ELSEVIER
Energy and Buildings 1295 (2000) 1–10
ENERGY AND BUILDINGS
www.elsevier.com/locate/enbuild

Cooling and preheating with buried pipe systems: monitoring, simulation and economic aspects

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Abstract

On basis of extensive monitoring and simulation work, we examine the fundamental difference between winter preheating and summer cooling potential of buried pipe systems under Central European climate, as well from an energetic as from an economic point of view. Care is taken to account for exhaustive energy balances, taking into account sensible and latent heat exchanges, as well as diffusion through soil.

Keywords: Earth-channel; Buried pipe system; Sensible and latent heat exchanges; Preheating/cooling of air

1. Introduction

As building envelopes improve, there is a rising interest for winter preheating or summer cooling systems based on renewables. One of them, which can fulfill both purposes, consists of forcing air from outside through a buried pipe system (hypocaust) before using it for air replacement (winter) or ventilation (summer), the building underground serving as a seasonal energy buffer. Basing on several analyzed installations, we will present an overview of ongoing analysis of such systems, including monitoring and simulation. After a description of a numerical modeling tool developed for this purpose (Section 2), we will outline hypocaust heating (Section 3) and cooling (Section 4) potentials which, although complementary, appear in Central European climate to be of distinct specificity and hence of unequal interest. Energetic analysis will be completed by a short discussion on economic aspects (Section 5).

2. Simulation tool for buried pipe systems using moist air

2.1. Sensible and latent heat exchanges

Start point for developing a simulation tool was an extensive monitoring campaign on daily storage of excessive solar heat gains in agricultural greenhouses, for reduction of fuel consumption during heating periods [1]. One of the analyzed storage devices of the "Geoser" experiment consists of 24 PVC pipes (16 cm diameter, 11 m length, 33 cm axial distance) running at 80 cm below the greenhouse. Layout as well as operation on a typical day is shown on Fig. 1. At night, when soil is warmer than lower set point, airflow through pipes allows for extraction of previously stored heat, and thus, lowers auxiliary heating demand; In turn, as soon as during daytime temperature of greenhouse rises above that of soil, excess solar gains are being stored again (simultaneous opening of windows still being necessary because of upper set point in greenhouse), with reversed airflow direction for sake of temperature stratification in ground.

Besides sensible heat exchanges (fall/rise of air temperature), one also observes latent heat exchanges to be at work: condensation during early morning storage, followed by evaporation as humidity lowers when windows are opened (Fig. 1).

If uncontrolled water infiltration is at work, as is often the case with earth channels used for preheating and cooling of air in buildings, such latent exchanges can also be at work with inlet from ambient, as will be seen further down. These considerations led us to develop a simulation model that could take evaporation and condensation into account.

2.2. Numeric simulation

Except for [3] (which does not have the flexibility of our tool) none of the known simulation models for air-to-earth

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PII: S0378-7788(00)00105-5

Nomenclature

c_{air}	specific heat of air (J/K kg)
c_{lat}	latent heat of water (J/kg)
c_{soil}	specific heat of soil (J/K m^3)
c_{tub}	specific heat of tube (J/K kg)
c_{vap}	specific heat of vapor (J/K kg)
c_{wat}	specific heat of water (J/K kg)
h	air/tube convective heat exchange (W/K m^2)
H	relative humidity (%)
k	heat conduction to neighbor node (W/K m^2)
$\dot{m}_{\mathrm{air}}$	convective air/tube exchange (kg/s)
$\dot{m}_{\mathrm{inf}}$	water infiltration (kg/s)
$\dot{m}_{\mathrm{lat}}$	condensation/evaporation (kg/s)
m_{wat}	free water (kg)
M_{air}	molar mass of air (kg/mol)
M_{wat}	molar mass of water (kg/mol)
P_{diff}	heat diffused by neighbor nodes (W)
P_{fric}	heat from frictional losses (W)
P_{int}	internal heat gain (tube/water) (W)
P_{lat}	latent air-tube heat exchange (W)
P_{sbl}	sensible air-tube heat exchange (W)
$\mathrm{Pr}_{\mathrm{air}}$	pressure of air (Pa)
$\mathrm{Pr}_{\mathrm{sat}}$	pressure of water at saturation (Pa)
S	heat exchange surface (m^2)
S_{tub}	total lateral heat exchange surface of tube (m^2)
T_{air}	temperature of air (°C)
T_{soil}	temperature of soil (°C)
T_{tub}	temperature of tube (°C)
V_{tub}	volume of tube node (m^3)
W_{air}	humidity ratio of air (kg$_{\mathrm{water}}$/kg$_{\mathrm{air}}$)
W_{tub}	humidity ratio of saturated layer at tube surface (kg$_{\mathrm{water}}$/kg$_{\mathrm{air}}$)

Greek symbols

ϕ_{air}	airflow in tube (m^3/s)
λ_{soil}	thermal conductivity of soil (W/K m)
ρ_{air}	specific weight of air (kg/m^3)
ρ_{tub}	specific weight of tube (kg/m^3)
Δt	time step (s)

Subscripts

i	neighbor node (soil or tube)
$t-1$	preceding time step

heat exchangers [4–6] are able to predict latent as well as sensible heat exchanges. On basis of a former work on a greenhouse solar storage similar to ours [2], we hence developed an explicit numerical model [7] which simultaneously accounts for both phenomena, as well as for frictional losses and water infiltration and flow along the tubes. It further allows for control of air flow direction as well as for flexible geometry (inhomogenous soils, diverse border conditions, use of symmetries or pattern repetitions for run-time economy, see Fig. 2) and is adapted to TRNSYS (a modular energy system simulation environment).

