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Manuscript title: On the Performance of Energy Walls by Monitoring Assessment and Numerical Modelling

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Abstract

Thermo-active diaphragm walls have proved their efficiency for the near-surface geothermal energy use. To get insights into the heat transfer process occurring between the heat exchanger pipes and the surrounding boundaries, an instrumented real case was taken as reference. Combining on-site monitoring data with computational simulations, the role of the basement space in governing the heat fluxes in the different seasons, and the energy performance of the diaphragm wall and of the Ground Source Heat Pump system, are highlighted. The numerical analysis represents an effective predictive tool, but also highly sensitive with respect to parameters of uncertain or complex definition, such as the boundary thermal conditions and the thermal input at the pipe inlet. Intermittent operation and idle periods require a refined simulation, discretizing the time dependency of the input variables in appropriate short time steps.

Introduction

The thermo-active geostructures represent an innovative solution in the field of the near surface geothermal energy to be directly used in the thermal conditioning of buildings and infrastructures, thus complying with the directives of governments and agencies about the increase of use of renewable energy sources in the building sector (e.g. European Parliament and Council 2010). Pipes circulating a heat carrier fluid are immersed in a concrete structure designed for geotechnical purposes, turning it into the so called "thermo-active" or "energy" geostructure (Laloui and Di Donna 2013, Bourne-Webb et al. 2016b). For instance, a reinforced concrete diaphragm wall, conventionally used to support an excavation, can host heat exchanger pipes to harvest or disperse heat respectively in winter or summer time (Amis et al. 2010, Soga et al. 2015).

Serving two functions, the design of thermo-active geostructures should be based on both concepts of optimal energy performance and structural functionality and safety, with an integrated approach. However, generally the design is driven by the structural function and, thereafter, the heat exchanger system (pipe loop configuration and position, fluid velocity, etc) is decided on the analysis of the energetic potential, namely the potential of the designed structure to exchange thermal energy with the subsoil.

Then, the possible consequences in terms of thermally induced stresses and strains in the structure are of concern, and thermo-mechanical analyses are often attempted, considering the geostructure subjected to combined mechanical and cyclic thermal loads, the latter induced by the heat transfer occurring during the seasonal geothermal system operations.

While energy piles have been a subject of comprehensive experimental and numerical investigations (e.g. Laloui et al. 2006, Amatya et al. 2012, Kalantidou et al. 2012, Stewart and McCartney 2014, Di Donna et al. 2016b), energy diaphragm walls are less applied and investigated. A large size application refers to the Bulgari Hotel at Knightsbridge, London (Amis et al. 2011), where 800 m wide diaphragm walls up to 36 m below platform level are equipped with slinky geothermal loops. The hybrid ground loop solutions, including energy walls and energy piles, will ultimately deliver 150 kW of peak heating and 150 kW of peak cooling to the hotel. Another example is represented by the Uniqa Tower in Wien (Adam and Markiewicz 2009) where 7800 m^2 of diaphragm walls are used to absorb energy from the ground to produce a heating capacity of 420 kW and a cooling capacity of 240 kW. The annual heating output reaches up to 818 MWh and the annual cooling output up to 646 MWh. Xia et al. (2012) measured the heat transfer performance of three diaphragm walls out of the energy walls system of the Shanghai Museum of Natural History. They found that the W-shaped heat exchanger has a 25-40% higher energy performance than the single U-shaped.

As far as diaphragm walls analyses are regarded, they are often based on simplifying assumptions, concerning for instance the geometry, the soil thermal properties, the thermal boundary conditions and their time-dependence. From monitored case studies and numerical investigations on the energy performance and on the geotechnical and structural response of energy walls (Xia et al. 2012, Bourne-Webb et al. 2016a, Di Donna et al. 2016a, Sterpi et al. 2017), it can be inferred that the thermal boundary conditions and the heating/cooling input, related to the building energy demand, play a relevant role in the overall behaviour. Moreover,

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methods conventionally adopted for the heat transfer analysis in borehole heat exchangers or in energy piles do not apply to walls, due to their specific features, and purposely conceived methods should be considered in this case (Kürten et al. 2015, Sun et al. 2013).

These issues highlight the need for a correct understanding of the time-dependent heat transfer process in an energy wall, in order to adopt proper design criteria. This contribution approaches the problem on a twofold basis: from one side, it takes advantage of a real case located in Northern Italy (Tradate, Varese province), where the primary circuit uses three ground heat exchange sources, namely the perimeter thermo-active diaphragm walls, a thermo-active floor slab and two groundwater wells. The geothermal system was equipped with monitoring sensors for the continuous data acquisition, and the experimental data were interpreted to get insights into the heat transfer process and the energy performance of the whole geothermal system.

On the other hand, the real structure was numerically modelled, by FEM three-dimensional, transient heat transfer analyses, to recognize the role of some of the most influent parameters and the sensitivity of the numerical analysis with respect to their variations. The commercial code Abaqus was used (Dassault Systèmes, 2014), which offers the possibility to combine conduction with forced convection governed domains, namely the domains of the soil mass and wall with the domain of the exchanger pipe. Allowing for stress/displacement analysis, the same code could be used for future investigations on the thermo-mechanical effects. Eventually, the numerical model can represent a suitable tool to predict the temperature

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variations, within the wall and in the soil mass, and the energy performance of the geostructure, also with reference to a long-term regime.

Description of the case study

A zero-energy residential building was recently built in Northern Italy (Tradate, Varese Province), with a six storeys elevation and a three floors basement (Bertani 2016). The excavation has an almost squared floor plan of 40 m side and reaches 10.8 m depth. It is supported by two pairs of facing diaphragm wall, having total height of 15.2 m and thickness of 0.5 m (Fig. 1). The entire perimeter comprises 66 single wall panels, each of them having 2.4 m width and being anchored to the ground with two 10 m long anchors.

Each panel is equipped with two HDPE exchanger pipes, each covering a width of 0.80 m (Fig. 2). The central part of the panel is left free to allow for the completion of the wall construction without the risk of damaging the pipes (phases of concrete casting and anchor installation). The pipes are fastened to the reinforcing steel cage on the soil side and therefore have a distance of about 5-8 cm to the soil face. Each loop has a length of 90 m and a shape arranged has shown in figure 2, with six vertical segments, having a distance from each other of about 16 cm.

