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# Long-term Performance Assessment of Ground Source Heat Pump (GSHP) Systems in Japan

Saeid Mohammadzadeh Bina, Hikari Fujii

Graduate School of Engineering and Resource Science, Akita University, Akita, Japan

s.bina@mine.akita-u.ac.jp

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## ABSTRACT

This study presents long-term performance predictions for ground source heat pump (GSHP) systems in various climatic regions of Japan. The research calculates the dynamic heat load of a typical Japanese building in various cities using their meteorological data and considers different schedules for heating and cooling seasons. The performance degradation of the GSHP system after 15 years of operation is analyzed due to imbalanced heating and cooling loads. The study also compares the changes in ground temperature and variations in the coefficient of performance (COP). Ground temperatures were observed to increase by a maximum of up to 4 °C in cooling-dominated regions due to higher accumulative loads of thermal imbalance. Conversely, in heating-dominated regions, ground temperatures decreased to around 1 °C. The model also indicated that the coefficient of performance (COP) decreased in the dominant operation for each case study due to induced thermal imbalance and changes in soil temperature. The system's cooling COP decreased by 0.015/year in Okinawa City and 0.006/year on average due to thermal imbalance.

## 1. INTRODUCTION

The building sector accounts for a significant portion of energy demand in many countries, notably in Japan, given its high population density and extensive housing units (Mohammadzadeh Bina, Fujii et al. 2022). It is projected that the demand for resources will increase due to the expected growth in population and an improvement in living standards (Ashrafi, Ahmadi et al. 2023). Japan has committed to reaching carbon neutrality by 2050, following in the footsteps of the United States and Europe (Mohammadzadeh Bina, Fujii et al. 2023). Enhancing the sustainability of urban energy is crucial to combat global warming and meet targets (Yu, Wang et al. 2021). Ground source heat pump (GSHP) systems are a highly efficient and reliable technology that has been extensively studied in recent decades. This technology benefits from the temperature difference between the ground and ambient air temperature in both summer and winter seasons (Mohammadzadeh Bina, Fujii et al. 2020). This system provides a more reliable solution for heating and cooling needs, particularly in colder climates, when compared to air source heat pump (ASHP) systems. This is because the system extracts heat from the ground which maintains a stable temperature throughout the year. In contrast, ASHPs extract heat from the outside air, which can be variable, especially in colder regions (Yao, Jiang et al. 2004, Maddah, Goodarzi et al. 2020). From 1995 to 2020, the installed capacity for direct applications grew at a significant rate, going from 1,854 MWt to 77,754 MWt worldwide (Lund and Toth 2021). However, in areas where heating and cooling are primarily needed during winter and summer, respectively, there may be an uneven distribution of these loads throughout the year. This can result in a decreased performance of the system over time (Zheng, Zhou et al. 2022). In these areas, the heat injected into or extracted from the soil exhibits a considerable difference over the course of a year's operation (Emmi, Bordignon et al. 2020). The Hybrid GSHP system, known as the HGSHP system, offers a solution to balance the load and maintain system performance over its long-term operations (Wang, Liu et al. 2015). In recent years, various researchers have focused on the impact of heating and cooling mismatches on soil properties and system performance over long-term operational periods. Li et al. (Li, Li et al. 2018) proposed an integrated method for assessing the long-term performance of the GSHP system, concentrating on the effect of thermal imbalance ratios on underground thermal conditions. A higher imbalance ratio in cooling-dominant cases led to a 15 °C temperature increase at the GHE outlet, compared to an increase of only 4.6 °C in another case. Zhao et al. (Zhao, Zhang et al. 2023) proposed a novel numerical model that considers the effect of groundwater seepage and building load on the dynamic long-term performance. The study found that imbalance loads significantly impacted system performance, resulting in an annual average ground temperature increase of approximately 0.72 °C/year (1st to 5th year) and 0.032 °C/year (15th to 20th year). The authors concluded that seepage effects were beneficial for overall energy efficiency and system stability, with SCOP improvements of around 5.6%, 7.2%, 8.7%, and 9.6% observed at seepage velocities of 15, 30, 60, and 90 m/year, respectively. Nevertheless, it was noted that while increased seepage velocity substantially enhanced GSHP operating energy efficiency in summer, it led to a slight decrease in efficiency during winter. The current study compares long-term performance in various climates and case studies, which has not been conducted specifically for Japan. Therefore, the main objective is to classify climates based on the magnitude of load imbalance and to differentiate regions based on their heating and cooling loads. The proposed research will provide a more realistic model to predict long-term performance and also help the industry to select the appropriate combination of hybrid system components.

