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Modeling and simulation of a reclaimed water source heat pump system based on TRANSYS[1]

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Abstract. For the purpose of demonstration in energy saving and environmental protection, a reclaimed water source heat pump (RWHP) system for heating life hot-water was built in university campus in Beijing. This paper presents the effects of operation properties of the RWHP system. A dynamic simulation model was developed based on TRANSYS. The simulation model was validated with the experimental values and later used to predict the operation behavior of the RWHP system and the gas-boiler hot water system in different seasons. The results show that the RWHP system has better energy saving effect than the gas-boiler heating water system, annual operation cost saving 45.7 %. Additionally, the energy saving operation mode for RWHP is given by simulation.

Key words. Reclaimed water source heat pump (RWHP), TRANSYS simulation, measured values, energy savings.

1. Introduction

Due to concern on climate change and energy resource depletion, the utilization of renewable energy for heating attracted increasing attention in the energy system design of heating system. Reclaimed water, which contains a large number of energy that can be used by heat pumps, has the characteristics of stable temperature and quality. When the low quality energy from the reclaimed water is used in heating and domestic hot water, traditional fossil fuel will be saved. The RWHP has significant energy-saving and environmental benefits [1–4]. In order to promote the heat pump technology in application for larger scale, a RWHP system project was built as demonstration project in university campus in Beijing, China. In this paper, the TRANSYS simulation model is used to simulate the domestic hot water system of the RWHP. Three energy parameters of the system (heating capacity, electric power consumption and COP) are used to analyze the energy-saving characteristics of the

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RWHP hot water system. The Simulation results of RWHP system and gas-boiler for hot water system are analyzed, with a view to provide a reference for the actual project.

2. Introduction of the RWHP hot water system

The demonstration project of RWHP water heating system which replaced gas-boiler system provides bath hot water (50 °C, 170 m^3/day) for students' bathrooms and school hotel. It consists of three parts: reclaimed water recycling system, hot water circulation system and user system, as shown in Fig. 1 and Table 1.

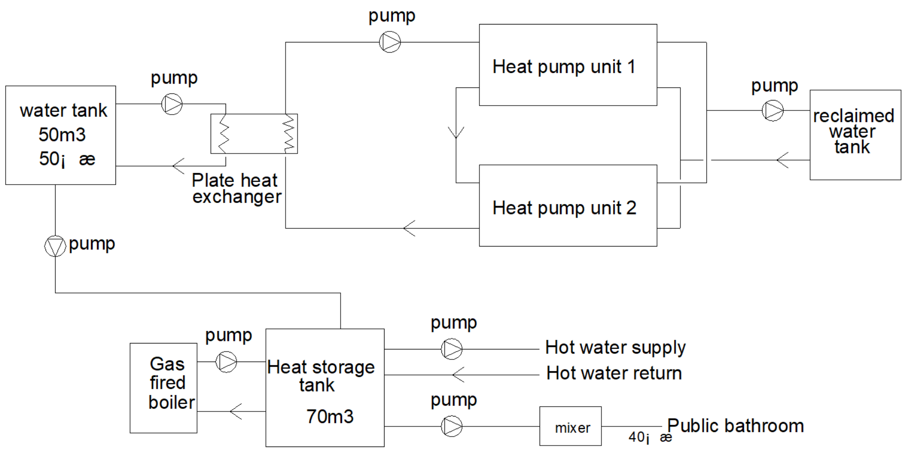

Fig. 1. RWHP water heating system's diagram

Table 1. RWHP system equipment's parameters

Equipments	Specification
Heat pump unit 1	Screw compressor, heating capacity: 450 kW
Heat pump unit 2	Scroll compressor, heating capacity: 600 kW
Internal circulation pump	Flow rate: 60 m^3/h, head: 20 m H_2O, power: 11 kW
Hot water circulation pump	Flow rate: 86 m^3/h, head: 20 m H_2O, power: 11 kW
Reclaimed-water circulation pump	Flow rate: 75 m^3/h, head: 15 m H_2O, power: 11 kW
Plate heat exchanger	Heat transfer area: 38 m^2, pressure: 1.6 MPa
Heat storage tank	Total volume: 120 m^3

The reclaimed water circulation system is mainly composed of reclaimed water tank (600 m^3), reclaimed water circulation pump, heat pump unit etc. The reclaimed water enters the heat pump unit 1 and then the heat pump unit 2 in series, the energy is used by the two heat pump units, and then water flows back to the tank for next circulation.

