# Modeling of central ground-source heat pump system in EnergyPlus

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## ABSTRACT

One of the effective ways to utilize geothermal energy in a central heating and cooling system for large-scale buildings is to make use of a central ground-source heat pump system (CGSHP) that consists of a series of chiller-heaters based on an irreversible vapor-compression cycle and a dedicated valve control system. The CGSHP system mixes fluids from the evaporator side and condenser side of the individual chiller-heaters. The mixed fluid flowing through either evaporator side or condenser side can be connected to the ground source water loop. These special features enable the central system to operate in a number of modes, providing simultaneous cooling and heating. This paper focuses on modeling this unique system in a whole building energy simulation program, EnergyPlus. It discusses approaches to address challenges in implementing the proposed model into the existing EnergyPlus program. It demonstrates input requirements to adequately model the performance of individual chiller-heaters and the central system. The simulation results from a case study are presented in this paper to evaluate the feasibility of the proposed model.

## KEYWORDS

Heat pump, EnergyPlus, Simulation, Heat recovery, Chiller

## INTRODUCTION

Heat pump technology has evolved rapidly in the last few decades and becomes a common and mature technology in the heating, ventilation and air-conditioning (HVAC) applications (Chua et al, 2010). Ground source heat pumps (GSHPs), also referred to as geothermal heat pumps, utilize the Earth as a heat source or sink and tend to have higher efficiency and reduced greenhouse gas emissions compared to other heating and cooling systems including air source heat pump systems. GSHPs have grown fast in many nations due to the aforementioned benefits (Lund and Boyd 2015, Liu et al. 2015). Lund and Boyd (2015) reported that the total installed capacity of GSHPs was about 49,9 GWt in 2015 and most installations of GSHPs occurred in North America, Europe, and China.

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Various configurations of GSHP systems exist (e.g., Liu et al. 2015), however for commercial buildings, those can mainly be categorized as decentralized and centralized GSHP systems. For decentralized GSHPs, a single heat pump is used to condition an individual thermal zone and multiple heat pump units are coupled with a common ground source loop while centralized GSHPs generate chilled and hot water centrally for space heating and cooling using multiple heat pump systems and utilize the ground loop to transfer heat to or from the ground. Many studies have been conducted to emphatically and mathematically model the decentralized GSHP systems and ground loop heat exchangers, and such models were implemented in many commercial and publicly available software tools (e.g., EnergyPlus, eQUEST, TRNSYS, etc.). However, not many studies have been reported on the modeling of the centralized GSHP systems to evaluate the system performance and environmental benefits. This paper presents the modeling of a centralized ground source heat pump system in a whole building energy simulation program, EnergyPlus, and the simulation results from a case study to show the feasibility of the proposed model.

## OVERVIEW OF CGSHP SYSTEM

The central ground-source heat pump system consists of multiple chiller-heater modules that are connected to a ground heat exchange loop. It may include two types of chiller-heater systems, such as heat recovery chiller-heater and a water-to-water heat pump chiller. Depending on thermal demand, the system can be controlled in different manners to provide cooling and/or heating. While the control logic for both types of chiller-heater component differs from each other, it can simultaneously meet both cooling and heating loads. That is, it can function as a chiller as well as a boiler at the same time, delivering both chilled and hot water simultaneously. To enable this function, the chiller-heater modules need to be connected to three loops: chilled water plant loop to provide cooling, hot water plant loop to provide heating, and a ground source loop to exchange heats with source water. An example of the system configuration is illustrated in Figure 1.

