2018 Building Performance Modeling Conference and
SimBuild co-organized by ASHRAE and IBPSA-USA
Chicago, IL
September 26-28, 2018

GROUND SOURCE HEAT PUMP WITH HORIZONTAL GROUND BURIED PIPES: MODELLING AND OPTIMIZATION WITH TRNSYS

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ABSTRACT

The energy consumption of HVAC systems in both residential and industrial buildings is always an important problem. Geothermal sources are becoming one of the most attracting source for building HVAC systems. However, geothermal system operation involves varied conditions, various heat pump parameters, dynamic building loads and different ground loop parameters. Inaccurate design of each component leads to a significant departure from efficient performance which results in high energy use. Objective of this work is to simulate and optimize a geothermal HVAC system with TRNSYS. A control strategy is used to the simulation to find out best parameters combination of heat pump, horizontal ground buried pipes, and the liquid to air heat exchanger. The system has been modeled in Birmingham, Alabama. The results show that there is delicate balance that has to be maintained between the fluid temperature exiting the ground loop and the amount of heat delivered by the heat pump to the house. As a result, the control system parameters are highly important.

INTRODUCTION

The operation of heating, ventilating, and air conditioning (HAVC) system in buildings consumes more than 30% of total energy consumption in United States. (Egg and Howard 2011) However, the problem is that only a small part of residential HVAC systems work efficiently. Most of HVAC systems installed in the US are conventional design which leads to high electricity consumption. Researches have shown that hybrid HVAC system with integrated renewable energy will increase the performance of conventional HVAC system as well as decrease cost of electricity.

Heat Pump is widely used in HVAC field. Large number of heat pump systems with assisted heating devices have been designed and built. Most of them are used to solve real energy saving problems such as solar-assisted heat pump combined with seasonal storage tank to meet multi-family building heat demand. (Taherian and Tehranian 2017) With combination of increasing utility of heat pump and promising geothermal energy, geothermal heat pumps (GHP) or ground source heat pumps (GSHP) are becoming popular nowadays in HVAC field all over the world including the United States. According to technical report of National Renewable Energy Laboratory (NREL), domestic resource of geothermal is equivalent to a 30,000-year energy supply at the rate of the current energy consumption. Although geothermal energy has already been utilized in all 50 U.S. states today, it has not reached the potential as an environmentally friendly and high efficiency resource yet. The estimated value of accessible geothermal resource is greater than other developable resource in U.S. (Green and Nix 2006)

Despite the fact that geothermal resources contribute significantly to developable resources in U.S., the exploitation and utilization of geothermal resources is not at the desirable level. The advantages of using geothermal resources have been summarized in large number of papers and reports. Three essential reasons are listed here. First, geothermal energy is considered as an eco-friendly resource in general. Although there are minor negative effects, they are negligible comparing to conventional resource such as coal and petroleum. Moreover, an average geothermal power plant releases the equivalent of 122 kg CO_2 for every MWh of electricity it generates. Therefore, carbon emission of geothermal power plant is much less than conventional power plant. It means, with further development of technology the low carbon footprint of geothermal power plant will play an important role in the fight against climate change. Second, a geothermal resource is naturally replenished as a renewable resource. In another word, unlike other conventional resources, geothermal resource can sustain by themselves. Third, comparing to other renewable energies such as solar and wind, which depend on weather, geothermal resource is stable. Based on advantages of geothermal resource and previous geothermal HVAC systems, the accurate design of geothermal HVAC system is an imperative task to development of geothermal technology.

In some previous research works, geothermal HVAC technologies have been studied and developed. Chargui and their team developed a mathematical description of GHP in heating mode on TRNSYS by applying HVAC techniques. They obtained numerical results of the heat pump from simulations (Chargui, Sammouda and Farhat 2012). A GHP system with assisted solar collector was also designed and introduced in a practical manner by Chiasson (Chiasson 2007). Solar assisted ground source heat pump (SAGSHP) HVAC system was also designed with latent heat energy storage tank (LHEST). A mathematical model was developed and transient numerical simulation were carried out. A series of simulations were conducted to determine COP of the heating system. The COP and stability of the HVAC system are improved due to utilizing solar collector and soil as heat source. (Han, et al. 2008). Chen and Yang carried out a numerical simulation of SAGSHP providing both space heating and domestic hot water (DHW). The SAGSHP systems were also implemented in different locations in northern China to determine optimum applicability. The result shows that the system works better having specific solar collector area and buried pipe length. The optimized design can offer annual heating requirement and DHW with good energy balance as well as applicability in the areas of northern China. (Chen and Yang 2012).