The total length of pipes embedded in the entire wall perimeter, summing 132 loops in 66 panels, is equal to about 12 km. In addition, exchanger pipes are placed also below the base slab, having a total surface of 1689 m^2. The total surface of the perimeter wall, available for the heat transfer, is equal to 2376 m^2. However, about two third of it represents a surface which is not fully embedded in the soil but exposed to the excavation on one face. These figures highlight the major influence that the thermal condition within the basement is expected to have on the overall energy performance of the wall.

The Heating Ventilating and Air Conditioning with Domestic Hot Water system (HVAC+DHW) of the building consists in a water-to-water polyvalent heat pump, connected to a multi-source ground heat exchanger, including the thermo-active walls, the thermo-active floor slab and two groundwater wells. During winter, the system extracts heat from the ground (evaporator side) and supplies both space heating (condenser side, connected to the radiant panels in the building and to the heating coil in the Air Handling Unit) and domestic hot water (de-super-heater side) to the building. During summer, the heat pump extracts heat from the building (evaporator side, connected to the radiant panels and to the cooling coil of the Air Handling Unit) and provides Domestic Hot Water (de-super-heater side and condenser side), by dissipating excess heat into the ground (condenser side). As far as the ground heat exchanger is concerned, thermo-active walls and floor slab are firstly used, while groundwater wells are activated when thermo-active structures are not sufficient.

Analysis of the energy performance

The geothermal system was equipped with a comprehensive data acquisition system (Todeschini 2016), monitoring the relevant parameters of the HVAC+DHW system with a 1 min time step. By monitoring the mass flow rates, the inlet and outlet fluid temperatures for the walls and the floor slab separately, and the heat pump electricity consumption, the heat rates exchanged by the heat pump and by the various ground sources can be derived, as well as the system energy efficiency. This allowed to analyse the various sources separately and to eventually compare the contribution of each of them on the overall performance.

Moreover, for a deeper insight into the thermo-active diaphragm wall behaviour, some temperature probes were embedded in a sample panel wall and into the soil (Fig. 1). The first probes were inserted into empty pipes fastened to the steel cages, at both faces of the walls, between the inlet and outlet positions (section x = 0.8 m, in figure 2), while the latter were fixed to the upper anchors of the same sample panel walls (section x = 0).

Long-term monitoring of temperature variations in the thermo-active walls and in the surrounding ground allows to detect any drift caused by a possible imbalance between heating and cooling demand of the building. In the following, only the first year of operation is considered, i.e. within the short-term transient period. The system is expected to tend to an energy equilibrium and to a long-term characteristic efficiency after some years of operation.

The experimental results regarding the energy performance of the ground-source system during 4 months in winter 2015/16 are summarized in figures 3 and 4. Figure 3 shows the average daily energy extracted by the various sources, namely diaphragm walls, slab and groundwater wells. The thermo-active walls provide the largest contribution, being 70%, 59%, 81% and 71% of the total energy daily extracted from the ground in December, January, February and March respectively. The groundwater wells contribute significantly only in January, when the building heating demand is the highest, since the monthly Degree Days, namely the sum over the month of the difference between indoor set point temperature 20°C and outdoor temperature, are 474, 523, 403 and 348 in the same four months. It should be also remarked that the system not always works in a continuous mode, but intermittent operations and idle periods are expected when the energy demand is low. In this regard, energy performance figures reported in figures 3 and 4 refer to 25.0 days, 27.9 days, 26.8 days and 13.4 days of operation of the system in the same four months.

Considering the sum of space heating and DHW as useful energy produced by the heat pump, the Coefficient of Performance (COP) on a monthly basis ranges from a minimum of 4.2 in March to a maximum of 5.0 in December, allowing to assess the system as highly efficient, considering that the secondary circuit is composed of a low temperature heating loop, made up of radiant panels, and a relatively high temperature Domestic Hot Water production loop. It can be remarked that the monthly COP decreases from December to March, both due to the extended running time of the heat pump and to the increasing intermittent operation when approaching Spring. Indeed the heat pump is on 92% of the time in December and only 68% of the time in March.

A performance comparison between the thermo-active systems should take into consideration the different surfaces, namely 2376 m^2 for the walls and 1689 m^2 for the slab. As reported in figure 4, the average monthly heat rate per unit surface ranges from 12.5 W/m^2 to 14.9 W/m^2 for the walls and from 3.2 W/m^2 to 8.6 W/m^2 for the slab. On average the wall unit surface extracts 2.7 times more heat than the slab unit surface. To this outcome clearly contribute the different boundary conditions acting on the walls and on the slab: the inside surface of the slab entirely faces the building underground storeys, while only two thirds of the inside face of the walls do.

Very few studies in literature report experimental data about energy performance of thermo-active diaphragms walls and slabs. Concerning walls, Xia et al. (2012) report about 38 m deep and 1 m large walls equipped with either single U shaped, W shaped and improved W shaped pipes. The measured heat rate per unit walls depth at 32°C inlet fluid temperature ranges between 33.6 W/m and 40.3 W/m, depending on the pipes layout. By reporting the present case study average heat rates per unit walls depth, namely 15 m, we find figures ranging between 30.0 W/m and 35.8 W/m, in good agreement with (Xia et al. 2012), considering that different inlet fluid conditions, injection or extraction mode, pipes layout and walls depth into the ground certainly play a role in these outcomes.

As far as thermo-active slabs are concerned, the slab performance figures of the case study here considered are comparable with the 5 W/m^2 average heat rate reported by (Kypry et al. 2008) derived from a long-term monitoring.

However further investigations are necessary to assess reference performance figures for thermo-active diaphragm walls and foundation slabs, depending on the different design, boundary conditions and operation modes.

The numerical modelling

A three-dimensional modelling, instead of the 2D plane strain scheme customarily adopted for the analysis of retaining walls, allows to accurately simulate the heat transfer process whenever the pipe loop is not uniformly arranged within the wall and different cross sections undergo different temperature variations. Given the symmetry planes that characterize the wall geometry (Fig. 2), it was possible to model only half of the single panel, i.e. a slice 1.2 m wide.

The structure is at the centre of the entire domain, 40 m wide and 30 m high, whose right side coincides with the central symmetry plane of the excavation.

