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HEAT TRANSFER ANALYSIS OF THERMO-ACTIVE FOUNDATIONS

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Abstract

A transient, three-dimensional finite volume method (FVM) numerical model was developed specifically for the purpose of modeling thermo-active foundations. Validation against a physical experiment was first carried out using measurements obtained from an experimental set-up of a thermo-active foundation. The model was then used to investigate three design parameters as they apply to thermo-active foundations including tube spacing, pier depth, and flow velocity. The model was also used to investigate the thermal interaction between the thermo-active foundation and the building above it using annual simulations based on hourly weather data for Boulder, CO. In particular, it is found that thermo-active foundation can increase a building's ground-coupled slab heat loss for 57% of hours during the heating season when compared to a standard foundation. A decrease in slab heat loss or increase in slab heat gain was seen for 32% of hours during the cooling season.

Keywords: buildings, ground-coupled heat transfer, heating and cooling, heat exchangers, thermo-active foundations

Introduction

As global primary energy resources rapidly decline, the importance of energy conservation is more evident now than ever before. Furthermore, the connection between fossil fuel use and global warming creates even more concern over the world's consumption of fossil-based energy. In the United States, the building sector accounts for 40% of all energy use and is the largest contributor to greenhouse gas emissions [1]. Moreover, most of the primary energy used by US commercial buildings, 27.3%, is used for heating and cooling [1]. Consequently, any technological developments in this area have the potential to have a far reaching effect.

Ground-source heat pumps (GSHP) have demonstrated 30% to 70% energy savings in heating mode and 20% to 50% in cooling mode when compared with air-source heat pumps and traditional air-conditioning systems [2-3]. Residential and commercial installations of GSHP have grown quickly and steadily, with installations growing an average of 10% per year in 30 countries from 1994 to 2004 and

becoming a commonplace space conditioning system in Europe [4-5]. A primary barrier to the further implementation of GSHP technology is the typically high upfront cost of these systems. A GSHP system can cost 20% to 40% more than a conventional heating/cooling system in commercial applications [3]. The majority of this cost lies in the installation of the geo-exchange system, which typically involves expensive drilling or digging.

Alternatively, the integration of geo-exchange systems with the structural foundations of buildings can significantly reduce the upfront cost of such systems by eliminating the need for additional drilling or digging [6]. These thermo-active foundation systems have been applied successfully and the implementation of the technology is growing rapidly [6-10]. However, there are still several challenges associated with these systems, and research on the structural and thermal interactions involved is necessary for proper implementation of the technology. In considering thermo-active foundations in light of vertical borehole GSHP systems, several design and operation issues arise and need to be evaluated. For instance, the magnitude of thermal short circuiting effect between inlet and outlet tubes needs to be properly assessed. The impact on overall thermal performance of shallower depth of the loops and closer proximity of foundation piers compared to GSHP systems should be quantified. Moreover, an analysis to estimate the thermal interaction between the geo-exchange system and the building above it should be carried out.

To address these issues, accurate modeling of thermo-active foundations is necessary. Existing numerical models of GSHP geo-exchange systems are capable of simulating the heat transfer associated with vertical boreholes with u-tube heat exchange loops [11-16]. Very few models of thermo-active foundations are available in the literature [17-18]. However, these models are based on simplified assumptions and do not account for the more complex geometries possible in thermo-active foundations, and, perhaps most significantly, are not validated against experimental data. This paper describes and validates a finite volume method (FVM) numerical model of a thermo-active foundation which has been developed with the eventual goal of integration into a whole-building simulation tool.

Model Description

Figure 1 shows a thermo-active foundation model including a cross-section of the building foundation with an embedded single U-tube heat exchanger and the 3-D rendering of the joint between the foundation pile and slab floor. The model is designed to simulate the transient behavior of a 3-dimensional of a thermo-active pier with the heat exchange loop embedded in the concrete. The pier extends above ground to form an exterior wall. A slab floor is simulated to be beneath the interior of the building.

