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Numerical Simulation of Seasonal Performance of Energy Pile

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ABSTRACT

This paper presents a numerical case study on seasonal thermal performance of PHC energy piles including W and 3U heat exchangers. In order to estimate thermal resistances of the energy piles, three dimensional finite element analyses of virtual thermal response tests were conducted adopting an efficient numerical scheme for forced convective heat transfer between circulating fluid and surrounding grout. By implementing the calculated thermal resistance values to a well-known design program, 2-year fluid temperature histories for energy piles were evaluated for an arbitrary base load profile balanced for heating and cooling. The fluid temperature histories were prescribed in the numerical simulations of two-year thermal performance of the energy piles, and larger heating thermal energy gains were predicted than the thermal loads considered in design stage as a result of seasonal thermal energy storage.

1. INTRODUCTION

Ground-coupled heat pump (GCHP) system is one of the most efficient and eco-friendly heating and cooling method of buildings (Stuart et al., 2012). It directly extracts geothermal energy from ground by circulating fluid in the closed-loop pipe heat exchangers. The heat exchangers are buried horizontally in the ground or vertically within a borehole filled with grout, and in usual, the latter case is preferred due to its larger heat exchange capacity and smaller land occupancy (Yang et al., 2010). In recent decades, GCHPs have been associated with foundation piles for efficient gaining of geothermal energy by saving grout borehole construction cost (Brandl, 2006).

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The vertical GCHP system generally requires several years of operation to withdraw high initial investment, and hence, it is essential to assess its long-term thermal performance for reliable evaluation of minimum withdrawal operation period. Accordingly, a lot of computer programs have been developed for design of vertical GCHPs (Hellstrom and Sanner, 2001; Spitler, 2000; Fisher, 2006; Kavanaugh and Rafferty, 1997). After determining a required thermal load, the programs mostly employ two distinct calculation processes to estimate thermal performance of GCHP: (1) conductive heat transfer in ground for the given heat injection/rejection from borehole surface with consideration of thermal interference among the vertical GHEs, (2) estimation of mean fluid temperature in each GHE based on ‘equivalent’ thermal resistance of grout borehole and mean borehole surface temperature predicted from (1). Based on the estimated mean temperature history from (2), fluid temperature input to vertical GHEs can be determined for the required entering water temperature of heat pump.

However, actual performance of GCHP can be different from the designed performance. First, the predetermined heat injection/rejection across borehole surface in the design process may not be realistic. Because actual heat exchange is induced by temperature difference and forced convective heat transfer between fluid and grout, amount of heat injection/rejection is governed by temperature of surrounding ground, which may significantly vary through seasonal operation. In this regard, the effect of seasonal thermal energy storage on design of GCHP’s energy efficiency may be significant in countries having very distinct seasons such as Korea. Second, because the conventional vertical GHEs have very small radius near 0.06 m and a few hours of time criterion necessary for the reach steady-state, most of design programs estimate thermal resistance of borehole based on assumptions of steady heat flow within cross section of boreholes and negligible effect of grout’s thermal capacity on heat flow (Bose et al., 1985; Hellstrom, 1991; Zeng et al., 2003; Lamarche et al., 2010). However, the assumption may not be valid for the GHEs with larger diameter such as energy piles due to longer time criterion to steady state. Even though some researchers (Yavuzturk et al., 2000; Li and Lai, 2012) have proposed numerical and analytical solutions for the estimation of short-term thermal resistance of borehole, few applications of them to actual works have been reported. Besides, heterogeneous thermal properties in the borehole can be problematic in the estimation of thermal resistance because conventional methods assume unique thermal property within a borehole. For instance, precast high-strength concrete (PHC) pile is used for energy pile construction in Korea, and in such a case, filling grout and PHC pile have different thermal properties.

This paper presents a numerical case study on seasonal thermal performance of PHC energy piles including W and 3U heat exchangers. Three dimensional finite element analyses of virtual thermal response tests were conducted to estimate thermal resistances of the PHC energy piles by adopting an efficient numerical scheme for forced convective heat transfer between circulating fluid and surrounding grout. By implementing the calculated thermal resistance values to a well-known design program, 2-year fluid temperature histories for energy piles were evaluated for an arbitrary base load profile balanced for heating and cooling. The fluid temperature histories were prescribed in the numerical simulations of two-year thermal performance of the energy piles, and the predicted thermal energy gains and ground temperature variations were discussed.

