SIMULATION OF THE IMPACT OF AQUIFERS ON THE GROUND TEMPERATURE IN GROUND-SOURCE HEAT PUMP OPERATION.

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ABSTRACT

The winter operation of ground-source heat pumps is expected to lead to drift phenomena in the zones surrounding the vertical ground heat exchangers. A moving aquifer tends to oppose the thermal drift, due to the advection groundwater phenomena. A modelling study of the quantitative influence of the groundwater flow on the thermal drift is performed, based on the moving infinite line source model. The analytical solution of this model is numerically solved and implemented in a computer software.
Referring to a particularly critical case study, an easy-to-use application of the model based on this analytical solution is then presented. The influence of the existing flow is assessed upon either improving the effective operating conditions of the heat pump plant or reducing of the total borehole length.

INTRODUCTION

Ground-Source Heat Pump (*GSHP*) systems are a particular *HVAC* solution which relies on the ground as a low enthalpy heat source or sink.
As it is well known, the thermal behaviour of these systems has to be investigated on the long term, i.e. over multiannual time horizons. This aspect was deemed crucial in the perspective of a long-lived and efficient operation of the designed plants.

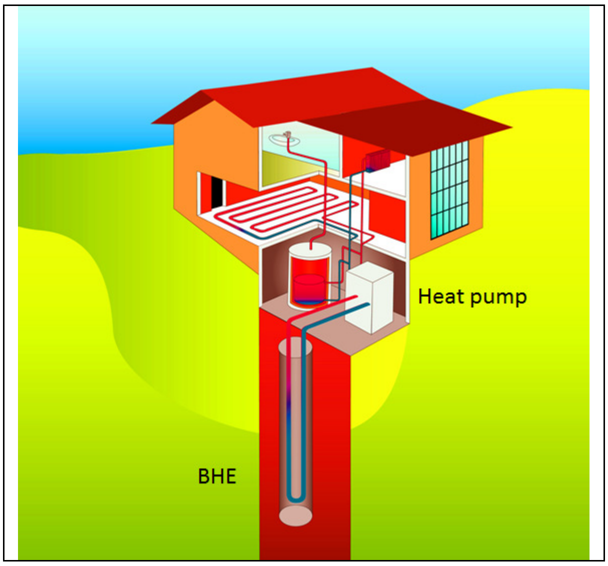

Figure 1 Scheme of a GSHP with vertical BHE

The most common solution is the *closed loop* system with vertically oriented borehole heat exchangers (*BHE)* (see ***Figure 1***), since they allow small land area requirements. The design of *BHE* is a crucial item, since an incorrect evaluation of its length strongly affects the energy efficiency and/or operation of the heat pump incongruously related to its capacity: which means, increases in investment/operation costs of the whole plant system. The groundwater flow plays a positive role in improving the thermal exchange and fostering such a pursued more accurate design.
An analytical simulation tool is presented in this paper, aimed at assessing and optimising *GSHP* systems when the groundwater flow is present. At a cost of obvious drawbacks for accuracy in space description, but in favour of less computing time and skilled personnel resources required by complicated 3-D numerical processing, this approach complies with designers' expectations of a tool not enslaved to computational issues, friendly enough to be used by not specialists people in the computational matter.
The developed tool has been validated and used to analyse the thermal behaviour of a real case study. In these particular conditions, the present paper quantifies the avoided costs that accounting for groundwater flow allows, from both the operation and the investment viewpoints.

LITERATURE REVIEW

Most design tools neglect the effect of the aquifer motion in the heat transfer, as its contribution is generally taken into account by means of an equivalent thermal conductivity of the ground. However, this assumption can be acceptable only for low velocity of the aquifer.
In literature, theoretical research contributions have then been proposed on this specific subject, which focused analytical and numerical approaches. The most diffused analytical methods derive from the Moving Infinite Line Source (*MILS*) model (Carslaw and Jaeger, 1959) which describes the thermal field produced into a uniform medium by a moving linear heat source. Diao et al. (2004) used the analytical and numerical approaches making use of the new function, introduced by Chaudhry and Zubair (1994) and termed *generalized incomplete gamma function*,

to describe the thermal field relevant to the moving infinite line source.