In the current research, a ground source heat pump with horizontal ground buried pipe system was simulated in Transient System Simulation Tool (TRNSYS). The aim of this paper is to examine the system in heating mode with different buried pipe length. The geothermal information used in this simulation is for Birmingham, Alabama. Both control system parameters and behavior of the system are examined using TRNSYS.

SIMULATION

The research reported in this paper features a geothermal heat pump system in heating mode. The schematic diagram of the GHP system is shown in Figure 1. The system is simulated in TRNSYS for 5 heating months from October to March and the TMY3 (typical meteorological year) data of Birmingham, Alabama is used to carry out the simulation.

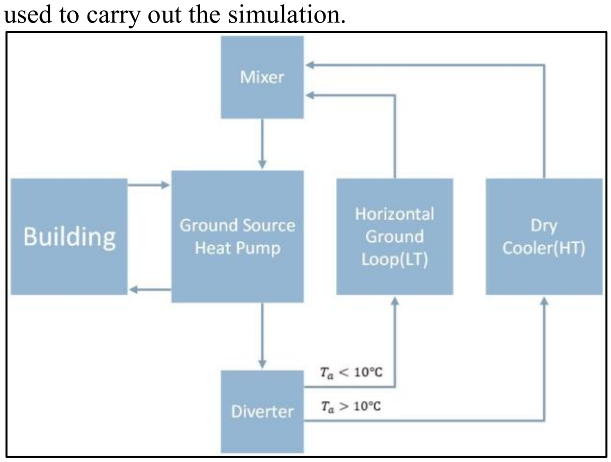

Figure 1 Schematic of designed system

The system is based on a water source heat pump. In heating mode, two heat exchangers are used in the system: horizontal ground heat exchanger loop to be used when the average room temperature is below 22°C, and dry fluid cooler to be used when average room temperature is above 20°C. The process is operated by a controlled flow diverter and a flow mixer. A schematic of this system in TRNSYS is shown in Figure 2. The entire system is running under control of two controllers: a heating thermostat and an On/Off thermostat. The On/Off thermostat is used to control the diverter which determines the flow direction of water, and the heating thermostat controls the water source heat pump. The heating thermostat is an N-stage controller which has several set points to achieve different goals.

The case study building used in this simulation is a single-family house whose 3D model was created in Sketchup (Abu-Hamdeh and Taherian 2015). This house is located in Birmingham, AL and has a total area of 200 m^2 (two floors in total, 100 m^2 each floor) to be heated. Space heating required is around 100 kWh/m^2. The model is imported to TRNSYS by utilizing Type 56 and all the parametric adjustments were done in TrnBuild.

Liquid Source Heat Pump

The component utilized in this simulation is a liquid source heat pump. In TRNSYS, It models a single-stage liquid source heat pump with an optional desuperheater for hot water heating. The heat pump conditions a moist air stream by rejecting energy to (cooling mode) or absorbing energy from (heating mode) a liquid stream. This heat pump model was intended for a residential application, but may be used in any liquid source application. In cooling mode, the desuperheater relieves the liquid stream of some of the burden of rejecting energy. However, in heating mode, the desuperheater requires the liquid stream to absorb more energy than is just required for space heating. The heat pump also works with 2-stages electrical auxiliary heating device when the heat energy is insufficient.

The heat pump parameters used in this simulation is shown in Table 1.