2. NUMERICAL EVALUATION OF ENERGY PILE'S THERMAL RESISTANCE

2.1 Specification of energy pile and ground

Fig. 1 depicts the PHC energy piles considered in this study, where PHC piles having 240 mm of inner diameter, 400 mm of outer diameter, and 10 m vertical length are filled with grout. As shown in Fig. 1, the 3U and W-shaped heat exchange pipes (in series) are symmetrically installed in contact with PHC piles, of which inner and outer diameters are 16 mm and 20 mm, respectively. The energy piles were assumed to be installed in a homogeneous ground of which undisturbed temperature is 8 °C. Table 1 summarizes thermal properties considered in the simulation.

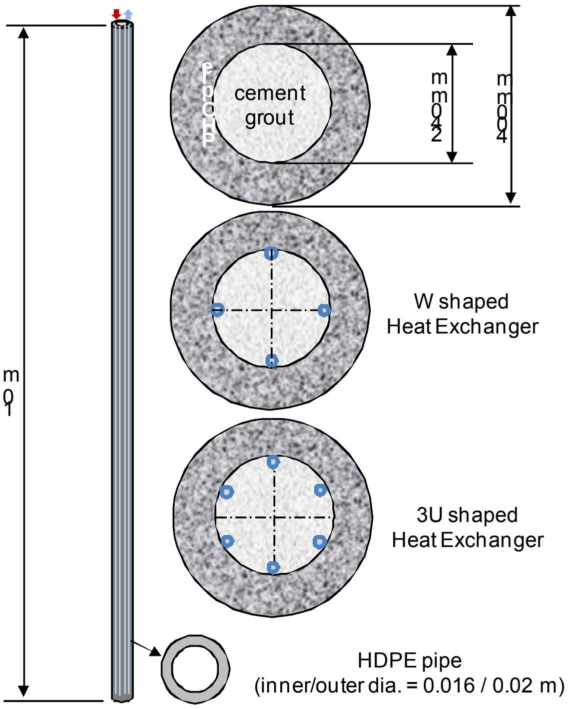


Fig. 1 Dimensions of PHC energy piles

Table 1 Thermal property of grout, PHC pile, ground, and fluid

Material	Thermal Conductivity ($Wm^{-1}K^{-1}$)	Specific Heat Capacity ($Jkg^{-1}K^{-1}$)	Density (kgm^{-3})
Soil (layer 1)	3.50	1028	2100
Grout	2.02	840	3640
PHC	1.62	790	2700
HDPE pipe	0.38	525	955
Fluid	0.57	4200	1000

2.2 Simulation of thermal response test

For determination of thermal resistance of the energy pile, estimation of mean fluid temperature and mean temperature at pile-soil interface under constant heat flow condition are essential. Hence, in this study, virtual simulation of 72-hour thermal response tests (TRTs) were performed for the energy piles shown in Fig. 1 using conductive heat transfer analysis method implemented in a commercial finite element analysis package ABAQUS/Standard (ABAQUS Inc., 2004). Two numerical schemes were considered to model heat transfer around pipe: constant heat flow from the pipe (scheme 1) and forced convection between fluid and grout (scheme 2).

Fig. 2 shows the finite elements developed for the TRT simulations, where the pipes were modeled as a group of nodes and elements near the nodes were finely discretized. In the modeling scheme 1, constant heat injection per each node was prescribed. In order to model scheme 2, numerical method proposed by Choi et al. (2011) was adopted, which imposes nodal convective heat transfer boundary conditions (Eq. 1) to the pipe nodes considering equivalent heat transfer coefficient between fluid-pipe-grout (Eq. 2) and quasi-steady-state heat transfer of circulating fluid (Eq. 3)

$$q\Big|_{\Gamma_p} = -\lambda \frac{\partial \theta}{\partial n} = h_{eq}\left(\theta_g - \theta_f\right) \tag{1}$$

$$h_{eq} = \left[\frac{D_{out}}{2\lambda_{pipe}} \ln\left(\frac{D_{out}}{D_{in}}\right) + \frac{D_{out}}{D_{in} h}\right]^{-1} \tag{2}$$

