Geocooling potential of borehole heat exchangers in low energy office buildings analysed with dynamic system simulations

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ABSTRACT

A reference office building has been defined in order to simulate its thermal behaviour and comfort and for assessing potentiality of geocooling with borehole heat exchangers. The building has low heating and cooling demands, a condition that makes it possible to use active concrete plates for heating and cooling. Starting from the reference case, a list of buildings has been defined varying the glazing ratio, internal or external solar protections, windows typologies and the heat distribution systems. A borehole heat exchanger field is coupled to a heat pump in winter and to the heat distribution system in summer through a flat plate heat exchanger. The cooling requirement satisfied by a direct heat transfer into the ground through the borehole heat exchangers is so called geocooling.

A dynamic system model has been developed to simulate the building, the emission of thermal energy, the technical installations including the borehole heat exchanger field and the interconnected thermal interactions. Comfort conditions are simulated to fulfil SIA Swiss regulations and standards. They determine the building thermal requirements that have to be covered by the geocooling system. A design procedure is presented for best system design.

Building design, system technical feasibility and limits of the ground coupled system are discussed and result from the analysis of the numerous system simulations. Geocooling potential depends on the quality of the building design and its heat emission. The importance of the ground thermal conductivity and the ground recharge ratio on the system design are highlighted.

1. INTRODUCTION

This research, dealing with geocooling, benefits from the large number of studies and applications of ground source heat pumps that is increasing constantly, especially in Switzerland. Core of these applications are borehole heat exchangers. A borehole heat exchanger is realised with a 10 to 15 cm diameter borehole drilled down to a depth of 20 to 300 m. Pipes are then inserted in the borehole for the circulation of a heat carrier fluid in a closed loop circuit. The most common pipe installation in Switzerland is the double-U pipe installation. The fluid flow rate circulates in parallel in the 2 U pipes that conduct the fluid down to the bottom of the borehole and then back up. A filling material is injected between the pipes and the borehole wall to ensure a good thermal contact with the ground and avoid vertical ground water circulation inside the borehole. A borehole heat exchanger is thus a heat exchanger with the ground and is normally coupled to a heat pump for heating purpose (SSG, 2010). It may also be used for the dissipation of waste heat in the ground for cooling purpose. The meaning of direct cooling or *geocooling* is to provide cooling without a cooling machine, i.e. by direct heat transfer from the cooling distribution to the ground flow circuit through a conventional heat exchanger.

Ground coupled systems with borehole heat exchangers are spreading fast in Switzerland. The total annual length of new installed boreholes is increasing every year and nearly reached 2’000 km in 2008 (GSP, 2010), which is equivalent to the borehole length requirement of about 20’000 new single family houses. Large systems are more and more usual and the design process relative to single family houses is more complex. The design process is not only limited to the sizing of a ground heat exchanger, but also has to take into account seasonal heat storage effects. A thermal recharge of the ground is necessary and can, ideally, be fulfilled by geocooling for best system thermal performances.

Such a design process has been studied in the past (Pahud, 2003) and requires a multidisciplinary approach that implies to take into account the building design itself (Hollmuller and al., 2005). In this study the ground coupled system is simulated together with the building, the heating and cooling distributions in order to analyse the technical feasibility and design of geocooling systems by dynamic system simulations.

The main objectives are to assess the geocooling potential related to office buildings and establish simple sizing rules for pre-design evaluation, highlighting also some design requirements for best system integration and efficiency.

2. METHODOLOGY

The initial step is the definition of an office building and location. A reference building geometry is used and the building envelope, building use and building thermal energy distributions are defined together with climatic data for the studied location.

2.1. Thermal requirements of the building

In a first step the building control parameters are adjusted so that winter and summer thermal comfort are met with a minimum of heating and cooling energy. According to the SIA norm 382/1 (2007), indoor air temperature should remain within 21 – 24.5°C in winter and 22 – 26.5°C in summer. The indoor air temperature may exceed the upper limit up to 100 hours per year. This tolerance is accepted for buildings cooled with the technique of geocooling.

A procedure has been established for the determination of the building control parameters. Those related to winter and summer management of solar protections are adjusted first with the help of one-year simulations of the building alone. The building indoor air temperature is kept between its minimum and maximum design values, set to respectively 20 and 26 °C. A simulated instant heat rate is added or removed from the building spaces if necessary. Then the parameters related to the technical installation and the thermal energy distribution system in the building are adjusted. The one-year simulations performed for this purpose are made with a simple heating and cooling production, to avoid the simulation of the ground coupled system. Heating is provided with a constant design heat rate, corresponding to the design heat rate of the heat pump, and cooling with a design fluid temperature and flow rate, corresponding to geocooling at a given temperature level. It is important not to have an oversized design heat rate for heating and a too low design fluid temperature for cooling. These two parameters result primarily from the building design and use. They are key factors for the design and success of a ground coupled system and the possibility of using geocooling for cooling.