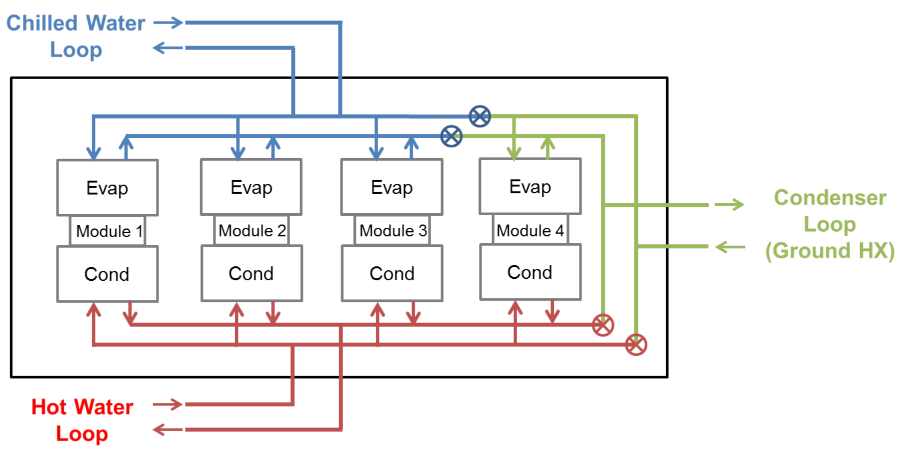


***Figure 1***. An example diagram of a central heat pump system with three chiller-heaters in heat recovery mode and one chiller-heater in heating-only mode

The fluid used in this central heat pump system is normally water. The central system controls fluid flows, received from interconnected plant loops and a source loop, and delivers conditioned flows by individual chiller-heater modules within the central heat pump system to the loops. The fluid flows through each chiller-heater are independent, so that flows for both evaporator and condenser of a chiller-heater are not shared with any other chiller-heater modules in the central heat pump system. The conditioned flows leaving each chiller-heater are then mixed in the central heat pump system, which in turn delivered to the plant loops to produce cooling or heating, or both simultaneously and to a source loop to exchange heats.

Two different flow control modes for individual chiller-heaters are applied: constant flow mode and variable flow mode. These flow control modes are only valid for individual chiller-heater modules in the central heat pump system. No flow control is applicable to the central system. The model calls each chiller-heater sequentially until all loads are met, which the central heat pump system should meet. In a constant flow control mode, the model assumes a fixed flow rate either defined by users or auto-sized design values determined by the program. Thus, it calculates temperature differences at the given flow rates for each chiller-heater and an inlet water temperature. Conversely, in the variable flow control mode, the central system controls the performance of individual chiller-heaters by varying water flows. The model thus calculates mass flow rates at a given temperature difference.

## MODULE DESCRIPTION

### Challenges

The implementation of the model should address a number of challenges. First of all, EnergyPlus simulates the plant loop and the condenser loop sequentially. The plant loop includes a chilled water loop for cooling and a hot water loop for heating. The conditions of water for cooling and heating are determined on the chilled water loop and hot water loop, respectively. The condenser loop dealing with source water follows. The challenge of the simulation of a CGSHP system using the existing sequential simulation over these loops is that a CGSHP system provides simultaneous cooling and heating in conjunction with a number of different operating modes. It also exchanges heats through a condenser water loop. The calculation of each node for a CGSHP system ranges across the plant loop and condenser loop. Thus, the determination of operating modes of a CGSHP system and the calculation of cooling and heating capacities are very difficult. Another challenge of modeling a CGSHP system is that it contains a series of chiller-heater units. The calculation of each model generally ends over a single loop or two loops separately. This approach is applicable to the calculation of a single chiller-heater unit. However, a CGSHP system treats multiple chiller-heater units and mixes a fluid from each chiller-heater unit in each side, i.e., chilled water and hot water. The mixture of the fluids from each chiller-heater unit on each side can be connected to the condenser loop. More importantly, the operating mode of each chiller-heater unit varies with the variation of loads, which affects determining the operating mode of the central system. The calculation of individual chiller-heater units and the central system are not completed during the simulations of each loop.

**Approach**

The new model should be fully coupled with the existing program modules in EnergyPlus. HVAC system simulation, which is followed by zone heat balance, includes an air loop and a plant loop. The plant loop consists of a chilled water loop (loop 1) and a hot water loop (loop 2). The current algorithm in EnergyPlus simulates the chilled water loop, the hot water loop, and the condenser loop (loop 3) in order. As a CGSHP system involves calculations across these three loops, the new model should simulate three loops in order to predict the performance of the system. The existing heat recovery chiller-heater model can be used to calculate cooling and heating capacities of individual chiller-heater units by adding a number of functions to handle distinctive characteristics of a CGSHP system.

