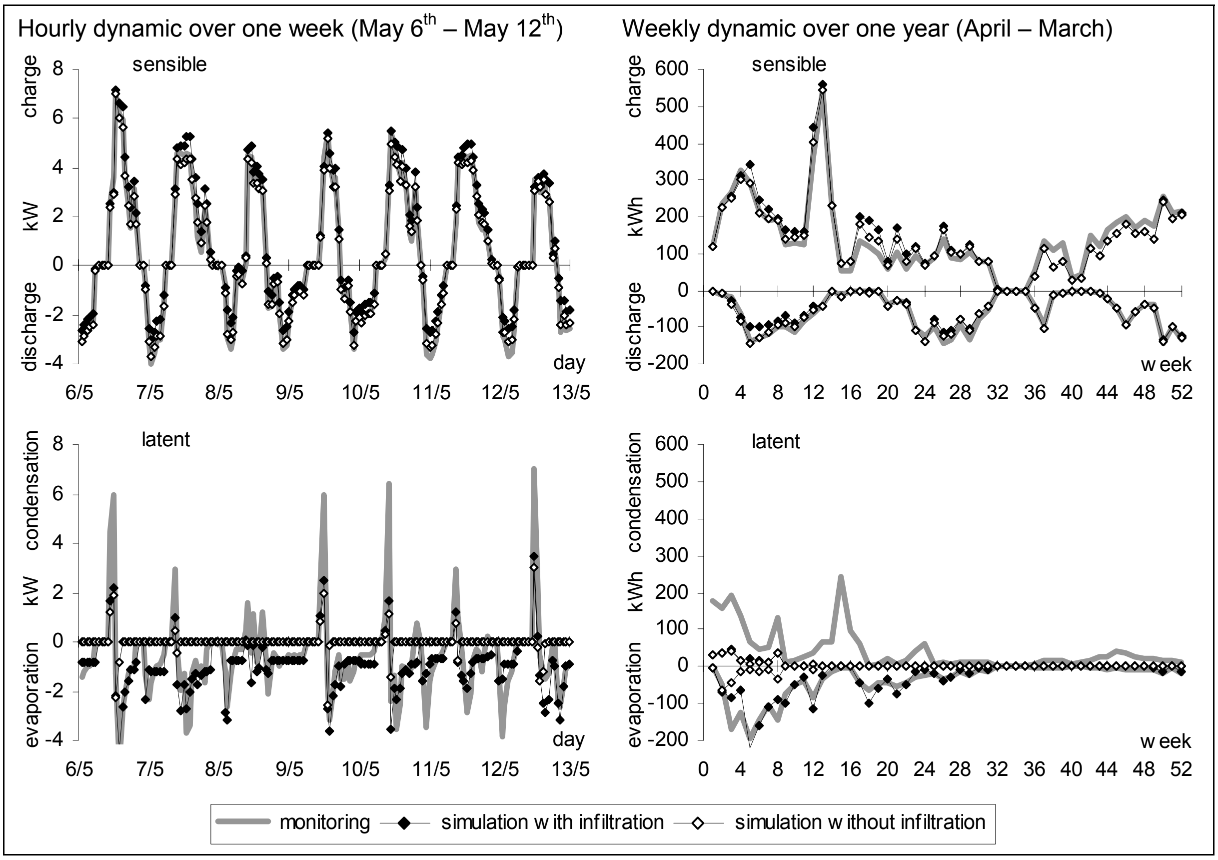

Figure 7 : Geoser, comparison of monitoring and numerical simulation.

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