Heart of the model are mass and energy exchanges between air and tube (Fig. 2). They are computed consecutively for each tube node,[1] from inlet towards outlet, and comprise:

- Sensible heat: lost by air, which is determined by the air/tube temperature difference

  $$P_{\mathrm{sbl}} = S_{\mathrm{tub}} h (T_{\mathrm{air}} - T_{\mathrm{tub}}) \tag{1}$$

  where, similar to the case of a convective air/plane surface heat exchange [8], h is assumed to be an afine function of air velocity.
- Latent heat: which is determined by the Lewis approach [9], considering preceding sensible heat exchange to result from an air mass exchange between the air flow and a superficial air layer on the tube surface, at latter's temperature and saturated in humidity. Analogy between heat and mass transfer readily yields exchanged air mass rate:

  $$\dot{m}_{\mathrm{air}} = \frac{P_{\mathrm{sbl}}}{c_{\mathrm{air}}(T_{\mathrm{air}} - T_{\mathrm{tub}})} = \frac{S_{\mathrm{tub}} h}{c_{\mathrm{air}}} \tag{2}$$

  This air exchange conveys a moisture transfer, which is determined by the humidity ratio difference between air flow and saturated layer:

  $$\dot{m}_{\mathrm{lat}} = (W_{\mathrm{air}} - W_{\mathrm{tub}})\dot{m}_{\mathrm{air}} = (W_{\mathrm{air}} - W_{\mathrm{tub}})\frac{S_{\mathrm{tub}} h}{c_{\mathrm{air}}} \tag{3}$$

  where, according to perfect gazes

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

  $$W_{\mathrm{tub}} = \frac{100\% \times \mathrm{Pr}_{\mathrm{sat}}(T_{\mathrm{tub}}) M_{\mathrm{wat}}}{\mathrm{Pr}_{\mathrm{air}} M_{\mathrm{air}}} \tag{4}$$

  According to its sign, this water transfer corresponds to condensation ($\dot{m}_{\mathrm{lat}} > 0$) or evaporation ($\dot{m}_{\mathrm{lat}} < 0$). In latter case $\dot{m}_{\mathrm{lat}}$ is furthermore limited by available free water on tube surface as well as by maximum moisture air can absorb (saturation pressure). Finally, latent heat exchange expresses as

  $$P_{\mathrm{lat}} = c_{\mathrm{lat}} \times \dot{m}_{\mathrm{lat}} \tag{5}$$
- Heat diffused: from the four lateral soil nodes as well as from the preceding and following tube nodes, which is given by

  $$P_{\mathrm{diff}} = \sum_{i \in \mathrm{soil}} S_i k_i (T_{\mathrm{soil},i,t-1} - T_{\mathrm{tub}}) + \sum_{i \in \mathrm{tube}} S_i k_i (T_{\mathrm{tub},i,t-1} - T_{\mathrm{tub}}) \tag{6}$$

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[1] These refer to nodes under consideration unless marked with i in which case they refer to the neighboring node.

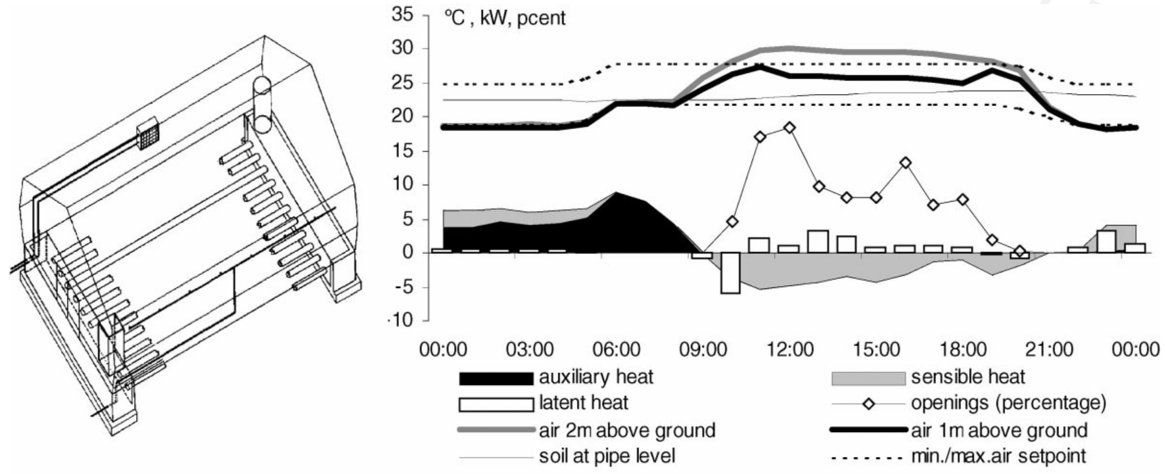

Fig. 1. "Geoser" experiment of underground heat storage in agricultural greenhouses: schematic layout and operation on 10 May 1994.

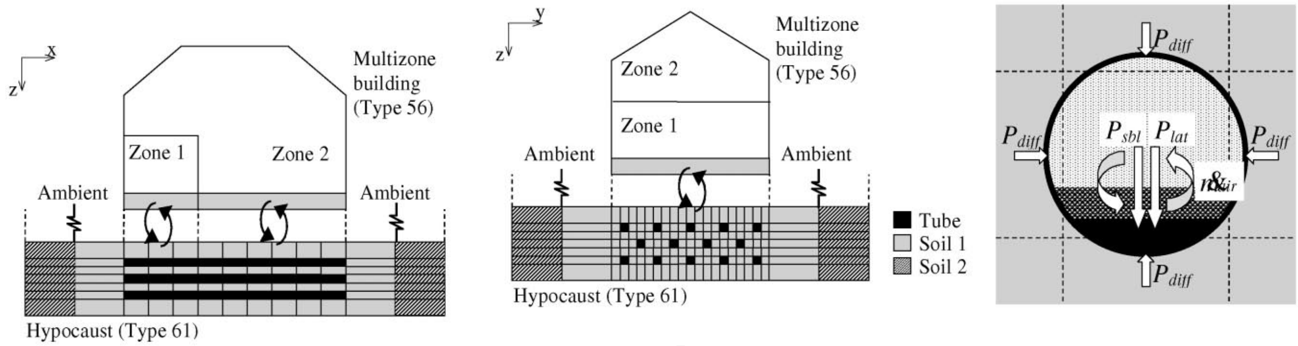

Fig. 2. Example of earth channel geometry (various pipe layers, inhomogenous soils, different border conditions) and linking to other TRNSYS simulation models, as well as detail of energy/moisture exchange between air and tube.

