PROPOSAL FOR THE UTILIZATION OF GROUND HEAT FOR JAPANESE GREEN BUILDING SYSTEMS

Keywords: ground-source heat pump, ground heat exchanger, energy piles, air-conditioning, single-family house, eco-campus, semi-transparent solar panel, efficient energy storage

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Daito Bunka University Itabashi Campus
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Photo1 left : Central Library Building, approached by a huge staircase and equipped with semi-indoor Spine Space which generates interpersonal communication and interchange

Photo1 center, right : Spine Space of the Lecture/Laboratory Halls, covered by semi-transparent soalar panels

Summary

The ground temperatures at 100m in depth range from 10 to 20 °C in Japan. In winter, these temperatures are quite higher than the ambient temperature, and quite lower in summer. Thus, efficient space heating or cooling can be achieved using ground heat.

The utilization of ground heat leads to a reduction in fossil fuel consumption and in carbon dioxide emissions. Also, the utilization of ground heat for space cooling contributes to a moderation of the heat-island phenomenon which is emerging as a serious issue in urban areas.

However, the utilization of ground heat has not been well promoted in Japan because of high drilling costs and high electric power cost. In order to promote ground-source air conditioning systems in Japan, it is essential to reduce construction costs significantly and to achieve substantially higher energy efficiency with the system.

The utilization of energy piles, foundation piles converted into ground heat exchangers, seems to be one effective way of reducing construction costs. In this report, a ground-source air conditioning system using energy piles installed at the Itabashi campus of Daito Bunka University is introduced. A newly developed ground-source air-conditioning system for single-family houses, which has been developed with the aim of reducing construction costs and improving the energy efficiency of the system, is also introduced.

2. First Approach: The Eco-Campus Scheme for Daito Bunka University Itabashi Campus

2.1 Outline of the Redevelopment Project of Daito Bunka University, First Phase

The first phase of the redevelopment project for Daito Bunka University, Itabashi Campus was completed in the year 2003. Over 27 ideas and techniques for comprehensive green building systems are tested and executed, making it a model example for urban campus green building projects.

Two main concepts for the eco-redevelopment of the campus are as follows; The first is to develop new values by creating communal spaces for students with a new internal quadrangle courtyard created by rearranging the setting of the buildings.The second is to create an eco-campus using comprehensively integrated techniques synthesized with architectural design, utility design and facility management systems.

2.2 Highlights of the eco-campus techniques

1. Creation of a semi-indoor Spine Space with minimum artificial air conditioning for un-specified purposes, encouraging students to communicate with each other and with the teachers.
2. Minimizing central conditioning. Small amount fresh air is heated or cooled in central system, by newly developed energies and more efficient systems, then discharged underneath of the rooms floor.

2.3 Newly developed energies

1. Semi-transparent Solar Electricity Generating Panels which cover approximately 750m2 of the southern facade and the roof of the Spine Space of Lecture Hall No.3,
2. Efficient utilization of the ground heat, represented by over 4.8 of COP, with a ground-source heat pump system that utilizes energy piles, i.e., foundation piles converted into ground heat exchangers.
3. Efficient energy storage with rain water storage, using the basement floor of the existing library building which has been demolished, and above which is created as a central community plaza, and the energy source of which is the efficient usage of the exhaust thermal energy of the gas co-generation system.

2.4 Eco-Campus Schemes

1. "The eco-campus, a fusion of the architectonic cross-section and the utility system"

As an eco-campus the importance of natural air flow, has been emphasized, and low-tech methods of air flow and heat flow have been comprehensively developed, integrating the architectonic cross-section and the utility system. The various techniques developed numbered 27 items, and successfully synthesised the overall space into one "flow."

2."Basic low-energy air-conditioning system, adding natural energy to the ventilation"

Air conditioning is limited to specific purpose spaces. An amount of fresh air appropriate for the ventilation is discharged into each room via the perimeter of the floor from an underground heat storage pit where humidity and temperature are controlled, where pre-cooling or heating takes place. Individual thermo-regulation with a GHP heat pump is done only when essential. Advantage is taken of the flow of air and heat created by the draft from above (wind tower effect). As far as possible, unused and ineffectively used energy are employed.