Hot water circulation system consists of heating water tank ($50\,\mathrm{m}^3$), internal circulation pump, brazed plate heat exchanger, and hot water pump. To ensure the stable amount of circulating water into the heat pump unit, the brazed plate heat exchanger was adopted in the internal circulating water for the heat pumps. Terminal hot water mainly supply to student bathrooms and campus hotel. Campus hotel need hot water for 24 hours, hence, the minimum hot water temperature should be kept above $45\,^{\circ}\mathrm{C}$ in the hot water tank. During the operation of the RWHP, the original gas boiler is sited as backup heat source to ensure hot water system supply reliably when the RWHP is in maintenance, or the temperature of the reclaimed water is too low.

3. Description of main simulation modules

TRANSYS is modular of dynamic simulation software. The system is composed of several small systems (i.e. modules), each module can achieve a particular function. Therefore, in the system simulation analysis, all we need to do is to call these modules and give the input conditions. When these modules is needed in other part, they can be used by giving input condition to the modules rather than compiling program separately to achieve these functions [5].

3.1. Water - water source heat pump unit module (Type 668)

The module simulates a single-stage water-water heat pump. The simulation process of the module relies on user-defined data files, the file consists of the heating (cooling) capacity and electric power of the heat pump that corresponding to the different temperature of the inlet water on the load side and heat source side. In the simulation, the module outputs the parameters such as the heating capacity, power and COP of the heat pump under the different conditions according to the inlet water temperature of the load side and the heat source side according to the interpolation calculation principle [6–7].

In the heat pump unit, the heating capacity of the condenser can be calculated using the formula

$$Q_{\mathrm{cond}} = \dot{m}_{\mathrm{ref}} \cdot \left(h_{\mathrm{cond-out}} - h_{\mathrm{cond-in}}\right) \,, \tag{1}$$

where $\dot{m}_{\mathrm{ref}}$ is the mass flow rate of refrigerant, while $h_{\mathrm{cond-out}}$ and $h_{\mathrm{cond-in}}$ are the refrigerant specific enthalpies at the inlet and outlet of the condenser.

The energy consumption of total system is the total energy consumed by the compressor and the water pumps during the period, it can be calculated using the formula

$$P_{\mathrm{sys}} = \sum \left(P_{\mathrm{comp}} + P_{\mathrm{pump}}\right) \,, \tag{2}$$

where P_{comp} is the energy consumed by the heat pumps and P_{pump} is the energy consumed by the pumps.

Heating coefficient $\mathrm{COP}_{\mathrm{hp}}$ of the heat pump can be calculated by the formula

$$COP_{\mathrm{hp}} = \frac{Q_{\mathrm{total}}}{P_{\mathrm{comp}}}\,, \tag{3}$$

where

$$Q_{\mathrm{total}} = \varepsilon C_{\min}(T_{\mathrm{hot-in}} - T_{\mathrm{cold-in}})\,. \tag{4}$$

Here, Q_{total} is the total heat transferred from heat exchanger, ε is the efficiency of the heat exchanger ,$C_{\min}$ is the fluid heat capacity of cold side, $T_{\mathrm{hot-in}}$ is the inlet water temperature of heat exchanger's hot side, and $T_{\mathrm{cold-in}}$ is the inlet water temperature of heat exchanger's cold side.