2.2. Sizing of the borehole heat exchangers

In a second step the ground coupled system is simulated. All remaining parameters are defined, from the technical installation to the ground, including number, depth and spacing between the borehole heat exchangers. The best system design is obtained when the heating and cooling criteria are met with the least borehole length. According to SIA norm 384/6 (2010), the criteria have to be met for a time horizon of 50 years, thus including long term effects in the system design.

The heating criterion is met as long as the inlet fluid temperature in the borehole heat exchangers is larger than the minimum allowed one. As the borehole heat exchangers are placed under the building, a minimum fluid temperature of 0 °C is fixed.

The cooling criterion is met as long as the annual tolerance for the maximum indoor air temperature is not exceeded. In other terms, the maximum fluid temperature from the borehole heat exchangers is conditioned by the design fluid temperature for cooling and the conventional heat exchanger between the cooling distribution and the ground flow circuit.

The best system design is found by successive iterations of 50-years simulations of the whole building and ground coupled system. A schematic view of the followed methodology is shown in figure 1.

Variations of the building envelope, building heat distribution systems, climatic data and ground thermal characteristics provide various system designs that allow us to evaluate the geocooling potential of such systems.

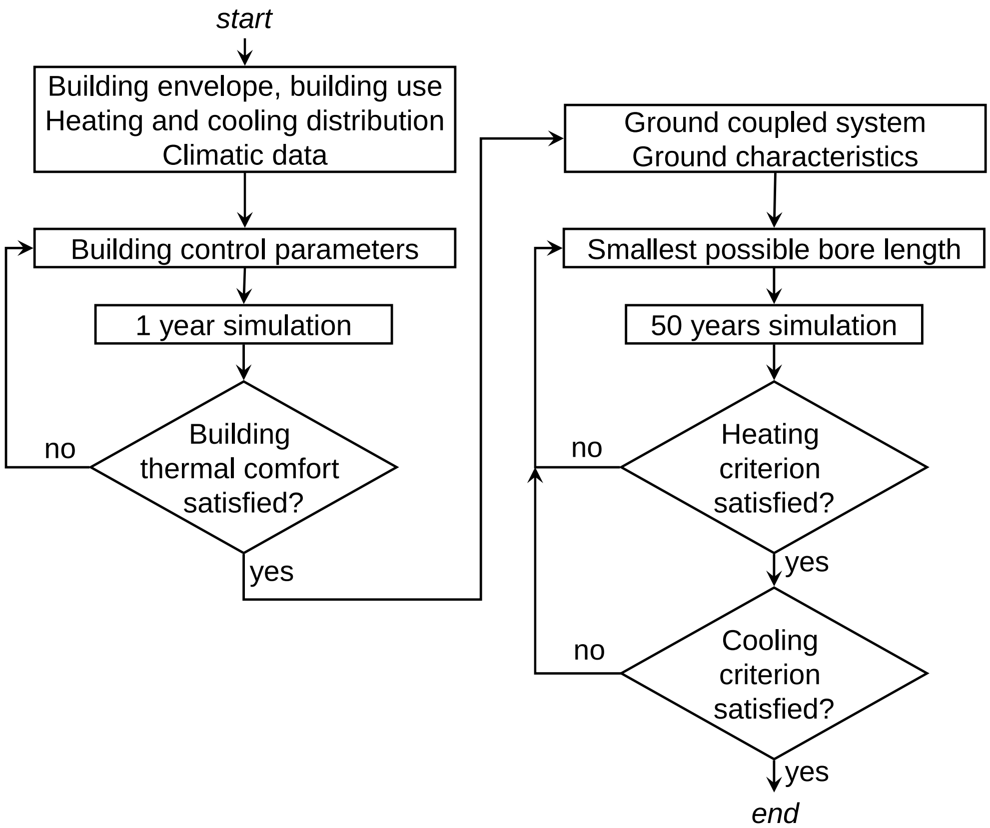

Figure 1 : Followed methodology for the determination of an optimal system design for a ground coupled system.

3. THE SIMULATION TOOL

TRNSYS is a well-known and widely used system simulation programme of transient thermal processes (Klein et al., 2005). This programme, chosen to develop a simulation tool of the building and its ground coupled system, provides libraries of subroutines that represent, for example, a multi-zone building, or HVAC components such as a heat pump, water tanks, pumps, pipes, valves, controllers and so on. A TRNSED application has been created and called COOLSIM (Pahud, 2008). COOLSIM is based on PILESIM (Pahud, 2007), another TRNSED application dedicated for the simulation of a borehole heat exchanger field, and the TRNSYS TYPE56 model, for the simulation of a building and its heat distribution system.

3.1. Building simulation

The building model TYPE56 is configured so that the building envelope, building mass, internal gains, air change rate and solar protections correspond to the desired values. Daily and weekly schedules are defined for building occupation and ventilation. A double-flux ventilation system with a heat recovery unit is simulated during the occupation hours of the building.