The flow chart shown in Figure 2 illustrates how the new model addresses the challenges. It starts from the current loop being simulated. If the current loop is the chilled water loop, the model verifies whether a cooling load is available. It continues to calculate the cooling capacity of each chiller-heater unit and the conditions of the water at the outlet nodes until the required cooling load is met by sequence order. It stores all variables for cooling in order to determine the operating mode in the following loop. In the same way, it calculates the heating capacity of individual chiller-heater units and the conditions of the hot water flow if a heating load is available during the hot water loop simulation. The operating mode of each chiller-heater unit and the central system is determined in the hot water loop as all variables for cooling and heating are known. For instance, the operating mode is set to be one of the simultaneous cooling and heating modes if a coincident cooling and heating load is available. During condenser loop simulation, it updates source water conditions by calling the existing ground heat exchanger model in the following condenser loop, which in turn becomes an inlet node of the source water side of a CGSHP system. It calculates the conditions of the chilled water side, the hot water side, and the source water side once the operating mode is set and source water conditions are updated.

**Input structure**

Two objects are needed to model a central geothermal application. One object defines the configuration of a CGSHP system. A series of inputs is required to specify the type and control of individual chiller-heaters embedded in the central system. The chiller-heaters for a CGSHP system are typically identical, but different types and sizes of chiller-heater can be used. The object should model a variety of chiller-heaters as well as identical units. It also specifies node connections between demand side equipment and the outlets of the central system. Users are required to specify the inlets and outlets of the central system on the three loops, i.e., the chilled water loop, the hot water loop, and the condenser water loop. The other object is to determine the performance of generic chiller-heaters. The standard performance curve object in EnergyPlus is used to obtain reference values such as cooling and heating capacities, temperatures, and power demands at the full load and part load conditions. The object requires a number of multipliers in order to calculate individual chiller-heaters' performance in the heating mode and the simultaneous cooling and heating modes. An example of the inputs for a chiller-heater object is given in Table 1 in the following sub-section.