Numerical methods consider less simplified models and pursue the solution by means of approaches based on the solution of a system of discretised equations. The literature is very rich of successful examples of these applications. Chiasson et al. (2000) carried out a study to analyse the effects of the groundwater flow on the heat transfer originated by a vertical closed loop heat exchangers by means of a finite element method. Fan et al. (2007) solved the energy equation, describing the non-isothermal groundwater flow in a saturated porous medium, by an in-house developed finite volume method adopting an unstructured mesh. Other researchers used already developed and existing computer codes, based on the numerical solution of the conservation equations and adopting the FEM - Finite Element Method (as in the case of FEFLOW in Nam and Ooka (2010)) or the Finite Difference Method (e.g. the use of TOUGH2-TOUGHREACT in Kim et al. (2010)). Studies on thermal processes between vertical *BHE*s and the ground were also extensively performed by means of commercial multi-purpose software. Chiasson (2010) used the FEM-based simulation package COMSOL to simulate horizontal ground heat exchangers, keeping into account the weather conditions. Corradi et al. (2008) performed the numerical simulation of a *thermal response test* by COMSOL too. Desideri et al. (2011) used the software package TRNSYS, which involves a simulation model of the borehole field developed after an original approach of Lund University (Hellstrom, 1989). In any case, most authors neglected the occurrence of the groundwater flow.

THEORETICAL MODELLING BACKGROUND

Open field single borehole heat exchanger

In a saturated porous medium the heat transfer takes place by conduction through the matrix solid/liquid as well as by convection because of the moving fluid. Considering the energy balance and assuming the thermal diffusion only in the horizontal plane x-y, with constant thermal physical properties of ground and uniform fluid velocity, the heat transfer into the saturated porous medium is expressed by Equation (1):

$$\frac{1}{\alpha_{eff}}\cdot\frac{\partial\Delta T}{\partial t}=\left(\frac{\partial^2\Delta T}{\partial x^2}+\frac{\partial^2\Delta T}{\partial y^2}\right)-\frac{U_{eff}}{\alpha_{eff}}\cdot\frac{\partial\Delta T}{\partial x} \qquad (1)$$

where ΔT [°C] is the variation of ground temperature compared with the undisturbed value T_g, α_{eff} [m²/s] and U_{eff} [m/s] are the effective thermal diffusivity and the effective fluid velocity given by:

$$\alpha_{eff}=\frac{\lambda_{eff}}{\phi\cdot\rho_f c_f+(1-\phi)\cdot\rho_s c_s}=\frac{\phi\cdot\lambda_f+(1-\phi)\cdot\lambda_s}{\phi\cdot\rho_f c_f+(1-\phi)\cdot\rho_s c_s} \qquad (2)$$

$$U_{eff}=\frac{\rho_f c_f}{\phi\cdot\rho_f c_f+(1-\phi)\cdot\rho_s c_s}\cdot\phi\cdot U=\frac{\rho_f c_f}{\phi\cdot\rho_f c_f+(1-\phi)\cdot\rho_s c_s}\cdot v \qquad (3)$$

ϕ [-] is the porosity of the medium, ρ [kg/m³] is its density, c [J/(kg·K)] is its specific heat, λ [W/(m·K)] is its thermal conductivity, U [m/s] is the seepage velocity of the fluid and λ_{eff} [W/(m·K)] is defined in Equation (2). The subscripts f and s denote the fluid and solid part of the porous medium, respectively.

It should be remarked that the quantity U_{eff} defined in Equation (3) does not correspond to the Darcy velocity v [m/s], which is plainly equal to ϕU.

The moving heat source approach is used to give due account to the groundwater flow when a single borehole heat exchanger is considered. With this approach, the borehole heat exchanger is modelled as an infinite line source. If the line heat source emits the rate q [W/m] constant per unit time and per unit length along the z-axis (***Figure 2***), the solution of Equation (1) can be obtained by the well-known moving infinite line source (*MILS*) model and it is expressed by the below Equation (4):

$$\frac{4\cdot\pi\cdot\lambda_{eff}}{q}\cdot\Delta T=\exp\left[\frac{Pe}{2}\cdot\bar{r}\cdot\cos(\beta)\right]\cdot\Gamma\left(0,\frac{(\bar{r})^2}{4Fo};\frac{Pe^2(\bar{r})^2}{16}\right) \qquad (4)$$

where Γ is the *generalized incomplete gamma function* introduced by Chaudhry and Zubair (1994):

$$\Gamma(\varepsilon,x;z)=\int_x^\infty t^{\varepsilon-1}\cdot e^{-t-zt^{-1}}dt \qquad (5)$$

and $Pe = U_{eff}\cdot r_{bore}/\alpha_{eff}$ is the Peclet number, $Fo = \alpha_{eff}\cdot t/r_{bore}^2$ is the Fourier number, r_{bore} [m] is the borehole radius, $\bar{r}=r/r_{bore}$, r and β are the radial and polar coordinate respectively. More information on the zonal solution adopted for the Equation (5) are available in (Capozza et al., 2013).