The technical installation is either providing heating or cooling to the distribution system of the building. As this latter is supposed to have massive concrete plates between floors, they are used for heat and cold emission. They are so-called “active concrete plates”; the water circulation pipes are imbedded in the middle of the floor concrete plate, by opposition to “floor heating”, where the pipes are imbedded in a light concrete layer over the floor concrete plate. Heat and cold emission occurs primarily through the ceiling, and the large heat capacity of the plates is providing a thermal storage between the technical installation and the heated and cooled spaces. Active concrete plates and floor heating are simulated with the help of fictive thermal zones in the TYPE56 model (Pahud and al., 2008; Pahud, 2002). Four fictive zones were defined for the simulation of the heating and cooling system, in addition to the two thermal zones for the simulation of the building itself. In this way it is possible to define 1 zone for the most critical part of the building.

Only sensible heat or cold are simulated. Humidity and dehumidification of the air are not taken into account. The ventilation system is only designed to guaranty hygienic quality of indoor air. It is assumed that if dehumidification is required, it would be achieved through the ventilation system without increase of the design air flow rate. Latent heat is not taken into account in the building simulation and the simulated technical installation is not coupled to the ventilation system.

3.2. Ground coupled system simulation

The borehole heat exchangers are simulated with the non standard TRNSYS duct store component TRNVDSTP, developed at Lund University in Sweden (Hellström, 1989; Pahud and Hellström, 1996), and further developed at the EPFL Lausanne (Pahud et al., 1996). This component is devised for the simulation of thermal processes which involve thermal energy storage in the ground, including a ground heat exchanger that can be a borehole field. It has been used and/or validated in numerous studies; see for example Chuard and al. (1983) or Pahud (1993).

The ground part of PILESIM is entirely used and integrated in COOLSIM. The simulated system is indicated by the system border shown in figure 2. No domestic hot water is covered by the system.

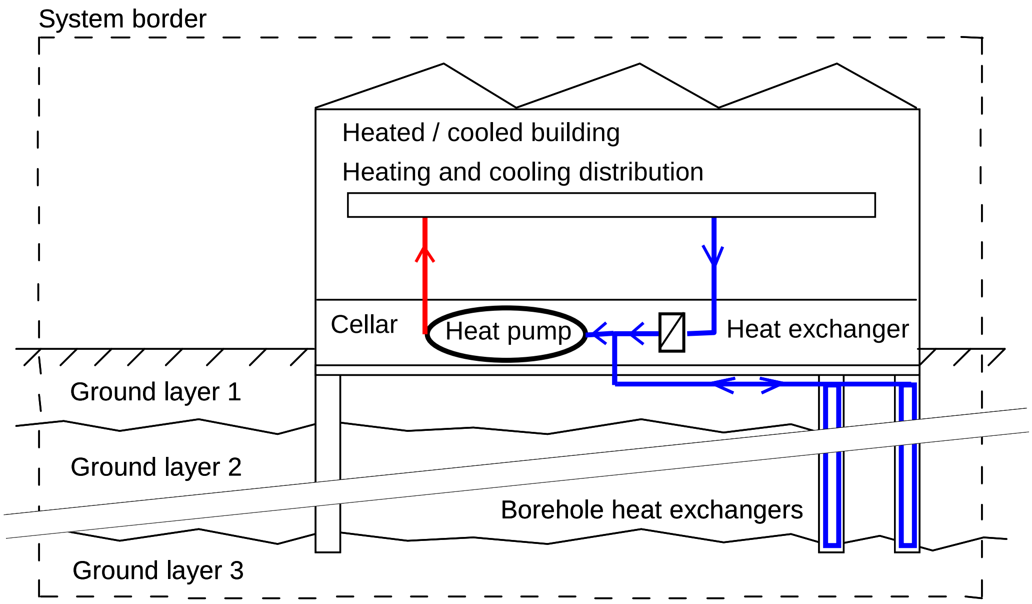

Figure 2 : The system simulated by COOLSIM, the TRNSED application of TRNSYS, is indicated by the system border.

A time step of 1 hour is fixed to ensure that the short-term thermal interaction between the different subsystems is taken into account. The simulations are performed over a long period of time (50 years), so that transient effects of the first years are included in the system design and system thermal performances.

4. BUILDING CHARACTERISTICS

4.1. The building reference case

A low energy building in Chiasso, south part of the Alps in Tessin, Switzerland, is selected for the definition of the reference case, thus fixing reference climatic data as well. The building, with five rectangular floors, has a heated floor area of 2'200 m^2 and a net heated volume of 5'700 m^3. Having a ground section area of 440 m^2 (53 m x 8.4 m), the building main façade is oriented toward south. It is 53 m wide and 16.6 m high, making a total area of 880 m^2. An east-west cross section of the building used to define the reference case is shown in figure 3.