Since the saturated humidity in (4) is non-linear in terms of temperature, the value of T_{tub} and of the preceding energy rates is determined by iterated resolution of the node energy balance:

$$P_{\mathrm{int}} - (P_{\mathrm{sbl}} + P_{\mathrm{lat}} + P_{\mathrm{diff}}) = 0 \tag{7}$$

where the internal heat gain of tube and free water is given by

$$P_{\mathrm{int}} = \frac{(c_{\mathrm{tub}}\rho_{\mathrm{tub}}V_{\mathrm{tub}} + c_{\mathrm{wat}}m_{\mathrm{wat},t-1})(T_{\mathrm{tub}} - T_{\mathrm{tub},t-1})}{\Delta t} \tag{8}$$

Water balance on its turn allows to compute the evolution of the free water content in the node

$$m_{\mathrm{wat}} = m_{\mathrm{wat},t-1} + (\dot{m}_{\mathrm{inf}} - \dot{m}_{\mathrm{lat}})\,\Delta t \tag{9}$$

while sensible energy and water balance on air finally yield air conditions of next node:

$$T_{\mathrm{air},i} = T_{\mathrm{air}} + \frac{P_{\mathrm{fric}} - P_{\mathrm{sbl}}}{(c_{\mathrm{air}} + c_{\mathrm{vap}}W_{\mathrm{air}})\rho_{\mathrm{air}}\phi_{\mathrm{air}}} \tag{10}$$

$$W_{\mathrm{air},i} = W_{\mathrm{air}} - \frac{m_{\mathrm{lat}}}{\rho_{\mathrm{air}}\phi_{\mathrm{air}}\,\Delta t} \tag{11}$$

where calculation can be pursued in 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 (adiabatic, in/out flowing energy rate, temperature).

2.3. Validation

Extensive validation was performed against as well analytical solutions as data from four in situ monitored systems (among which the ones discussed in this article). Example of the model's ability to reproduce operation of systems with complex water flows is shown for the previously introduced "Geoser" pipe system, in hourly as well as weekly time steps[2] (Figs. 3 and 4), with model parameters h, λ_{soil} and c_{soil} fitted from measured data.

Sensible heat exchanges are well reproduced (yearly bias of 1% for storage, 3% for discharge) and are not much influenced by water infiltration into the tubes (yearly bias of 5% for storage, 10% for discharge). Not so for evaporation and condensation, which are hardly reproduced when no

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[2] This refers to the present time step unless marked with $t-1$ in which case it refers to the preceding time step.

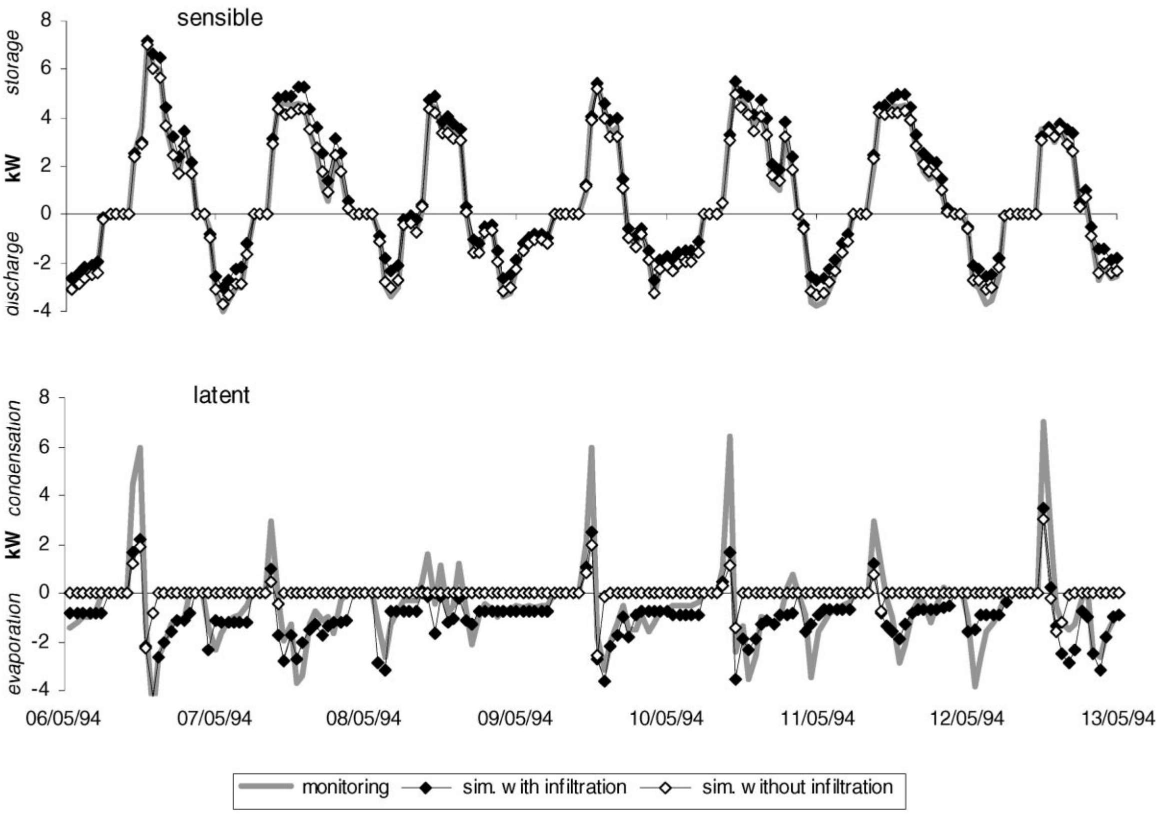

Fig. 3. Hourly sensible and latent energy exchanges (from air to soil) for ''Geoser'' earth-channel over one spring week.