## 2. METHODOLOGY

This research focuses on eight different cities in Japan, which are located in various climatic regions. These regions have different dominant heating and cooling patterns, resulting in imbalanced loads during the summer and winter seasons. The reference case for this study is Akita City, which has an actual GSHP system that allows us to create an accurate and validated model using experimental measured data. After developing and validating the model based on the available data in Akita City, the input data, such as meteorological data and ground temperature, were changed for the next case study. In order to estimate the hydro-thermal parameters of the ground, the existing GHE in Akita City was numerically modeled using MATLAB software and with the help of the MLS (moving line source) method. The parameters, including groundwater velocity and thermal conductivity, were derived through iterative simulation until the simulated results aligned with the TRT data. These parameters were subsequently employed as input values in the GHE module in TRNSYS software. The building was also modeled in TRNBuild software to calculate the required heating and cooling load in the case studies. It uses weather data from the case study regions to compute heating and cooling loads based on monthly schedules and set temperatures during winter and summer seasons. Finally, the GSHP system, including all components, was modeled in TRNSYS software to analyze long-term operation for all cases. This model uses the building and GHE modules from the previous steps, serving as the load side (building loop) and source side (ground loop) for the GSHP system. To validate the GSHP model, the outlet temperature of the GHE and recorded room temperatures were matched with the simulated results.

**2.1 Load calculation for the building**

An actual student office building situated in Akita City was selected as the target for modeling and calculating the heating and cooling load for all case studies. The building model was created in TRNBuild software based on the characteristics of the sample office building. The office has a total conditioned area of about 100 m$^2$, with a floor-to-ceiling height of 3 m, and is considered as a single zone. The office is operational from 8 am to 8 pm on weekdays (Monday to Friday) and has reduced occupancy on weekends (Saturday and Sunday). For all case studies, the thermostat set points were set to 21 °C and 24 °C for heating and cooling modes in winter and summer, respectively. Details related to the building envelope characteristics and other operational settings for heating and cooling, including internal heat sources and daily air change rate, are listed in Table 1.

Table 1. Building characteristics and settings in load calculation.

| | |
|---|---|
| Room area | 100 m$^2$ |
| Heating and cooling period | Based on the schedule for each city |
| Daily heat gains | • 25 students working based on schedule during weekdays (130 W/person) *<br>• Lights (10 W/m2)<br>• Personal computers and printers |
| Daily air change | 0.4 × Participation schedule ** |

* ASHRAE: Degree of activity IV (moderately active office work).
** The constant value is multiplied by the students' weekly presence timetable described above.

The model mentioned above calculates dynamic hourly loads for different case studies by altering the weather data for each case study in the input file. The model shown in Figure 1 is the same for all case studies, but the modules for "weather data" and "seasonal schedule" differ. Weather data files in TM2 format were prepared for the cases, which were then used to replace the weather module and calculate heating and cooling loads.