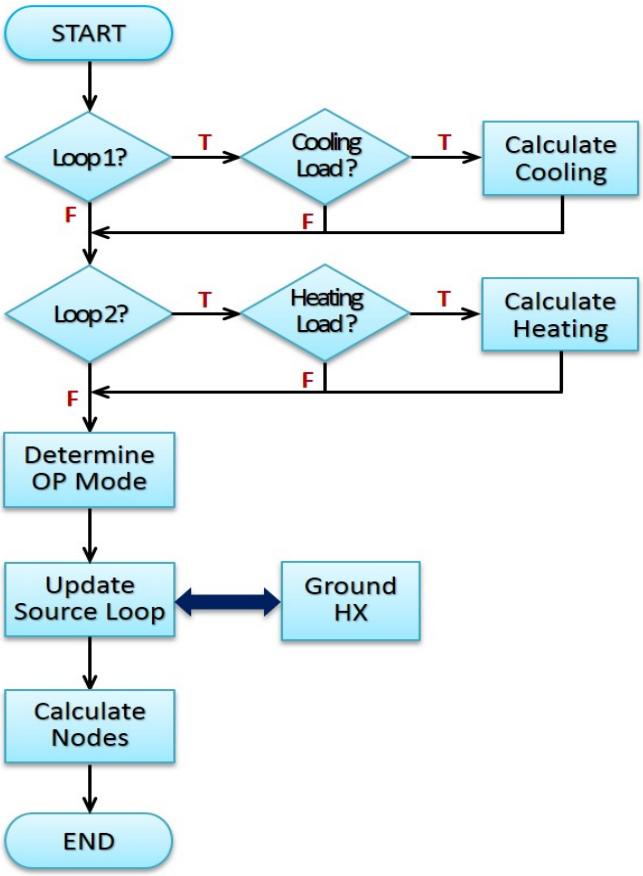


***Figure 2****. The modeling process for a CGSHP system*

***Table 1.*** Main input parameters for a chiller-heater unit

| *Input Fields* | *Values* |
|---|---|
| Reference Cooling Mode Evaporator Capacity {W} | 10000 |
| Reference Cooling Mode COP {W/W} | 1.5 |
| Reference Cooling Mode Leaving Chilled Water Temperature {C} | 6. 7 |
| Reference Cooling Mode Entering Condenser Fluid Temperature {C} | 29.4 |
| Reference Cooling Mode Leaving Condenser Water Temperature {C} | 35 |
| Reference Heating Mode Cooling Capacity Ratio | 0.74 |
| Reference Heating Mode Cooling Power Input Ratio | 1.38 |
| Reference Heating Mode Leaving Chilled Water Temperature {C} | 6.7 |
| Reference Heating Mode Leaving Condenser Water Temperature {C} | 60 |
| Reference Heating Mode Entering Condenser Fluid Temperature {C} | 29.4 |
| Heating Mode Entering Chilled Water Temperature Low Limit {C} | 5 |
| Chilled Water Flow Mode Type | Variable |

## RESULTS

### Simulation overview

A case study was designed to see whether or not the new model adequately predicts the performance of a CGSHP system. One story rectangular building with the floor area of 463.6 $m^2$ was chosen. The building was divided into 4 exterior and one core conditioned zones and an unconditioned return plenum. Terminal reheat systems through constant volume single duct air loop condition the conditioned thermal zones. A central plant provides the chilled water and the hot water with the water coils. The chiller system was a CGSHP system with two identical chiller-heater units. Table 1 lists main input parameters in order to predict the performance of the chiller-heater units of the central system. A vertical ground heat exchanger was set to be condenser equipment. The thermostat was set at 22°C with 19°C setback for heating and at 24°C with 28°C setback for cooling. A TMY 3 weather file for Chicago International Airport was used with 10-minute time steps.

### Simulation results

Tables 2 and 3 summarize the performance of the CGSHP system that provided simultaneous cooling and heating. It is noted that this paper presents a set of outputs during the occupied hours on one spring day, which represents unique features of a CGSHP system. The simulation results indicated that the central system is more energy efficient when it meets a relatively higher heating load with a lower cooling load. This is possible because the system generates heats solely from the vapor-compression cooling cycle. The system uses less electricity in the simultaneous cooling and heating mode if the cooling load is low, meeting a heating load simultaneously. For instance, the electricity consumption at 8 AM was 12,747 watts and the system provided 14,347 watts of cooling and 9,867 watts of heating. The COP of the system at this operating hour was 1.9. As the cooling load increased, it met the highest cooling load at 1 PM and used electricity most. However, the COP value (1.3) at this operating hour decreased significantly due to the increase of electricity use and the reduction of the total loads.

The first chiller-heater unit operated in the simultaneous cooling and heating mode. The first chiller-heater unit met 40% to 60% of the total cooling loads as shown in Table 2 and approximately 55% of the total heating loads. The other identical chiller-heater unit then met the remaining total cooling and heating loads. For instance, the total cooling and heating loads at 8 AM were 14,347 watts and 9,867 watts, respectively. The first chiller-heater provided 8,574 watts of cooling and 5,271 watts of heating. The remaining cooling and heating loads, which the central system should meet, was then met by the second chiller-heater. In addition, the chiller-heater unit interacted with the ground heat exchanger for only a couple of time steps. It operated in the heat recovery mode with no source water heat exchange for all the other operating hours as shown in Table 2.