Table 1 Parameters of heat pump

Parameter	Unit	Value
Rated heating capacity	KW	15.1
Rated heating power	KW	2.68
Blower power	KW	0.56
Controller power	KW	0.01
Capacity of stage 1 auxiliary	KW	5
Capacity of stage 1 auxiliary	KW	5

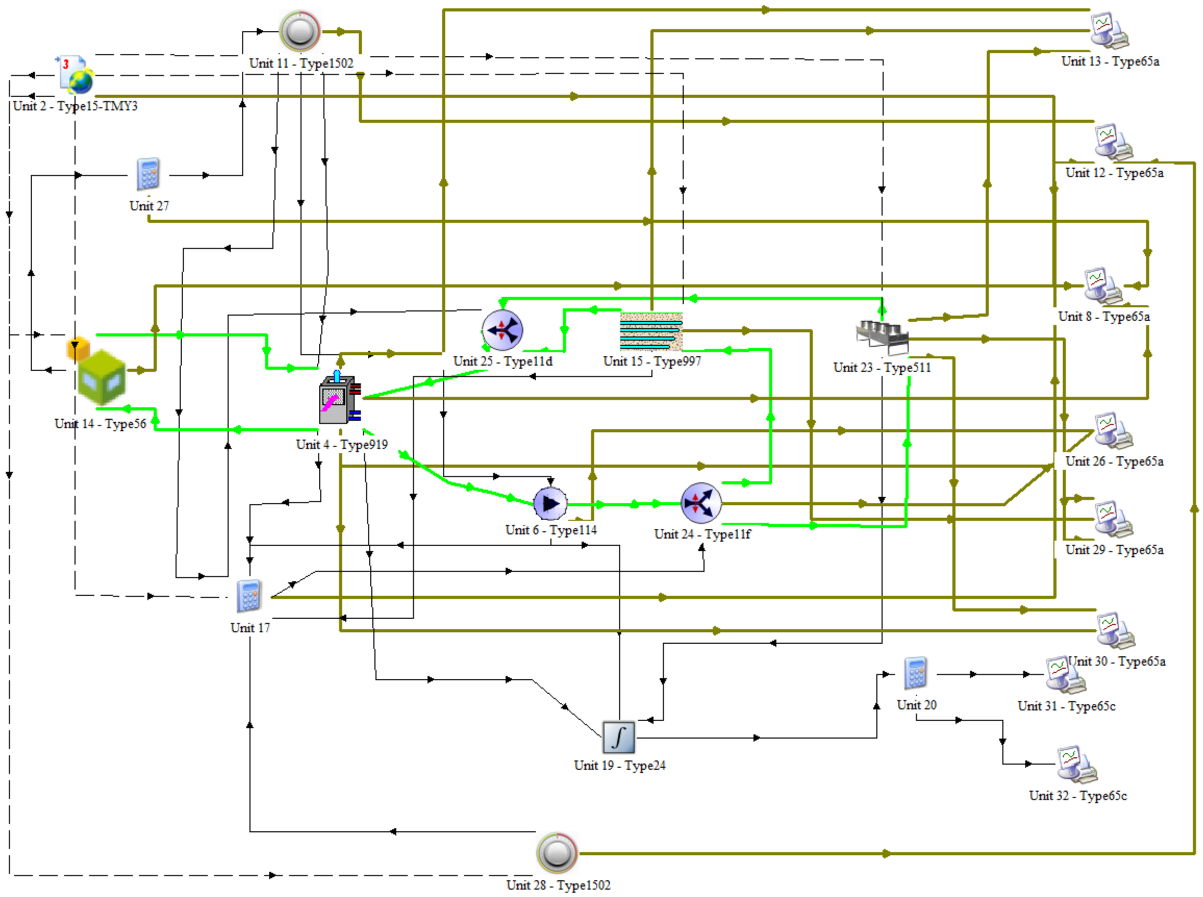

Figure 2 Schematic of ground source heat pump system in TRNSYS

Heat Exchanger

The heat pump in this simulation works with different heat exchangers in specific ambient temperature. Two heat exchangers are utilized as described here: horizontal ground heat exchanger and dry fluid cooler. Horizontal Ground Heat Exchanger is a buried heat exchanger consisting of one or more layers of horizontal pipes that interacts thermally with the ground. In this design, only one layer is considered and simulated. When the system is working, water circulates through the pipes where it absorbs heat from surrounding soil. Heat transfer occurs by convection within pipes and then by conduction through the pipe walls and the soil. Heat transfer from the soil surface to the surrounding occurs by radiation and convection. The soil that thermally interacts with the heat exchanger pipes is divided into a 3-D mesh solved using a fully implicit finite-difference approach; different possible boundary conditions can then be applied to simultaneously solve for the soil temperatures. The soil temperature data is exported to an external file. For the sake of simulation speed, the model breaks the ground along two axes of symmetry and simulates only one quarter of the field, multiplying energy transfer results to arrive at the total effect. (TRNSYS 2012) The horizontal buried pipes used in this research has are consisted of 15 pips in each layer, installed in a depth of 3 meters. The total length of pipe varied from 200 m to 600m with different pipe numbers which was part of the results of this research.

Dry fluid cooler is a device used to cool a liquid stream by blowing air across coils containing the liquid. The model assumes that the device can be modeled as a single-pass, cross-flow heat exchanger: which is typically how these devices are constructed.

Controllers

In this system, two controllers are used. Both of the two controllers are N-stage aquastat. This controller commands first stage heating at cool fluid temperature, second and third stage heating at cooler fluid temperatures and N-stage heating at even lower fluid temperature levels. Same as many other controllers, instabilities may occur when system temperature is at or

very near to their set point values. In order to solve the instability problems, these can be reduced by adding dead bands (hysteresis) to the controller such that the controller signal does not change until the system temperature has reached its set point plus or minus a small delta temperature. In this simulation, the hysteresis is set to 2℃. Hysteresis effects can be included in the model by supplying the optional dead band temperature difference DT_{db}.
The temperatures are set as follows:

$$T'_{Hn} = T_{Hn} - \gamma_1 DT_{db} + \gamma_{setback} DT_{setback} \qquad (1)$$