The temperature and flow within the tubes are subject to Equation (1) [18-20]:

$$\alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial t} + v_x \left(\frac{\partial T}{\partial x} \right) + v_y \left(\frac{\partial T}{\partial y} \right) + v_z \left(\frac{\partial T}{\partial z} \right) \quad (1)$$

The temperature within the soil and the building foundation elements such as the foundation footings and the slab-on-grade floor is subject to the conduction equation [19]:

$$\alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial t} \quad (2)$$

Inside the pipes embedded in the foundation piles, the fluid –typically water- is circulated to exchange heat through mainly convection. The convection heat transfer coefficient of this fluid is determined with the Dittus-Boelter correlation [19]:

$$h = \frac{Nu k}{D} \quad (3)$$

And

$$\begin{cases} Nu = 3.36 \text{ if } (Re < 2300) \text{ for laminar flow} \\ Nu = 0.023 Pr^n Re^{0.8} \text{ else for turbulent flow} \end{cases}$$

With $n=0.4$ for heating and $n=0.3$ for cooling

Using the Cartesian coordinate system, the boundary conditions imposed for both Equations (1) and (2) are defined as listed in Table 1.

A Finite Volume Numerical Method (FVM) is used to solve Equations (1) and (2) following the implicit formulation. In particular, Equations (1) and (2) are discretized into the form of Eq. (4) [20]:

$$a_p T_p = a_e T_e + a_w T_w + a_n T_n + a_s T_s + a_t T_t + a_b T_b + a_p^o T_p^o \quad (4)$$

With

$$a_p^o = (\rho_m c_{p,m} \Delta x \Delta y \Delta z) / \Delta t$$

$$a_p = a_e + a_w + a_n + a_s + a_t + a_b + a_p^o$$

Inside the soil and concrete the coefficients in Equation (4) are defined as follows:

$$a_{e,w} = \frac{k \Delta y \Delta z}{\Delta x}; \quad a_{n,s} = \frac{k \Delta x \Delta z}{\Delta y}; \quad a_{t,b} = \frac{k \Delta x \Delta y}{\Delta z}; \quad (5)$$

At all solid/fluid boundaries, the coefficients in Equation (4) are defined as follows:

$$a_{e,w} = h_f \Delta y \Delta z; \quad a_{n,s} = h_f \Delta x \Delta z; \quad a_{t,b} = h_f \Delta x \Delta y; \quad (6)$$

Due to its accuracy, speed, and reliability, the coupling of diffusion and convection was discretized using the power-law scheme. Inside the fluid, the coefficients in Equation (4) are defined as follows:

$$a_w = \{D_w A(|Pe_w|) + [F_e, 0]\} \Delta y \Delta z; \quad a_e = \{D_e A(|Pe_e|) + [-F_e, 0]\} \Delta y \Delta z; \quad (7)$$

$$a_n = \{D_n A(|P_{\theta_n}|) + [F_n, 0]\} \Delta x \Delta z; \quad a_s = \{D_s A(|P_{\theta_s}|) + [-F_s, 0]\} \Delta x \Delta z; \quad (8)$$

$$a_t = \{D_t A(|P_{\theta_t}|) + [F_t, 0]\} \Delta x \Delta y; \quad a_b = \{D_b A(|P_{\theta_b}|) + [-F_b, 0]\} \Delta x \Delta y; \quad (9)$$

And employing the power-law scheme,

$$D_e = \frac{k_e}{\Delta x}; \quad D_w = \frac{k_w}{\Delta x}; \quad D_n = \frac{k_n}{\Delta y}; \quad D_s = \frac{k_s}{\Delta y}; \quad D_t = \frac{k_t}{\Delta x}; \quad D_b = \frac{k_b}{\Delta x}; \quad (10)$$

$$F_e = (\rho_f c_{p_f} v)_e; \quad F_w = (\rho_f c_{p_f} v)_w; \quad F_n = (\rho_f c_{p_f} v)_n; \quad F_s = (\rho_f c_{p_f} v)_s; \quad F_t = (\rho_f c_{p_f} v)_t; \quad F_b = (\rho_f c_{p_f} v)_b; \quad (11)$$