Attention was paid to the modelling of the pipe location and layout. In fact, previous analyses have shown the influence of the loop shape (distance between warmer and cooler pipe portions) and of the loop position (distance to the soil/excavation sides) on the overall energy performance (e.g. Sterpi et al. 2014). The soil mass and the wall are modelled with 4 node linear tetrahedron elements suited to conductive heat transfer, integrating the heat energy balance and heat conduction equation; while the exchanger pipe is modelled with 8 node linear hexahedron elements suited to forced convection, integrating the thermal equilibrium equation for a flowing fluid. Only the presence of the HDPE circular tube, with its thickness and thermal properties, was neglected in the modelling. Therefore, the finite element analyses were based on the transient heat transfer processes of convection in the pipe and conduction in the soil and wall (Habibzadeh Bigdarvish and Jalili, 2017).

In absence of on-site thermal response tests and laboratory characterization, the soil thermal properties were established as weighted averages of the properties of single solid and fluid phases (Rees et al. 2000, Beier et al. 2011, Vieira et al. 2017): the properties of the solid phase were based on literature data (Thomas and Rees, 2009, Hillel, 2003), and the condition of porosity and water content was based on a hydro-geological site surveying. For the homogeneous well graded silty sand characterizing the subsoil, and given medium density and saturated conditions, the physical and thermal properties could be established as reported in Table 1. As to the groundwater regime, responsible for a possible thermal energy recharge during the seasonal operations (Angelotti et al. 2014), a hydrostatic condition was assumed. Given the soil coarse nature and the ground water conditions, the couplings of the heat transfer process with the soil hydro-mechanical response and with hydrological processes were neglected and uncoupled heat transfer analyses were performed. As a consequence, porosity and water content, and the derived thermal properties, remain constant throughout the analysis.

The thermal loads are determined by the inlet thermal input, i.e. by the fluid flow mass rate and the fluid temperature at the pipe inlet, both provided by the data acquisition system. Since the data are recorded with a 1 min time step, average values on longer time steps have to be worked out for the computational purpose. The average values on a monthly basis are enough accurate if sharp variations of the input data are not expected and the analysis is focused on the system response in the long timeline. Conversely, when the operating system is intermittent, due to milder climate conditions and lower energy demand, or the focus is on the short-time response, a finer time interval is necessary for an accurate simulation of the on/off alternate periods and its relevant effects (Faizal et al. 2016).

These thermal loads are applied on the domain initialised with a temperature field, that represents the undisturbed condition. This is set, as first step, by boundary conditions that will remain unchanged throughout the analysis, namely a constant 13.4 °C at the base, adiabatic front, back and lateral surfaces, and yearly cyclic temperature variations at the ground surface and within the excavation. The adiabatic conditions were set because, in absence of a groundwater flow, the front, back and right lateral surfaces are symmetry planes, and the left lateral surface can be considered representative of the far field, being at a distance of 20 m from the thermal source represented by the wall.

The temperature variations at the ground surface are established based on environmental monitoring provided by the public Agency ARPA-Lombardia (Environmental Protection Agency of Lombardy Region, Italy). Over the years 2010-2015, the ground surface air temperatures exhibited an average seasonal fluctuation with a mean value of 13.4 °C, a maximum of 24.5 °C (July) and a minimum of 3 °C (January). Concerning the condition at the basement, used as unheated parking lot, the hypothesis was introduced that the temperature seasonal fluctuation is characterized by the same mean value, but damped amplitude. The damping coefficient, equal to 0.66, was calibrated based on the monitoring data during the first period of inactive geothermal system, when the temperature within the wall at the excavation side (probes ES) is likely equal to the temperature of the basement.

Monitoring data and numerical results

With respect to the temperature variations induced in the soil mass by the heat transfer process, an insight is provided by probes AS fixed to the anchors (Fig. 5). The temperature fluctuations, which appear delayed and damped with increasing depth, are affected by both the boundary conditions (at the ground surface and at the excavation side) and the fluid temperature, and the extent of this influence depends on the depth of the probe position with respect to the boundaries. The steel anchor itself could ease the heat transfer along its axis.

According to the analytical solution of semi-infinite space subjected to sinusoidal temperature variation at the surface (e.g. Hillel 2003), even the deepest position, reaching a

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depth of 7 m from the ground surface and a distance of 5.5 m from the diaphragm wall, lays within the zone of influence of both boundaries and of the heat carrier fluid. The closeness of this point to the walls and the presence of combined factors of influence complicate the use of these monitoring data for possibly assessing the soil thermal properties on a site experimental basis, confirming the need to rely on literature data.

The numerical results (symbols in figure 5) simulate the temperature damped fluctuation at depth with some accuracy (probe AS7), but a marked difference is obtained closer to the excavation side (e.g. probe AS1.5).

A similar discrepancy is observed at positions within the diaphragm wall. As representative result, the variation of temperature at the soil side, at a depth of 7 m, is shown in figure 5 as SS7. The numerical solution tends to overestimate the values of temperature. Moreover, the sharp variations measured at the beginning of October and in June, when the system starts respectively the heating and the cooling phases, are not correctly reproduced in the analyses. A refined calculation of the heat flux input should be attempted in these two periods, by considering shorter time steps in the calculation of the average input data.

An insight into the role of the basement space in the heat transfer process is provided by figures 6 and 7, that show the temperature differential arising in horizontal cross sections of the wall, at depths in the one case above the base slab (7 m deep probes SS7 and ES7 shown in figure 6) and in the other case below the base slab (13 m deep probes SS13 and ES13 shown in figure 7). In the plots a positive value indicates that the soil side is warmer than the excavation side, therefore the heat flows from the pipe (soil side) to the excavation side.

At the depth of 7 m (Fig. 6) the positive temperature differential measured in the winter period indicates that the circulating fluid is losing heat towards the basement space. Conversely, the negative differential measured in the summer period indicates that the fluid is absorbing heat from the basement space. In both seasons, the basement space does not contribute to a positive heat transfer with the heat carrier fluid.

The more efficient heat transfer process is the one occurring at the larger depth of 13 m, where the diaphragm wall is fully embedded (Fig. 7). In fact, the temperature differential is negative in the winter period (the fluid absorbs heat from the soil at the right side) and positive in the summer period (the fluid disperses heat). At this depth the whole soil mass, fully surrounding the wall, positively contributes to the heat transfer with the geothermal system.