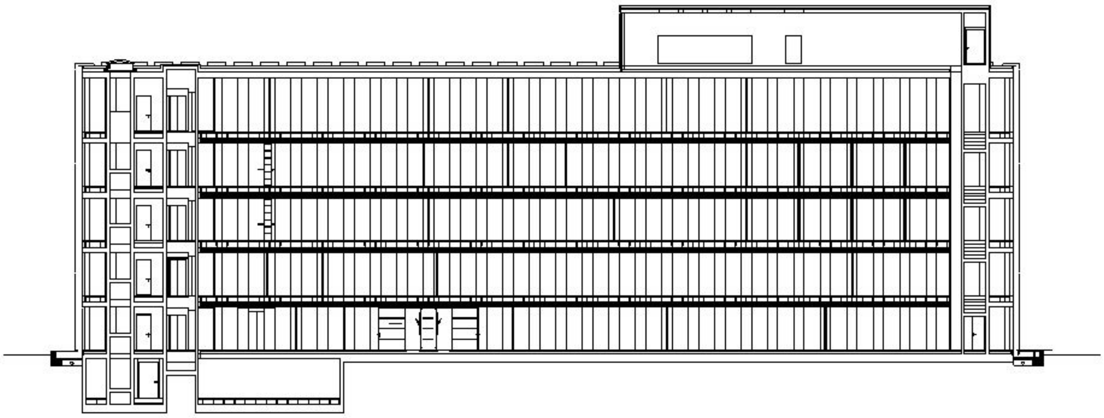

Figure 3 : East-west cross section of the Chiasso-Brogeda building used for the definition of the reference building.

Opaque parts of the building envelope are well insulated on the outside, keeping the wall thermal mass inside. Outside vertical walls have an inner concrete layer of 18 cm thickness. As the window's frame is integrated into the opaque walls of the building, the wall U-value is rather large (1 $W/(m^2K)$). The roof, insulated with a layer of 20 cm foam-glass, has a U-value smaller than 0.2 $W/(m^2K)$. Due to heating and cooling with the 30 cm thick concrete plates, the ceiling presents large surface of concrete in direct contact with the rooms. The total area of active concrete plates is about 1'900 m^2. The building thermal capacity is rather important and corresponds to 150 $Wh/(m^2K)$.

The glazing ratio, defined by the windows glazing area over the façade area, is set to 50% for every façade. External solar protections are providing shading on the triple glazing windows (glazing U-value and g-value of respectively 0.7 $W/(m^2K)$ and 0.4). When solar protections are completely closed, the overall g-value is reduced to 0.15.

Internal gains from people, lighting and appliances are fixed according to profiles given in the Swiss technical handbook defined for an open space office (SIA, 2006). Expressed in terms of square meter of internal area (supposed to be 80% of the heated floor area), they reach 26 W/m^2 during a working day. On a yearly basis, internal gains correspond to a mean and constant heat emission of 6 W/m^2 (1 W/m^2 for people, 3.3 W/m^2 for lighting and 1.7 W/m^2 for appliances).

As the building envelope is tight, a low but constant infiltration air change rate of 0.1 h^{-1} is fixed. Mechanical ventilation is operating every day from 8:00 to 18:00 and provides an air change rate of 0.5 h^{-1}. Ventilation heat recovery is simulated with an air to air heat exchanger whose efficiency is set to 80%.

The specific transmission and ventilation heat losses of the reference building are assessed to 2.3 kW/K. Together with the internal thermal heat capacity, the time constant of the building is estimated to 120 h.

4.2. Building design variation

Various building designs are contemplated relative to the reference one. The glazing ratio (85% instead of 50%), the glazing type (double (U-value: 1.4 W/m^2K, g-value: 0.6) instead of triple), the solar protections (internal instead of external), and the heat and cold distribution system (floor heating instead of active concrete plates) are analysed. The internal heat capacity of the building designs ranges from 95 to 150 $Wh/(m^2K)$, the total specific heat losses from 2.3 to 3.3 kW/K and the time constant from 60 to 120 hours. The characteristics of the external solar protections are such that the overall g-value is 0.15 for both glazing. With internal solar protections the overall g-value results from the solar protection characteristics, and it is calculated to 0.32 for triple glazing and 0.45 for double glazing.

5. BUILDING THERMAL PERFORMANCES

Solar protections, heating and cooling controls have to be adjusted so that the thermal requirements of the building are satisfied. Summer and winter periods are defined according to cooling and heating requirements. They are defined with the daily running mean outdoor air temperature to avoid unnecessary alternation of heating and cooling. For the building reference case, solar protections are lowered if global solar radiation exceed 100 W/m^2 in one of the façade during summer. In winter they also have to be lowered to avoid overheating. The threshold is found to be at 400 W/m^2. Heating and cooling are controlled with the indoor air temperature. Simulated indoor air temperature are shown in figure 4 for the building reference case. The temperature limits according to SIA 382/1 (2007) are also indicated.

