# Cooling and preheating with buried pipe systems : monitoring and simulation of installations in Switzerland

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# COOLING AND PREHEATING WITH BURIED PIPE SYSTEMS : MONITORING AND SIMULATION OF INSTALLATIONS IN SWITZERLAND

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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 as from an energetic as from an economic point of view.*

## 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 two existing installations, we will present an overview of ongoing analysis of such systems, including monitoring and simulation. After a description of the computer-aided modeling tool developed for this purpose (Ch. 2), we will outline hypocaust heating (Ch. 3) and cooling (Ch. 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 (Ch. 5).

## 2 Simulation tool for buried pipe systems using moist air

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 (*Lachal*). One of the system consisted in having (relative humid) greenhouse air cooled/heated through buried pipes, in which latent heat exchange (condensation/evaporation) sometimes happened to be at work along with sensible one (fall/rise of temperature) : in spring time humid air leads to condensation during early morning storage, followed by later on evaporation as greenhouse humidity lowers with further rise in air temperature due to solar gains (Fig 1). On basis of a former work on a similar system (*Boulard*) we hence developed a model (*Hollmuller*) 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).

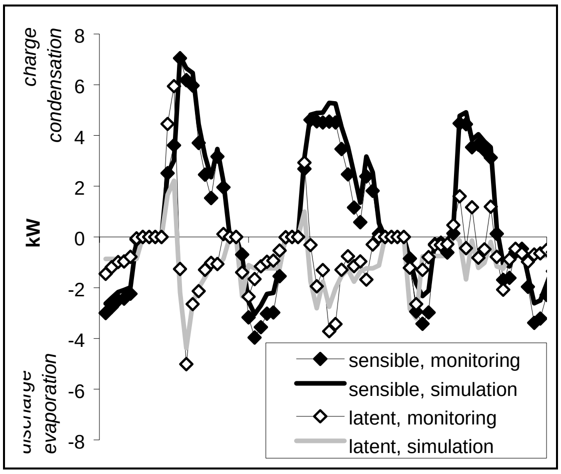



Fig. 1 : Daily heat storage and discharge (sensible and latent) in agricultural greenhouse buried pipe system : hourly data over 3 days.

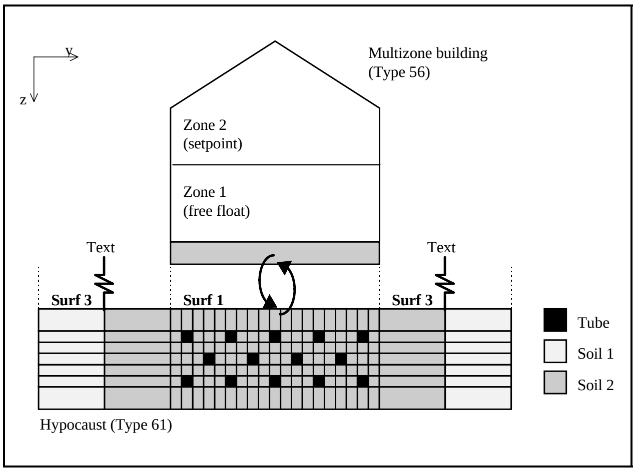



Fig. 2 : Example of hypocaust model geometry (different pipe layers, inhomogenous soils) and coupling to other TRNSYS simulation models.

Validation work (*Hollmuller*) yielded good results on both sensible and latent heat storage (latter under condition of precise monitoring of humidities, needing careful calibration and control of sensors). As will be seen further down, latent heat exchanges can also play a (potentially) important role with inlet from ambient, as in hypocausts used for air preheating and cooling in buildings, in which case the characteristics of this particular model again turns out to be of special interest.

# 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$^2$ for standard ventilation rates of 0.5 vol/hr. In well insulated buildings (national recommendation of 300 MJ/m$^2$ 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 being a heat exchanger on exhaust air or a solar air collector (collecting of fresh air under a metal roof).