***Table 2.*** *An example of hourly load variation and node temperatures in the simultaneous cooling and heating mode*

| *Time [h]* | *Outdoor Air Temperature [°C]* | *Cooling Demand Rate [W]* | *Heating Demand Rate [W]* | *Electricity Consumption [W]* | *Cooling Inlet Temperature [°C]* | *Heating Inlet Temperature [°C]* | *Source Inlet Temperature [°C]* | *Cooling Outlet Temnerature [°C]* | *Heating Outlet Temperature [°C]* | *Source Outlet Temperature [°C]* | *Ground HE Inlet Temperature [°C]* | *Ground HE Outlet Temperature [°C]* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | 13.0 | 14347 | 9867 | 12747 | 15.5 | 57.6 | 22.7 | 6.7 | 60.0 | 22.7 | 21.5 | 21.5 |
| 9 | 14.5 | 16224 | 7899 | 14622 | 15.7 | 58.0 | 22.7 | 6.7 | 60.0 | 22.7 | 21.5 | 21.5 |
| 10 | 15.4 | 18116 | 4586 | 16332 | 15.7 | 58.8 | 23.2 | 6.6 | 60.0 | 23.4 | 22.7 | 22.7 |
| 11 | 16.2 | 19132 | 3393 | 17277 | 15.8 | 59.1 | 21.6 | 6.6 | 60.0 | 22.6 | 24.3 | 21.7 |
| 12 | 16.4 | 20024 | 3157 | 18092 | 15.8 | 59.2 | 22.0 | 6.7 | 60.0 | 23.4 | 22.1 | 22.1 |
| 13 | 16.1 | 20351 | 3886 | 18406 | 15.8 | 59.0 | 23.3 | 6.7 | 60.0 | 24.6 | 24.7 | 22.1 |
| 14 | 15.8 | 19975 | 3739 | 18045 | 15.7 | 59.0 | 21.9 | 6.7 | 60.0 | 22.9 | 22.5 | 22.5 |
| 15 | 15.3 | 20222 | 3532 | 18282 | 15.9 | 59.1 | 22.8 | 6.7 | 60.0 | 23.8 | 23.9 | 23.9 |
| 16 | 15.0 | 20344 | 3906 | 18399 | 15.9 | 59.0 | 22.6 | 6.7 | 60.0 | 23.9 | 23.7 | 23.7 |
| 17 | 14.4 | 20150 | 5371 | 18214 | 15.8 | 58.6 | 23.1 | 6.7 | 60.0 | 23.5 | 23.4 | 20.8 |

***Table 3.*** *An example of hourly variation of the performance of the first chiller-heater unit in the simultaneous cooling and heating mode*

| *Time [h]* | *Cooling Rate [W]* | *Heating Rate [W]* | *Electricity Consumption [W]* | *Cooling Inlet Temperature [°C]* | *Cooling Outlet Temperature [°C]* | *Chilled Water Flow Rate [kg/s]* | *Heating Inlet Temperature [°C]* | *Heating Outlet Temperature [°C]* | *Hot Water Flow Rate [kg/s]* |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 8574 | 5271 | 7316 | 15.5 | 6.7 | 0.234 | 57.6 | 60.0 | 0.529 |
| 9 | 8633 | 4458 | 7682 | 15.7 | 6.7 | 0.228 | 58.0 | 60.0 | 0.529 |
| 10 | 8633 | 2587 | 7682 | 15.7 | 6.7 | 0.228 | 58.8 | 60.0 | 0.529 |
| 11 | 8633 | 1914 | 7682 | 15.8 | 6.7 | 0.227 | 59.1 | 60.0 | 0.529 |
| 12 | 8633 | 1781 | 7682 | 15.8 | 6.7 | 0.226 | 59.2 | 60.0 | 0.529 |
| 13 | 8633 | 2192 | 7682 | 15.8 | 6.7 | 0.227 | 59.0 | 60.0 | 0.529 |
| 14 | 8633 | 2109 | 7682 | 15.7 | 6.7 | 0.228 | 59.0 | 60.0 | 0.529 |
| 15 | 8633 | 1992 | 7682 | 15.9 | 6.7 | 0.224 | 59.1 | 60.0 | 0.529 |
| 16 | 8633 | 2203 | 7682 | 15.9 | 6.7 | 0.225 | 59.0 | 60.0 | 0.529 |
| 17 | 8633 | 3030 | 7682 | 15.8 | 6.7 | 0.226 | 58.6 | 60.0 | 0.529 |

## CONCLUSION

This paper demonstrates the implementation of a CGSHP system in the existing simulation program EnergyPlus. GSHP systems are a highly energy efficient system and they have been increasing employed as a building application for cooling and heating. The work was intended to model a centralized GSHP system in a whole building energy simulation program, EnergyPlus as it has not been readily available in the existing building simulation programs. A case study was designed to verify whether or not the proposed model adequately predicts the performance of a CGSHP system and it is fully coupled with the EnergyPlus program. The simulation results ensure that the proposed model reads demand side node conditions and predicts the supply side node conditions for the CGSHP system and embedded chiller-heater units in the system. It also provides a variety of outputs for simulation users to analyze the feasibility of a CGSHP system when it serves a building. It is expected that the proposed model would be a great part of the decision-making process.

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