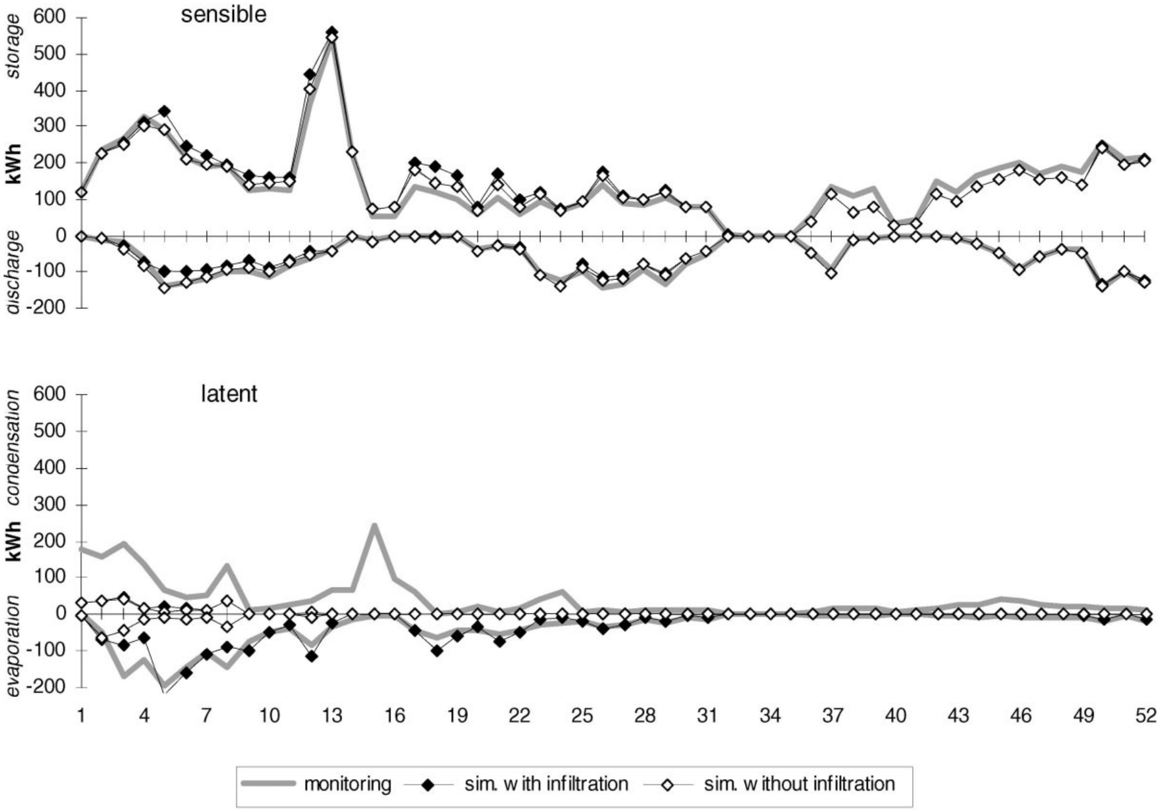

Fig. 4. Weekly sensible and latent energy exchanges (from air to soil) for ''Geoser'' earth-channel over 1 year (April 1994 to March 1995).

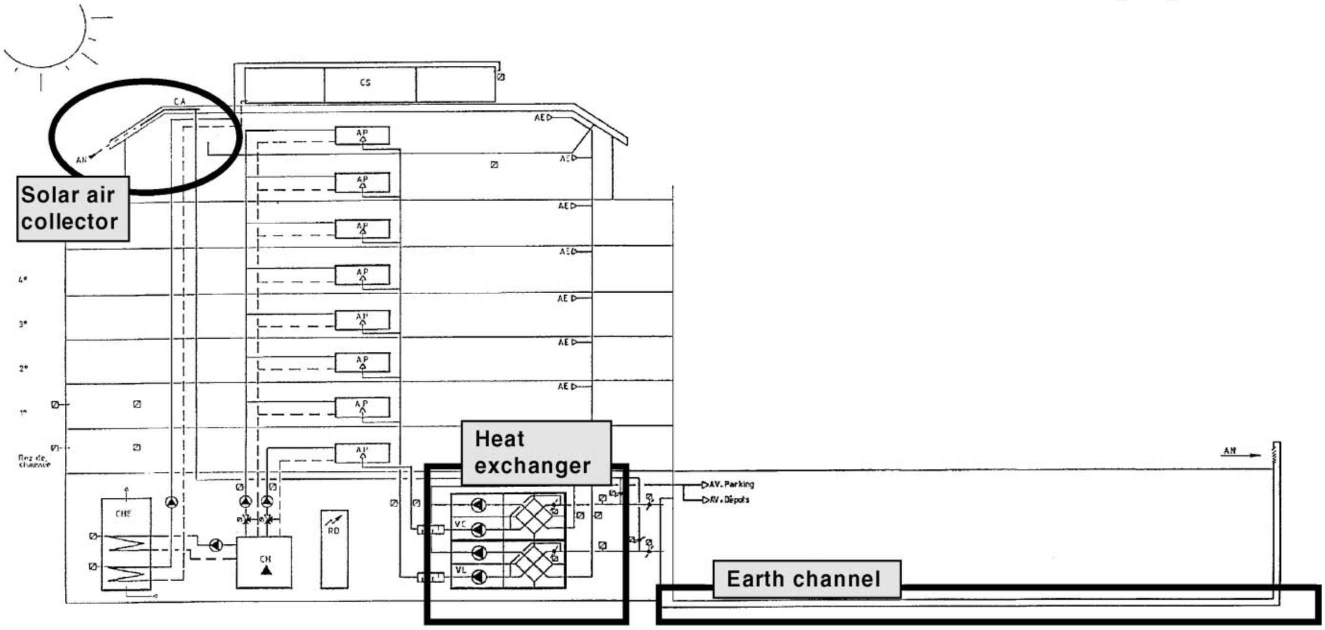

Fig. 5. General layout of heating and fresh air preheating system for the "Geoser" building.

water infiltration is at work (yearly bias of 90% for condensation and evaporation). A detailed study of the monitored data in 5 min step in fact enables to presume that the air flow carried fine water droplets from the greenhouse fog system into the tubes, which explains the yearly water balance default (excessive evaporation and drainage in regards to condensation). Simulation with proper water infiltration (daily monitored water default) enables to correct the simulated evaporation to a fairly good extent (yearly bias of 10%), whereby condensation yet still remains way too low.

Concerning dynamical aspects, although simulation and monitoring seem to fairly correlate (Figs. 3 and 4), instantaneous correspondence given by standard deviation during operation turns out rather poor: up to 30% for sensible, more than 100% for latent. A much better agreement between hourly measured and simulated values is obtained with ambient air entering the hypocaust (slower temperature variations) and when only sensible exchange occurs (see Section 3.1 and Fig. 6).

3. Heating potential

3.1. Comparison with competing alternatives

Heating season in Switzerland covers some 7 months of the year (3000 degree-days) during which air replacement plays a negative role on energy balance of buildings, requiring around 100 MJ/m^2 per year for standard ventilation rates of 0.5 V/h. In well insulated buildings (national recommendation of 300 MJ/m^2 per year for heating index) this fraction turns out to be an important part of the overall heating demand, energy saving measures concerning this particular point hence ranking among the important although not only ones. Buried pipes are one of the possible responses for fuel-free preheating of fresh air, other alternatives including heat exchangers on exhaust air and solar air collectors (collecting of fresh air under a metal roof).

The "Caroubier" multifamily and commercial building (heating index of 250 MJ/m^2 per year for 2900 m^2 heated surface) standing in the city of Geneva [10] is equipped with all three systems (Fig. 5): depending on solar radiation, fresh air (3000/2400 m^3/h in day/night time) is alternatively taken from under the roof or from the buried pipes, before going through a heat exchanger on exhaust air (which is injected in the parking lot for an ultimate thermal service). The hypocaust consists of 49 pipes (12.5 cm diameter, 50 m length, 30 cm axial distance, 980 m^2 total pipe exchange surface) that are running at 50 cm beneath the underground parking, approximately 10 cm above underground water level.