$$A(|P_{\theta_e}|) = [0, (1 - 0.1|P_{\theta_e}|)^5]; \quad A(|P_{\theta_w}|) = [0, (1 - 0.1|P_{\theta_w}|)^5]; \quad (12)$$

$$A(|P_{\theta_n}|) = [0, (1 - 0.1|P_{\theta_n}|)^5]; \quad A(|P_{\theta_s}|) = [0, (1 - 0.1|P_{\theta_s}|)^5]; \quad (13)$$

$$A(|P_{\theta_t}|) = [0, (1 - 0.1|P_{\theta_t}|)^5]; \quad A(|P_{\theta_b}|) = [0, (1 - 0.1|P_{\theta_b}|)^5]; \quad (14)$$

$$P_{\theta_e} = \frac{F_e}{D_e}; \quad P_{\theta_w} = \frac{F_w}{D_w}; \quad P_{\theta_n} = \frac{F_n}{D_n}; \quad P_{\theta_s} = \frac{F_s}{D_s}; \quad P_{\theta_t} = \frac{F_t}{D_t}; \quad P_{\theta_b} = \frac{F_b}{D_b}; \quad (15)$$

The model utilizes a geometric grid to minimize calculation time while maintaining accuracy. The grid is generated based on Equation (16):

$$\Delta x_{qv} = \Delta x_0 \times G^{(node)} \quad (16)$$

The geometric constant G is determined iteratively using Equation (17), based on the user-specified number of nodes in the sequence.

$$\frac{L}{\Delta x_0} = \frac{1 - G^{N+1}}{1 - G} \quad (17)$$

An example of a geometric grid applied to a thermo-active foundation model is shown in Figure 2. Note that the grid is fine at the tubes and the non-adiabatic boundaries and graduates to a coarser configuration far away from these areas.

Table 1 gives the values of the parameters for the base model used for the sensitivity analyses.

The impact of the grid type and size on the accuracy of the numerical solution is evaluated through a detailed analysis [21]. The goal of this analysis was to determine the grid which gives the most accurate solution with the least CPU time. The model was set for convergence using a maximum difference between solutions for each iteration with a 0.00001 °C tolerance. Table 2 summarizes the impact of grid size on the accuracy and the CPU time of the numerical solution for six grid configurations. The finest grid (Grid 1) is uniform with each grid cell's length and width equal to the inner diameter of the tubes (0.0196m). Each successive grid has approximately half the total number of nodes as the grid before it, and is configured geometrically. Grid 1 has a total of 1,160,627 nodes, and Grid 6 has 16,836 nodes.

The grids are compared to each other using Normalized Root Mean Squared Error (NRMSE) and percent CPU (central processing unit) time using Grid 1 as the baseline. Because of its combination of speed and accuracy, Grid 3 was chosen for the validation and the sensitivity analyses.

Validation Analysis

In order to validate the solution approach described above, the model is configured to represent a physical experiment performed by Rosenberg [22]. Transient simulations are run in an attempt to recreate the measured results and validate the numerical model. The experiment involves the evaluation of a scale-model thermo-active foundation. The purpose of the experimental study was to understand the effects of temperature fluctuations on the structural capacity of thermo-active foundations under representative building loads.

The tested foundation was a cylindrical concrete pier with aluminum tubing to represent the heat exchange tubes in a thermo-active foundation. Silicon fluid was pumped through the tubes in a closed loop while being heated or cooled by a heat pump. The pier was embedded in soil inside an insulated cylindrical container designed for use with a centrifuge. The distribution in temperature within the soil layer was measured using three temperature profile probes. These consist of a steel rod with 6 RTD thermocouples spaced evenly at 45 mm from the bottom. Three RTD thermocouple probes were embedded within the soil to a depth of 270 mm below the soil surface. Figure 3 gives the dimensions of the thermal pile, the schematics of the experiment set-up, locations of the probes in the soil, and a photograph of the container. The measurements at Probe 'B' were used in this validation.