Despite the uncertainties that lead to inaccuracies in the numerically evaluated temperatures within the soil mass and the wall, the temperature variation of the fluid between inlet and outlet points is correctly simulated by the numerical analyses, as shown in figure 8. The larger discrepancies remain in August 2015 and May 2016, when the geothermal system underwent idle periods and intermittent operation.

The average thermal power is calculated from the fluid temperature difference between inlet and outlet, knowing the fluid specific heat and the fluid flow rate as monthly based average. A decrease in fluid temperature is assumed as positive; consequently, a positive thermal power is calculated during the cooling mode operation. Figure 9 reports the thermal power of the single heat exchanger; an estimate of the thermal power of the entire diaphragm wall is obtained by multiplying by the total number of loops (132 loops). The latter can be considered an estimate on the safe side, considering that it neglects positive side effects regarding the heat exchangers located nearby the 4 corners of the entire perimeter, approximately a square with 40 m side. The comparison between monitored and computed values shows discrepancies likely due to both inaccuracies in the numerical computation of fluid outlet temperatures (Fig. 8) and uncertainties in averaging the monitored fluid flow rate on a monthly base.

In spite of the approximations introduced in the numerical modelling and some inaccuracies in the prediction of the temperature field, the results in terms of pipe outlet temperature and thermal power can be considered rather satisfactory in the periods of stable and continuous operation.

Given the testing conditions of the first months and the transient nature of this phase, a balance between injected and extracted thermal energy on a yearly basis is not expected and the energy performance might be not representative of the steady state long-term conditions.

Long-term monitoring campaign and numerical simulations on the case study will provide a clearer picture of the thermal and energy behaviour of the system. From the numerical results presented here, together with the confirmation of the good performance of energy walls, it is also possible to identify some critical issues for the energy walls design. Namely these the necessity to properly take into account the influence of the excavation side and the necessity to discretise the time dependency of the input variables in appropriate time steps to accurately predict the energy performance.

Conclusions

Thermo-active diaphragm walls have proved their efficiency for the near-surface geothermal energy use, but their optimal design requires preliminary insights into the heat transfer process occurring between the heat exchanger pipes, with their specific shape and position, and the surrounding boundaries, i.e. the subsoil and the basement space.

To this purpose, an instrumented real case of shallow geothermal integrated system (energy diaphragm walls, floor slab and groundwater wells) was taken as reference and, combining the interpretation of monitoring data with computational simulations, the role of the thermal boundary conditions and the factors that influence magnitude and direction of the thermal fluxes could be highlighted.

The following conclusions can be drawn:

- The differential in temperatures across the wall width (soil side and excavation side) at different depths (fully embedded or laterally exposed positions), confirms that the basement space never contributes positively to the heat transfer of the circulating fluid. In fact, while the surrounding soil mass acts as a heat source in heating periods and a heat sink in cooling periods, the basement space draws heat from the fluid during heating and transfers heat to it during cooling. Such remarks could lead to design a more effective layout of the heat exchanger pipes as a future research step.
- The monitoring results show that the diaphragm walls extract on average 2.7 times more energy than the slab per unit surface, remarking the highly positive contribution of the fully embedded structure. Energy performance figures for the monitored structures

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are in general agreement with the few available literature data, but further efforts are needed to provide reference figures in the different operating conditions. The measured energy performance or COP of the GSHP system is generally good and consistent with literature figures, although it may suffer from intermittent operation in mild climate periods.

- The monitoring data could not provide an information about the soil thermal properties, because influenced by factors that make the interpretation uncertain. In absence of suited thermal response tests carried out at the specific site and laboratory thermal characterization, the estimation of the soil thermal properties was based on information from the hydro-geological site survey on the soil nature and state and on thermal properties of soil/rock classes from literature databases (Rees et al 2000, Thomas and Rees, 2009, Hillel, 2003).
- For the temperature variations and the energy potential, the numerical analysis is an effective predictive tool but highly sensitive with respect to parameters of uncertain definition, i.e. the boundary thermal conditions and the heat flux input. For the excavation side, a hypothesis is required about the temperature fluctuations, based on the actual use of the basement space. The heat flux at the pipe inlet depends on the building energy demand and is subjected to sharp variations, especially in periods of low energy demand and intermittent system operation, that lead to inaccuracies if the average values, to be used as input data in the numerical analysis, are worked out on a long time basis.

Once the thermal problem is correctly calibrated, the numerical modelling could provide more reliable insights into the thermo-mechanical behaviour of the energy wall, addressing issues such as the wall axial strain and bending moment variations during cyclic thermal loads.

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Figure 1. Cross section of the diaphragm wall and positions of the temperature sensors (dots): along the upper anchor (AS), at the soil side (SS) and at the excavation side of the wall (ES) (unit m, the anchors are shortened for the sketch purpose)