3.2. Plate heat exchanger module (Type 5b)

The module is based on the minimum heat capacity of the heat exchanger. User can input the total heat transfer coefficient of the heat exchanger, the inlet conditions of the heat source side and the cold source side. The module determines the minimum heat capacity side as the cold side or the hot side according to the input condition, and then calculates the total heat transfer efficiency and the outlet parameter of the heat exchanger.

3.3. Water pump module (Type 114)

The prototype of the module is a single-stage constant-speed pump with constant outlet flow. The outlet flow rate of the pump depends on the value entered in the parameter setting of the module, the start and stop of the pump is based on the control signal that controls the start and stop of the pump. If the signal value is less than 0.5, then the pump is off, the signal value is greater than or equal to 0.5, then the pump is turned on. As the pump is turned on, the parameters of the pump will reach the set value in one step.

Figure 2 shows the main components of the simulation system, the connection between the components and the data needed to integrate and output. The simulation system can not only output the relevant parameters of the heat pump unit, but also can integrate and calculate the output data of each part, and output the performance coefficient of the whole water-source heat pump system.

4. Simulation analyses of RWHP and gas-boiler system

4.1. Verification of simulation model for heat pump unit

The basic running data is inputted into the TRANSYS simulation model, and the simulation results of the heating capacity, power consumption and COP of the heat pump unit is outputted. Taking into account the heat transfer between the brazed

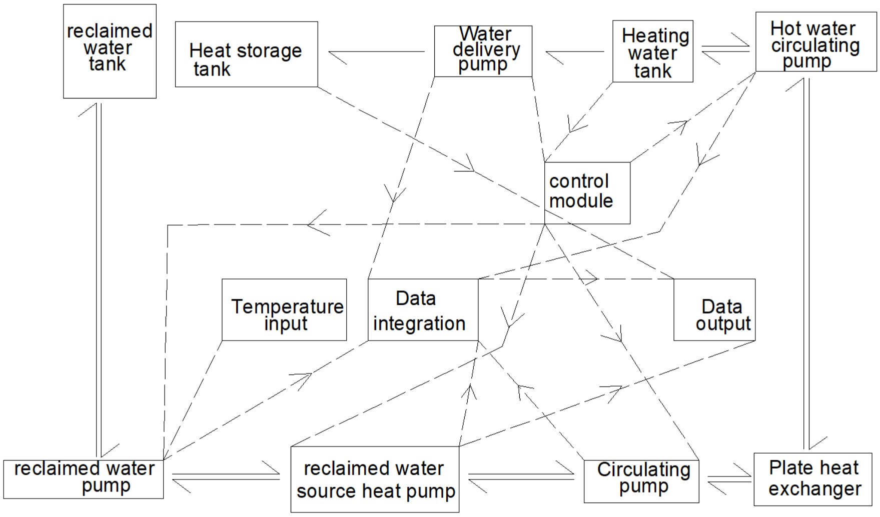

Fig. 2. Simulation module

plate heat exchanger and the environment, the temperature of the hot water on the hot side of the plate heat exchanger was modified by the factor of 0.95. According to the system operation test data, the heating capacity, power consumption and COP of the heat pump unit was calculated and compared with the simulated value.

Figures 3, 4 and 5 depict the heating capacity, power consumption and COP of the heat pumps, respectively. The deviation between simulation values and measured values of heating capacity, power consumption and COP is less than 10 %, which shows that the simulation model is accurate and reliable. So it can be used to simulate the operational characteristics of each season and provide reference for practical project.