Several tests were performed in which the foundation and surrounding soil were slowly heated and/or cooled while the pier was loaded with a simulated building load. For the test used in this validation, the entire apparatus began at ambient room temperature. Once the soil and foundation had fully settled from the force imposed by the centrifuge, the fluid began to be pumped through the tubing with the heat pump on in heating mode. Inlet fluid temperatures, along with the outlet temperatures and the soil depth temperatures, were measured and logged every 6 seconds for the duration of the test. The test was carried out for 120 minutes.

The measurements obtained from the small-scale experimental set-up of Figure 3 are utilized to validate the numerical solution predictions. Due to the fact that the numerical model was developed using Cartesian coordinates, the cylindrical container was modeled in 3D as a rectangular prism. Table 3 lists the input values for the baseline model of the experimental thermo-active foundation used for the calibration analysis. After calibration based on uncertainties in the soil and concrete properties as well as the initial state of the soil domain, the 3-dimensional model produced results matching the experiment to within an RMSE of 0.5 °C at each time stamp. Table 4 compares the values of the input parameters set for the baseline and calibrated models. Figure 4 directly compares the calibrated simulation results with the experimental data at each time stamp. Table 5 gives the RMSE values for each of time period used in the validation. As indicated in Figure 4 and Table 5, good agreement

between the model predictions and the experimental results for various time periods and temperature probe locations.

Design Parameter Sensitivity Analyses

The developed and validated thermo-active foundation model is used to perform a series of sensitivity analyses to assess the impact of specific design configurations for full scale model parameters given in Table 6. The specifications listed in Table 6 are representatives of thermo-active foundations for small office buildings.

Design Parameter: Tube Spacing

A sensitivity analysis was performed to investigate the effect of tube spacing on the overall heat transfer from the heat exchange tubes in cooling mode. For this analysis, the spacing between tubes was varied from 0.1m to 1.5m to represent the full range of likely spacing lengths in a thermo-active foundation. The temperature difference between the inlet and outlet tubes given by the simulation for each spacing length was used to calculate the total net heat transfer from the tubes.

As can be seen in Figure 5, greater spacing between tubes results in greater heat transfer, consistent with the findings for standard GSHP boreholes in a previous research study [14]. The higher spacing between the tubes reduces the thermal short circuiting and enhance the heat exchange between the fluid and its surrounding including the concrete foundation pile and ground medium. The relationship between tube spacing and heat transfer for this set of simulations can be approximated by a linear relationship. On average, it was found that the heat transfer for the cases simulated increases by 4.24% for every 0.1m increase in tube spacing ($R^2=0.985$).

Design Parameter: Fluid Velocity

The velocity of the fluid in the tubes of a thermo-active foundation affects the heat transfer through the tubes, the temperature of the outlet fluid, and the power required to pump the fluid. A sensitivity analysis was performed to determine the effect of fluid velocity on the heat transfer from the tubes and the temperature difference between the inlet and outlet tubes. To perform this analysis, the velocity was varied from 0.02 m/s (6.034×10^{-6} m³/s) to 0.24 m/s (7.241×10^{-5} m³/s) while all other parameters were held constant. Figure 6 presents the percent increase seen in heat transfer as the velocity increases. The results show that heat transfer always increases as velocity increases. Indeed, the fluid circulating at higher velocity has the capability to exchange more heat with its surroundings. However, a clear discontinuity is seen from 0.11 m/s to 0.12 m/s. This is due to the fact that the Reynolds number reaches 2300 at a velocity between these two values, indicating a shift from laminar flow to transitional and turbulent flow. The result is a large increase in the convection coefficient at the tube walls. Though further investigation is warranted, it can be inferred that the optimal point of operation will be at the lowest velocity when the fluid is in a turbulent flow. If the fluid is pumped to higher velocities than this threshold velocity, the losses due to pumping power will likely dominate the gains seen in tube heat transfer.

Design Parameter: Pier Depth

Increasing the depth of a thermo-active pier increases the length of the heat exchange tube which in turn increases the total heat exchange area. However, increased pier depth requires more drilling or digging as well as more concrete and rebar. Hence, there is a cost penalty with increasing the depth of a pier.