Monitoring over a 20 day winter period (Fig. 6) allowed to validate simulation of the hypocaust (2% bias, 2% standard deviation on hourly data), as well as to determine the efficiency of the subsequent heat exchanger (60% resp. 66% for higher and lower flow rates), while performance of the solar air collector was not analyzed so far. Simulated heating potential of the coupled hypocaust/heat-exchanger system (only when solar air collector is inactive) is roughly evenly shared between both subsystems (Table 1) and amounts to a total of 59.0 MWh on the overall heating period. If dropping buried pipes (fresh air directly to heat exchanger when solar air collector is inactive) this value would still amount to 49.6 MWh, so that the net gain of the coupled hypocaust ($59.0 - 49.6 = 9.4$ MWh) actually remains very low. With a more carefully sized heat-exchan-

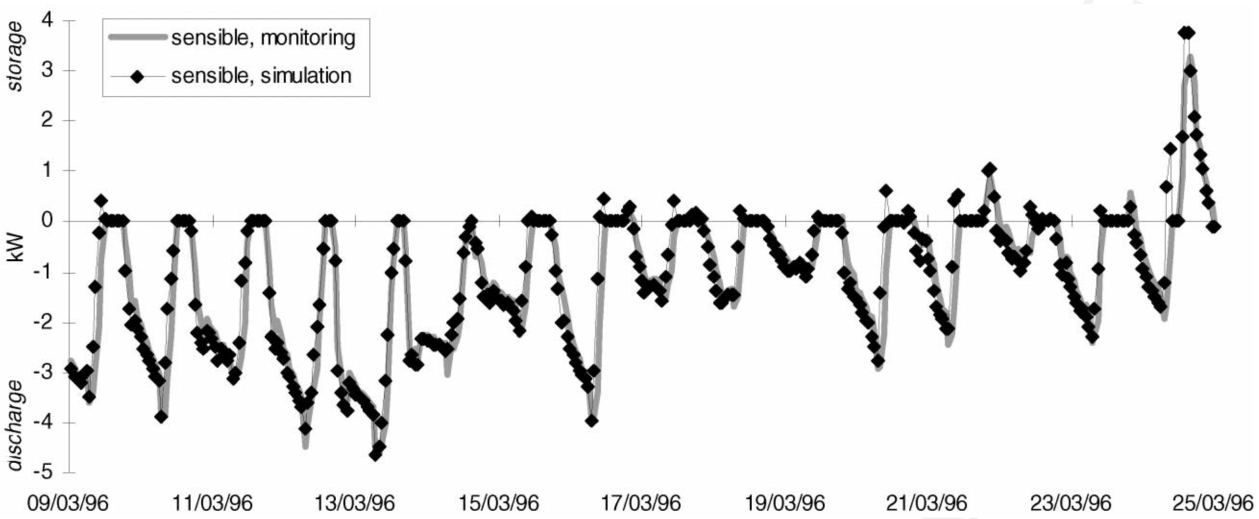

Fig. 6. Hourly sensible energy exchanges (from air to soil) for one of the two branches of the ''Caroubier'' earth-channel: monitored and simulated data over a winter month.

ger (exchange surface doubled, leading to 80% resp. 85% efficiency for both flow rates) the production of the stand alone heat exchanger could further more easily be raised to some 64.2 MWh, to the contrary of the oversized hypocaust, whose efficiency could hardly be improved anymore (see approaching heat gains for half-sized model, bearing in mind exponential drop of efficiency with length).

Hence the heat-exchanger clearly turns out to be a better preheating technique than the buried pipe system, and expensive implementation of both techniques does not bring substantial gains. Absence of solar air collector would reinforce this conclusion, since during sunny hours preheating would not be as effective by earth channel any more (soil temperature close to, or lower than ambient), but only by heat-exchanger.

3.2. *Overall energy balance and effect of water infiltration*

Overall energy balance of a buried pipe system has to take into account not only the effect of heating (or cooling) of the airflow, but also of heat diffusion through boundary surfaces as well as of water evaporation (or condensation) inside the pipes. The ''Schwerzenbacherhof'' commercial and administrative building (heating index of 144 MJ/m^2 per year for 8050 m^2 heated surface) standing near the city of Zurich [11] gives a good example of the possible importance and implication of these flows. The hypocaust (Fig. 7) 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). A varying air flow during office hours (6000–12 000 m^3/h in winter, 18 000 m^3/h in summer) yields winter preheating as well as summer cooling of the building.

Extensive monitoring over a 1 year period handed out by the Federal office of energy indicates that infiltration of underground water could have been at work (comparison of measured enthalpy balance with sensible heat exchange yields evaporation within the tubes all over the year, without any water deposit by condensation ever), as observed by ourselves on other systems in Geneva. Simulation in presence/absence of infiltration helps to understand the potential effect of such phenomena on the energy balance of both the hypocaust and the building (Fig. 8).

Hence, one observes that in presence of water winter preheating of air decreases because of heat for evaporation, but only by some 20%. Main influence goes for higher heat

Table 1
Heating potential of a coupled hypocaust/heat-exchanger system (with optional solar air collector)[a]

Layout				Heat gains		
Description	Hypocaust length (m)	Heat exchange efficiency (%)	Solar air collector	Hypocaust (MWh per year)	Heat exchange (MWh per year)	Total (MWh per year)
As constructed	50	60/68	Yes	27.1	31.9	59.0
Hypocaust half sized	25	60/68	Yes	21.7	35.1	56.8
Heat exchange alone	–	60/68	Yes	–	49.6	49.6
Heat exchange alone, optimized	–	80/85	Yes	–	64.2	64.2
Solar collector inactive	50	60/68	No	27.5	39.3	66.8

[a] Gains by heat exchanger are calculated with exhaust air at 22.5°C, as measured over 20 days.