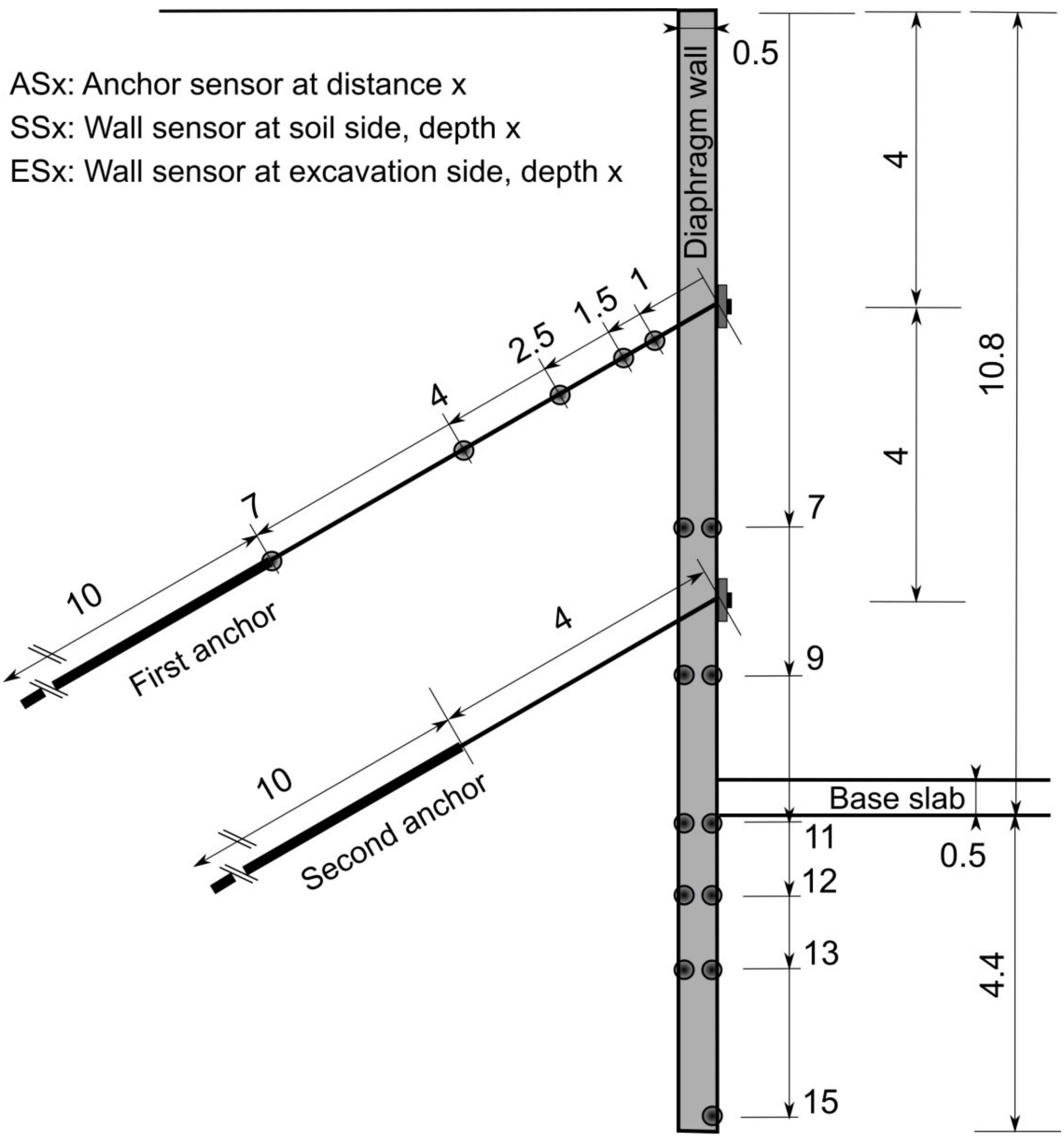

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Figure 2. Sketch of the wall single panel, with detail of one of the two exchanger pipes (dashed lines), and indications of the tubes hosting the wall sensors in the cross section x=0.8 m (dotted line) and of the upper anchor in the central cross section x=0 (unit m)

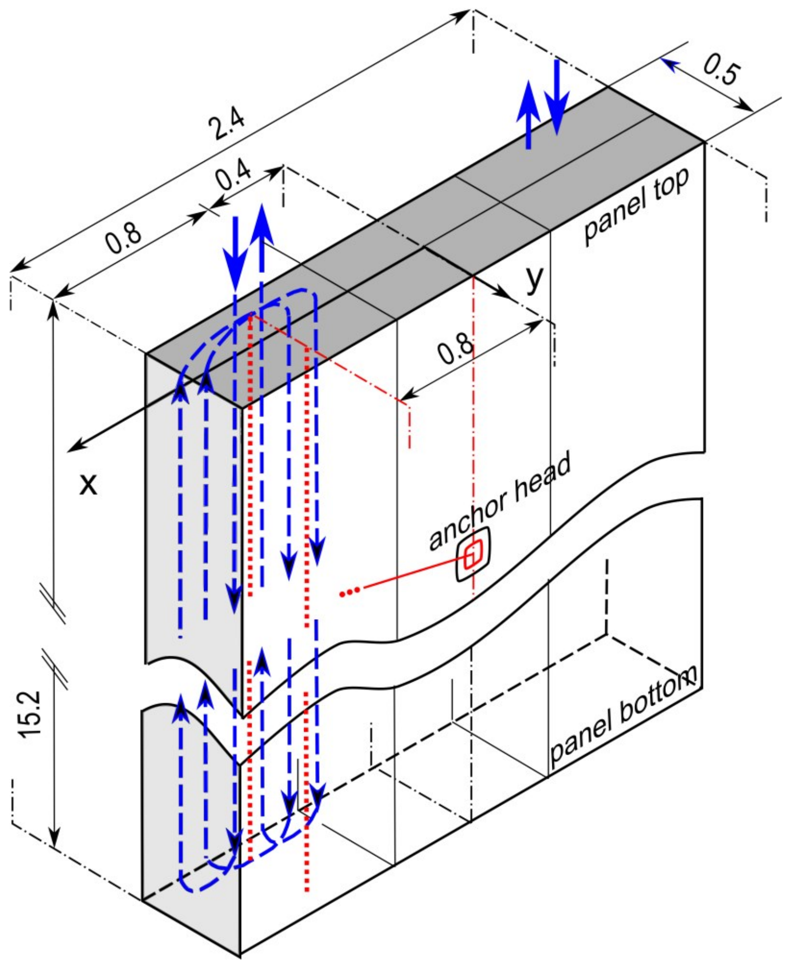

Figure 3. Daily extracted energy from the various ground sources and COP for winter months of the first year