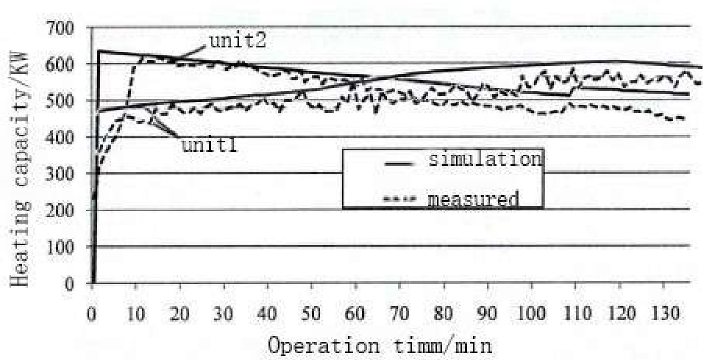

Fig. 3. Comparison of simulation value and measured value of heating capacity of the heat pump (unit 1, unit 2)

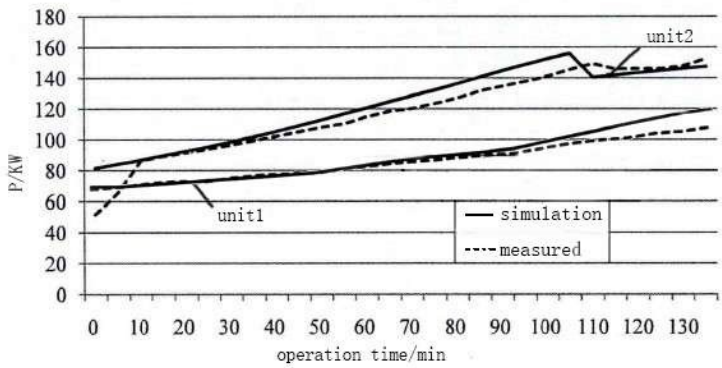

Fig. 4. Comparison of simulation value and measured value of power consumption of the heat pump (unit 1, unit 2)

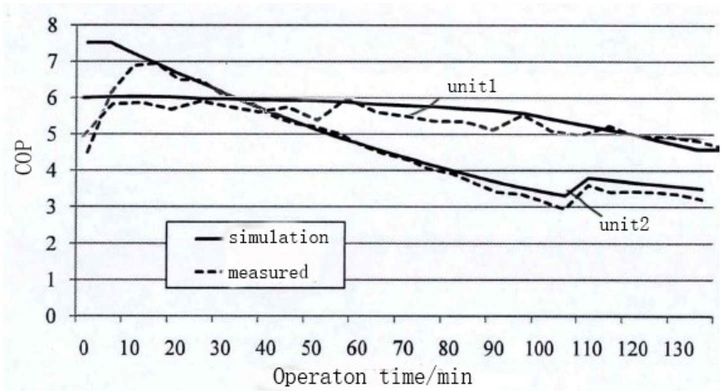

Fig. 5. Comparison of simulation value and measured value of COP of heat pump (unit 1, unit 2)

4.2. Simulation analysis of heat pump system operation in different seasons

Both the reclaimed water temperature and the tap water temperature change with the seasons, which results in different operating modes of the heat pump system in different seasons. Using the simulation model to simulate the operation characteristics of RWHP heating water system in winter, analyze the operation characteristics and energy-saving properties of RWHP and provide guidance for energy-saving operation.

4.2.1. Simulation and operation analysis of heat pump system in winter During the winter, the system operates in two periods: 0:00∼5:00 and 13:00∼21:00 running 13.5 hours per day. Through the operation optimization analysis, the energy saving operating mode is developed, as shown in Table 2.

Table 2. Operation mode of the heat pump system

Time	Operation status
$0 \sim 2:50$	Heating the low-temperature water in water tank and transporting hot water
$2:50 \sim 3:40$, $13:50 \sim 16:40$, $16:40 \sim 19:50$, $19:40 \sim 20:30$	Adding water to the water tank and heating the low-temperature water
$5:00 \sim 13:00$	The system stops operation
$13:00 \sim 13:50$, $16:00 \sim 16:40$, $19:00 \sim 19:40$	Transporting constant temperature hot water

As can be seen from the Fig. 6, the COP of unit 1, unit 2 and the system changed in a larger range due to the system operating mode conversion, in some cases even less than 3.0. During the adding water phase, both the heat pump system and the heat pump unit have high COP because the lower temperature of the hot water will result in high COP. The average COP of the heat pump unit 1, unit 2 and heat pump system is 4.8, 4.5 and 3.6, respectively, as shown in Table 3.