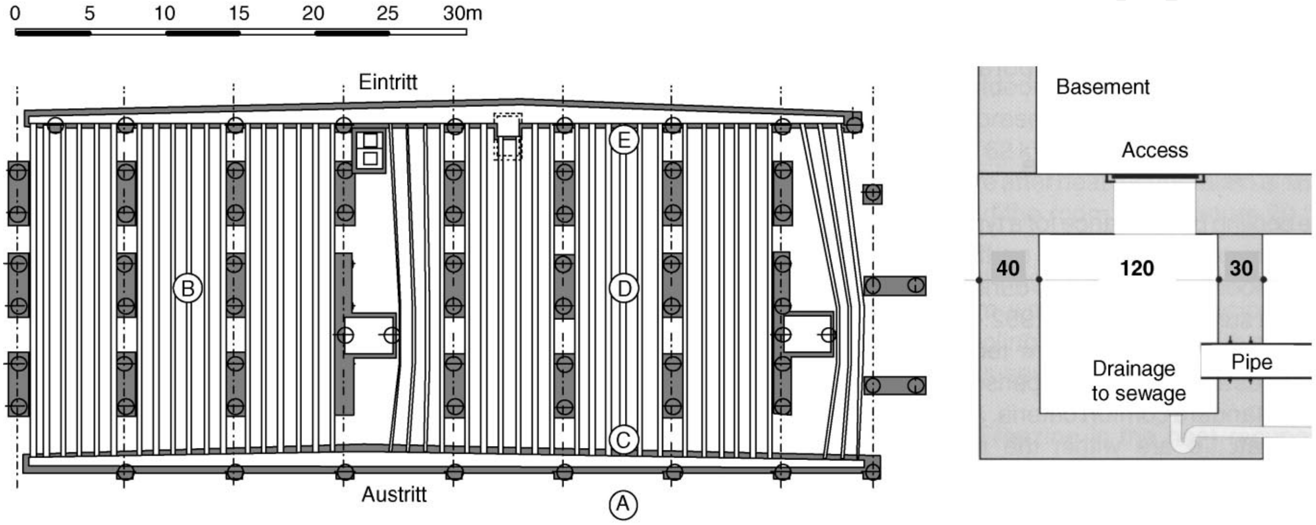

Fig. 7. General layout and construction detail of ''Schwerzenbacherhof'' cooling and preheating system.

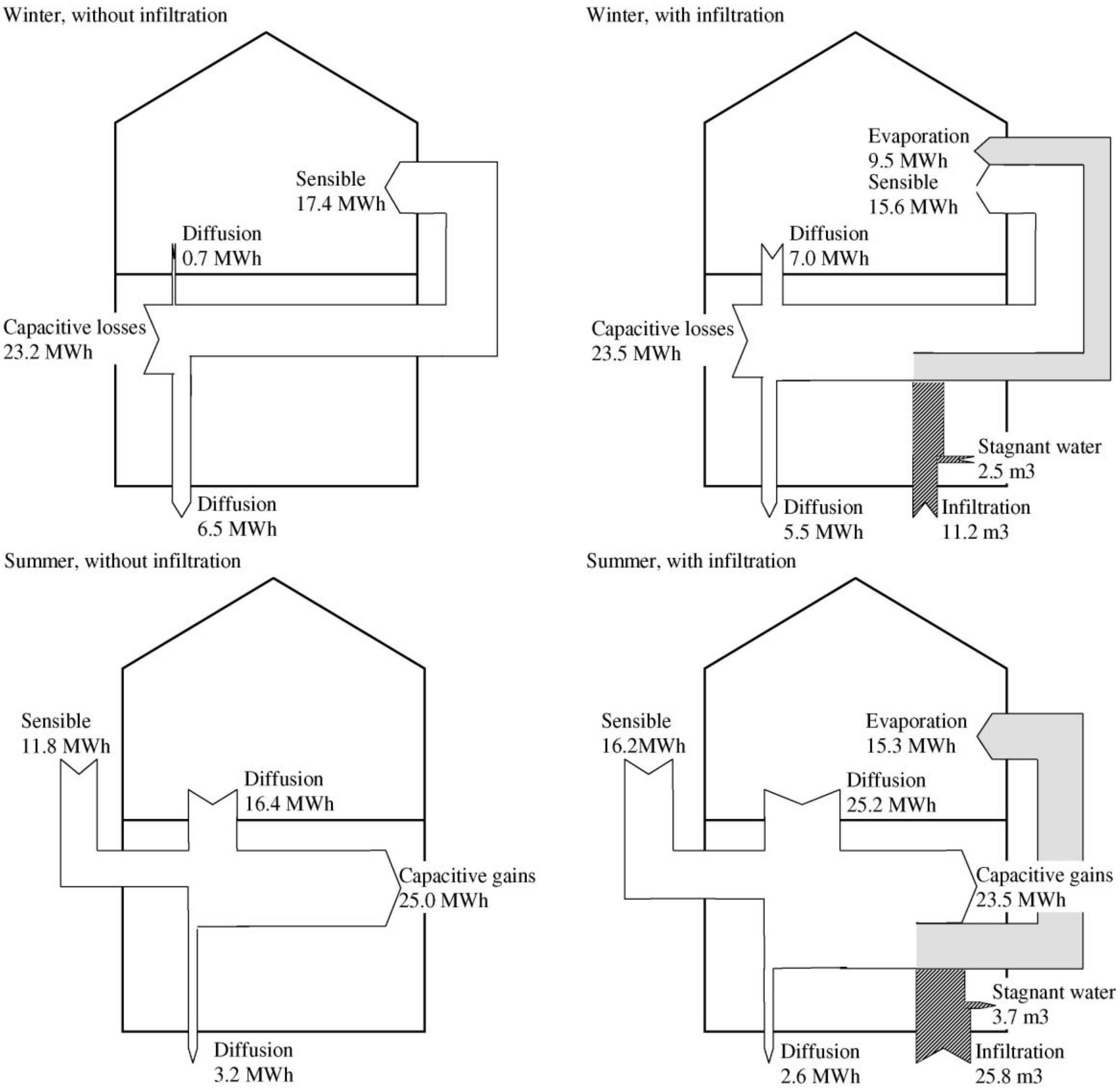

Fig. 8. Seasonal energy and water balance for ''Schwerzenbacherhof'' buried pipe system, with and without infiltration.

diffusion from building. Summed up, these two variations still do have an important consequence on the building energy balance, lowering the global hypocaust performance by 50% ($15.6-7.0=8.6$ instead of $17.4-0.7=16.7$ MWh). The summer behavior will be discussed in Section 4.2.