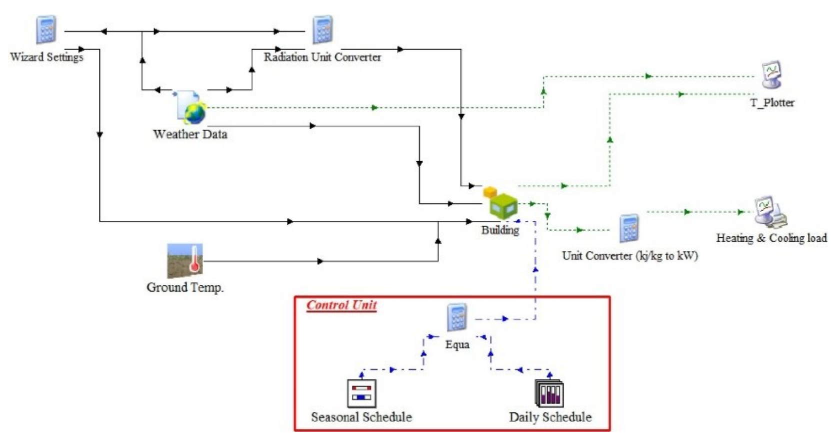



**Fig. 1. Simulation model for heating and cooling load calculation using sample building sketch**

## 1.1. Ground source heat exchanger model

In this section, we modeled the existing Ground Heat Exchanger (GHE) located on the Akita University campus as a key component of the Ground Source Heat Pump (GSHP) system. Although the GHE module already exists in the TRNSYS software, the main purpose of this section was to estimate the ground properties necessary for the module's input tab. The GHE is an un-grouted well with a depth of approximately 60 meters and a diameter of 230 millimeters. A steel casing with an outlet diameter of 150 millimeters was inserted up to the bottom of the GHE. From 45 meters to 50 meters of the well was slotted to allow the groundwater to flow into the GHEs. Finally, small gravel with a grain size of 5-15 millimeters was used to fill the gap between the ground and the casing.

In order to simplify the numerical model, the ground surrounding the GHE (geothermal heat exchanger) was assumed to be a homogenous porous medium that was saturated with groundwater. This allowed for the estimation of the overall average thermal conductivity and groundwater velocity for the entire system. The heat transfer around the BHE (borehole heat exchanger) can be expressed as a combination of conduction and convection through a saturated porous medium consisting of both soil and groundwater in its pores.

$$\rho c \frac{\delta T}{\delta t} + \rho_w c_w \vec{V}.\nabla T = \nabla.(\lambda \nabla T) \quad (1)$$

Where $\lambda$ and $\vec{V}$ represent the overall effective thermal conductivity and the average groundwater velocity of the porous medium, respectively; $\rho c$ denotes the volumetric specific heat of the porous medium including soil ($s$) and water ($w$) in its pores. While $\rho_w c_w$ is the volumetric specific heat of only water. It can be concluded from the first and second parts of the above equation that heat is conducted through both water and soil. However, only water causes heat convection.

The solution of the Eq. 1 assuming the infinite porous medium with an initial temperature ($T_0$) and a constant line source with heat flow rate per unit length ($q_l$), can be an accepted approximation of thermal response of a GHE during TRT. The BHE was modeled using the MLS method, which replicates and reproduces the temperature increases during TRT based on polar coordinate ($\theta$), distance from the borehole wall ($r$), and time ($t$) [19]. This equation calculates the temperature increase at the borehole wall ($T(r,\theta,t) - T_0$).

$$T(r,\theta,t) - T_0 = \frac{q_l}{4\pi\lambda} \exp\left(\frac{Ur\cos\theta}{2\alpha}\right) \int_0^{\frac{r^2}{4\alpha t}} \frac{1}{\eta} exp\left\{-\frac{1}{\eta} - \frac{U^2 r^2 \eta}{16\alpha^2}\right\} d\eta \quad (2)$$

In this equation, $\eta$ is the integration parameter, $U = u\rho_w c_w/\rho c$, and the effective thermal diffusivity is $\alpha = \lambda/(\rho c)$. According to the Eskilson model [20], it is assumed that the groundwater velocity is uniform and parallel to the ground surface in the whole model. Therefore, $u$ is the Darcy velocity that crosses the borehole in the $x$-direction (direction parallel to the ground surface). This model accurately predicts the overall thermal conductivity and groundwater velocity when the simulation data fits and aligns with the TRT data.