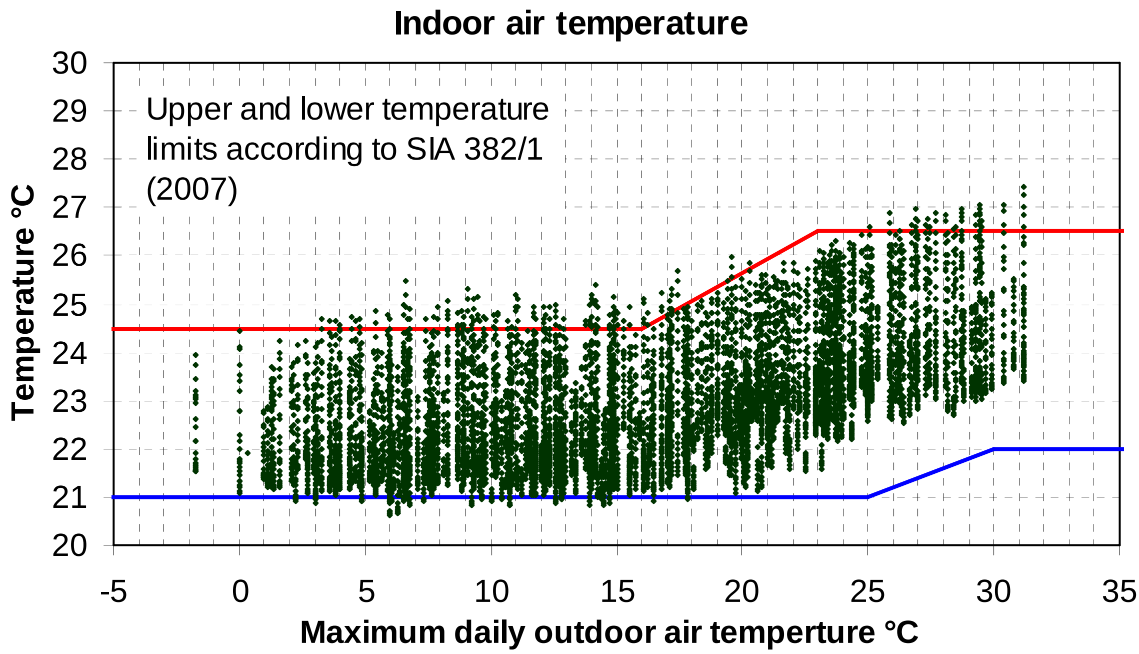

Figure 4 : Simulated indoor air temperature for the building reference case.

The indoor air temperature does not exceed 26.5 °C more than about 40 hours per year, thus satisfying the summer tolerance. The thermal requirements are met with a heating power of 75 kW and a forward cooling temperature of 21°C in the active concrete plates, providing up to 60 kW cooling power. The energy requirements are simulated to 130 MJ/(m^{2}y) for heating and 60 MJ/(m^{2}y) for cooling.

It can be observed how the indoor air temperature limits are difficult to be satisfied. This is also due to the large time constant of the distribution system which does not respond immediately to a thermal solicitation. Depending on the building design, the indoor air temperature can not be controlled to satisfy the thermal comfort requirements. This is particularly true with internal solar protections or a larger glazing ratio. Floor heating also presents more difficulties than active concrete plates to keep indoor air temperature within minimum and maximum limits.

Building designs that present difficulties for the control of indoor climate normally require larger heating and cooling powers, which means a lower forward fluid temperature for cooling. Large power and low temperature for cooling are not compatible with geocooling. This study has clearly highlighted that only low energy buildings that integrate passive climate control such as efficient external solar protections and active concrete plates can take benefice of the geocooling potential.

Most of the heating and cooling energy has to be distributed through the heat distribution system and not the ventilation system. This is the reason why indoor air temperature comfort requirements have to be satisfied without air conditioning in the simulation model. If this is not possible a geocooling solution has no sense and the first step of the procedure shown in figure 1 is aborted.

6. GROUND COUPLED SYSTEM

The ground coupled system is formed by the borehole heat exchangers, placed under the building, the heat pump and the geocooling heat exchanger. Typical parameters values are entered in the programme to make the borehole heat exchangers correspond to double-U pipe installation. The boreholes are supposed to be 100 m deep and spaced by 8 m. A variable performance coefficient is simulated using the heat pump model implemented in PILESIM (Pahud, 2007). The thermal performance of the heat pump is defined by a COP of 4 at B0W35 fluid conditions. The geocooling heat exchanger is a counter-flow heat exchanger whose design heat transfer coefficient is set to 30 kW/K.

In absence of a local ground water flow, the ground characteristics that condition the system design are primarily given by the average ground thermal conductivity and the initial ground temperature. It is supposed that the initial ground temperature near the ground surface is given by the mean annual air temperature plus about 1 °C. For example, the annual air temperature is 11.1 °C in Chiasso. The initial ground temperature is supposed to be 12 °C near the surface. A geothermal gradient of 25 K/km is assumed with the depth, giving a mean average temperature of 13.3 °C for the initial temperature of the ground layer crossed by the 100 m deep boreholes. The ground thermal conductivity is varied between 1 and 4 W/(mK), as it is strongly dependent on the local geological conditions.