$$\theta_{f,i} = \begin{cases} \theta_{f,i-1} - \dfrac{q_i + q_{i-1}}{2} \dfrac{\pi D_{out} dL}{\dot{m} c_f} & \text{(for cooling)} \\ \theta_{f,i-1} + \dfrac{q_i + q_{i-1}}{2} \dfrac{\pi D_{out} dL}{\dot{m} c_f} & \text{(for heating)} \end{cases} \tag{3}$$

where Γ_p is the boundary domain for the outer wall of pipe, n is the unit vector normal to the pipe axis, θ_g is the temperature of the grout on the boundary, θ_f is the temperature of the circulating fluid, h_{eq} is the equivalent convective heat transfer coefficient, D_{out} is the outer diameter of the pipe, D_{in} is the inner diameter of the pipe, λ_{pipe} is the thermal conductivity of the pipe, h is the convective heat transfer coefficient of the circulating heat fluid in the pipe that can be estimated from the Dittus-Boelter correlation, q_i is the heat flux amplitude of the grout at node i, $\dot{m}$ is the mass flow rate of the circulating fluid, dL is the distance between the two neighboring nodes in the flow direction, and c_f is the specific heat capacity of the circulating fluid.

1,000 W of total heat injection was considered in the TRT simulations, and consequently, 4.065 W and 6.0975 W of nodal heat flow was imposed for scheme 1. On the other hand, for circulating velocity of fluid as 0.59 m/s, inlet fluid temperatures shown in Fig. 3a were prescribed in the simulations adopting the scheme 2, and about 1,000 W of total injections after 1,000 minutes were predicted as plotted in Fig. 3b.

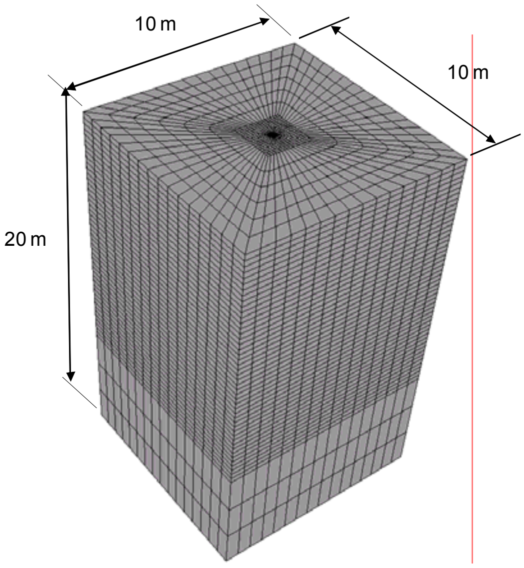
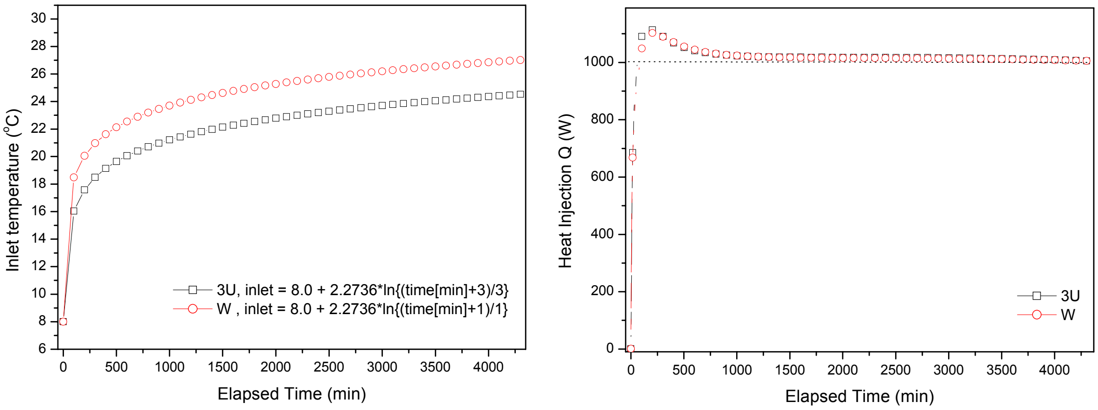