Afterwards, the mean working fluid temperature ($T_{mf}$) from TRT can be obtained by using the thermal network resistance concept by Eq. 3 that includes borehole resistance ($R_{bh}$) [21].

$$T_{mf} = T(r,\theta,t) + T_0 + ql.R_{bh} \quad (3)$$

$$= \frac{q_l}{4\pi\lambda} \exp\left(\frac{Ur\cos\theta}{2\alpha}\right) \int_0^{\frac{r^2}{4\alpha t}} \frac{1}{\eta} exp\left\{-\frac{1}{\eta} - \frac{U^2 r^2 \eta}{16\alpha^2}\right\} d\eta + T_0 + ql.R_{bh}$$

An electrical heater with a maximum power of 6 kW was used for a Thermal Response Test (TRT). The monitoring and data collection module measured the inlet and outlet fluid temperatures and the flow rate. The TRT lasted for 48 hours, with a heat load and a fluid circulation flow rate of 3 kW and around 20 L/min, respectively. Fig. 2 shows the best fit of TRT data and estimated ground parameters corresponding to the minimum RMSE equal to 0.1 °C. The solution revealed that the overall thermal conductivity and groundwater velocity of the existing Ground Heat Exchangers (GHEs) in the field were λ = 3.79 W/m K and v = 14.83 cm/day, respectively. These values were used as input parameters in the GHE module for the Ground Source Heat Pump (GSHP) system model in TRNSYS software. However, the average ground temperature in the GHE module was changed based on available data in literature, while these parameters were identical for all cases.

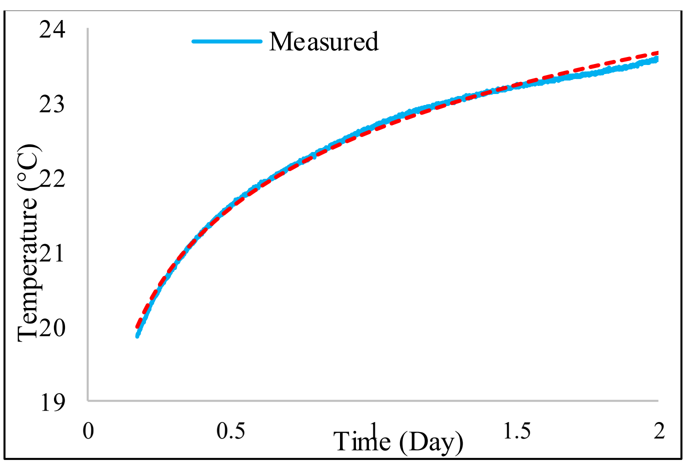



**Fig. 2. Best fit of MLS model ($T_{mf}$) and TRT data.**

## 1.2. GSHP model simulation

The GSHP system was developed in TRNSYS, comprising the building and GHE modules from the previous steps. Moreover, a water-to-water heat pump unit with a variable-speed compressor, which maintains a constant set temperature of water on the load side, was integrated into the system. This unit is configured to supply two fan coils inside the room (load side) with temperatures of 40 °C in winter and 8 °C in summer during the heating and cooling operations, respectively. On the source side (ground side) of the heat pump unit, the working fluid circulates within two double U-tube GHEs in two parallel boreholes, each with a depth of approximately 65 m and spaced 5 m apart. The system is controlled by On/Off thermostats that control and maintain room temperature at set temperatures of 21 °C and 24 °C for heating and cooling modes, respectively. In addition, the heat pump, fan coil, pump, and GHE circulation are controlled based on signals received from the control unit, which was programmed in accordance with hourly, daily, and seasonal schedules for air conditioning. The simulation of the GSHP-based HVAC system is shown in Fig. 3.