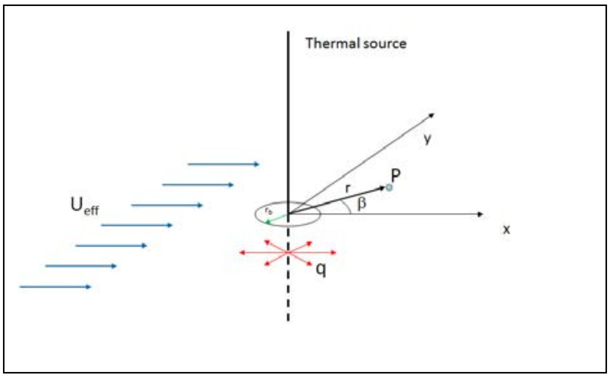

Figure 2 Approach of the model

Borefield model

When the analysis of a real borefield is involved, made up of *NB* borehole heat exchangers, some Authors (Diao et al. 2004) (Bernier et al., 2008) suggest to evaluate the thermal field in the ground as a superposition of the effects individually produced by each *BHE*. The temperature at point $\vec{P}$ of the borefield is then obtained as:

$$T(\vec{P},t) = T_g + \sum_{i=1}^{NB} \Delta T(r_i, \beta_i, t) \qquad \textbf{(6)}$$

where:

r_i is the distance of $\vec{P}$ from the centre of the i-th borehole, β_i is the angle between the vector radius $\vec{r_i}$ and the groundwater velocity $\overrightarrow{U_{eff}}$ and T_g [°C] is the average ground undisturbed temperature.

The shape of the resulting field depends on the considered geometry, the ground thermal physical parameters and the groundwater flow.

This model was implemented in a software termed *LENGTH* (Low ENthalpy Ground THermal exchange), involving either still or moving aquifer.

This activity has made available and easily implementable the analytical solution of the model involving groundwater flow. Details on the numerical evaluation of the analytical solution in LENGTH can be found in (Capozza et al, 2013). On the base of this approach, no need occurs to carry out a preliminary discretization of the computational domain. This tool then relieves the designer from using complicated and specialized pre- and post-processing operations, aimed at meshing the integration domain or performing a 3-D visualization of results. In addition, such a tool does not require to extend the solution to a whole computational domain, since the adopted analytical methodology allows its application even to few and focused points. This characteristic matches a frequently evidenced requirement of insiders, who very often need accurate but very localized evaluations of the thermal field.

VALIDATION

Building, plant system and ground characteristics

Results of in-house monitoring activities were exploited to validate the developed tool, due to the greater chances they offer for critical analysis and processing with respect to the previously described literature.

Figure 3 Case study: views of the two residential blocks

The considered plant is relevant to a residential building placed in North Italy, namely in the Padan Plain, characterised by 2,559 HDD [°C·day] (i.e. heating degree day). It is made up of two facing twin blocks (***Figure* 3),** parted by a shared green space which accommodates the borefields; the position of the boreholes is schematically outlined in the same figure. Each of the two blocks entails from two to three floors, beside a ground floor hosting garages and cellars. Moreover, each block holds twelve middle-size lodges (about 80 m^2 each), which are supplied with central heating, whose internal distribution is performed by floor radiant panels. A plant representation of the block and its borefield is shown in ***Figure 4***, where the boreholes are pointed out with capital letters.