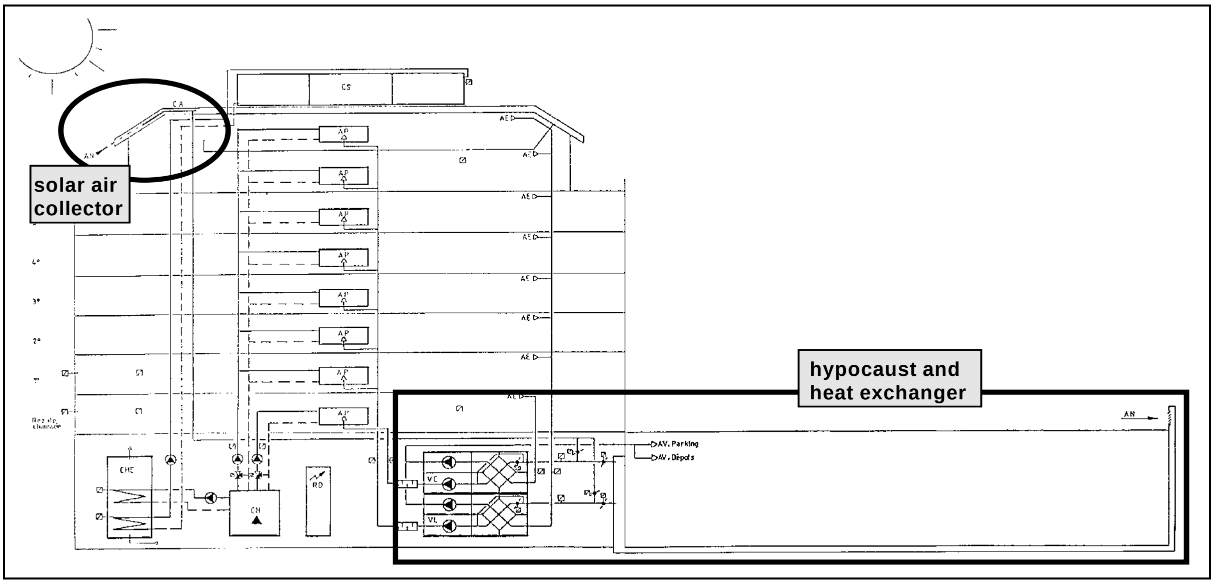



Fig. 3 : General layout of heating and fresh air preheating system for the « Caroubier » building.

The « Caroubier » multifamily and commercial building standing in the city of Geneva (*Putallaz*) is equipped with all three systems (Fig. 3) : fresh air (3000/2400 $m^3$/hr in day/night time) is, depending on solar radiation, alternatively taken from under the roof or from the buried pipes, themselves coupled to a heat exchanger on exhaust air (latter being 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 m2 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 allowed to validate simulation of the hypocaust (mean square deviation of 2% on hourly as well as daily heat gains), 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 (Tab. 1) and amounts to a total of 59'000 kWh 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 49’600 kWh, so that the net gain of the coupled hypocaust (59'000 - 49'600 = 9'400 kWh) actually remains very low. With a more carefully dimensioned model (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 64’200 kWh, 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).

Table 1 : Heating potential of a coupled hypocaust/heat exchanger system (with optional solar air collector).

| **Layout** | | | | **Heat gains** | | |
|---|---|---|---|---|---|---|
| description | hypocaust length [m] | heat exch. effic. [%] | solar air collector | hypocaust [kWh/yr] | heat exch. [kWh/yr] | total [kWh/yr] |
| as constructed | 50 m | 60 / 68 | yes | 27’100 | 31’900 | 59’000 |
| hypocaust half sized | 25 m | 60 / 68 | yes | 21’700 | 35’100 | 56’800 |
| heat ex. alone | - | 60 / 68 | yes | - | 49'600 | 49’600 |
| heat ex. alone, optimized | - | 80 / 85 | yes | - | 64'200 | 64’200 |
| solar collector inactive | 50 m | 60 / 68 | no | 27’500 | 39’300 | 66’800 |

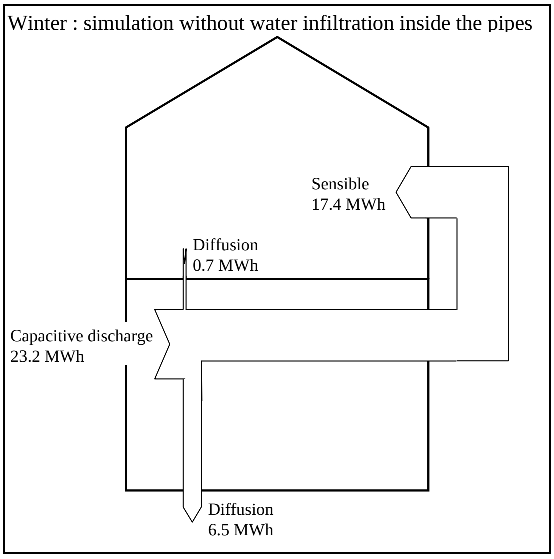
Gains by heat exchanger are calculated with exhaust air at 22.5 °C, as measured over 20 days.

