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A Foundation Wall Heat Exchanger Model and Validation Study

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ABSTRACT

Making use of foundation substructural elements as ground heat exchangers is an attractive option for larger non-residential buildings. An alternative to Energy Piles is to use wall substructures – so called diaphragm or screen walls – with embedded pipes that are partly below ground and partly exposed to basement spaces. This paper will describe the development of a model of such a heat exchanger that uses a weighting factor approach known as Dynamic Thermal Networks (DTN). This approach allows for detailed representation of the wall section geometry and multiple boundary conditions. In this case thermal boundary conditions are applied at surfaces representing the adjacent ground and the semiexposed basement wall surface in addition to the pipe surface. The weighting factors for the model have been derived using a parametric numerical model that has been developed using the OpenFOAM library. Validation of the model has been carried out using data from an extended series of thermal response test (TRT) measurements at a full-scale diaphragm wall heat exchanger in Barcelona. In this paper, development of the model using the DTN approach will be briefly described along with the parametric numerical modelling approach used to derive the weighting factor data. Validation test procedures will be presented along with comparisons between the predicted and measured fluid temperatures and heat transfer rates. Given some uncertainty in the experimental thermal properties, the model was able to predict the dynamics of thermal response over a range of operating conditions with reasonable accuracy and using very modest computational resources.

INTRODUCTION

One of the grand challenges confronting the world today is to meet the growing demand for energy while addressing the environmental and climate impacts of fossil fuels consumptions. A large portion of energy consumptions in developed countries corresponds to heating of residential and commercial buildings (Pérez-Lombard et al., 2008). Exploitations of sustainable and renewable energy resources for direct use as thermal energy in such spaces can significantly reduce the need for conventional fuels and therefore decrease greenhouse gas emissions. To that end, geothermal energy represents an indispensable choice for its applicability in variable atmospheric conditions. Depending on its application geothermal energy can be extracted from deep or near surface reservoirs. Shallow geothermal energy is mainly used for the purpose of heating and cooling of buildings, referred to as its direct use. One important aspect of direct geothermal use is its applicability in almost all geographic locations (Lund et al., 2011).

To extract energy from the ground reinforced substructural elements equipped with heat exchanger pipes are used (Florides and Kalogirou, 2007). The ground works well as a heat exchanger since the underground temperature stays constant throughout the year and the ground temperature below 10m underground is not affected by the seasonal changes in outdoor air temperature (Droulia et al., 2009). Using substructures as heat exhchangers started in

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the 1980s, starting from ground-bearing slabs with the first adoption of diaphragm walls as heat exchangers being reported in 1996 in Austria and Switzerland (Brandl, 2006).

To date, numerious investigations into performance of thermos-active piles have been carried out (Esen and Inalli, 2009; Hepbasli et al., 2003; Li et al., 2006; Lim et al., 2007) while diaphragm wall heat exchangers (DWHE) are less researched (Rees, 2016). Brandl (2006) studied heat transfer in diaphragm walls applied in three main pilot projects including a rehabilitation centre, a traffic tunnel, and metro stations in addition to further smaller projects. Adam and Markiewicz (2009) performed finite element simulations to calculate heating and cooling performance of absorber elements such as diaphragm walls at different absorber distances. They reported that with larger distances the thermal power will decrease as well as the installation cost tending to an optimum. However, it was emphasized that their results are only valid for the studied case and may vary significantly for other geothermal systems while the method is applicable to any geothermal energy system installed in foundation elements. Xia et al. (2013) made the first attempt to experimentally investigate heat transfer performance of DWHEs and through comparison with borehole heat exchangers (BHE) revealed heat transfer characteristics of DWHEs and the factors influencing heat exchange rate in such geostructures. Sun et al. (2013) developed two-dimensional heat transfer models for DWHEs according to the structural features, i.e. over and under the excavation line, based on which a design model for such energy geostructures was proposed. Their models showed good agreement with numerical solutions and measured data.