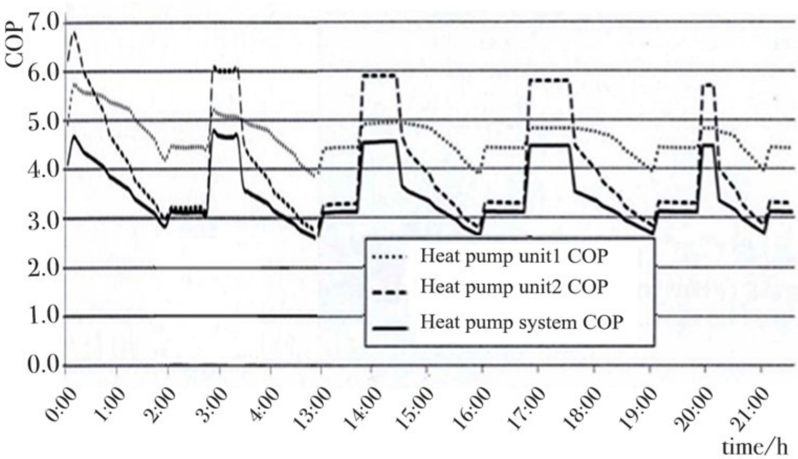

Fig. 6. COP variation of heat pump units and the heat pump system

Table 3. Average COP of the heat pump system and heat pump units in winter

Statistical term	COP
Average COP of the heat pump unit 1	4.8
Average COP of the heat pump unit 2	4.5
Average COP of the heat pump system	3.6

The simulation results showed that the operation energy efficiency of the RWHP system reached the national standards (COP>4.5), so the RWHP should be applied in larger scale in the situation that the energy contains in the reclaimed water matches the heating demand.

4.2.2. Simulation analysis of heat pump system operation in summer and transition seasons The average water temperature in the summer and transition seasons is higher than in winter, so the coefficient of performance of the RWHP will be improved. The operation strategy of heat pump system in summer and transitional seasons are similar to winter, so the simulation process is no longer presented in details here. Simulation results of the system COP is showed in Table 4.

Table 4. Average COP of the heat pump system and heat pump units in summer and transition seasons

Statistical term	In summer	In transition seasons
Average COP of the heat pump unit 1	5.9	5.5
Average COP of the heat pump unit 2	4.7	4.6
Average COP of the heat pump system	4.2	4.0

4.3. Simulation analysis of gas-boiler hot water system

The main energy consumption of gas-boiler hot water system is natural gas consumption and power consumption of the hot water circulating pump. Gas-boiler hot water system simulation model is established in the TRNSYS system, as shown in Fig. 7. The main factors affecting the gas-fired boiler system are tap water. The water temperature varies greatly in different seasons. In this paper, the average temperature of tap water in winter, summer and transition season is 10 °C, 20 °C, and 15 °C, respectively. Using TRNSYS to simulate and predict the energy consumption of the gas-boiler hot water, as shown in Fig. 8,and the pump energy consumption, as shown in Fig. 9. By comparing the simulation values with recording values (the power and gas consumption in last), it is found that the deviation is within 7 %. So the simulation model of gas-boiler hot water is reliable. The simulation results showed that the annual operating cost of the RWHP and the gas-fired hot water boiler system is 34.3 and 63.2 million Yuan, respectively, as shown in Table 5.