Hence the heat exchanger clearly turns out to be a better preheating technique than the buried pipe system, and expensive implementation of both techniques doesn’t bring substantial gains. Even more so in absence of solar air collector, since inactivation of latter during sunny hours (all fresh air through hypocaust/heat exchanger system) does not affect preheating of air by ground (whose temperature are no longer higher 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. Good example of the possible importance and implication of these flows is given by the « Schwerzenbacherhof » commercial and administrative building standing near the city of Zurich (*Zimmermann*). The hypocaust 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 (6’000 - 12’000 $m^3$/hr in winter, 18'000 $m^3$/hr in summer) yields winter preheating as well as summer cooling of the building.

Extensive monitoring over a one 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 results in presence/absence of infiltration help to understand the potential effect of such phenomena on the energy balance of both the hypocaust and the building (Fig. 4).



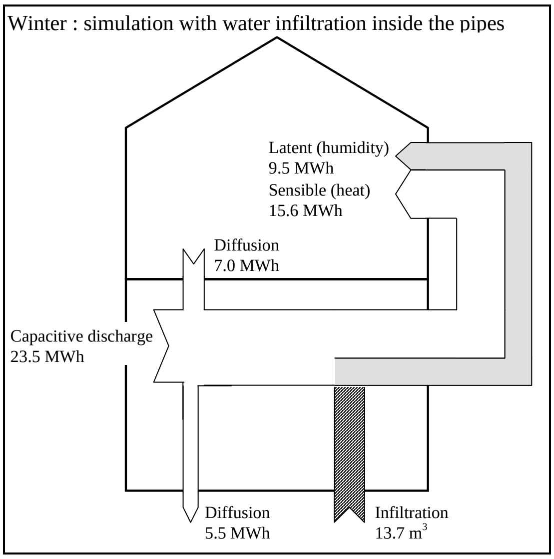




Fig. 4 : Winter and energy balance (plain flows, white and gray) and water balance (grey flows, plain and hatched) for « Schwerzenbacherhof » buried pipe system, with and without water infiltration.

Hence one observes presence of water and subsequent necessary heat for evaporation to lower winter preheating of air, but only of some 20%. Main influence goes for heat diffusion from building, which summed up to variation of sensible heat carried by airflow hence does have an important consequence on building energy balance, globally lowering hypocaust performance of 50% (15.6 - 7.0 = 8.6 instead of 17.4 - 0.7 = 16.7 MWh).

# 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 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. 5). 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 hours or a few days, for counter balancing of diurnal overshoots and high solar flows. It follows that insofar 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, in which 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 (2’800 kWh 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 19’600 kWh. Real demand for the so defined cooling potential will of course depend on the building envelope (heat insulation and solar protection) and function (internal heat gains).

- Air replacement, which has a negative energetic effect in winter and is therefore kept at minimum rates, hence turns out positive in summer when using 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 vol/hr, yielding a proportional raise in cooling power (limitation of this elasticity is given by characteristic length for smoothening of amplitude which, as monitoring and preliminary analytical and simulation studies seem to show, obey less constraining rules than for a rise of temperature in winter). As an example, simulation of an alternative configuration of the « Caroubier » system with 3.5 times higher summer than winter flow rates (4000 $m^3$/hr all day round) and bigger pipe diameter (21 cm) for control of friction losses (same fan power) allows to rise cooling power to some 66'800 kWh, leaving winter preheating potential almost unchanged (25'700 instead of 27'100 kWh).