Kürten et al. (2013) proposed a new numerical approach for the thermal analysis of DWHEs and verified their findings with laboratory tests. Bourne et al. (2016b) conducted numerical analysis to establish the heat exchange mechanisms in DWHEs, and reported that the main mechanism is between the air-void and wall rather than the ground. In another study Bourne-Webb et al. (2016a) identified communalities and differences between the methods used for evaluating BHEs and energy geostructures. Sterpi et al. (2017) investigated the energy performance and short and long term influence on the soil temperatures using finite element therml analysis. Furthermore, they carried out finite element thermo-mechnical analysis to highlight the wall geothecnical and structural response. Coletto and Sterpi (2016) used coupled thermo-mechanical analysis to study the heat transfer effects on the soil temperatures, the wall internal actions and the soil-structure interaction. Di Donna et al. (2016) used numerical simulation and statistical analysis to highlight the parameters governing energy efficiency in DWHEs. Soga and Rui (2016) summerised the current understanding on the performance of energy geostructures and discussed some design considerations. They suggested that more work is required to build confidence in the use of such substructure heat exchangers.

Major insights into heat transfer processes between DWHEs and their surrounding boundaries can be provided by monitoring temperature data from full-scale in-situ cases which conventionally is carried out using a thermal response test (TRT) for substructure heat exchangers. In the present work, a TRT apparatus that injects heat energy at a constant rate into one end of the loop and measures the outflow temperature at the other end is used to stimulate the heat exchanger and derive data for model validation. In contrast to a TRT we are not seeking to parametrically evaluate the ground or concrete thermal properties. To interprete such temperature data and evaluate temperature evolution in the circulating fluid as a function of time a suitable heat transfer mathematical model is required. Various mathematical models are inrtroduced for the analysis of heat exchange processes whithin a borehole heat exchanger and pile foundations, however, there are few models concerning DWHE due to their complexity. Temperature profiles predicated by the two-dimensional heat transfer model developed by Sun et al. (2013) show limited consistency with the experimental data but have been considered adequate by the authors. A thermal resistance model that takes rotational symmetry, number of pipes, and the spatial separation into account was presented and implemented into a finite difference code by Kurten et al. (2015). Their model does not consider seasonal fluctuation of the near surface temperature and the groundwater. In the present work, a combination of finite volume analysis and an approach known as dynamic thermal networks (DTN) proposed by Claesson (2002) and Wentzel (2005) is used for calculating dynamic conduction heat transfer in DWHEs. DTN is a response factor method that can provide efficient simulation of complex three-dimensional geometries such as DWHE with the basement, pipe and adjacent ground as temperature boundaries. To that end, the corresponding geometry of a DWHE is created and dicretized in

OpenFOAM (Weller et al., 1998). OpenFOAM was also employed to obtain the weighting factor series required as inputs to the DTN model. The experimental inlet temperature, ambient temperature, and the thermal properties of the ground and concrete were employed in the model to predict the outlet temperature of the DWHE over a period of 8 weeks. The method is verified against experimental data collected from an in-situ DWHE installation.

DIAPHRAGM WALL HEAT EXCHANGER (DWHE)

A schematic representation of a diaphragm wall equipped with heat exchanger pipes is illustrated in Figure 1-a and Figure 1-b. The wall depth varies depending on its application. High density polyethylene pipe (HDPE) or cross-linked polyethene (PEX) pipe is typically used to contain the heat exchange fluid in a closed loop. The pipes are installed by attachement to the reinforcement steel cage of the concrete wall closer to the side facing the ground. There are various possible layouts for arranging the pipe whithin the wall; the one shown in Figure 1 is a common configuration. Walls are typically constructed in panels depending on the practicalities of assembly and lifting and it is often convenient to arrange pipe circuits to be divided accordingly, with some consideration to available pipe lengths and limiting hycraulic pressure drops.