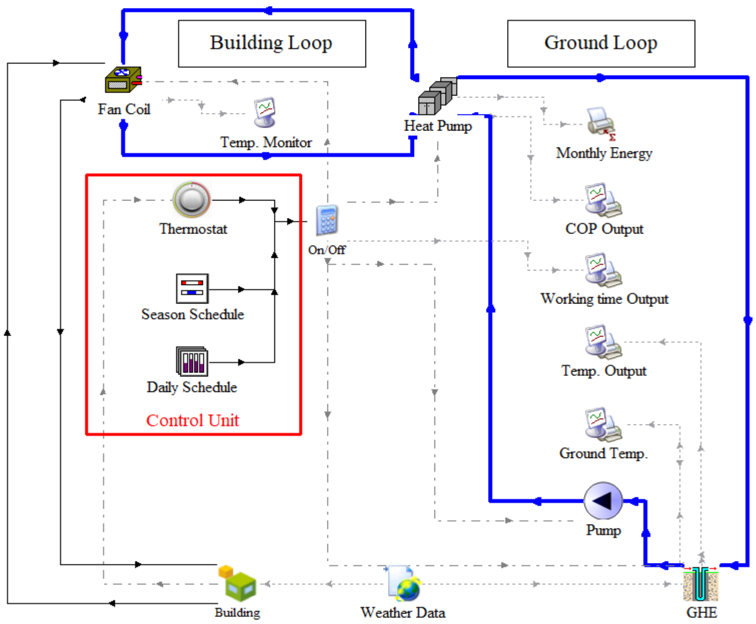



**Fig. 3 Simulation model of GSHP system in TRNSYS software.**

## 2. RESULTS AND DISCUSSION

### 2.1. Hourly dynamic heating and cooling loads

The study examines different cities in Japan that have varying climates. The cities were chosen from different regions with different heating and cooling seasons, leading to a significant difference in the cumulative heating and cooling loads. The study uses the same GSHP system setup and layout for all the cities, however, the heating and cooling loads are calculated based on the recorded weather data and monthly air-conditioning schedules. The loads are calculated for winter, summer, and off-season for each city, based on the needs and preferences of the inhabitants. To understand the imbalance load, some case studies were selected from the same climatic region with identical heating-cooling schedules, but different in cumulative and peak loads. The heating and cooling schedules for each city are listed in Table 2. Notably, Okinawa City does not require heating operation as it is located in a hot island in the southwestern part of Japan. On the other hand, Sapporo City requires cooling in August, although residents only use the cooling system partially on select days during this month.

Table 2. Heating and cooling schedule for the case studies.

| Case study | Heating period | Cooling period |
|---|---|---|
| Sapporo | Oct – May | Aug |
| Akita | Nov – Apr | July – Sep |
| Sendai | Nov – Apr | July – Sep |
| Tokyo | Nov – March | Jun – Sep |
| Osaka | Nov – March | Jun – Sep |
| Kyoto | Nov – March | Jun – Sep |
| Fukuoka | Nov – March | Jun – Sep |
| Okinawa | - | May – Nov |

The dynamic hourly heating and cooling loads were calculated for the case studies using their meteorological data in TRNSYS software, based on the building envelope characteristics of a typical Japanese house. After the load calculation, the cumulative values, peak points, and the differences in heating and cooling loads within a year were determined for the case studies and listed in Table 3.