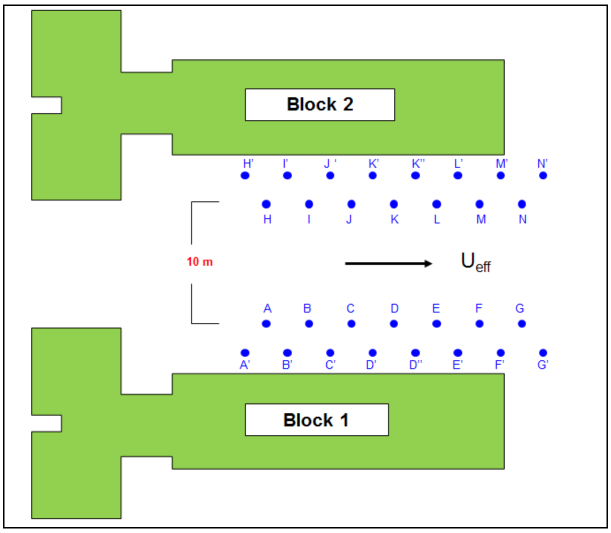

Figure 4 Case study: map of the considered building

Each apartment is fed autonomously and it is provided with a meter devoted to the measurement of the consumed heat and domestic hot water. A central plant for summer air conditioning for the whole building was not envisaged. The validation exploits the data relevant to the left block (block 1), which was the only existing at the time of the analysis.

The main characteristics of the building-plant system of the block 1 are reported in *Table 1*.

Table 1 – Characteristics of the heating system

Building thermal energy need E_b	173,000 kWh/year
Initial seasonal COP of the heat pump $SCOP_0$	3.14
Annual average BHE heat exchange rate Q_g	13.46 kW
Operation time for the evaluated thermal drift t_o	10 years
Heat pump condensing temperature T_{hot}	42 °C
Initial heat pump evaporating temperature $T_{cool,0}$	11 °C

The ground-source heat pump adopts R407C as a refrigerant fluid; its measured seasonal COP is 3.14.

The value of the heat exchange rate Q_g [kW] between BHE and ground is given by the annual average of the continuously measured values. The BHE cluster is made up of 15 elements arranged in two rows shaped as a triangular matrix.
Each *BHE* is made up of a single U-tube, with external diameter equal to 40 mm and thickness equal to 3 mm (*Table 2)*. The use of the results of an experimental test campaign, still being operated by *RSE SpA - Ricerca sul Sistema Energetico* on the plant (Bazzocchi and Croci, 2010), allowed better understanding of the quantitative aspects of the issue.

Table 2 - Characteristics of the borehole heat exchangers

Type	Single U-tube
Borehole length H	100 m
Total exchange length with ground L	1,500 m
Borehole spacing B	4.5 m
Borehole radius r_b	0.05 m

Knowledge of the ground stratigraphy results from experimental ground field tests performed by the designers of the real plant and reported in Bazzocchi and Croci (2010). Evaluated thickness and lithology of the single ground layers are shown in *Table 3*, including the information of possible occurrence of saturated aquifer.

Table 3 – Case study: ground stratigraphy

Depth	Thickness	Lithology	Aquifer	Temp
(from / to) *m*	*m*			*°C*
0 / 9	9	Clayey silt		
9 / 16	7	Sand and gravel	yes	14.0
16 / 24	8	Fine silty sand		
24 /28	4	Sandy silt		
28 / 35	7	Sand and gravel	yes	
35 /42	7	Fine gravel	yes	
42 /53	11	Silty clay		
53 /60	7	Middle-fine sand	yes	
60 /71	11	Silty clay		
71 /80	9	Clayey silt	yes	15.5
80 /85	5	Fine clean sand	yes	
85 /92	7	Sandy silt	yes	
92 /95	3	Dark clay including sand layers	yes	
95 /100	5	Clean sand	yes	16.0

The values of the ground thermal physical quantities are shown in *Table 4*. The values of λ_{eff} e α_{eff} were determined as an average of those relevant to the single horizontal layers which compose the ground, using the definitions given by the equation (2); the values of the thermal conductivity and diffusivity, specific heat and density of both ground and aquifer were found in the specialised literature (Clauser and Huegens, 1995)(Waples and Waples, 2004).
Relying on the above detailed knowledge, no further Ground Response Test was deemed necessary by the designers of the plant.