In this equation, T_{Hn} is old heating set point temperature for stage n. T'_{Hn} is new heating set point temperature for stage n. γ stands for control signal. DT_{db} is dead band temperature difference for hysteresis effects and $DT_{setback}$ is dead band temperature difference for set up effect.

RESULTS

Control Function

The controller is set to a 3 stage on/off controller for the heat pump and 2 auxiliary heating devices. The requirement to heat for a certain stage is judged by parameter γ. For example, when $\gamma_p = 1$, ground source heat pump is working to heat the building. And $\gamma_p = 0$ indicates that heat pump is not working. As shown in Figure 3, heat pump signal is 1 most of the time after October. However, the auxiliary signal keeps at 0 throughout the simulation, which indicates the auxiliary heating devices don't work during simulation process for the reason the selected heat pump's heating capacity is high enough to keep the temperature above the auxiliary heating stage temperature.
The other control function used in this simulation serves the diverter. When ambient temperature is above 10℃, water which exits from heat pump goes to dry fluid cooler. And water diverts to horizontal ground loop when ambient temperature is below 10℃. As shown in Figure 4, most of the time water flows through dry fluid cooler in October because temperature is not below the set point and dry fluid cooler is good enough to supply heat to the heat pump that in turn supplies heat to the building. However, the working fluid is basically running through horizontal ground loop because of lower ambient temperature.

Temporal evolution of temperatures

Three temperatures are monitored during the simulation: ambient temperature which is given by TMY3 file, average temperature of the building (This building is modeled in Sketch-up, which has two floors and $100m^2$ living space. The average temperature is derived from temperatures of first and second floor) and heat pump outlet temperature. Temporal evolution of those three temperatures is shown in Figure 5. Purple line represents the change of ambient temperature, red line indicates room average temperature and blue line is the heat pump outlet fluid temperature. From the Figure, average temperature keeps stable between 22℃ and 25℃, which indicates the GHP works efficiently. The ambient temperature never goes below -10 ℃ because Birmingham is located in ASHRAE climate zone 3A (Green and Taherian 2017) which is considered hot and humid. The heat pump outlet temperature varies during winter. When the heat pump outlet temperature is around 45 ℃, it means the working fluid flows through horizontal ground loop. Otherwise, the working fluid is going through dry fluid cooler when the heat pump outlet temperature is lower. However, the outlet temperature is a little bit higher than expected because heat pump parameters used in this simulation is from a heat pump on market which has higher heating power than required by the house.