Table 3. Annual building load for different case studies in Japan.

| Case study | Peak load (kW) | | Cumulative load (kW) | | Cooling and heating difference (kW) |
|---|---|---|---|---|---|
| | Heating | Cooling | Heating | Cooling | |
| Sapporo | 71.45 | 47.11 | 43,147.02 | 12,986.93 | 30,160.09 |
| Akita | 62.00 | 54.22 | 39,414.30 | 20,350 | 19,063.46 |
| Sendai | 49.24 | 44.70 | 24,482.75 | 16,020.29 | 8,462.46 |
| Tokyo | 36.19 | 46.29 | 13,211.68 | 27,313.06 | -14,101.39 |
| Osaka | 42.38 | 48.38 | 16,371.19 | 33,560.14 | -17,189 |
| Kyoto | 47.26 | 47.49 | 20,785.36 | 31,583.37 | -10,798 |
| Fukuoka | 39.27 | 49.75 | 14,303.84 | 31,085.58 | -16,781.7 |
| Okinawa | 0 | 46.93 | 0 | 53,456.73 | -53,456.73 |

These values demonstrate the differences in climate and the imbalance between heating and cooling loads in various case studies. Positive load difference values indicate areas dominated by heating, while negative values represent regions dominated by cooling. In this study, Sapporo and Okinawa cities ranked as heating-dominated and cooling-dominated regions, respectively, with the highest negative and positive values. Following Sapporo, Akita and Sendai City were the second and third heating-dominated regions. Similarly, in the cooling-dominated group, Osaka, Fukuoka, Tokyo, and Kyoto were followed by Okinawa City. However, ranking these case studies solely based on their cumulative loads can be challenging due to the presence of peak points in their heating and cooling loads. It should be noted that the rank of cities in the cooling and heating groups based on the cumulative load may not reflect their ranking based on the peak load. For instance, even though Sapporo is considered the most heating-dominated area, its heating peak point is higher than that of the strongest cooling-dominated case study (Okinawa). Conversely, the second-ranked heating-dominated area (Akita City) experienced a larger cooling peak point than some of the cases classified as cooling-dominated. Therefore, peak points are essential parameters in addition to cumulative loads, as explained in the following sections.

## 2.2. Long-term efficiency assessment

The ground temperature around the GHE was predicted for all case studies over a 15-year operation period, a typical lifespan for HVAC systems in previous studies [16]. The temperature showed severe change for the cities with a higher TIR, such as Okinawa City.

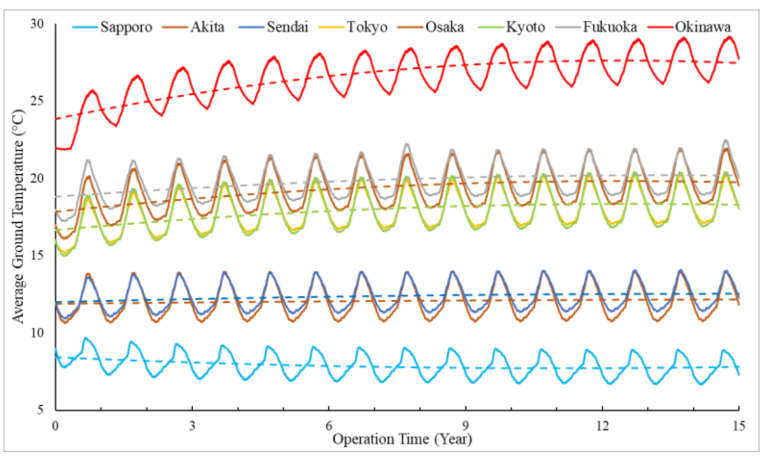
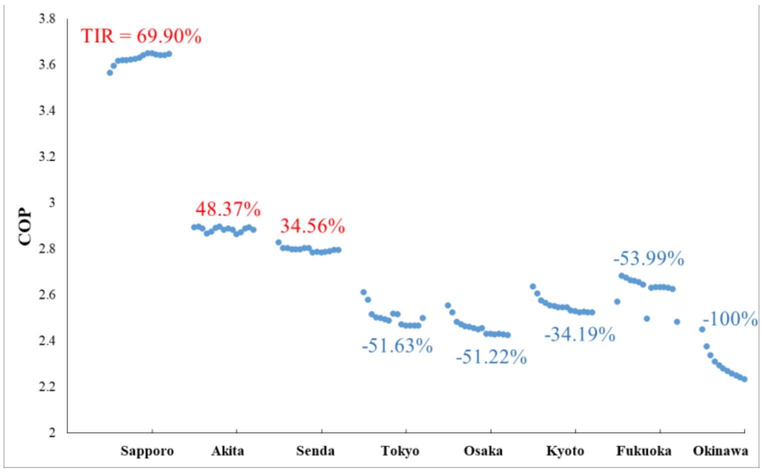