Table 4 – Ground thermal physical quantities

Porosity ϕ	0.3
Effective ground thermal conductivity λ_{eff}	1.8 W/(m K)
Effective ground thermal diffusivity α_{eff}	$7.6{\cdot}10^{-7}$ m^2/s
Effective groundwater velocity U_{eff}	4 m/year
Undisturbed ground temperature T_g	15 °C

An average value of the hydraulic conductivity K equal to $2.5{\cdot}10^{-4}$ m/s was assumed, on the base of the above stratigraphy and of information given by Heath (1983). Besides, an average hydraulic gradient i equal to $5{\cdot}10^{-4}$ m/m was adopted, which derives from field tests on the groundwater flow (De Lotto and Mazza, 2005) performed in the analysed district. Values for Darcy velocity v equal to 2.3 m/year, seepage velocity U equal to 7.7 m/year and effective velocity U_{eff} equal to 4.0 m/year were finally evaluated from the above field test on groundwater flow. The arrangement of the borefield with respect to the nearby river allows to assume a direction of the seepage velocity as parallel to the longitudinal development of the borefield.
The value of the undisturbed ground temperature T_g , averaged on a depth of 100 m, was assumed equal to 15 °C. This assumption is based on an averaged value among those obtained during the above ground stratigraphic tests, as shown in Table 4.

Experimental field test and *LENGTH* validation

A specific experimental field test was performed by the Authors on the above plant, aimed at a long-term monitoring of the quantities relevant to the operation of the heat pump, the related BHE loop and heat distribution system in the building. The field test is based on a continuous monitoring and it has been running since 2009. An exhaustive description of the monitoring test performed on the real plant of the case study can be found in Bazzocchi and Croci (2010).
The values of the ground thermal perturbation field (in this case, the temperature decrease, referred to the undisturbed ground temperature) were computed after the operation time of one year. The above referenced *LENGTH* software was adopted as computational tool. A direction parallel to the longitudinal development of the borefield was assumed for the aquifer velocity. This study offered a valuable chance of a comparison with the experimental data acquired in the field test. In particular, the monitoring results were considered at a time $\bar{t}$ at the end of the summer season and after a

winter operation (see ***Figure 5***), when the heat pump was switched off for about five hours whereas the pump of the *BHE* loop was still running. In these conditions, substantial thermal equilibrium was reasonably assumed between the fluid in the *BHE* loop and the thermally disturbed (but uniform in temperature) ground (Capozza and Madonna 2011). The measured return temperature in the BHE loop could then represents as a very good evaluation of the average ground temperature. The ***Figure 5*** shows the results of the measurement in the day when this evaluation had been performed. The detected temperature (about 12 °C) in the considered instant $\bar{t}$ was affected by a 3 °C decrease with respect to the 15 °C ground undisturbed value. This value has to be compared with 3.3 °C evaluated by the adopted model. The quite remarkable agreement proved the soundness of the adopted model.

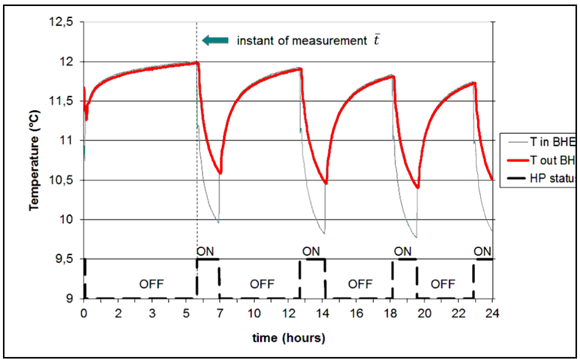

Figure 5 Case study: evaluation of the average ground temperature after an operation of one year

SIMULATION

The parametrical analysis

Once the reliability of *LENGTH* was assessed, a parametric study was undertaken for the above plant. A direction parallel to the longitudinal development of the borefield was assumed for the aquifer velocity too. Due to the *MILS* model features, all the thermal physical ground quantities were averaged over the whole depth of the *BHE*s and as a consequence the temperature field has to be ascribed to a generic horizontal plan, so renouncing at full 3-D description of the thermal field.

The ground thermal perturbation field (namely, the decrease ΔT [°C] of the local temperature field referred to the undisturbed ground temperature T_g) after an operation of ten years was then assessed by *LENGTH* computation on a horizontal plane. Its absolute value is shown in ***Figure 6***.

An important design parameter, the *penalty temperature*, was also kept into account, which is connected to the thermal drift in the ground hosting the borefield. Very roughly, the penalty temperature gives a quantitative idea of the thermal interaction among the *BHEs* belonging to a cluster and of the global disturbance that they involve in the surrounding ground after a given operation time.