Table 5. Fuel price, coefficient of perform and annual operation costs [8–9]

	Calorific value	Power consumption	Gas consumption	price	COP	Annual operation costs
RSHP	3600 kJ/(kW·h)	700000 kWh	–	0.448 yuan/(kW·h)	5.0	34.3 million yuan
Gas fired boiler	35700 kJ/m^3	30000 kWh	231000 m^3	2.67 yuan/m^3	0.9	63.2 million yuan

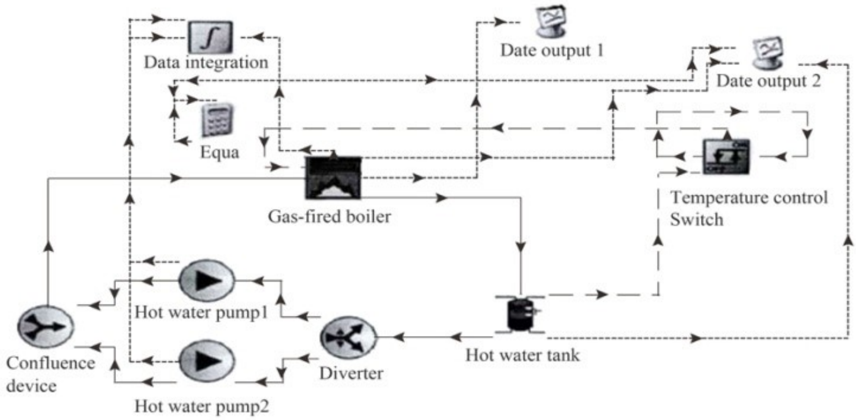

Fig. 7. Program of the gas - fired hot water boiler system

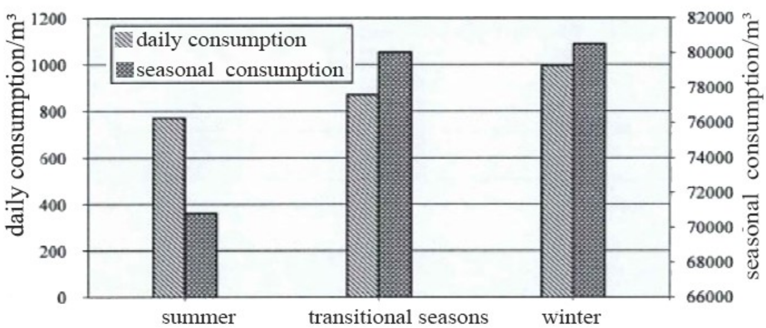

Fig. 8. Gas consumption of gas-boiler in different seasons

4.4. Energy saving operation mode analysis of RWHP system

Figure 10 presents the simulation results of COP for heat pump unit 2 and the RWHP system. With the temperature of hot water rising, the COP of heat pump units and systems decrease seriously. This paper suggests that the optimized temperature of hot water is 50 °C when RWHP is used to produce life hot water. Although the system COP is higher when hot water temperature is low than 50 °C, it cannot meet the requirements for water temperature [10].