7. SYSTEM SIZING

The ground system is sized according to the second step of the procedure shown in figure 1. The nominal thermal power of the heat pump is known from the first step of the procedure, which deals with the simulation of the building. Then the total borehole length (or the borehole number) has to be sized in function of the building thermal requirements, the heat pump, the geocooling temperature level and heat exchanger, and the ground conditions. Both the heating and cooling criteria have to be met. It is thus the criterion that requires the longest borehole length that conditions the total length of the borehole heat exchangers.

7.1. Ground thermal conductivity

The ground thermal conductivity has a strong influence on the system design. Typical values lie between 2 and 3 W/(mK). In figure 5, the borehole length is expressed in terms of nominal heat extraction rate of the heat pump.

The heating criterion is satisfied if the borehole length ensures that the fluid temperature remains over 0 °C during the first 50 operation years of the system. For a ground thermal conductivity of 2 W/(mK), the bore length has to be sized with a key value of 31 W/m at the maximum.

The cooling criterion is defined by the annual number of hours for which the indoor air temperature exceeds 26.5 °C. The criterion is met as long as the number of hours is not diverging and remains close to its minimum value. For a ground thermal conductivity of 2 W/(mK), the bore length has to be sized with a key value of 35 W/m at the maximum.

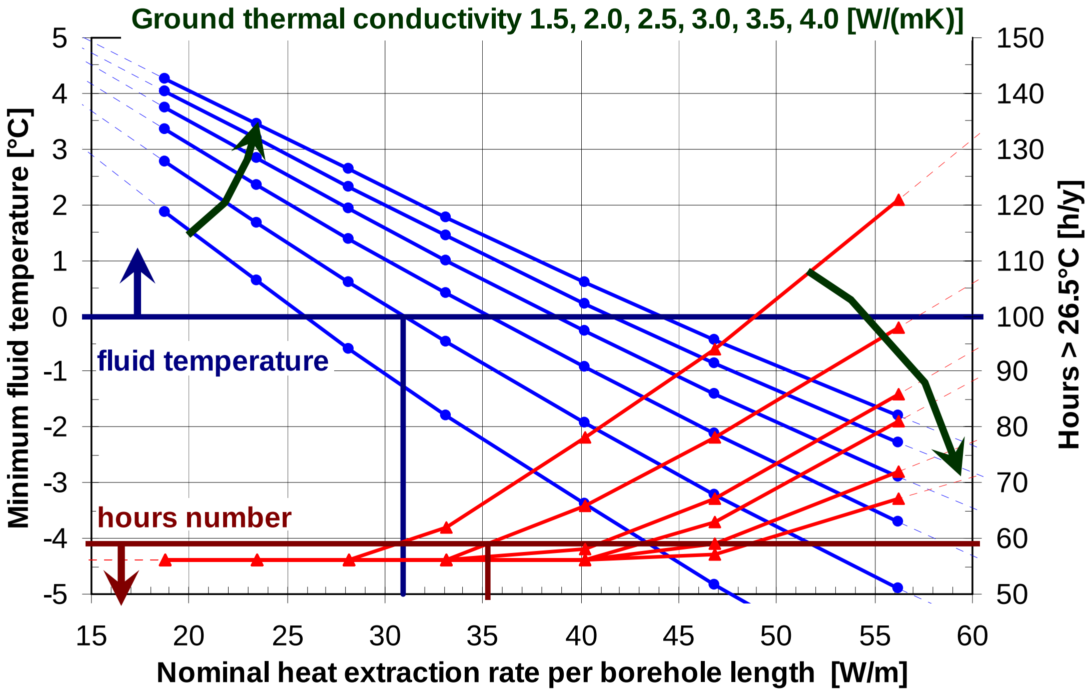

Figure 5 : Influence of the ground thermal conductivity on the system design. The borehole length is expressed in terms of nominal heat extraction rate of the heat pump, both for the heating and cooling criteria.

For the reference case, sizing of the borehole length has to be done with 31 W/m at the maximum. The nominal heat extraction rate of the heat pump is, with a nominal heating power of 75 kW at B0W35 (COP of 4), established to 56 kW. The total borehole length is then 1'800 m, corresponding to 18 boreholes of 100 m each.

An important parameter in the sizing of such a system is the ground recharge ratio. This parameter, defined as the ratio of the annual injected energy in the ground by the annual extracted one, is equal to 0.6 for the reference system. This parameter is related to the ground storage effect and plays an important role in a geocooling system sizing. The influence of the ground recharge ratio is discussed in the next section.