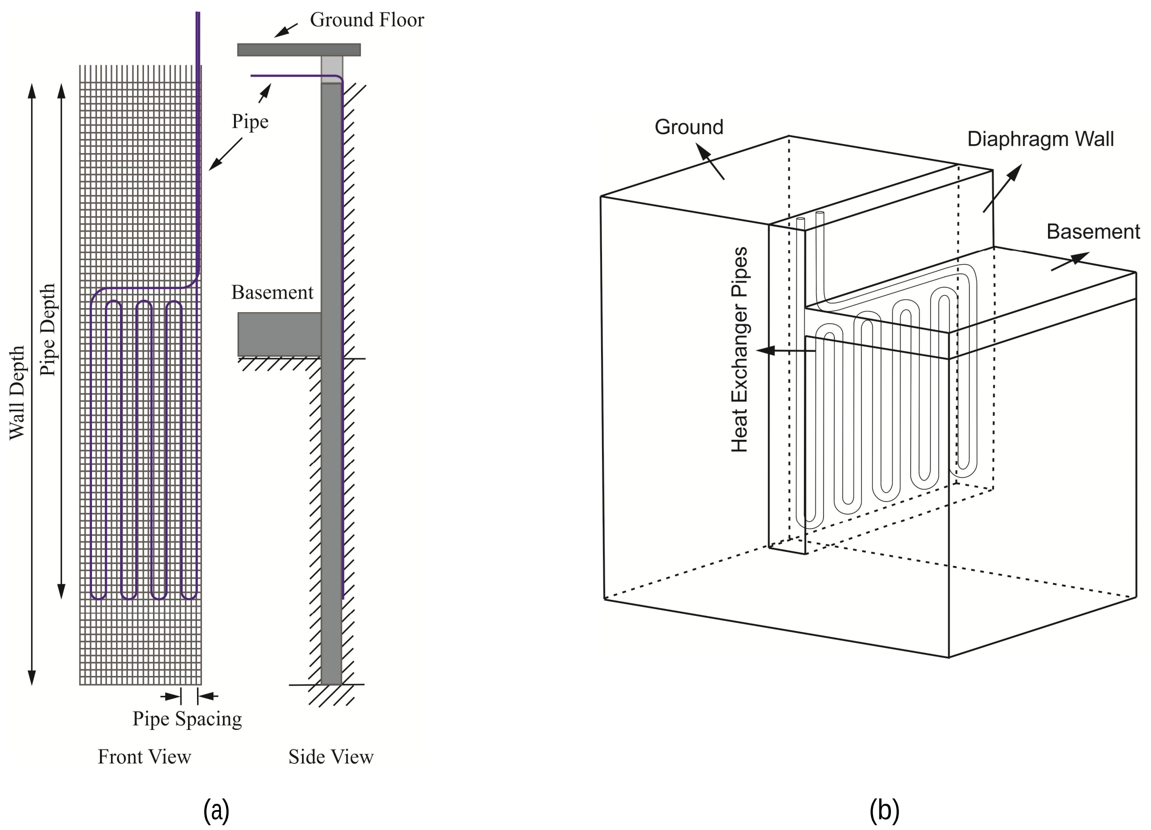
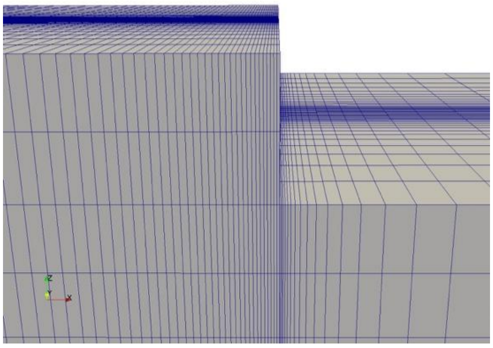


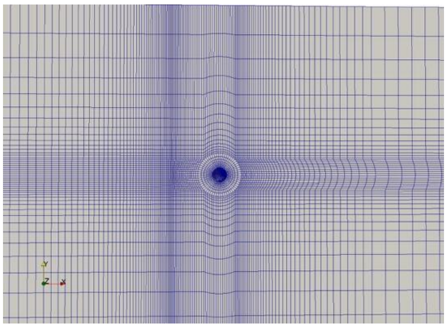
Figure 1 Schematic representation of a diaphragm wall heat exchanger and its surrounding boundaries.