To study the effect of this parameter on heat transfer from the tubes, the depth of the pier (and the embedded tubes) was varied from a minimum of 6m to a maximum of 18m to represent the range of likely depths for a thermo-active pier. Figure 7 graphs the total heat transfer from the tubes as a function of pier depth. As can be seen, a linear relationship exists with heat transfer increases by 7.23% for every meter of increased depth.

Investigation of Building Thermal Interaction

In this section, the magnitude of thermal interactions between a thermo-active foundation and the building above it is investigated. Specifically, the question of how the heat transfer from the soil to the slab floor, or vice versa, is altered by the presence of a thermo-active foundation is addressed.

As a first step, the model was run under steady-state conditions to simulate a thermo-active foundation in heating mode and, as a separate model, in cooling mode. The heat transfer between the building interior and the slab floor was calculated along the length of the floor from the exterior wall to the edge of the model domain. Moreover, a new numerical model was developed to simulate a standard foundation under the same conditions as the thermo-active foundation model. Table 7 lists the parameters used in these models. Figure 8 summarizes the comparative analysis results for thermo-active and standard foundations.

The results of the steady-state analysis show that the majority of heat transfer occurs closest to the junction pier/wall. This is due to the fact that this is the area most influenced by exterior temperatures as well as the underground temperatures introduced by the thermo-active pier. It can also be seen that, at steady-state, the thermo-active pier increases heat loss when in heating mode and heat gain during cooling mode.

As a next step in this investigation, an annual transient simulation was carried out using hourly weather data for Boulder, CO. For Boulder, the annual average outdoor temperature is 9.7°C while the annual heating and cooling degree-days at base 18.3°C are 3448°C-days and 312°C-days, respectively [25]. The building was assumed to be in heating mode when the outdoor temperature is below 13 °C, and cooling mode when the temperature is equal to or greater than 13 °C. To account for the fact that the heat exchange loop temperatures change depending on the amount of heating or cooling required, the inlet temperature of the glycol solution was adjusted at each time step.

The net heat flux through the slab of the building was calculated and recorded for each hour of the simulation. As a comparison, an annual simulation was run using identical parameters except that the foundation did not have any heat exchange tubing. Figure 9 shows the temperature profiles in the

ground noon on a summer day (i.e., July 2) for the thermo-active and the standard foundations. Figure 10 illustrates the hourly heat transfer results along with the daily average for outdoor temperature.

The results of the annual simulation show significant increases in the amplitude of the heat transfer over the course of a year for a thermo-active foundation as compared to a standard foundation. Furthermore, heat loss from the building is increased during the heating season, and vice versa for the cooling season. To gain more insight into this effect, the percent difference in heat transfer between the standard foundation and the thermo-active foundation was plotted against outdoor temperature. Figure 11 is divided into hours when the building requires heating and those when it requires cooling. These data are further separated into hours when the thermo-active foundation increases heat loss and those when it decreases heat loss.

As indicated in Figure 10 and Table 8, the majority of hours when then the thermo-active foundation causes increased heat loss from the building occurs when the building is in heating mode, and vice versa for decreased heat loss. In particular, thermo-active foundation can increase a building's ground-coupled slab heat loss for 57% of hours during the heating season when compared to a standard foundation. A decrease in slab heat loss or increase in slab heat gain was seen for 32% of hours during the cooling season.

Summary and Conclusions

A transient numerical model was developed to model the thermal performance of a building thermo-active foundation under heating and cooling conditions. A validation analysis of the model predictions has been carried out using measured data obtained from a laboratory experimental set-up. The temperature field predicted by the numerical solution was found to agree with those obtained from the experiment to within an RMSE of 0.5 °C.

The developed model was then used to investigate three design parameters as they apply to thermo-active foundations: Tube spacing, pier depth, and flow velocity. The model was also used to investigate the thermal interaction between the thermo-active foundation and the building above it using an annual simulation based on hourly weather data for Boulder, CO.