Fig. 2 Finite element models for simulation of TRTs



(a) Inlet temperature (b) Predicted heat injection

Fig. 3 Results of TRT simulations based on numerical scheme 2

2.2 Simulation of thermal response test

Thermal resistance of energy pile R_{EP} can be determined as $R_{EP} = (\theta_{f,m} - \theta_{PHC,m}) / q_l$, where $\theta_{f,m}$ is the mean fluid temperature (K), $\theta_{PHC,m}$ is the mean temperature at PHC outer surface (K), and q_l is the mean radial heat exchange rate at PHC outer surface (W/m). Table 2 represents the numerically estimated R_{EP}s at 72 hours, where slight discrepancies are found between the R_{EP}s obtained from scheme 1 and scheme 2. However, numerically calculated R_{EP}s were found to be much smaller than R_{EP} values obtained from the conventional series model (Bose et al., 1985). On the other hand, the R_{EP}s estimated by the multi-pole method (Hellstrom, 1991) appear to be nearly close to the numerical predictions.

Table 2 Comparisons of thermal resistance of the energy piles (unit: mKW^{-1})

Case	FEA (scheme 1)$^{+}$	FEA (scheme 2)	Series Model	Multi-pole method^{++}
3U	0.0823	0.0881	0.2291	0.0934 / 0.1070
W	0.1041	0.1142	0.2472	0.0936 / 0.1101

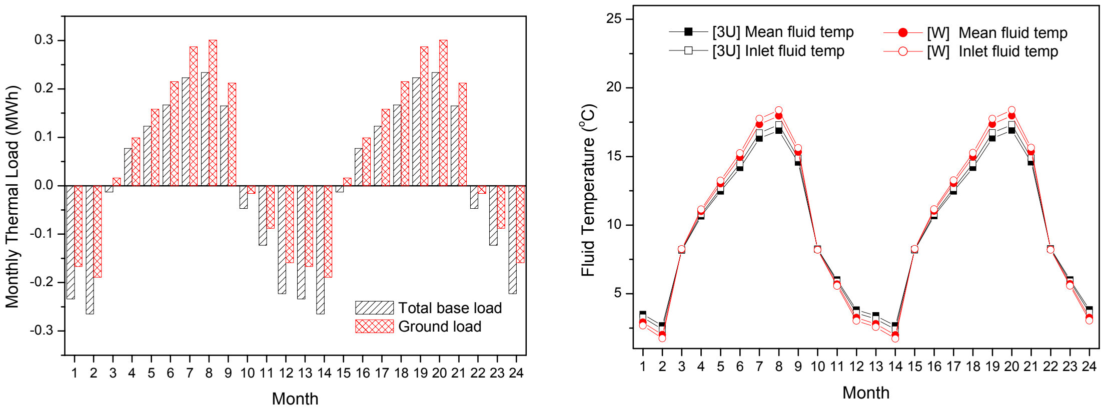
$^{+}$ $\theta_{f,m}$ was calculated by $\theta_{f,m}$ = q_{node}/h_{eq} + $\theta_{g,node}$, where q_{node} is the prescribed heat injection, h_{eq} is equivalent heat transfer coefficient in Eq. (1), and $\theta_{g,node}$ is the grout temperature where heat injection was prescribed.
$^{++}$ The same thermal conductivities of grout and PHC pile were assumed (2.02 Wm^{-1}K^{-1} / 1.62 Wm^{-1}K^{-1}), respectively

3. SIMULATION OF 2-YEAR PERFORMANCE OF ENERGY PILES

3.1 Base load and determination of fluid temperature histories

Before conducting 2-year performance simulation based on FE analysis with scheme 2, it needs to determine fluid temperature histories for a given thermal load. In this study, EED 3.16 (Blocon, 2010) was employed. The software employs multi-pole method for calculation of borehole thermal resistance and a combination of the numerical finite difference method and a finite line source solution for conduction analysis considering borehole thermal interference.

Fig. 4a shows the balanced cooling and heating base load profile and actual ground thermal load considered in the analysis by EED corresponding to seasonal performance factor 3.5. The actual ground load is higher and smaller in cooling and heating seasons than the balanced load due to the performance factor, and consequently, unbalanced cooling load of 0.669 MWh is annually added to ground through energy piles. Thermal resistances of energy piles obtained from the numerical simulation with scheme 2 were applied in fluid temperature estimation, and the resultant mean fluid temperatures are depicted in Fig. 4b. From the ground thermal load profile, difference of fluid temperature between inlet and outlet $\Delta\theta_f$ was estimated by $\Delta\theta_f = Q/\dot{m}c_f$, where Q is the heat injection or rejection (W), $\dot{m}$ is the mass flow rate (kg/s), and c_f is the specific heat capacity of circulating fluid. The inlet temperature histories are also plotted in Fig. 4b.