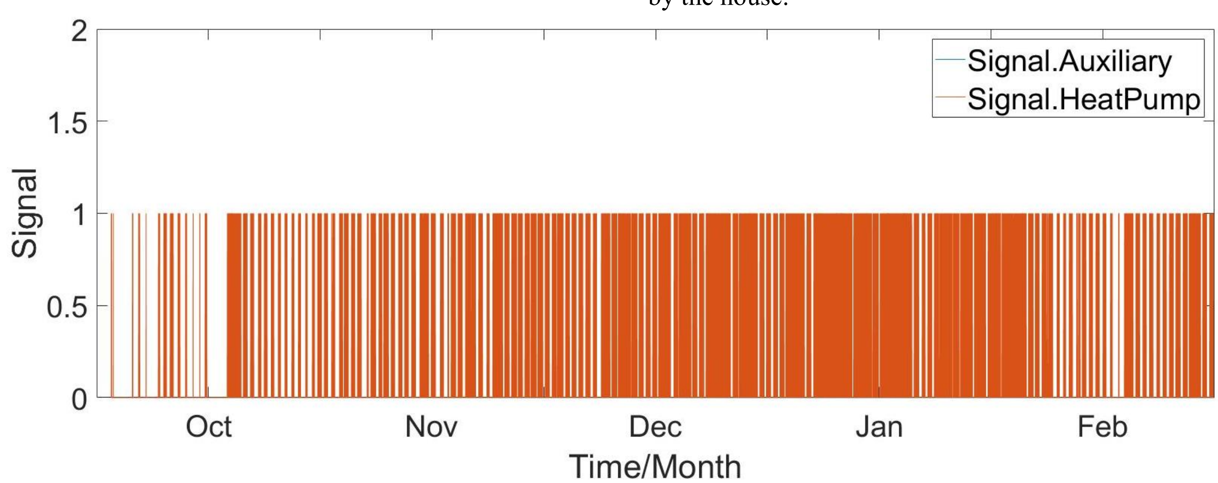

Figure 3 Control Signal of Heat Pump and Auxiliary Heating Device

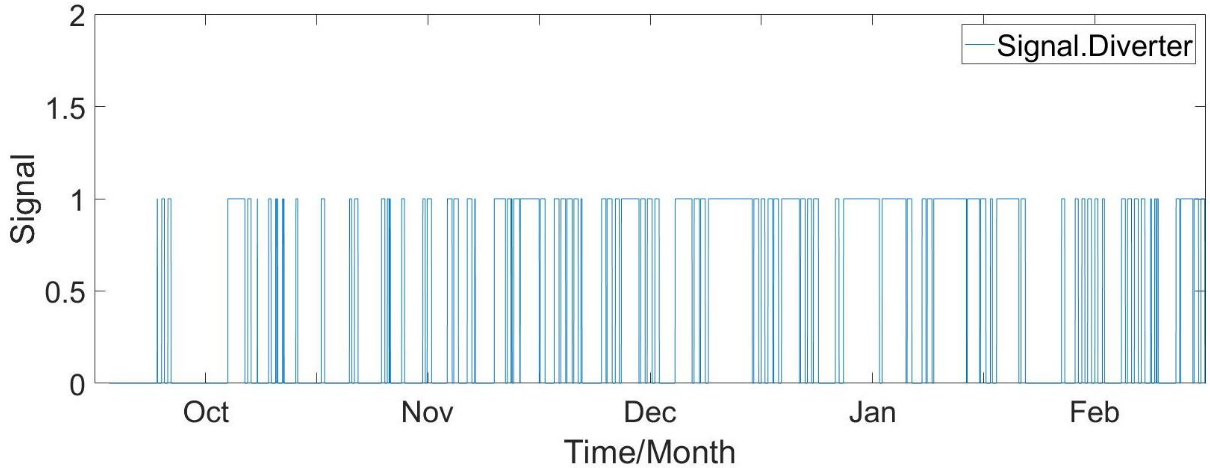

Figure 4 Control Signal of Diver

COP of the heat pump

The coefficient of performance of pump (COP) is the ratio of delivered power by the consumed electric power.