HEAT TRANSFER MODEL

The DWHE studied here consists of a diaphragm wall of 17m depth and thickness of 0.6m embedded with a 93m long pipe cuircuit looped in veritical orientation (4 loops as shown in Figure 1). Pipe inner and outer diameters are 21mm and 25mm, respectively. To simplify the calculations and considering the symmetric configuration of the wall an isolated section containing only one pipe is considered. The corresponding geometry was created and dicretized in OpenFOAM (Weller et al., 1998) using the respective blockMesh utility, as shown in Figure 2. This parametric mesh generation tool allows generation of meshes in an automatied manner. An additional utility was developed to allow generation of DWHE meshes from relatively few design parameters.

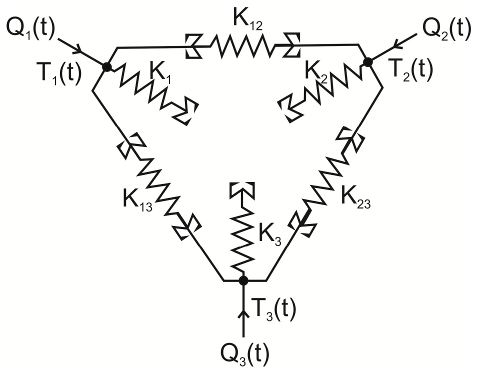


(a)

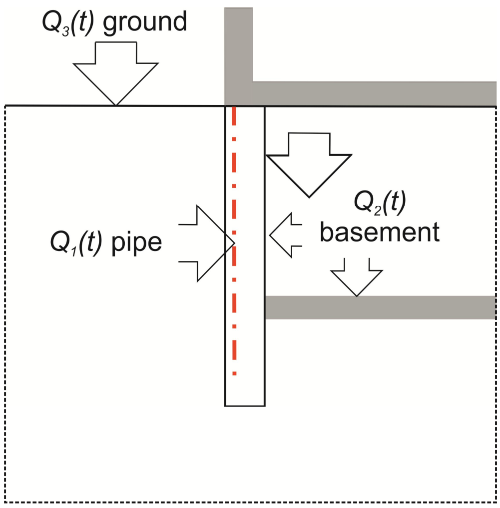


(b)

Figure 2 The validation model numerical mesh showing the top of the wall (a) and the pipe (b).



(a)



(b)

Figure 3 A three-surface form of Dynamic Thermal Network showing the resistance and nodes (a) and the corresponding surfaces in a DTN representation of a DWHE problem (b).

For DTN calculations, the time-dependent thermal processes are represented as a network to describe the relationship between boundary temperatures and heat fluxes. This network includes a combination of admittive and transmittive heat paths and time-varying conductances that are characterized by a series of response factors (Figure

3-a). The method can be shown to be exact in both continuous and discrete forms and can be applied, in principle, to arbitrary geometries with heterogeneous thermal properties (Claesson, 2002; Rees and Fan, 2013; Wentzel, 2005). This makes the method very attractive for energy pile and DWHE problems. In such situations we are interested in specifying complex geometries with two sets of thermal properties (concrete and ground) and representing three boundary condtions: (1) the pipe surfaces, (2) the basement surface and (3) the upper gorund surface. The fluxes at these boundaries are denoted Q_1, Q_2 and Q_3 respectively as shown in Fig.3.