For the cases simulated, it was found that an increase in overall heat transfer of 4.24% is obtained for every 0.1m increase in spacing between inlet and outlet tubes. Overall heat transfer is always increased as flow velocity is increased. However, once turbulent flow is achieved, the increase in heat transfer is increasingly small. The greatest impact is seen when the flow moves from laminar to turbulent flow. Overall heat transfer increases linearly as pier depth increases. For the cases simulated, an increase in heat transfer of 7.23% is seen for every meter of increased pier depth.

Additionally, it was found that a thermo-active foundation can increase a building's ground-coupled slab heat loss for 57% of heating mode hours annually when compared to a standard foundation. A decrease in slab heat loss or increase in slab heat gain was seen for 32% of cooling mode hours annually.

In this study, a single U-tube heat exchange loop is considered for the thermo-active foundation, extension of the developed model to include multiple loops in one foundation pier and multiple piers

under one building should be considered. Moreover, methods for increasing the speed of numerical modeling should be further explored to integrate the developed model into whole-building simulation tools in order to compare the energy performance thermo-active foundation to other heating and cooling systems for various building types and climates.

Nomenclature

Variables

c_p	Specific heat capacity [J/kg.K]
CPU	Central Processing Unit
k	Thermal conductivity of the solid medium [W/m.K]
h	Convection coefficient at a solid/fluid boundary [W/m ² .K]
Pe	Peclet number [-]
T	Temperature [°C or K]
$\dot{Q}$	Heat flux [W]
t	Time [s]
v	Velocity of the fluid [m/s]
x	Length in the x-direction [m]
y	Length in the y-direction [m]
z	Length in the z-direction [m]
α	Thermal diffusivity of the solid medium [m/s ²]
ρ	Density [kg/m ³]
$node$	The number of nodes the control volume is from the control volume at the critical boundary
G	Geometric Constant [-]
L	Length of the physical domain [m]
N	The total number of nodes in the x-direction

Subscripts

p	Present calculation node
w	Calculation node immediately to the west of node 'p'
e	Calculation node immediately to the east of node 'p'
n	Calculation node immediately to the north of node 'p'
s	Calculation node immediately to the south of node 'p'
t	Calculation node immediately to the top of node 'p'
b	Calculation node immediately to the bottom of node 'p'
m	Designates a property of the medium
f	Designates a property of the fluid
cv	Designates a particular control volume

o Designates the control volume at the critical boundary

Superscripts

o Designates a value from the previous time step

Operators

$\left[\begin{smallmatrix} \text{ } \\ \text{ } \end{smallmatrix} \right]$ Designates that the larger of the values inside the brackets is to be used

References

- [1] U.S. Department of Energy, Energy Efficiency, and Renewable Energy. (2008). Energy Efficiency Trends in Residential and Commercial Buildings, report available on-line (www.doe.gov), Washington DC.
- [2] Omer, A. (2006). Ground-source heat pump systems and applications. *Renewable and Sustainable Energy Reviews* , 12 (2), 344-371.
- [3] Retscreen International. (2005). Ground-source heat pump project analysis. In *Clean Energy Project Analysis: Retscreen Engineering and Cases Textbook*.
- [4] Lund, J. (2004). Geothermal (ground-source) heat pumps-- A world overview. *Geo-Heat Center Quarterly Bulletin* , 25 (3), Oregon Institute of Technology, Klamath Falls, OR.
- [5] Rybach, L., and Sanner, B. (2000). Ground-source heat pump systems: The European experience. *Geo-Heat Center Bulletin* , 25 (3), Oregon Institute of Technology, Klamath Falls, OR.
- [6] Brandl, H. (2006). Energy foundations and other thermo-active ground structures. *Geotechnique*, 56(2), 81–122.
- [7] Preg, R. (1997). Saving energy with concrete. *IEA Heat Pump Centre Newsletter*, 15(1), 10-15.
- [8] Hamada, Y., Nakamura, M., Kubota, H., and Ochifuji, K. (2007). Field performance of an energy pile system for space heating. *Energy and Buildings* , 39 (5), 517-524.
- [9] Carlson, S. (1998). Geoexchange at a hotel with an innovative ground loop. *Second Stockton International Geothermal Conference*, pp: 120-128.
- [10] Pahud, D., Fromentin, A., and Hubbich, M. (1999). Heat exchanger pile system for heating and cooling at Zurich Airport. *IEA Heat Pump Centre Newsletter* , 17(1), 15-16.
- [11] Eskilson, P. (1987). Thermal Analysis of Heat Extraction Boreholes. Technical report, University of Lund, Lund, Sweden.
- [12] Hellstrom, G. (1991). Thermal Analysis of Duct Storage Systems: Part 1 Theory. Technical report, University of Lund, Lund, Sweden.
- [13] Thornton, J., McDowell, T., Shonder, J., Hughes, P., Pahud, D., and Hellstrom, G. (1997). Residential Vertical Geothermal Heat Pump System Models: Calibration to Data. *ASHRAE Transactions* , 103 (2).
- [14] Muraya, N., O'Neal, D., and Heffington, D. (1996). Thermal interference of adjacent legs in a vertical U-tube heat exchanger for a ground-coupled heat pump. *ASHRAE Transactions* , 102 (2).
- [15] Rottmayer, S., Beckman, W., and Mitchell, J. (1997). Simulation of a Single Vertical U-Tube Ground Heat Exchanger in an Infinite Medium. *ASHRAE Transactions*, 103 (2).