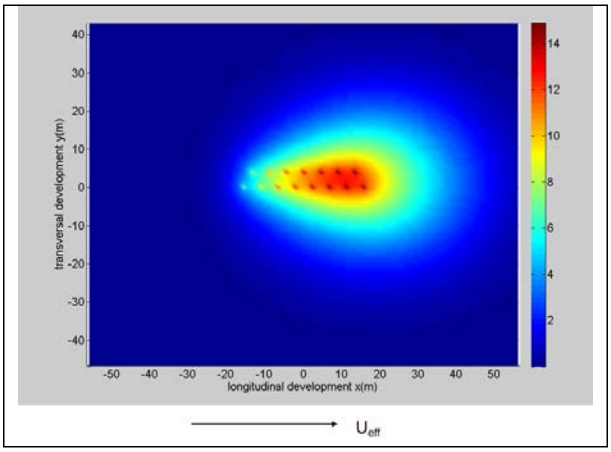

Figure 6 Case study: ground temperature decrease after 10 years

The evaluation of the penalty temperature was performed by the use of the following Equation (7), according to Bernier et al. (2008) and Capozza et al. (2012):

$$T_p = \frac{1}{NB}\sum_{i=1}^{NB} T_{c,ave,i}(r_b) - T_{s,ave}(r_b) \quad \textbf{(7)}$$

where $T_{c,ave,i}(r_b)$ is the average wall temperature of the *i-th* borehole of the *BHE* cluster and $T_{s,ave}(r_b)$ is the average wall temperature of the borehole of an open-field *BHE*.

Normally, the penalty temperature is referred to a period of operation of ten years, as in this case.

The result is T_p equal to -7.7 °C. The negative value is coherent with the circumstance of heat removal from the ground by *BHE*s during the considered operation period. The maximum value ΔT_{Max} [°C] of the space temperature variation ΔT is equal to -14.9 °C. It is detected at the G borehole (***Figure 4***), which is affected by the cumulative effect of the thermal plumes produced by the aquifer flow on all the upstream boreholes.

For purpose of comparison, the results of a further calculation are shown, which differ from the previously examined one for the absence of moving aquifer. The maximum temperature decrease (about -15.5°C) is not so different from the situation with aquifer motion. However, this value was detected in the central borehole of the upper row (borehole D in ***Figure 4***), where the highest interaction among the clustered BHEs is found. The penalty temperature T_p is equal to -9.2 °C.

A further case was examined, where a transversal development is assumed of the aquifer velocity with respect to the borefield layout. The maximum temperature decrease (about -12.7 °C), is located at the central borehole of the upper row (borehole D in ***Figure 4***). The identified decrease is less severe than with longitudinal development of the flow (-14.9 °C).

In fact, in these circumstances a less penalising "shadow" effect is only produced on the upper row of seven boreholes by the lower row of eight boreholes. The penalty temperature T_p is equal to -6.1 °C.

A supplementary analysis was performed, relevant to higher intensity of the aquifer flow. The considered case is the same above described; yet, an effective aquifer velocity U_{eff} equal to 40 m/year is assumed. In this situation, the highly manifest effectiveness of the groundwater flow definitely prevails over the conductive heat transmission in the ground. The maximum temperature decrease is very limited and amounts at about -3.5 °C, regardless of the development of the aquifer flow with respect to the borefield layout. In fact, in these conditions each of *BHE*s behaves as single open-field one, whose interaction with the other *BHE*s is negligible. Very small values are expected for the penalty temperature, regardless of the direction of the velocity U_{eff} : the evaluated value of the penalty temperature T_p was -0.8 °C in both cases.

The developed model is also suitable to analyse the consequences of the simultaneous operation of the ground-source plant relevant to the twin block 2, facing the considered block 1. This plant shows a specular symmetry with respect to the existing one. The symmetry axis between the two borefields is parallel to the longitudinal development of the layouts and it is placed at a distance of 5 m from each of the two rows of seven boreholes.

The considered further case study involves an aquifer flow developed longitudinally with respect to the borefield geometry, where the effective velocity U_{eff} is still equal to 4 m/year. The same geometrical data of the existing borefield are assumed for the new one, as well as for the thermal physical ground parameters. Same thermal need is also adopted for both blocks, though the new plant is started up with a delay of two years with respect to the old one.