7.2. Ground recharge ratio

In order to explore the sensitivity of the system design to the ground recharge ratio, building design and climatic data are varied. The various building designs are simulated for 2 climatic data in the south part of the Alps (Chiasso and Bologna) and 2 in the north part (Geneva and Zurich). Nearly all building cases having internal solar protections or a 85% glazing ratio were rejected, as no solution providing acceptable thermal comfort was possible. With climatic data from Bologna, only 1 case lead to a feasible geocooling solution (external solar protection, 50% glazing ratio, concrete plates and double pane windows). One reason is the initial ground temperature, with an average value of 16.3°C for the first 100 m, which is rather high for a geocooling solution.

In figure 6 all the cases that lead to a geocooling solution are reported. In order not to have the influence of the ground thermal conductivity, an average value of 2 W/(mK) is fixed for all the cases. For each case, the length of the borehole is calculated relatively to the nominal heat extraction rate of the heat pump, whose nominal power results from the building design and climatic data.

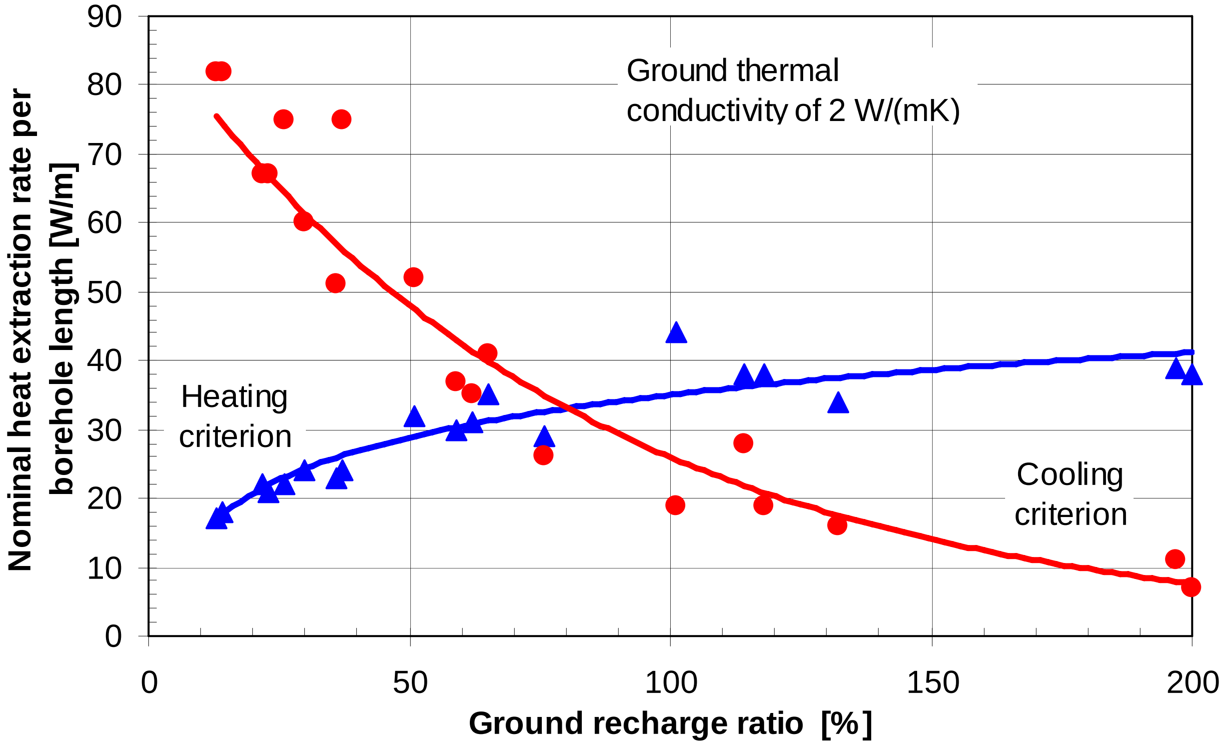

Figure 6 : Influence of the ground recharge ratio on the system design. The borehole length is expressed in terms of nominal heat extraction rate of the heat pump, both for the heating and cooling criteria. The nominal power of the heat pump is adapted from case to case according to the building design and climatic data.

An optimal system design is obtained when the ground recharge ratio lies between 50 to 90%. As expected, the heating criterion is dominating when the ground recharge ratio is low, i.e. when the cooling requirements are small relatively to the heating ones. When the ground recharge ratio exceeds 100%, the borehole length is increasing rapidly, leading to an unrealistic geocooling solution. When a geocooling solution is searched for, it is worth trying to have a ground recharge ratio that lies between 50 and 90%, in order to minimise the total borehole length. In this way the borehole heat exchangers are used in a way that maintains a fresh ground storage in the long term.

Other analyses will still be carried out. For example the importance of the temperature difference between the cooling distribution and the initial ground temperature has to be highlighted. It will also help drawing geographical maps were geocooling solutions are possible or not.