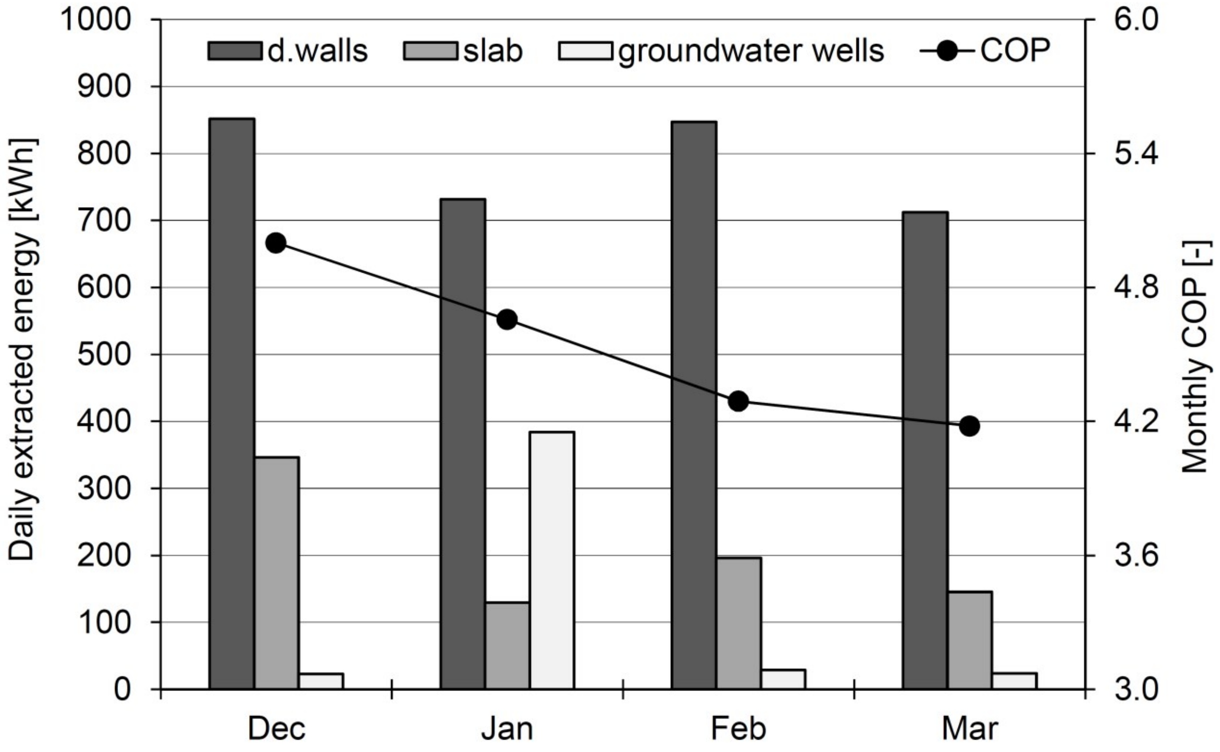

Figure 4. Average specific heat rate for the diaphragm walls and the slab for the winter months of the first year

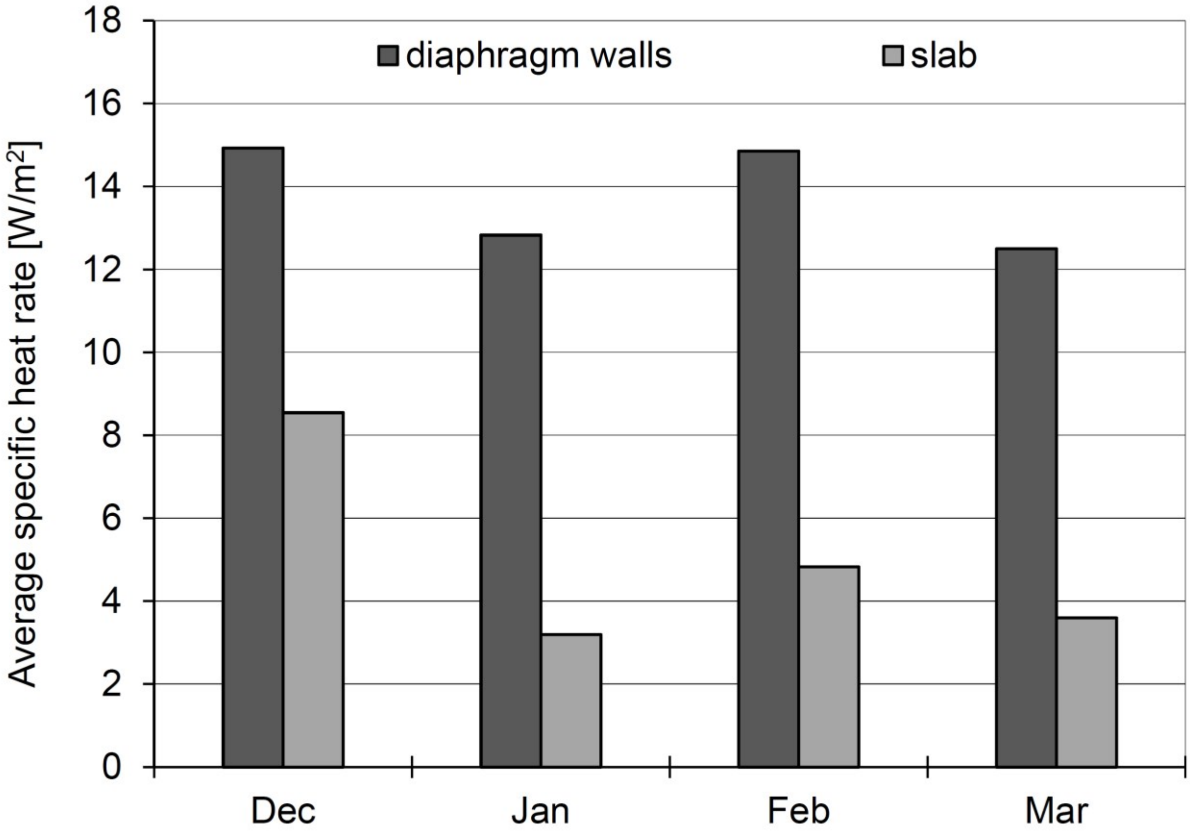

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Figure 5. Temperature variations at 3 positions along the upper anchor and within the wall at the soil side at depth 7m, from monitoring data (lines) and numerical modelling (dots)