$$\mathrm{COP} = \frac{\dot{Q}_{hp}}{\dot{Q}_{ei}} \quad (2)$$

As shown in Figure 6, COP of heat pump can be divided into two phases. In the first phase, COP is higher at approximately 4.2. When heat pump is working at this higher COP mode, working fluid is going through ground source loop where the soil preserves higher thermal energy. Following that state, the COP starts going down along temporal variation because soil extracts heat throughout winter by conduction. With more heat extracted from soil, the preserved potential thermal energy is lost. In the second phase, COP keeps around 3 where the working fluid is going through dry cooler because of relative higher ambient temperature. The variation of COP is same as the trend of heat pump outlet temperature in Figure 5. The temperature is relatively high when water is circulating through ground loop and lower when it goes through dry cooler.

Electric power Consumption for different pipe lengths

Buried pipes are the essential part of geothermal heat pump system. Although the horizontal ground loop is set to a one layer buried pipe, different pipe numbers (PN) and pipe lengths (PL) are affecting the performance of the system. The total pipe length (TPL) is the product of PN and PL. Various PN and PL combinations are used in simulations (in Table 2) without changing the heat pump liquid flow rate. The total electricity consumption difference varies with the TPL. According to the simulation results, the electricity consumption difference of heat pump with various PN decreases along with increasing TPL. When the TPL is small enough, more pipe numbers lead to higher electricity consumption, because the system is horizontal buried pipes in parallel, increasing pipe numbers will decrease the flow velocity of liquid inside the pipes. This in turn will decrease the overall heat transfer coefficient between the liquid and the surrounding soil. As shown in Figure 7, the relationship between electricity consumption and different buried pipe configuration can be observed directly.

Table 2 Heat Pump Power Consumption based on pipe numbers and pipe lengths

	PN=6	**PN=8**	**PN=10**
TPL=200m	1664 kWh	1675 kWh	1683 kWh
TPL=300m	1584 kWh	1587 kWh	1590 kWh
TPL=400m	1536 kWh	1535 kWh	1535 kWh
TPL=500m	1506 kWh	1505 kWh	1505 kWh
TPL=600m	1491 kWh	1490 kWh	1488 kWh