- [16] Shonder, J., & Beck, J. (1999). Determining Effective Soil Formation Thermal Properties from Field Data Using Parameter Estimation Technique. ASHRAE Transactions , 105 (1).
- [17] Abdelaziz, S.L., Olgun, C.G., and Martin, J.R., II (2011). "Design and Operation Considerations of Geothermal Energy Foundations." GeoFrontiers 2011. Dallas, TX. ASCE, pp. 450-459.
- [18] Rouissi, K., Krarti, M., and McCartney, J.S. (2012). "Analysis of Thermo-Active Foundation using U-Tube Heat Exchangers." ASME Solar Energy Engineering journal, 134(2).
- [19] Holman J.P., (1986), Heat Transfer, Sixth Edition, McGraw-Hill Book Company, New York, NY.
- [20] Patankar, S. (1980). Numerical Heat Transfer and Fluid Flow. Hemisphere, New York, NY.
- [21] Kaltreider, C., (2011), Numerical Modeling of Heat Transfer in Thermo-Active Foundations, MS Thesis Report, University of Colorado, Boulder, CO.
- [22] Rosenberg, J. (2010). Centrifuge Modeling of Soil Structure Interaction in Thermo-Active Foundations. MS Thesis report, University of Colorado, Boulder, CO.
- [23] ASHRAE, (2013). American Society of Heating, Refrigerating, and Air-Conditioning Engineers, inc. Fundamentals, Atlanta, GA.
- [24] Cengel, Y., Turner, H., & Cimbala, J., (2008). *Fundamentals of Thermal-Fluid Sciences*. McGraw-Hill, New York, NY.
- [25] Krarti, M. (2010). Energy Audit of Building Systems: An Engineering Approach, Second Edition, CRC Press, Boca Raton, FL.

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Table 1: Boundary conditions of Equations (1) and (2)

Boundary	Boundary condition	Equation
At the bottom of the domain	Imposed temperature	$T = T_{\text{bottom}}$
On the two sides	Adiabatic	$\frac{\partial T}{\partial x} = 0$
Foundation/soil interface	Continuity of conduction heat flux	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial x}$
Fluid/tube wall	Continuity of convection heat flux	$h_{\text{fluid}}(T_{\text{fluid}} - T_{\text{wall}}) = -h_{\text{wall}}(T_{\text{wall}} - T_{\text{soil}})$
At the ground surface	Convection w/ fixed air temperature	$h_{\text{air}}(T_{\text{air}} - T_{\text{surface}}) = -k_{\text{soil}} \frac{\partial T}{\partial x}$
Inlet tube	Imposed temperature	$T = T_{\text{inlet}}$
Outlet tube	Adiabatic (flow is out of domain, $x > 10$)	$\frac{\partial T}{\partial x} = 0$

Table 2: Sensitivity Analysis of the Impact of Grid Size on Model Prediction Accuracy and CPU Time