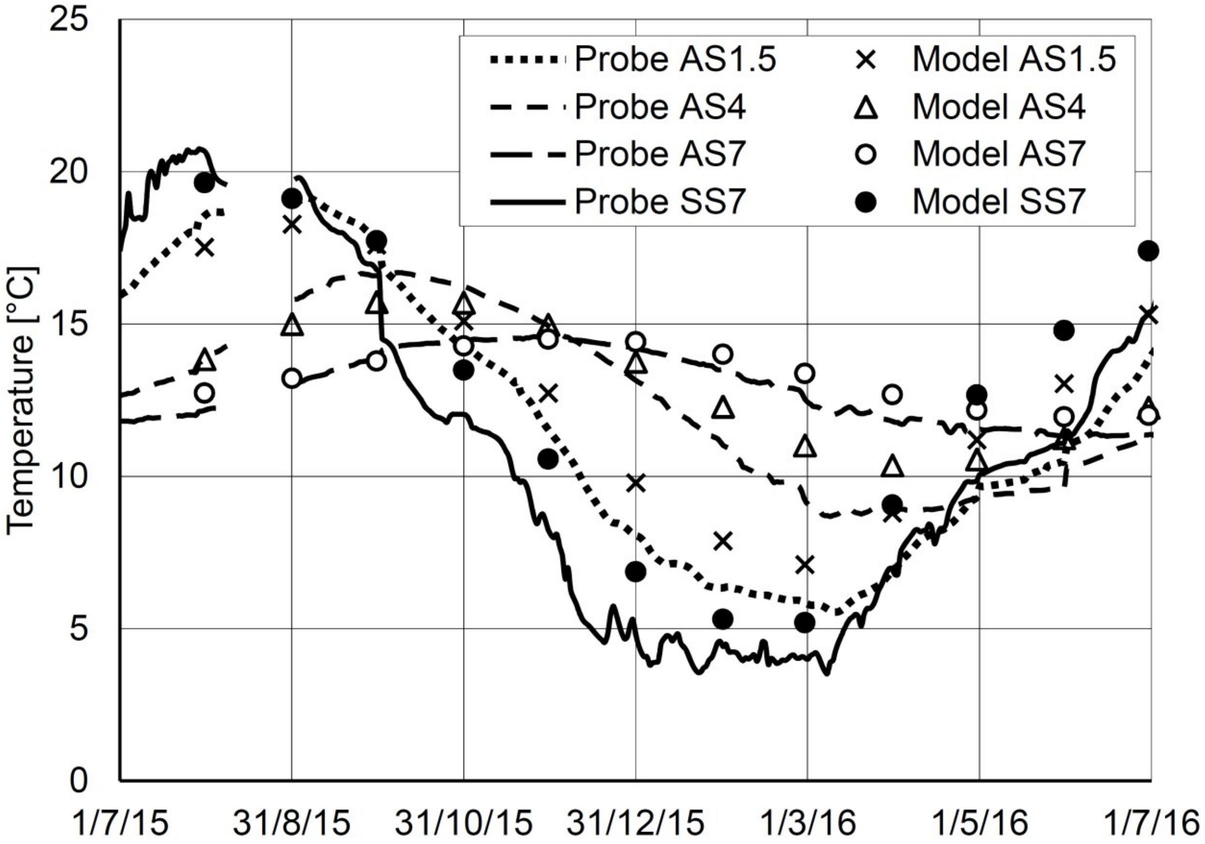

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Figure 6. Temperature difference between probes at the same depth 7 m (above the base slab): at the soil side SS7 and at the excavation side ES7

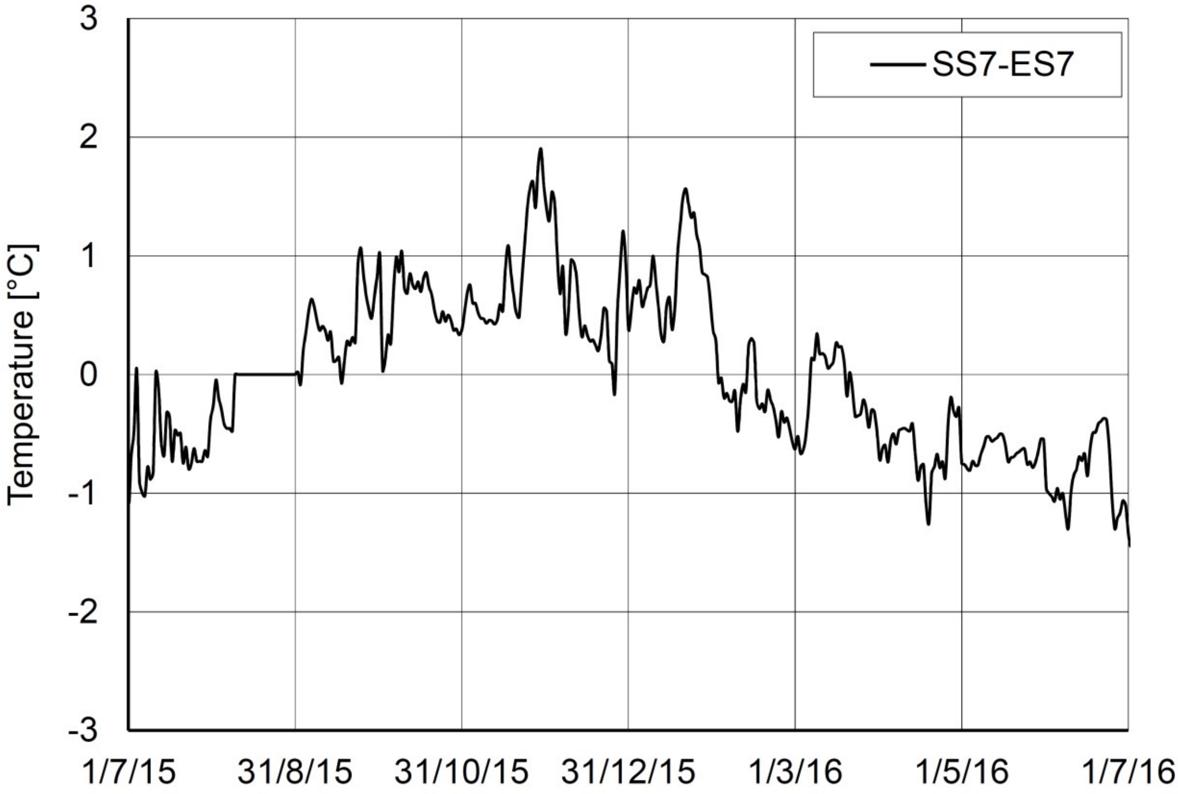

Figure 7. Temperature difference between probes at the same depth 13 m (below the base slab): at the soil side SS13 and at the excavation side ES13