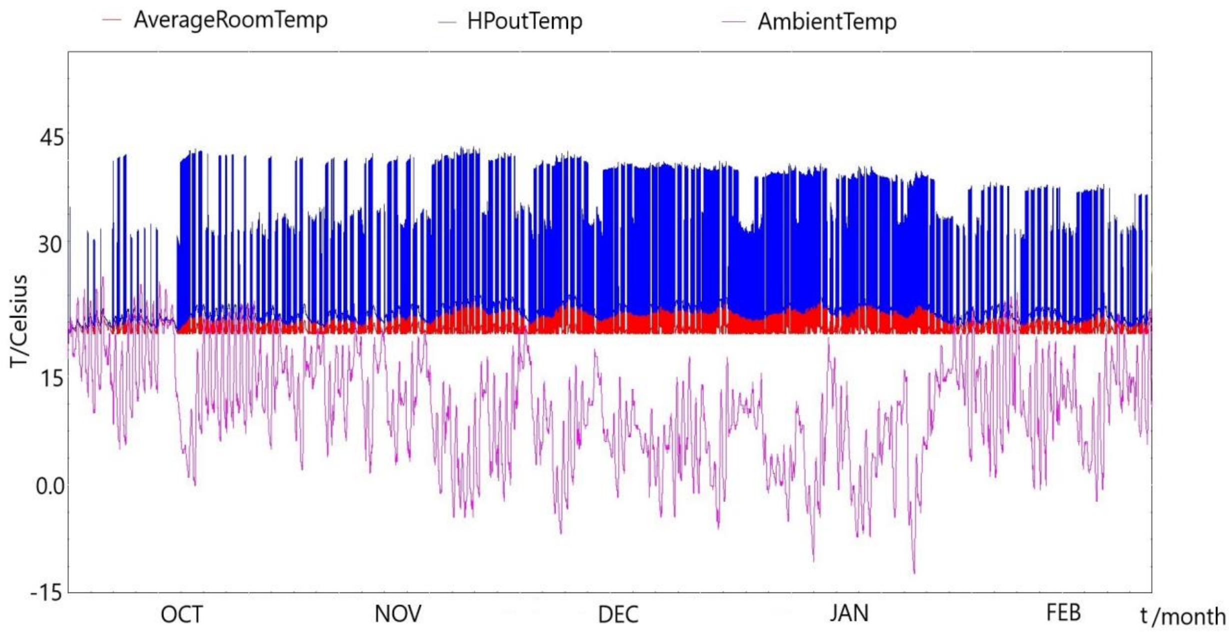

Figure 5 Temporal evolution of temperature

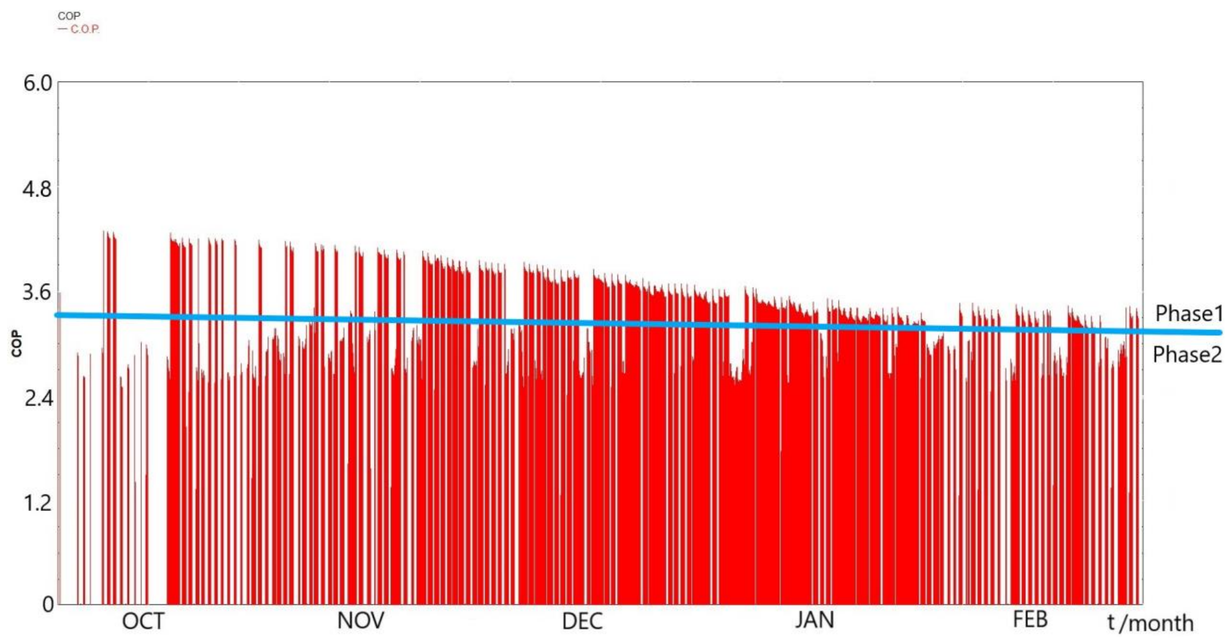

Figure 6 Temporal evolution of COP

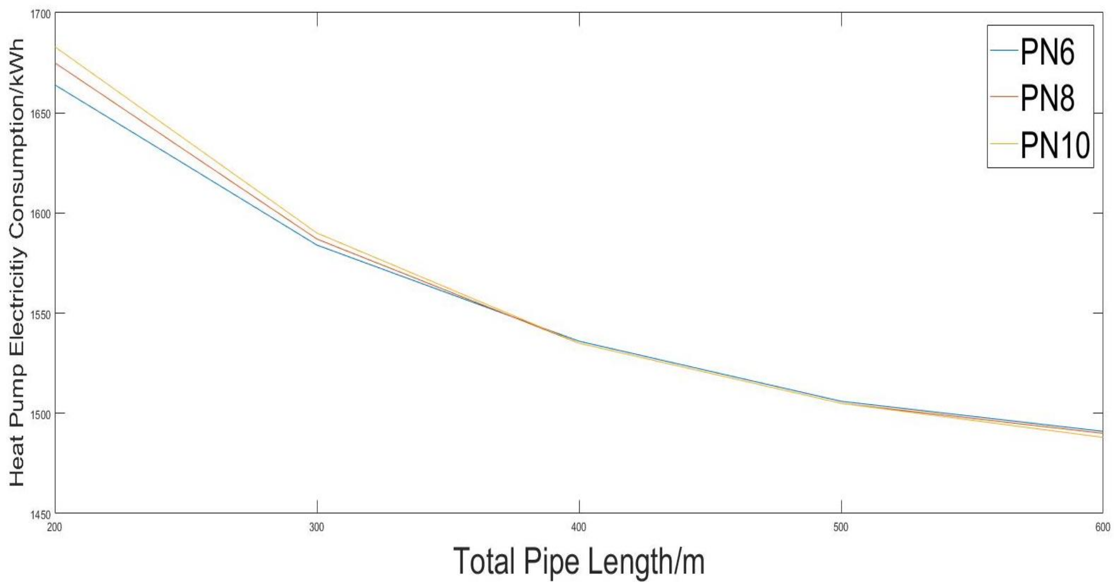

Figure 7 Heat Pump electricity consumption with various PL and PN from OCT to FEB (simulation time

CONCLUSION

A Study on ground source heat pump with horizontal ground loop and liquid dry cooler has been carried out using TRNSYS. With two on/off controllers, the relationship between temporal evolution of weather and ground source heat pump performance has been tested and discussed. According to the results, there are two COP modes of operation: first mode with relative high COP when working fluid is going through buried pipes and second mode with a relatively lower COP when working fluid passes through dry cooler. Although COP is lower when the working fluid goes through dry cooler, the overall efficiency increases for the reason that it reserves more soil energy which helps keep the ground temperature balanced. Obviously, dry cooler working as auxiliary heat exchanger helps increase efficiency of GSHP system. The number of pipe branches can influence heat pump power consumption with minor changes while the total pipe length stays the same. Although less pipe numbers in parallel configuration could reduce just a little electricity consumption, it should be considered as an energy conservation method. Based on what we learned from this research, we are going to improve the system with more auxiliary heating devices such as solar collector and cooling tower. Heat pump behavior in cooling mode will be considered and tested in the future as well. Moreover, computational optimization methods will be applied to this system to obtain the best configuration and parameters. For future research, comparative study between different layouts will be conducted to examine effectiveness of various assisted components.

NOMENCLATURE

T_{Hn}	Old heating set point temperature for stage n
T'_{Hn}	New heating set point temperature for stage n
T_a	Ambient temperature
DT_{db}	Dead band temperature difference for hysteresis effects
$DT_{setback}$	Dead band temperature difference for set up effect
γ_1	Heating control signal at the previous time step for stage 1
$\gamma_{setback}$	Set back control signal
γ_p	Heating control signal at the previous time step for stage p
$\dot{Q}_{hp}$	Delivered power by heat pump
$\dot{Q}_{ei}$	Electrical power consumed by heat pump
HVAC	Heating, ventilating, and air conditioning
GSHP	Ground source heat pumps
GHP	Geothermal heat pumps
DHW	Domestic hot water
SAGSHP	Solar assisted ground source heat pump
LHEST	Latent heat energy storage tank
TRNSYS	Transient System Simulation program
COP	Coefficient of performance

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