An essential feature of the DTN method is that fluxes at each surface are separated into transmittive and absorptive components. So that, using node 1 as an example, the transient heat balance equation is expressed as:

$$Q_1(t) = Q_{1a}(t) + Q_{12}(t) + Q_{13}(t) \tag{1}$$

where Q_{1a} is the absorbtive flux and Q_{12} and Q_{13} are the transmittive fluxes. Rather than these fluxes being functions of instantaneous node temperatures and conductances as in a steady-state network representation, the transient fluxes are experessed as functions of constant conductances and weighted average node temperatures so that for node 1:

$$Q_1(t) = K_1 \cdot \left[T_1(t) - \bar{T}_{1a}(t)\right] + K_{12} \cdot \left[\bar{T}_{12}(t) - \bar{T}_{21}(t)\right] + K_{13} \cdot \left[\bar{T}_{13}(t) - \bar{T}_{31}(t)\right] \tag{2}$$

where $T_1(t)$ is the current boundary temperature and $\bar{T}_{1a}(t)$ is the weighted average absorbtive temperature and $\bar{T}_{12}(t)$ and $\bar{T}_{13}(t)$ are the weighted mean transmittive temperatures. In discrete form these temperatures are expressed as summations of past temperatures multiplied by respective weighting factors as follows:

$$\bar{T}_{ia,n} = \sum_{\rho=1}^{\infty} \kappa_{ia,\rho} \cdot T_{i,n-\rho} \quad \text{and} \quad \bar{T}_{ij,n} = \sum_{\rho=0}^{\infty} \kappa_{ij,\rho} \cdot T_{i,n-\rho} \tag{3}$$

where $\kappa_{ia,\rho}$ is an absorptive weighting factor and $\kappa_{ij,\rho}$ is a discrete transmittive weighting factor in a finite series of such weighting factors. These weighted average temperatures are updated from one timestep to the next. This gives a heat balance equation for boundary 1 of the problem in the following form:

$$Q_{1,n} = \bar{K}_1 \cdot [T_{1,n} - \sum_{\rho=1}^{\rho_s} \kappa_{1a,\rho} T_{1,n-\rho}] + K_{12} \cdot \sum_{\rho=0}^{\rho_s} \kappa_{12,\rho}(T_{1,n-\rho} - T_{2,n-\rho}) + K_{13} \cdot \sum_{\rho=0}^{\rho_s} \kappa_{13,\rho}(T_{1,n-\rho} - T_{3,n-\rho}) \tag{4}$$

This equation is a computationally cheap summation of temperatures multiplied by weighting factors and so the model is very efficient. Some effort is required in deriving the sets of weighting factors, however, these can be conveniently derived by applying step-changes in temperatures at each boundary in turn. In our case we use the OpenFOAM numerical model described above to do this. The time-series fluxes from these calculations are then used to derive the weighting factors. Details of the process are desicribed in Wentzel (2005) and Rees and Fan (2013) along with detailed descriptions of the boundary condtion treatment for the pipe and exposed surfaces.

RESULTS AND DISCUSSIONS

Model validation has been attempted by making comparisons with experimental DWHE data over a period of 6 weeks and the results are displayed in Figure 4. The experimental testing program was conducted during the construction of a demonstration building in Barcelona. A series of heat rejection pulses were applied using thermal response test (TRT) equipment. In these experiments the inlet and outet fluid temperatures into and from the diaphragm wall were measured at 5 min intervals from 18th September to 30th October 2017. During the experiments the heat pump was switched on and off intermittently while the circulating pump ran continuously. Figure 4-a to Figure 4-c show the profile of the inlet, outlet, and ambient temperatures measured during the test as well as measured heat transfer rate. Predicated outlet temperature and heat trasnefr rate using the DTN DWHE model are also pesented. The wall dimensions and properties are detailed in Table 1. Three stages of measurements can be identified during this test series as shown in Figure 4. During the first stage, the pump ran for relatively longer hours before being switched off. The length of the cycles was reduced in stage two and are shorter again (2 hours) in stage three.