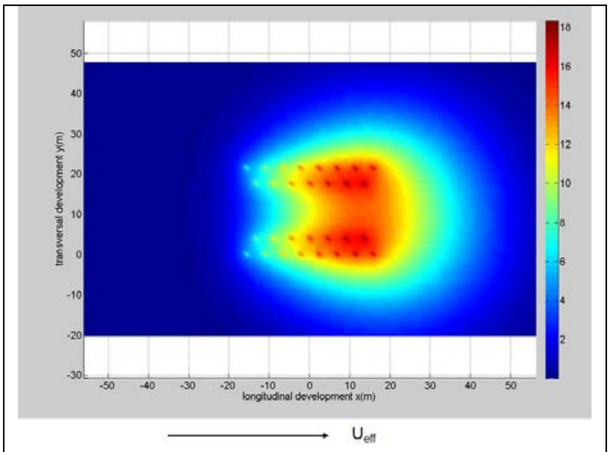

Figure 7 Simultaneous operation of the twin blocks - Ground temperature decrease after 10 years

The result of the computed evaluation of the thermal perturbation after an operation of the old plant of ten year, when the new plant had been working for eight years, are shown in ***Figure 7*** in terms of absolute value. The maximum temperature decrease, about -18.3 °C, results from the superposition of the thermal field produced by both plants. It is placed on the wall of the G borehole(***Figure 4***). The penalty temperature T_p is equal to -9.6 °C.

A last comparison can be made with the evaluation of the thermal perturbation produced by the operation of both borefields, when no aquifer flow occurs. In these conditions, the maximum temperature decrease is equal to -20 °C and it is placed at the wall of the D borehole (see ***Figure 4*** again). The penalty temperature T_p is equal to -12.8 °C.

Technical-economic analysis

A technical-economic analysis is below performed on the considered case study, aimed at evaluating the avoided costs brought about by the occurrence of the aquifer flow. The examined avoided costs are originated in the following sectors:

- operation of the existing plant, owing to the expected improvement of the seasonal heat pump *SCOP* with respect to the design one
- investment in the design phase, due to the less penalty temperature in presence of groundwater flow and consequently to the reduced total *BHE*s length, all other parameters being unchanged.

The analysis relies on the evaluation of the heat pump seasonal coefficient of performance $SCOP_{10,sa}$ and $SCOP_{10,ma}$ after an operation of 10 years, with still or moving aquifer flow respectively.

The yearly decrease of electric power $\Delta E_{e,y}$ [kWh/year] which follows from the *SCOP* improvement due to the aquifer flow, being equal the building thermal need, is given by:

$$\Delta E_{e,y} = E_b\left(\frac{1}{SCOP_{10,sa}} - \frac{1}{SCOP_{10,ma}}\right) = E_b \cdot \frac{1}{M} \cdot \frac{\Delta T_p}{273.14 + T_{hot}} \qquad \textbf{(8)}$$

where ΔT_p [°C] represents the variation of the penalty temperature from still to moving aquifer conditions, E_b is the building thermal energy need and M [-] is a proportionality coefficient problem-dependent and equal to 0.31 in the present case. A complete description of the method to determine all these quantities is available in Capozza et al. (2013), which widest reference has to be acknowledged too. Assuming this value as representative of an average operation relevant to the ten previous years and the following ten years, the less electricity consumes ΔE_c [kWh] over an assumed plant life of twenty years is given by:

$$\Delta E_e = 20 \cdot \Delta E_{e,y} \qquad \textbf{(9)}$$

Finally, the corresponding avoided operation costs ΔC_0, [€] which are a consequence of the improved efficiency, can be approximately evaluated as:

$$\Delta C_0 = 0.2 \cdot \Delta E_e \qquad \textbf{(10)}$$

where the assumed cost of electricity is equal to 0.2 €/kWh.

Conversely, if the *BHE* design had been performed keeping into account the aquifer flow, all the other conditions being unchanged (then, with equal evaporating temperature and equal *SCOP*) and only considering the less penalty temperature due to the moving aquifer, a decrease ΔL [m] of the total heat exchange length would have occurred. Its quantitative evaluation is provided by the ASHRAE design procedure (ASHRAE, 2011), where the value of the penalty temperature is forced to the new assumed one, all the other parameters being unchanged.