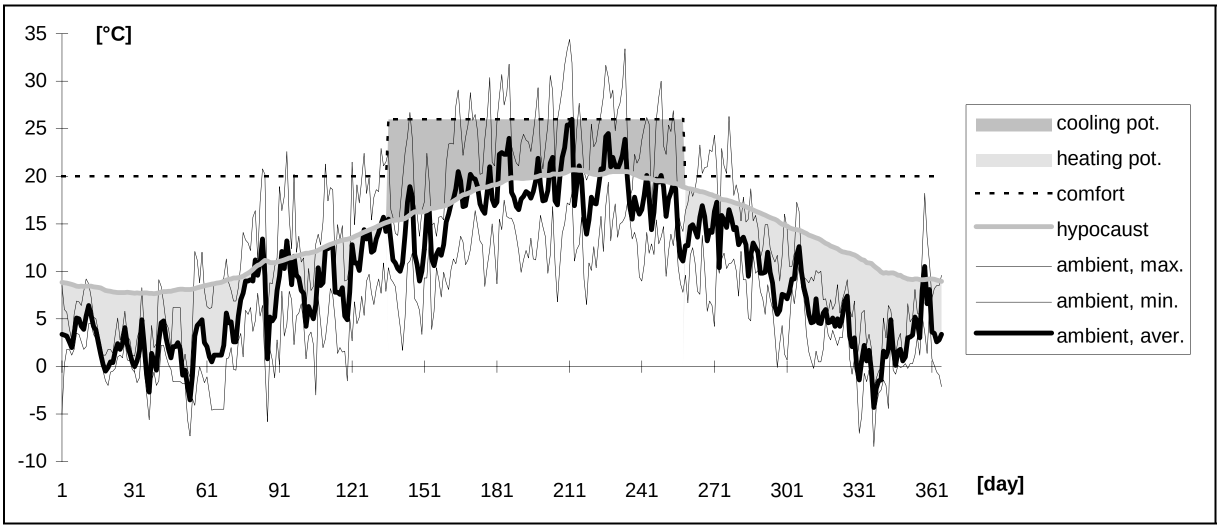



Fig. 5 : Ambient temperature profile for the city of Geneva, as well as cooling and heating potential of the « Caroubier » buried pipe system as constructed.

### 4.2 Effect of water infiltration

One finally notes from analysis on the « Schwerzenbacherhof » mentioned before that water infiltration in tubes, while having a negative effect in winter, on the contrary rises energy balance of building in summer : again only partly via air flow, a bigger part of evaporation energy being taken from increase in heat diffusion from building to soil (*Hollmuller*). Latter part of this rather accidental increase in cooling potential cannot be easily controlled though, and should hence not be counted with.

## 5 Economic aspects

We performed a technico-economical optimization of the « Caroubier » hypocaust (*Putallaz*) which mainly concerns the heating potential actually used in this particular realization, but also gives some insight on possible costs of cooling power. In addition to the « as constructed » (Ch. 3) and « high ventilation rate » (Ch. 4) simulations presented before we also analyzed a possible configuration with twice shorter pipes running immediately underneath parking paving, which allows for a heating potential very close to the simple « half sized » model (Ch. 3), but with capital costs almost cut by three by simultaneous saving on oversized length and costs for excavating/refilling. Because of the altogether distinct service and substituted energy forms, repayment of capital cost (without electricity cost for fans, which belongs to accounting for air replacement) will be reported alternatively on heating and cooling gains (Tab. 2), the other energy form thus being considered as an additional free service.

Economic comparison with traditional techniques, taking into account 75% overall efficiency of auxiliary heating battery, yields an energy cost of 24 resp. 10 cts (Swiss cents) per extracted kWh on preheating for the actual and the optimized half sized model (disregarding competing dynamic with heat exchanger). These value clearly remain higher than the saved fuel price of 3 cts/kWh.

Cooling potential on the other hand has to be compared to alternative air conditioning with overall coefficient of performance of 2, yielding an energy cost of 33 resp. 26 cts/kWh for the half sized model with standard flow rates and the actual model with higher ventilation flow rates in summer. These value have to be compared to the price of electricity (average and peak prices of 20 resp. 28 cts/kWh,) summed up with repayment of capital costs for air conditioning, which unlike for heating can be avoided by use of hypocaust, so that inertial cooling can easily turn out cheaper than traditional techniques.

Table 2 : Cost (Swiss francs) of heating or cooling energy from the « Caroubier » hypocaust.

| | **Capital** | | **Heating only** | | | **Cooling only** | | |
|---|---|---|---|---|---|---|---|---|
| | invest. Fr | repay. Fr/yr | gains kWh/yr | cost cts/kWh | eq. cost cts/kWh | gains kWh/yr | cost cts/kWh | eq. cost cts/kWh |
| as constructed | 137'000 | 8'691 | 27'050 | 32.1 | 24.1 | 19'589 | 44.4 | 88.7 |
| half sized + under paving | 48'000 | 3'045 | 22'395 | 13.6 | 10.2 | 18'394 | 16.6 | 33.1 |
| as const. + high ventilation | 137'000 | 8'691 | 25'675 | 33.9 | 25.4 | 66'771 | 13.0 | 26.0 |

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

## 6 Conclusions

Detailed analysis of existing hypocaust installations in Switzerland bring us to following conclusions regarding the interest and limits of this 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.
- Cost of air preheating with buried pipes remains in all cases much higher than fuel price, 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 avoided air conditioning and allows to save simultaneously on electricity, capital costs and CFC gases. Regarded in this way, winter air preheating than becomes an additional free service, which can be coupled to other preheating techniques.
- Buried pipe systems may be subject to water infiltration. While this can affect winter performance in negative, summer performance in positive way, it 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 hence will further be working on simplified thumb rule methods. In this regard, one of the (economically quite important) parameters to deal with is that of pipe depth and related coupling to surface temperature, preliminary results tending to show that excavation should be kept at minimum values.

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