It was not possible to obtain independent measurements of concrete and ground thermal properties at the site. Consequently, we have investigated a range of property values (somewhat heuristically) to investigate the sensitivity of the model results. Accordingly, calculations using the DTN diaphragm wall model have been performed using thermal conductivity values ranging from 1.8–3.0 $Wm^{-1}K^{-1}$ for concrete and 0.6–2.0 $Wm^{-1}K^{-1}$ for the ground. In addition, volumetric heat capacity values of 1.6×10^6–3.75×10^6 J $m^{-3}K^{-1}$ are examined for concrete while one single value of 1.6×10^6 J $m^{-3}K^{-1}$ is used for ground. The results indicated that there is sensitivity to both the concrete and the ground thermal conductivities. Data from the shortest cycle periods was used to guide the choice of concrete properties as heat transfer variations are mostly limited to within the concrete in such conditions. Conversely, data from the longer cycles of heat rejection were more sensitive to ground thermal properties.

Table 1. DTN DWHE Model Parameters for the TRT Test Conditions

Model Parameters	Value	Units
Wall Depth	17.0	m
Pipe Depth	15.6	m
Basement Depth	6.5	m
Pipe outer diameter	25	mm
Pipe inner diameter	21	mm
Pipe horizontal spacing	0.40	m
Pipe circuit length	93.0	m
Number of loops	4	-
Pipe thermal conductivity	0.39	W $m^{-1}K^{-1}$
Fluid conductivity	0.625	W $m^{-1}K^{-1}$
Fluid specific heat	4178	J $kg^{-1}K^{-1}$
Fluid density	994.0	kg m^{-3}
Fluid viscosity	0.000714	Pa

Table 2. Thermal Properties of Concrete and Ground Used in Figure 2

Thermal Properties	Value	Units
Concrete thermal conductivity	2.25	W $m^{-1}K^{-1}$
Ground thermal conductivity	1.6	W $m^{-1}K^{-1}$
Concrete volumetric heat capacity	3.5×10^6	J $m^{-3}K^{-1}$
Ground volumetric heat capacity	1.6×10^6	J $m^{-3}K^{-1}$