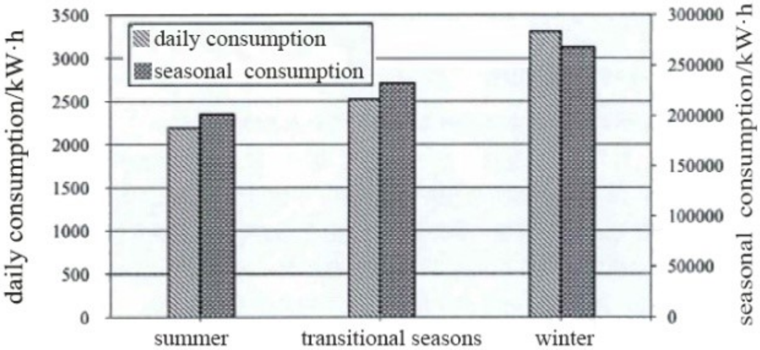

Fig. 9. Power consumption of gas-boiler in different seasons

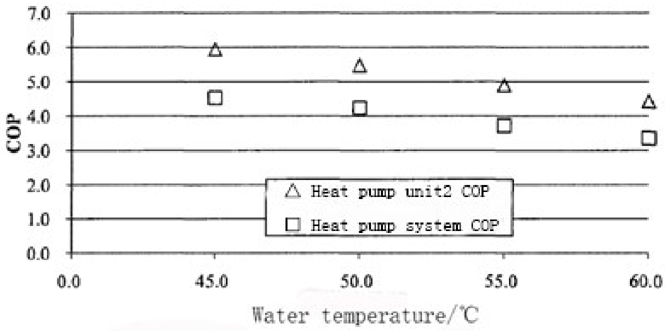

Fig. 10. Relation between COP and hot water temperature

5. Conclusion

Based on TRANSYS software, this study developed the dynamic simulation model of the RWHP water heating system and the gas-boiler hot water system, and simulated the operating process in different seasons. The following major conclusions are drawn from the simulation results:

1) Comparing the simulation results with the measured values for the heat pump units (the heating capacity, power consumption and COP), the deviation of the three groups of data is within 10 %, indicating that the simulation model is reliable. The model can be used to analysis the operation properties of other water source heat pump systems.

2) The simulation model was used to simulate all-day operation in different seasons. The average coefficient of performance of RWHP system is 4.2, 4.0 and 3.6 in summer, transition seasons and winter, respectively. Energy efficiency of operating reached the national standards; the operation of demonstration project with RWHP is stable, reliable and energy saving, so the RWHP should be applied in larger scale.

3) The dynamic simulation values of RWHP hot water system showed that there is

an important reduction in operating cost with regard to the simulation values of gas-boiler hot water system. The RWHP system saves 45.7 % of the annual operating cost compared with the gas boiler system. From the energy and environmental considerations, the heat pump system replaces the gas boiler has a huge advantage.

4) The simulation results show that there is optimal operation mode when the RWHP system works at diffident condition. The optimized temperature of hot water is 50 °C when RWHP is used to produce hot water in this project.

References

[1] M. Y. Haller, E. Bertram, R. Dott, T. Afjei, F. Ochs, J. C. Hadorn: *Review of component models for the simulation of combined solar and heat pump heating systems.* Energy Procedia *30* (2012), 611–622.

[2] K. J. Chua, S. K. Chou, W. M. Yang: *Advances in heat pump systems: A review.* Applied Energy *87* (2010), No. 12, 3611–3624.

[3] H. Willem, Y. Lin, A. Lekov: *Review of energy efficiency and system performance of residential heat pump water heaters.* Energy and Buildings *143* (2017), 191–201.

[4] C. Sebarchievici, D. Dan, I. Sarbu: *Performance assessment of a ground-coupled heat pump for an office room heating using radiator or radiant floor heating systems.* Procedia Engineering *118* (2015), 88–100.

[5] E. Bonamente, A. Aquino, F. Cotana: *A PCM thermal storage for ground-source heat pumps: Simulating the system performance via CFD approach.* Energy Procedia *101* (2016), 1079–1086.

[6] R. Chargui, H. Sammouda, A. Farhat: *Geothermal heat pump in heating mode: Modeling and simulation on TRNSYS.* International Journal of Refrigeration *35* (2012) No. 7, 1824–1832.

[7] H. W. Wang, B. Bai , G. H. Feng, L. Yu, X. Liu, Y. Luo: *Simulation and analysis of air-soil dual source heat pump energy consumption in cold regions.* Procedia Engineering *121* (2015), 1397–1405.

[8] J. An, D. Yan, G. W. Deng, R. Yu: *Survey and performance analysis of centralized domestic hot water system in China.* Energy and Buildings *133* (2016), 321-334.

[9] K. Wang, N. Li, J. Peng, X. Wang, C. Wang, M. Wang: *A highly efficient solution for thermal compensation of ground-coupled heat pump systems and waste heat recovery of kitchen exhaust air.* Energy and Buildings *138* (2017), 499–513.

[10] W. Wu, T. You, B. Wang, W. Shi, X. Li: *Simulation of a combined heating, cooling and domestic hot water system based on ground source absorption heat pump.* Applied Energy *126*, (2014), 113–122.

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