3. "External insulation and air tightness capacity of basic body performance"

Besides using external insulation, wooden sash frames, pair glass insulation and a high basic body of air tightness, use has been made in the second phase of construction of multi-service tunnels as cool tubes, geothermic availability of ground energy through hollow piles and a method of thermal storage cogeneration of exhaust heat. Thus has been achieved a fusion of the outside air introduction type air conditioning method, (a principle of the middle phase), with the architectonic cross-section form. A room temperature of 12-15°C is maintained even in winter.

2.5 Specified Topics from the eco-design ideas

1. "Ground heat pump using hollow piles"

Though the ground heat pump using hollow piles has been adopted here experimentally, the result of using 2 U-tubes in 23 piles at about 25m was a heated (cooled) energy performance of 50-70KWH. Also the cost performance is good, and even in temperate zone monsoon areas, it can be a very effective method of tapping future unused energy. This is explained in detail in the second chapter.

2. "Development of a 750m² see-through type photovoltaic power generator panel"

See-through type photovoltaic power generator panels enclosing solar battery cells in laminated glass are used on the south façade of Building No. 3 and on the roof surface. Units of stainless steel pipes are arranged alternately with these, bamboo-blind fashion, the spine enclosed by a screen. The modular solar battery cells on the wall and roof are sensitised so that each cell knows exactly when to soften the glare of the south summer sunlight or encourage the warm inflow of winter light. This screen creates a bright and open architectural space. Moreover, it has the effect of reflecting the movement of the people in the spine as a moire pattern. In Phase 2 of the construction, when the demolition of the old library is completed, the complete shape of the screen facing the courtyard will become apparent.

3. "Natural illumination with light shelf"

According to the lighting plan, in Lecture Hall, a skylight is introduced through the north-facing light shelf. By means of a section form, light from the skylight reflected on the ceiling of the outside terrace is brought inside. Zone lighting control is used as a lighting energy conservation measure.

4. "Load reduction policy"

Countermeasures taken to reduce the impact of solar radiation from the west include deep eaves on the south and east sides of spine space; wood insulation for the external wall; tree planting on the roof and the fixing of cross-vertical louvers made of polyester on the west side of the Central Block. During execution, various materials were verified with the wind tunnel experiment, and photo catalyst techniques were used to prevent pollution.

2.6 Specific topics from the eco-design ideas

1. "Utilization of Ground Heat in the Itabashi Campus of Daito Bunka University"

(1) Use of Ground Heat with Hollow Piles

We have implemented a method for gathering ground heat by using 23 hollow piles (PHC piles of 20m to 25m), which are structurally required in the lecture building, and inserting heat-exchange tubes into the hollow part of the piles. Water is circulated in the tubes through a sealed channel where it gathers ground heat (about 17ºC) that is stable throughout the year, and then the water is supplied as cooling/heating water through a water-cooled heat pump chiller. The cooling/heating water is supplied to the primary coil of an "air conditioner for treatment of outside air" in the lecture building, where it is used as a heat source for treating outside air.

In order to confirm the responsiveness of ground heat exchange, which is expected to fluctuate according to area, we carried out a thermal response test after insertion of the heat-exchange tubes during the construction of the lecture building. As a result of the thermal response test, we determined that a heat radiation load of 73w/m can be obtained during air-cooling seasons, and a heat collection load of 52w/m can be obtained during air-heating seasons (Fig. 5). These were the predicted results.

According to measured values obtained after the lecture building was completed, it was confirmed that a heat radiation load of 64w/m could be obtained during air-cooling seasons, and a heat collection load of 78w/m could be obtained during air-heating seasons. Thus, we obtained favorable results that were equivalent to the predicted thermal response values.

As a result of having calculated the equipment efficiency of the water-cooled heat pump using ground heat from the input energy and output energy amounts of the same device, we obtained a COP of 3.9 for air-cooling seasons and a COP of 4.8 in air-heating seasons, both of which were very good values.

Furthermore, from measurement temperature progress graphs for the inside of the pile, the outside of the pile, and the background (part which is not thermally affected) when ground heat is used, we ascertained that the outside of the pile and the background are less affected by the use of ground heat, and that the influence of outside air temperature is observed only slightly at the shallow level of GL-5m. Although the drop in temperature on the inside of the pile when ground heat is used was a little larger than we originally estimated, the temperature rise (recovery) after equipment operation was stopped progressed within an estimated period of time. Therefore, we consider the long-term balance between income and expenditure of energy using ground heat to be valid (Fig. 6).