**Fig. 4 The comparison of ground temperature during 15-year operation for the case studies.**

In Figure 4, it is shown that the mean ground temperature in a particular city has increased from 21.87 °C to 26.18 °C, which is a substantial increase of 4.31 °C. This significant rise could have a potential impact on the performance of the system in the later years of its operational life. The efficiency of a Ground Source Heat Pump (GSHP) system depends on the temperature difference between the ground and the operating temperature of the system. As the temperature difference decreases, the ability of the system to reject heat also decreases. This is because rising ground temperatures reduce the temperature differential, which in turn reduces efficiency. As a result, the Coefficient of Performance (COP) of the system decreases, meaning that more energy is required to supply the same amount of cooling load. Similarly, Osaka City, which holds the second position in the TIR among cooling-dominant climates, has also experienced a relatively significant rise of approximately 2.27 °C. Tokyo, Kyoto, and Fukuoka have better conditions with only an increase of around 1.93 °C, 1.91 °C, and 1.70 °C, respectively. On the other hand, in Hokkaido City, which is a heating-dominated area, the ground has experienced heat loss, decreasing from 7.76 °C to 6.68 °C, a change of 1.09 °C, after 15 years of operation. Fortunately, the ground temperature remained almost constant for Akita (0.12 °C) and Sendai (0.47 °C) cities. This stability may be due to the monthly schedule for heating and cooling. When comparing these two cities to Sapporo, which is a city dominated by heating, it becomes clear that Sapporo has only one month of cooling and eight months of heating. In contrast, these two cities have three months of cooling and six months of heating. As a result, the heat is partially replenished by injecting heat during those three months.

## 2.3. COP degradation in 15-year operation

The following text describes a comparison of the COP (Coefficient of Performance) of GSHP (Ground Source Heat Pump) systems over a 15-year period across different case studies. The trends of the cooling and heating COP are shown separately in Fig. 5. For cities that are mainly cooling-dominated areas, the cooling COP decreased while the heating COP improved during the system's lifetime. This happened due to the cumulative heat injection into the ground and an imbalance load that increased the ground temperature over the long-term operation. However, for Okinawa City, where there was no heating period and the system was solely used for cooling, the heating COP was not depicted in the figure. Compared to other cooling-dominated cases, the cooling COP experienced a harsher decrease with the maximum decline rate of around 0.015/year, whereas the average value was calculated around 0.006/year for other cases in their heating or cooling COP based on the region and climate they were located in. For the other cooling-dominated areas, the decrement rate of cooling COP was around 0.0075/year, 0.0085/year, 0.0074/year, and 0.0059/year for Tokyo, Osaka, Kyoto, and Fukuoka, respectively. On the other hand, the heating COP decreased at a rate of 0.00124/year for Hokkaido City due to severe load imbalance and dominant heating load compared to the cooling load in this city. However, the conditions for the other two cities (Akita and Sendai City) were more favorable, as their COP remained nearly constant throughout the long-term operation. As mentioned earlier (Fig. 10), this might be due to small difference in the absorbed and reinjected energy to the ground and consequently, smaller ground temperature change of the ground. To analyze the influence of TIR (Thermal Interaction Ratio) on COP, the TIR value is shown for each case study on top of the COP trend in a 15-year operation. This value is written in red and positive for heating and blue and negative for cooling areas.