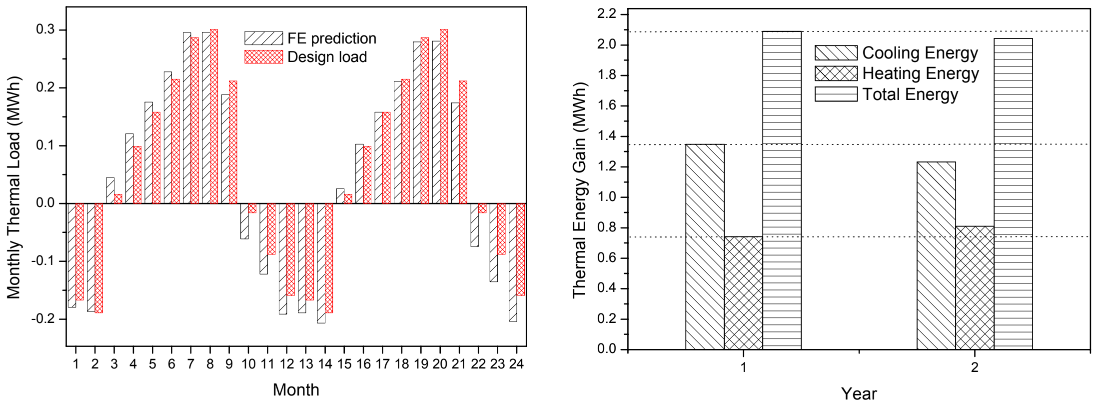
(a) Monthly total and ground base load (b) Monthly fluid histories

Fig. 4 Monthly ground load and fluid temperature histories estimated by EED program

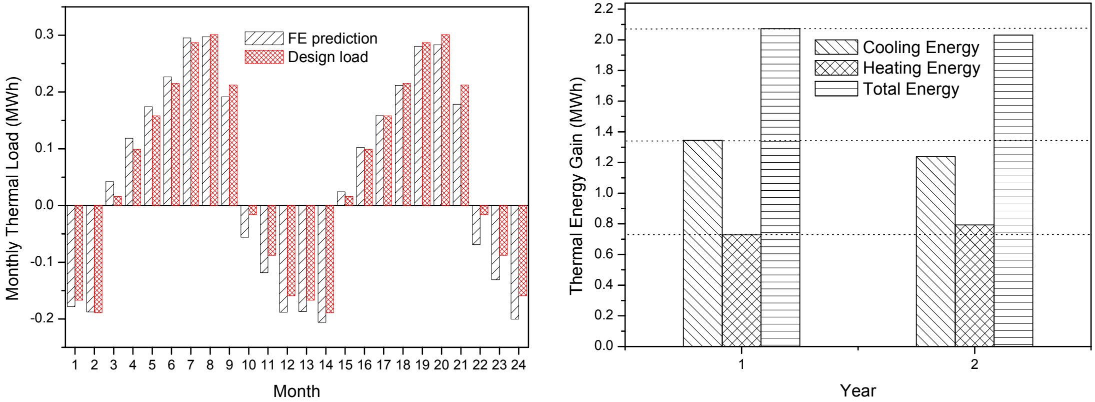
3.2 Simulation results and discussion

By prescribing the inlet temperature histories shown in Fig. 4b, performance of a single energy pile including 3U or W heat exchanger for 2-year continuous operation was simulated. Fig. 5 shows the predicted monthly and annual thermal energy gains, where negligible difference is found in thermal energy predictions between the analyses with 3U and W heat exchangers. Compared to the ground thermal load considered in EED analysis, larger thermal energy gains were predicted from the numerical simulations, which are mainly caused by 23% higher heating energy than the design load. In cooling period, only 0.3 % increase of thermal energy gain was predicted.