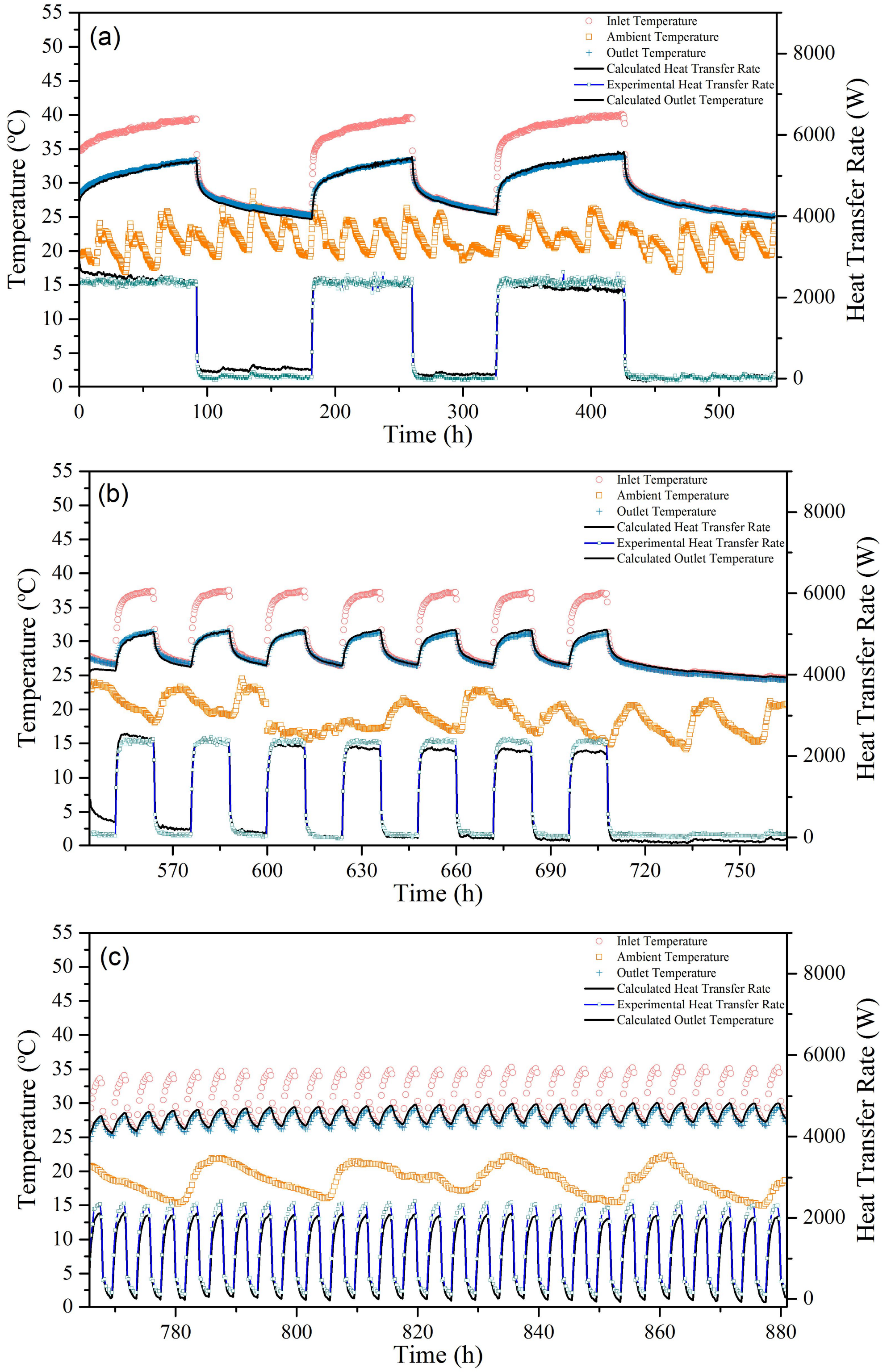


Figure 4 Hourly variations in measured temperatures and heat transfer rate compared with calculated data.

Calculated time series in Figure 4 represents the best fit with the experiments for which corresponding thermal properties of ground and concrete are shown in Table 2. Predicted outlet temperature and heat trasnefr rate follow the experiments closely over the operation period. The root mean square error (RMSE) between the calculated and measured outlet temperatures over the 6 weeks operation period is 0.4K which represents a good level of agreement for modelling purposes. Data in Table 2 indicates that the closest agreement is found with higher values of ground and concrete thermal conductivities and relatively high value of concrete volumetric heat capacity. We believe using values that are higher than that for plain concrete are justifyable in view of the significant level of reinforcement steel surrounding the pipes. In this model the wall thermal properties are effective or composite values for the wall material. The issue of the impact of the reinforcement on the nature of short timescale response is worthy of further investigation.

The validity of the DTN DWHE analogy to define heat transfer at the wall in the proposed model has been investigated by examining prediction of ground heat transfer over the operation period. The model compares favourably with the experimental data. The measured heat rejection over the whole period is 999.7 kWh and this compares with a predicted value of 988.7 kWh which corresponds to a 1.10% relative error and this seems an acceptable value. Completing calculations for the whole experimental data series required of the order of one minute of computing time.

CONCLUSIONS

A heat transfer model has been proposed that combines a numerical finite volume representation of a diaphragm wall heat exchanger and surrounding ground and basement boundaries and a Dynamic Thermal Network (DTN) representation derived from the numerical data. The model validation testing has been carried out using a thermal response test (TRT) approach over an extended period with different periods of cyclic operation. It has been shown that the results are sensitive to thermal property values of the ground and concrete. Values of effective thermal capacity were chosen at the upper end of the usual range and this seems justifyable in view of the large amount of reinforcement steel in the wall. The relative errors in outlet temperature between the DTN model and the measured data are no more than 0.4K for an operation period of about 880h. The levels of agreement in predicted dynamic performance are concluded to be more than satisfactory for heat exchanger design and TRT analysis purposes. The model is relatively efficient and so well suited to analysis of long-term performance analysis.

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