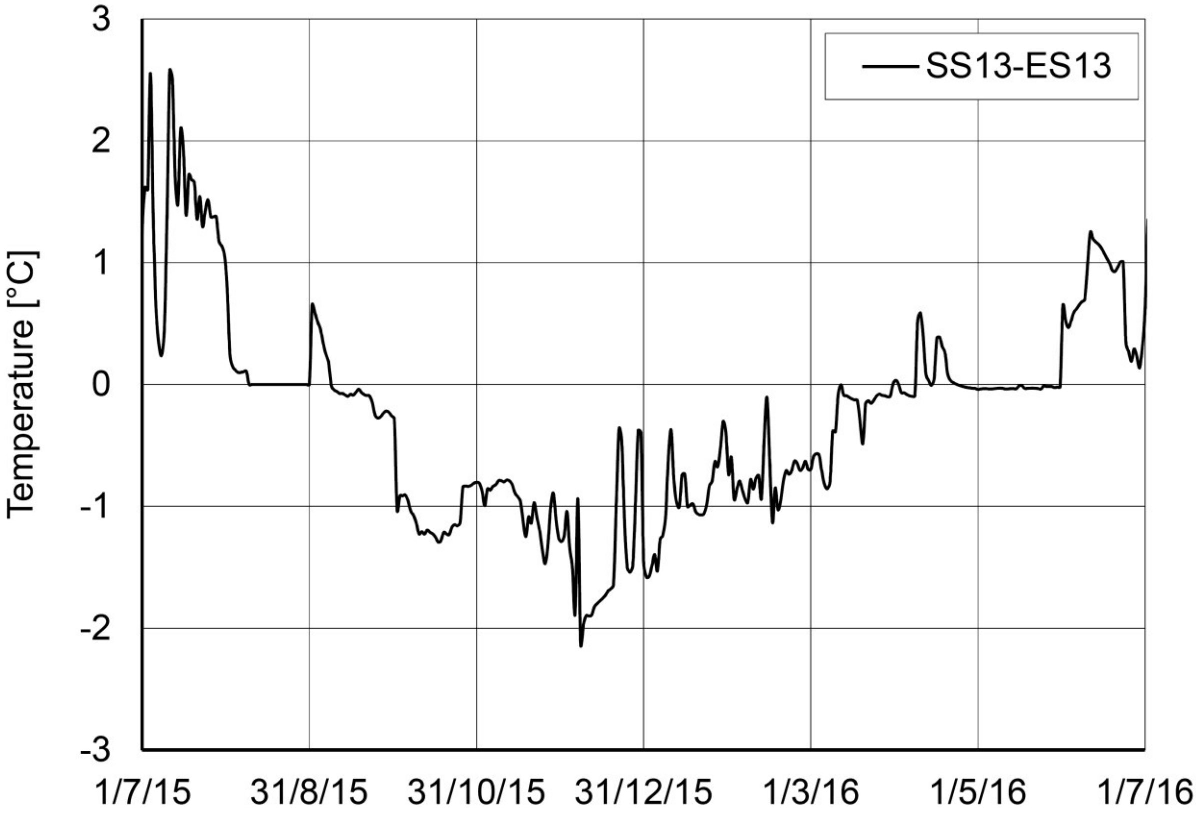

Figure 8. Pipe inlet and outlet temperatures from monitoring data (dashed and solid lines) and numerical modelling (dots)

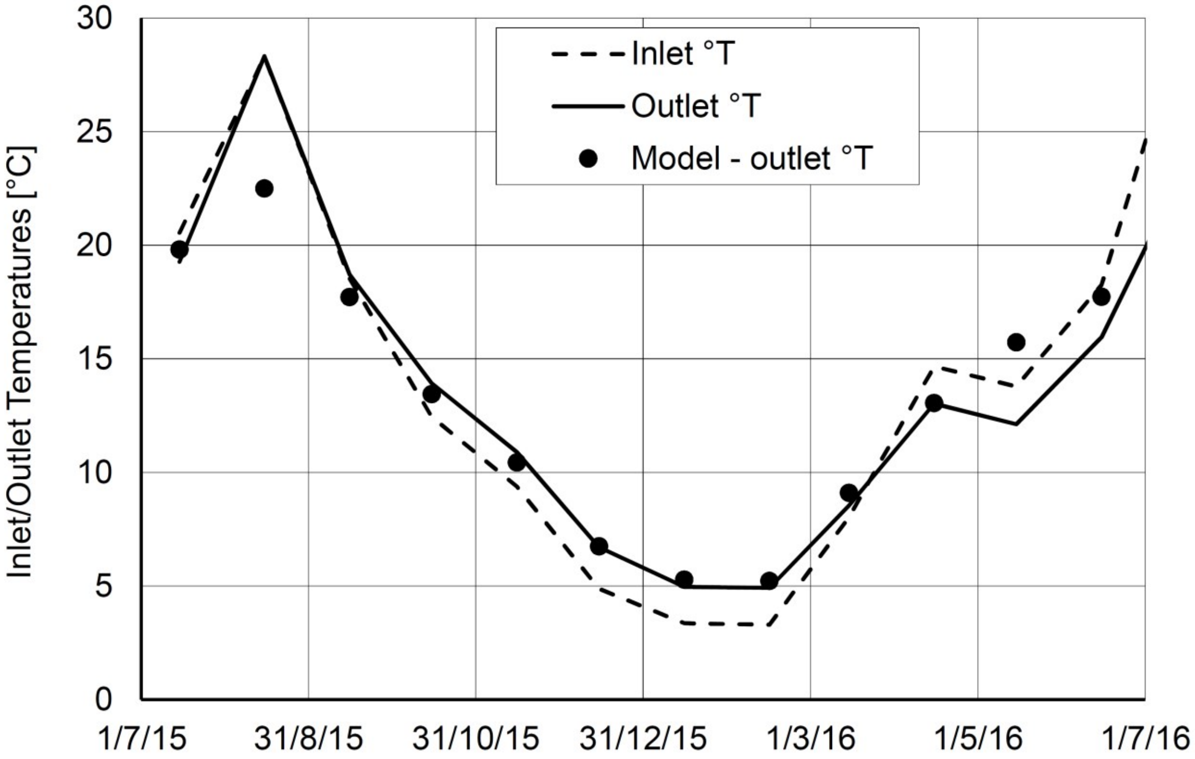

Figure 9. Thermal power of one heat exchanger from monitoring data and numerical modelling