The decrease ΔL of the borehole length obviously entails an avoided investment cost ΔC_p [€] given by:

$$\Delta C_p = 50 \cdot \Delta L \qquad \textbf{(11)}$$

where an economic saving of about 50 € per meter of not drilled borehole was assumed. A computation was performed on the base of the outcomes of the case study, when a single borefield is operating. The results are shown in *Table 5* and they are discussed below. First of all, a reference situation was assumed (i.e. the case A), where no groundwater flow occurs. Afterwards, the case B (groundwater flow of 4 m/year developed longitudinally) and the case C (groundwater flow of 4 m/year developed transversally) were examined. The case D is relevant to an aquifer velocity of 40 m/year, regardless of the flow direction.

For each case, *Table 5* shows the values of electricity savings ΔE_e and of the relevant avoided operation costs ΔC_o [Equations (9) and (10)] when account is taken of the less *SCOP* worsening due to the aquifer flow. The same table shows the decrease ΔL of the total *BHE* length and the consequent avoided investment costs ΔC_p [Equation (11)] that would result from the design if a less thermal drift (deriving from the groundwater flow) were considered, all the other parameters remaining unchanged.

Finally, the results are shown in *Table 5* in the case of two borefields simultaneously operating, with no groundwater flow (case E) and with a 4 m/year flow longitudinally developed (case F).

DISCUSSION AND CONCLUSIONS

The analysis of the results relevant to the above case study showed that the temperature perturbation in the ground is sensitive to some particular flow conditions: its development with respect to the layout of the borefield and its intensity.

In fact, in case of a highly *directional* geometry, the performed simulations with two different flow directions show that decrease in the maximum and average values of the thermal disturbance may be expected from the presence of the flow, depending on whether the produced thermal plume expands outside or inside the *BHE* perimeter. See cases A, B and C in *Table 5*.

As for the *intensity* of the flow velocity, high values (i. e. greater than 10-15 m/year) normally succeed in keeping the thermal disturbance within acceptable ranges, since the weight of the more efficient advective component of the heat exchange prevails over the conductive one. Nevertheless, simulations with less intensive flow showed results depending on the particular geometry (e. g. plain shifts in the location of the thermal disturbance, being unchanged its maximum value). See also case D in *Table 5*.

All the above considerations have been applied to the examined case study to show how the developed models and their implementations in *LENGTH* can be used to evaluate the economic repercussions that can be expected on the behaviour of the plant or on possible more suitable sizing, because of due account given to the presence of moving groundwater. To this purpose, further studies were performed, which finally allowed to assess the impact of the aquifer flow on either a more efficient operation or a more appropriate design of the plant, then leading to avoided costs: investment costs (due to a reduced total *BHE* length, being the heat pump performance *SCOP* unchanged) in the latter case; operation costs (due to a *SCOP* improvement, being *BHE* length unchanged) in the former case. However, also in this context a more favourable direction of the flow was found to bring about improved operation conditions, then higher avoided costs (compare case B and C in *Table 5*).

Nevertheless, the avoided operation costs, at least in conditions similar to those of the present case study, are quite greater than the avoided investment ones (until about twice, according to the intensity of the aquifer motion). Generally speaking, the obtained results suggest to consider the aquifer flow first of all in the design phase, as a process which can lead to possible investment saving if suitably kept into account. A subsequent optimisation phase can then consider further savings coming from a more efficient operation of the plant, still connected to the aquifer motion.

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Table 5 – Results of the technical-economic analysis on the case study

Case	working borefields	U_{eff}	Direction of U_{eff}	ΔT_{Max}	T_p	ΔT_p	*SCOP*	ΔE_e	ΔC_o	ΔL	ΔC_p
		m/year		°C	°C	°C		kWh	€	m	€
A	1	0		-15.5	-9.2		2.42				
B	1	4	Longitudinal	-14.9	-7.7	1.5	2.52	53,318	10,664	162	8,100
C	1	4	Transversal	-12.7	-6.1	3.1	2.62	110,191	22,038	301	15,050
D	1	40		-3.5	-0.8	8.4	3.06	298,582	59,716	472	23,600
E	2	0		-20.0	-12.8		2.22				
F	2	4	Longitudinal	-18.3	-9.6	3.2	2.40	227,491	45,498	630	31,500

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