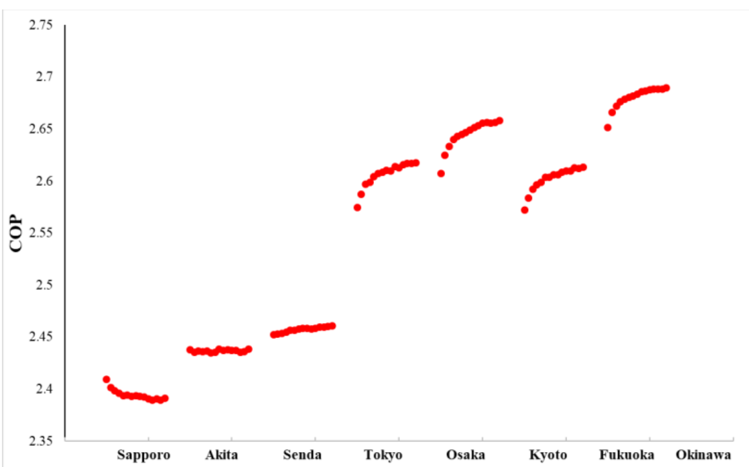




**Fig.5 cooling (top) and heating (below) COP of the GSHP system over the 15-year operation in all case studies (TIR values are shown for each city in positive for heating dominated and negative for cooling dominated regions)**

**CONCLUSION**

This study presents a comparative and predictive model for the GSHP system, which assesses its long-term performance across various climatic regions in the country. The model comprises three interrelated parts, each modeled in different software: TRNBuild for the building, MATLAB for the GHE, and TRNSYS for the GSHP system. To validate the models, actual recorded data from the existing GSHP system in Akita City was used as a reference case study. The thermal imbalance ratio (TIR), a parameter that explains the behavior of the system in different cities, was introduced to provide clear insights into the level of load imbalance in different cities, categorizing them into heating- and cooling-dominated cases. The key findings of this research can be summarized as follows:

- A model was proposed to evaluate the long-term performance of a Ground Source Heat Pump (GSHP) system by taking into account the load cumulative load imbalance in different climatic regions of the country. The model's accuracy was tested by using actual recorded data from an existing system in one of the considered case studies. Additionally, the accuracy of the Ground Heat Exchanger (GHE) module was independently tested using TRT field-test data.

- Various cities from different climatic regions in Japan were chosen, and their meteorological data was utilized for calculating the heating and cooling loads. The cumulative heating and cooling loads, as well as their respective peak loads, differed significantly among the case studies. These variations were due to differences not only in their climates but also in their unique monthly schedules for heating and cooling operations.

- It was found that in some case studies, the level of cumulative loads did not correspond with the peak heat load points. This means that the city with the highest cumulative heating or cooling load did not necessarily have the highest peak load. The conclusion was drawn that the peak heat load point is mainly affected by the stability of the weather or the fluctuation in ambient temperature in the case study.

- The cities with the highest cumulative and peak load ratios were ranked as heating-dominated cities (Sapporo, Akita, Sendai City) and cooling-dominated cities (Okinawa, Fukuoka, Tokyo, Osaka, Kyoto City).

- The ground temperature trend over the long-term performance of a system, after 15 years of operation, was affected by the cumulative load ratio's magnitude. In hot climates with dominant cooling operations, the ground temperature change was more severe.

- Cases with more significant disruptions in ground temperatures experienced greater COP decrements in their dominant operation. The COP decreased during the dominant season for each city, while it slightly improved for the next operation mode.

- It's important to note that, for all case studies, the ground geology was assumed to be the same and the hydro-thermal parameters were based on the calculated values in the reference case study (Akita City). However, using actual geology data or available TRT data in each city would be much more accurate to calculate the actual thermal conductivity and groundwater velocity. Further research in this area is needed.

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