The simulation results in Fig. 5b and Fig. 5d indicate slight annual decrease of thermal energy gain from the energy pile, of which magnitude was about 2 % of 1st year’s total thermal energy (≈ 0.04 MWh). In detail, considerable annual variations of cooling and heating energy are found: 7.9 % decrease and 8.9 % increase of cooling and heating energy in the 2nd year, respectively. As a consequence, the unbalanced cooling thermal load reduced from 0.6 MWh (1st year) to 0.4 MWh (2nd year).



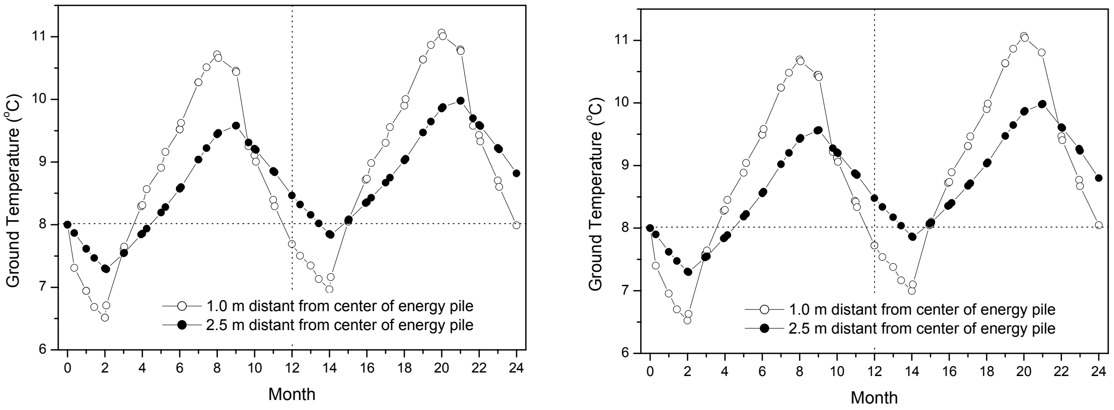
(a) Monthly thermal energy gains (3U) (b) Annual variation of thermal energy gain (3U)



(c) Monthly thermal energy gains (W) (d) Annual variation of thermal energy gain (W)

Fig. 5 Numerically predicted thermal energy gains

On the other hand, the thermal energy obtained during initial 2-month heating operation seems to be nearly identical to the design load. However, heating energy subsequent to cooling period was predicted to be much larger than the design load, and more heating energy gains were predicted in the second year even though cooling energy decreased. In the same context, Fig. 6 shows the ground temperature variation during operation, where ground temperature annually increases in common. Temperature at ground 1 m distant from the energy pile exhibits negligible temperature variation after 2-year operation, while larger temperature rise was predicted at ground 2.5 m distant from the energy pile. These results may imply positive effect of seasonal thermal storage on energy pile's thermal efficiency in heating period. In other words, the ground temperature increase during cooling operation provided beneficial condition for gaining heating energy, and it may lead to reduction of unbalance thermal load, which can considerably lower the thermal efficiency.



(a) 3U heat exchanger (b) W heat exchanger

Fig. 6 Predicted ground temperature variation

4. SUMMARY AND CONCLUSIONS

From the numerical simulations and discussion on the results, following conclusions can be deduced.

(1) Based on three dimensional FE analyses, thermal resistance of PHC energy piles including 3U and W heat exchangers were estimated. The estimated values were compared with solutions of series model and multi-pole methods, and close agreements were found between numerical estimations and multi-pole methods' evaluations.

(2) For an arbitrary base load, fluid temperature histories were determined by EED program by implementing numerically estimated PHC energy piles' thermal resistances. They were applied to the simulation of 2-year continuous operation of GCHP with a single energy pile.

(3) The 2-year simulation results for 3U and W heat exchangers indicated negligible difference of thermal efficiency. It can be inferred that, for base load, increasing pipe length has minor influence on heat injection/rejection capacity.

(4) For seasonally varying thermal load, positive effect of seasonal thermal storage on energy pile's thermal efficiency in heating period was numerically identified. The ground temperature increase during cooling operation is thought to provide beneficial condition for gaining heating energy. In addition, seasonal operation was predicted to reduce unbalance between heating and cooling load, which can considerably lower the thermal efficiency.

ACKNOWLEDGEMENT

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