4. Cooling potential

4.1. Cooling versus heating

Winter heating potential described further up clearly relates to the capacitive role of the underground which acts as a seasonal energy buffer, pointing out the reciprocal cooling potential for summer. Care has to be taken though to understand the fundamentally different characteristics of these two services and the role played here by buried pipe systems:

While mean daily ambient temperature remains way below lower comfort threshold of 20°C in winter, in summer it does not exceed upper comfort threshold of 26°C (Fig. 9). In opposition to winter preheating (rise of inlet temperature), inertial cooling using underground as a short term energy buffer hence mainly consists in smoothening of ambient temperature over 24 h or a few days, for counter balancing of diurnal overshoots and high solar flows. It follows that whereas the heating potential of a buried pipe system is proportional to the outlet-inlet temperature difference (heating of fresh air), cooling potential is proportional to comfort-outlet temperature difference (cooling of air within building, replacing an air conditioning system). Good example of this often misunderstood phenomena is the previously discussed ''Caroubier'' building (Section 3.1), in which the air flow is running at close vicinity of the parking lot (up to 23°C in summer) and is, hence, globally heated up by the hypocaust (2.8 MWh over the summer period). Use of the hypocaust nevertheless smoothens inlet air to very stable temperatures (daily outlet amplitude less than 0.2 K) below 26°C, yielding a cooling potential of 19.6 MWh.

Air replacement, which has a negative energetic effect in winter and is, therefore, kept at minimum rates, hence turns out to have a positive function in summer when coupled to an inertial buffer like a hypocaust. Flow rates may in this case very well be risen to more important ventilation values of up to several volts per hour, yielding a proportional raise in cooling power. As an example, simulation of an alternative configuration of the ''Caroubier'' system with 3.5 times higher summer than winter flow rates (8800 m^3/h all day round) and bigger pipes for control of friction losses (21 cm diameter, same fan power) allows to rise cooling power by almost the same factor (66.8 instead of 19.6 MWh), leaving winter preheating potential almost unchanged (25.7 instead of 27.1 MWh, loss being presumably due to modified geometry, in particular lower storage capacity between pipes).

Seeking of higher cooling power by rising of the flow rate will augment the characteristic length for summer amplitude smoothening and is, therefore, limited by the system pipe length. An analytical approach [12], however, reveals that because of smaller penetration depth, heat exchange between air and undisturbed soil is more effective for daily than for seasonal oscillations, i.e. the characteristic length shorter. Even for a correctly dimensioned system for air replacement in winter, the flow rate in summer could hence be risen to some more important ventilation values.

4.2. Effective cooling and overall energy balance

To the contrary of the preheating potential, which is always useful, real demand for the previously defined cooling potential will of course depend on the building envelope (solar protection, heat insulation and thermal inertia) and functionality (internal heat gains). In the case of the

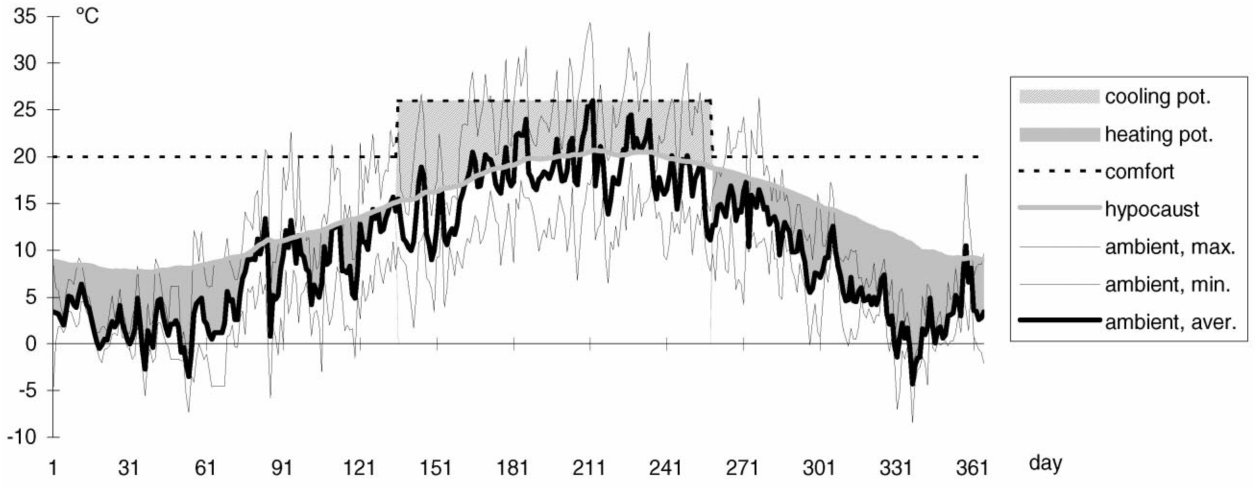

Fig. 9. Ambient temperature profile for the city of Geneva, as well as cooling and heating potential of the ''Caroubier'' buried pipe system as constructed.

"Schwerzenbacherhof" building discussed before (Section 3.2) and in absence of water infiltration, effectively developed summer cooling, as derived from the office room–pipe outlet temperature difference, amounts to 17.0 MWh (relating to the 11.8 MWh sensible heat stored in soil). This corresponds to 84% of the potential computed with a 26°C-pipe outlet temperature difference, indicating that room temperature generally remains below this upper set point (330 h overshoot, with a maximum at 27.6°C).

As can be seen from Fig. 8, during summer season water infiltration into pipes affects sensible heat extracted from air flow in a positive way, rising it up to 16.2 MWh and leading to 21.4 MWh (+26%) effective cooling. Again, an important fraction of the evaporation energy is being taken from increase in heat diffusion from building. Latter increase takes place all around the clock though and should not be counted with for damping of diurnal temperature overshoots.

5. Economic aspects

We performed a technico-economical optimization of the "Caroubier" hypocaust, mainly concerning the heating potential actually used in this particular realization, but also giving some insight on possible costs of cooling power. In addition to the "as constructed" (Section 3) and "high ventilation rate" (Section 4) layouts presented before, we also analyzed an alternative version of the "half sized" layout (Section 3), however, with pipes running immediately underneath the parking paving. Capital costs — which include excavation (15 F/m^3), supplying and laying out of PVC pipes (15.3 F/m comprising tightness) and of refilling concrete (135 F/m^3), as well as engineering (28% of preceding items) — thus could almost be cut by three (Table 2).

Because of the altogether distinct service and substituted energy forms, repayment of capital over 50 years at a 6% interest rate (but not electricity for fans, which belongs to air replacement) is alternatively being reported on heating or cooling gains, the other energy form being considered as an additional free service. For the sake of comparison, equivalent final energy prices (oil/electricity) are finally calculated by taking into account conversion efficiencies of traditional heating/cooling techniques (75% for auxiliary heating, 200% for air conditioning system), but disregarding latter's capital costs.