Grid	1 (finest)	2	3	4	5	6
Number of Nodes	1160627	842952	167897	83657	45762	16836
NRMSE	0.00%	0.01%	0.52%	1.33%	2.75%	6.53%
% CPU time	100.0%	35.1%	5.3%	1.4%	0.4%	0.1%

Table 3: Model Parameters Used for Simulation of Physical Experiment

Parameter	Value	Units	Source/Reference
Thermal Conductivity of Soil	1.43	W/m-K	Experimental Measurement [22]
Specific Heat of Soil	1480	J/kg-K	Assumed based on Soil Type
Density of Soil	1765	kg/m ³	Experimental Measurement [22]
Thermal Conductivity of Concrete	1.00	W/m-K	Experimental Measurement [22]
Specific Heat of Concrete	900	J/kg-K	ASHRAE Fundamentals [23]
Density of Concrete	2080	kg/m ³	ASHRAE Fundamentals [23]
Thermal Conductivity of Silicon Fluid	22	W/m-K	Manufacturer Specifications [21]
Specific Heat of Silicon Fluid	1370	J/kg-K	Manufacturer Specifications [21]
Density of Silicon Fluid	920	kg/m ³	Manufacturer Specifications [21]
Kinematic Viscosity of Fluid	0.00002	m ² /s	Fluid Supplier (J.D. Instruments) [21]
Fluid Velocity	11.05	m/s	Experimental Average [22]
Thermal Conductivity of Aluminum Tube	237	W/m-K	Cengel et al. [24]
Tube Wall Thickness	0.0016	m	Experimental Measurement [22]
Tube Diameter	0.0048	m	Experimental Measurement [22]
Exterior Air Convection Coefficient	71.03	W/m ² -K	Calculated based on Specifications of the Experiment [21]

Table 4: Calibration Adjustments Made to the numerical Model

Adjusted Parameter	Base Model Value	Calibrated Model Value
Thermal Soil Conductivity	1.43 W/m-K	1.80 W/m-K
Thermal Concrete Conductivity	1.00 W/m-K	1.50 W/m-K
Initial Soil Temperature	15 °C	16 °C

Table 5: Comparison of Validation Results for Various Time Periods

RMSE (°C)				
Time	30 Min	60 Min	90 Min	120 Min
3D Base Model	1.16	1.38	1.55	1.54
3D Calibrated Model	0.24	0.12	0.35	0.42

Table 6: Full Scale Thermo-active Foundation Model Parameters

Base Model Parameters	
Domain Width	19 m
Domain Height	24 m
Pier Width	1 m
Pier Depth	10 m
Outside Temperature	27 °C
Inside Temperature	22 °C
Deep Ground Temperature	11 °C
Domain Side Boundary Conditions	Adiabatic
Ground Thermal Conductivity	1.43 W/m-K
Concrete Thermal Conductivity	1.76 W/m-K
Outside Convection Heat Transfer Coefficient	22.7 W/m ² -K
Inside Horizontal Convection Heat Transfer Coefficient (Downward Heat Flow)	6.13 W/m ² -K
Inside Horizontal Convection Heat Transfer Coefficient (Upward Heat Flow)	9.26 W/m ² -K
Inside Vertical Convection Heat Transfer Coefficient	8.29 W/m ² -K

Table 7: Parameters Used for Evaluating Building Thermal Interactions

Model Parameters	Cooling Mode	Heating Mode
Outside Temperature	27 °C	0 °C
Inside Temperature	22 °C	22 °C
Inlet Heat Pump Loop Temperature	37 °C	7 °C
Deep Ground Temperature	18 °C	18 °C

Table 8: Effect of a Thermo-active Foundation on Building Heat Loss and Gain during Heating and Cooling Modes

Effect of a Thermo-active Foundation on Slab Heat Loss/Gain	
Mode	Annual Percentage of Hours
Heating Mode, Increased Slab Loss	57%
Heating Mode, Decreased Slab Loss	3%
Cooling Mode, Increased Slab Loss	8%
Cooling Mode, Decreased Slab Loss or Increased Slab Gain	32%

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