8. CONCLUSION

A low energy office building heated and cooled with active concrete plates has been used to analyse the geocooling potential with borehole heat exchangers. A dynamic simulation tool has been developed, based on well validated tools of such ground systems. A procedure has been established for the simulation and the analysis of the whole building and system. Thermal requirements of the building are first simulated in order to fulfil indoor thermal comfort conditions. The ground system is simulated in a next step to assess its technical feasibility and size the borehole heat exchangers.

Various building designs and various climatic data were taken into consideration. Simulations have shown that the building design has a strong influence on the feasibility of a geocooling system. If thermal comfort conditions can not be ensured primarily without air conditioning, a geocooling solution has no chance to succeed. Design prerequisites such as efficient external solar protections, large thermal mass and not too important glazing ratio were highlighted.

The total length of the borehole heat exchangers is also strongly influenced by some key parameters, such as the local ground thermal conductivity. The ground recharge ratio, which defines how much heat is injected back into the ground during an annual cycle, is strongly penalizing a geocooling system when it is larger than unit. Optimal values were found between 0.5 and 0.9. Other key parameters will be investigated to highlight their influence on the system design.

The developed simulation tool is used to establish design guidelines. It should help designing future buildings and borehole heat exchanger fields in order to take the maximum benefit of the geocooling potential.

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REFERENCES

Chuard P., Chuard D., Van Gilst J., Hadorn J.-C. and Mercier C. (1983) The IEA Task VII Swiss project in Vaulruz: design and first experiences. International conference on subsurface heat storage in theory and practice. pp. 195 – 206. Swedish Coucil for Building Research.

GSP(2010) Groupement promotionnel Suisse pour les pompes à chaleur. www.pac.ch

Hellström G. (1989) Duct Ground Heat Storage Model, Manual for Computer Code. Department of Mathematical Physics, University of Lund, Sweden.

Hollmuller P., Lachal B. and Pahud D. (2005) Rafraîchissement par geocooling: bases pour un manuel de dimensionnement. Rapport final, Office fédéral de l'Energie, Berne, Suisse.

Klein S. A. et al. (2005) TRNSYS. A Transient System Simulation Program. Version 15.3. Solar Energy Laboratory, University of Wisconsin, Madison, USA.

Pahud D. (1993) Analyse énergétique de l'immeuble industriel "Marcinhès" à Meyrin (GE). Thèse n° 2645. GAP, Section de Physique, Univ. de Genève. Atelier d'impression de la Section de Physique.

Pahud D. (1996) Simulation of Central Solar Heating Plants Using a Duct Store: an Application for Switzerland. Swiss grant Nr: 8220 – 042846. Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden.

Pahud D. (2002) Active Solar Heating System with Concrete Plate Heating Analysed with Dynamical Thermal Simulations. Eurosun 2002, the 4th ISES Europe Solar Congress, Solar Thermal Systems, ref. 85.

Pahud D. (2003) Optimisation par simulation calée de l'installation de stockage Wollerau. Rapport final, Office fédéral de l'Energie, Berne, Suisse.

Pahud D. (2007) PILESIM2: Simulation Tool for Heating/Cooling Systems with Energy Piles or multiple Borehole Heat Exchangers. User Manual. ISAAC – DACD – SUPSI, Switzerland.

Pahud D. (2008) COOLSIM : Simulation Tool for the System Design of Borehole Heat Exchangers or Energy Piles for Geocooling with TABS in Office Building. User Manual. ISAAC – DACD – SUPSI, Switzerland.

Pahud D., Fromentin A. and Hadorn J.-C. (1996) The Duct Ground Heat Storage Model (DST) for TRNSYS Used for the Simulation of Heat Exchanger Piles. User Manual, December 1996 Version. Internal Report. LASEN - DGC- EPFL, Switzerland.

Pahud D. and Hellström G. (1996) The New Duct Ground Heat Model for TRNSYS. In Proceedings of Eurotherm, Physical Models for Thermal Energy Stores, 25-27 March, pp. 127 – 136. Eindhoven, The Netherlands, A.A. van Steenhoven and W.G.L van Helden (eds).

Pahud D., Caputo P., Branca G. et Generelli M. (2008) Etude du potentiel d'utilisation de "geocooling" d'une installation avec sondes géothermiques verticales appliqué à un bâtiment administratif Minergie à Chiasso. Rapport final, Office fédéral de l'énergie, Berne, Suisse

SIA (2006) Merkblatt 2024. Standard-Nutzungsdedingungen für die Energie- und Gebaüdetechnik. Schweizerischer Ingenieur- und Architektenverein, Zurich.

SIA (2007) Norme SIA 382/1. Installations de ventilation et de climatisation – Bases générales et performances requises. Société Suisse des ingénieurs et des architectes, Zurich.

SIA (2010) Norme SIA 384/6. Erdwärmesonden. Schweizerischer Ingenieur- und Architektenverein, Zurich.

SSG (2010) Société Suisse pour la Géothermie. www.geothermie.ch