In the case of preheating, the optimized half sized model leads to an equivalent oil cost of 10 cts/kWh (Swiss cents), which is 2.4 less than for the constructed system, but still much higher than the saved fuel/gaz price of 4–6 cts/kWh. For summer cooling on the other hand, the high ventilation layout brings about an equivalent electricity cost of 26 cts/kWh (33 cts/kWh for the half sized model), which competes with the electricity prices of 20–28 cts/kWh. Unlike for preheating, which does not allow to cut short with an auxiliary heating battery, additional capital costs for air conditioning may in this case furthermore be avoided, so that inertial cooling can easily turn out cheaper than traditional techniques.

6. Conclusions

Detailed analysis of existing hypocaust installations in Switzerland brings us to following conclusions regarding the interest and limits of the technique:

- In Central Europe stress between climate dynamic and comfort threshold induces a fundamental asymmetry between heating and cooling potentials of ground used as a seasonal energy buffer: Winter preheating of fresh air (rise of ambient temperature) acts as a saving function on energy demand, to which it is inherently linked by limitation of flow rate; Summer inertial cooling (smoothening of ambient temperature below comfort threshold) can on the other hand be risen along with flow rate and hence becomes an energy producing service on its own.
- Air preheating with buried pipes remains in all cases more expensive than with fuel, which it cannot substitute completely. This technique furthermore enters in competition with more effective heat recovery on exhaust air. Buried pipe inertial cooling on the contrary turns out competitive with an (avoided) air conditioning system and allows to save simultaneously on electricity, capital costs and CFC gases. Regarded in this way, winter air preheat-

Table 2
Cost (Swiss francs) of preheating or cooling energy for the "Caroubier" hypocaust[a]

	Capital		Heating only			Cooling only		
	Investment (kF)	Repayment (kF per year)	Gains (MWh per year)	Cost (cts/kWh)	Equivalent cost (cts/kWh)	Gains (MWh per year)	Cost (cts/kWh)	Equivalent cost (cts/kWh)
As constructed	137	8.7	27.0	32.1	24.1	19.6	44.4	88.7
Half sized + under paving	48	3.1	22.4	13.6	10.2	18.4	16.6	33.1
As constructed + high ventilation	137	8.7	25.7	33.9	25.4	66.8	13.0	26.0

[a] Repayment based on a 6% interest rate and a 50 year lifetime.

ing becomes an additional free service, which can be coupled to other preheating techniques.

- Buried pipe systems may be subject to water infiltration, which can lower winter performance and enhance summer one, but also points out the sanitary question of stagnant water. Latter problematic can be avoided by replacing buried pipes with a closed water underground circuit coupled to the fresh air system via a water/air heat exchanger. Such a configuration, actually set up in Geneva and nowadays analyzed by us, further seems to benefit from lower capital investments.
- As for any system based on renewables, set up of buried pipes needs careful dimensioning with ad hoc tools. Besides developing of detailed simulation models that are not always within means of engineers, we will, hence, further work on simplified thumb rule methods. In this regard, one of the (economically quite important) parameters to deal with is the pipe depth, which relates to surface temperature, preliminary results tending to show that for cooling purposes excavation should in our climates be kept at minimum values.

Acknowledgements

We wish to thank Thierry Boulard (from the Institut national de recherches agronomiques of Avignon, France) for handing us over the original moist-air hypocaust routine developed in his institute; Markus Koschenz and Robert Weber (from the Swiss federal laboratories for materials testing and research, Dübendorf) for critical reading and valuable advices for the TRNSYS a daptation; Antoine Reist (from the Station agronomique de Changins, Conthey), Pierre Jaboyedoff (from Sorane SA, Lausanne) and Javier Gil (from P&A Partners, Cochabamba, Bolivia) for their collaboration during the GEOSER experiment; Jean Putallaz (Ingénieur-conseil, Geneva) for collaboration in the technico-economical study of the Caroubier building; Mark Zimmermann (from the Swiss federal laboratories for materials testing and research, Dübendorf) for handing us over the monitoring data of Schwerzenbacherhof; The Federal office of energy (Bern) and Cantonal office of energy (Genève) for financial support.

References

[1] B. Lachal, P. Hollmuller, J. Gil, Stockage de chaleur: résultats de GEOSER, in Stockage de chaleur, gestion de l'énergie et du climat dans les serres horticoles, recueil des exposés du colloque GEOSER du 15 février 1996 au RAC Conthey, Office fédéral de l'énergie, 1996 (see also final report, in press).

[2] T. Boulard, E. Razafinjohany, A. Baille, Heat and vapour transfer in a greenhouse with an underground heat storage system (Parts 1 & 2), Agriculture Forest Meteorology 45 (1989) 175–184.

[3] C. Gauthier, M. Lacroix, H. Bernier, Numerical simulation of soil heat exchanger-storage systems for greenhouses, Solar Energy 60 (1997) 333–346.

[4] G. Mihalakakou, M. Santamouris, D. Asimakopoulos, Modelling the thermal performance of earth-to-air heat exchangers, Solar Energy 53 (1994) 301–305.

[5] M. Bojic, N. Trifunovic, G. Papadakis, S. Kyritsis, Numerical simulation, technical and economic evaluation of air-to-earth heat exchanger coupled to a building, Energy 22 (1997) 1151–1158.

[6] A. Huber, St. Remund, Wiederstands-Kapazitäten-Modell, WKM_Lte, Program for the Simulation of Air-Earth Exchangers, IEA Low Energy Cooling Task (Annex 28), Design Tools for Low Energy Technologies, 1999.

[7] P. Hollmuller, B. Lachal, TRNSYS compatible moist air hypocaust model, Final report, Centre universitaire d'étude des problèmes de l'énergie, CH-1200 Genève, 1998.

[8] W.C. McAdams, Heat Transmission, 3rd Edition, McGraw Hill, New York, 1954.

[9] A.C. Kent, Mass Transfer, in: Ashrae Handbook, Fundamentals, 1989 (Chapter 5).

[10] J. Putallaz, B. Lachal, P. Hollmuller, E. Pampaloni, Evaluation des performances du puits canadien de l'immeuble locatif du 19 rue des Caroubiers, Expertise, Centre universitaire d'étude des problèmes de l'énergie, CH-1200 Genève, 1996.

[11] M. Zimmermann, J. Andersson, The Schwerzenbacherhof Office and Industrial Building, in Case Studies of Low Energy Cooling Technologies, IEA Low Energy Cooling Task (Annex 28), 1998.

[12] P. Hollmuller, B. Lachal, in press.