(2) Utility-Tunnel Cool/Hot Tube

Fresh outside air (54,000m3) introduced into the building is supplied from an air supply tower installed at the "community square" using part of a utility-tunnel (total of 150m) constructed under the building as a supply conduit. Outside air is cooled or heated by the "cool/hot tube effect" in the utility tunnel, which is treated with anti-fungal coating, and is sent to the air conditioner for treatment of outside air. According to measured values obtained after the lecture building was completed, it is clear that the amount of outside-air reduction energy attributable to the cool/hot tube effect could be 1,858MJ/day during air-cooling seasons and 1,805MJ/day during air-heating seasons. It has been confirmed that the effect is particularly large at the day time of the cooling season and at the morning and evening time of the heating season, and that there is a difference of 5ºC at the cooling season, and 4.4ºC from the outside air temperature.

2.7 Discussions

The construction costs for the project in Daito Bunka University, which utilized double U-tubes in 23 hollow piles (25m deep), was significantly low. The see-through type solar energy generation panel installed on the same building generates 30kw of energy and cost 75 million yen, whereas the piping and the heat pump system utilizing these hollow piles collect approximately 70kw of energy and cost as little as 18 million yen for 46 sets.

Utilizing the fundamental piles eliminates well-digging cost; therefore simply the piping and the heat pump system accounted for the costs.

In order to identify how much energy could be utilized, however, the investigation had to be carried out with testing piles, and the heat collection interval and the heat pump capacity had to be decided according to the results.

For the future, the prediction technique by means of ground heat conductivity and the engineering capability to design with less drilling surveys in the field should be further developed and improved.

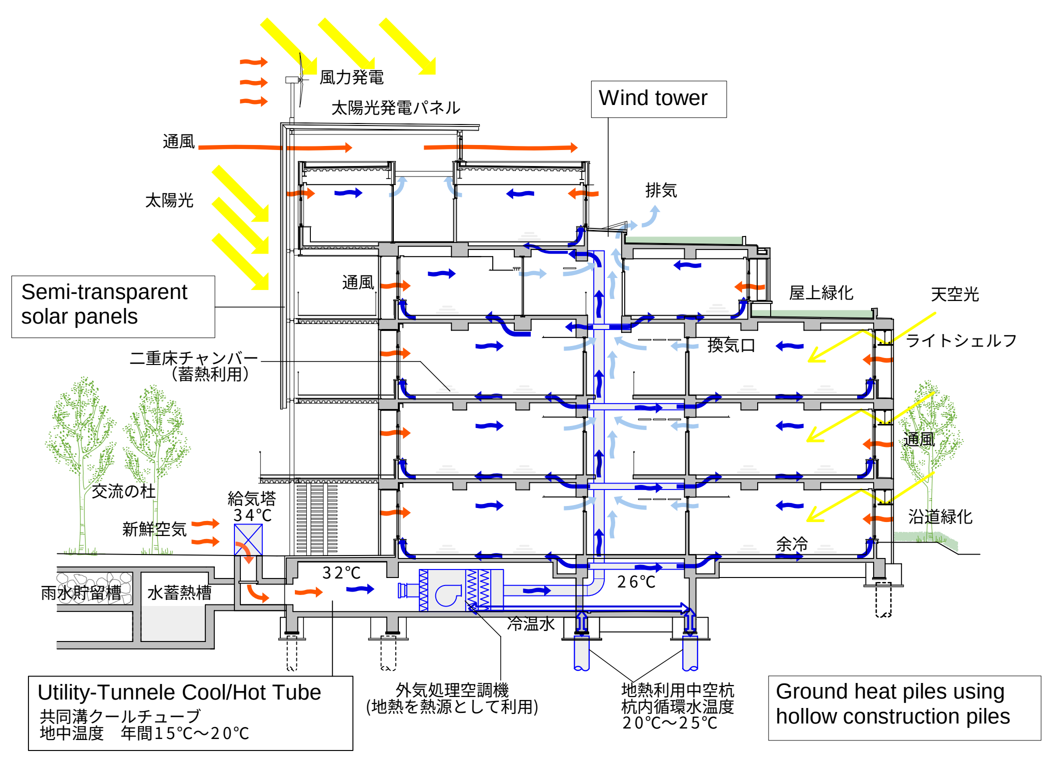


Fig2, Cross-section of the Lecture-Hall & Laboratory Building, showing the natural energy flow system

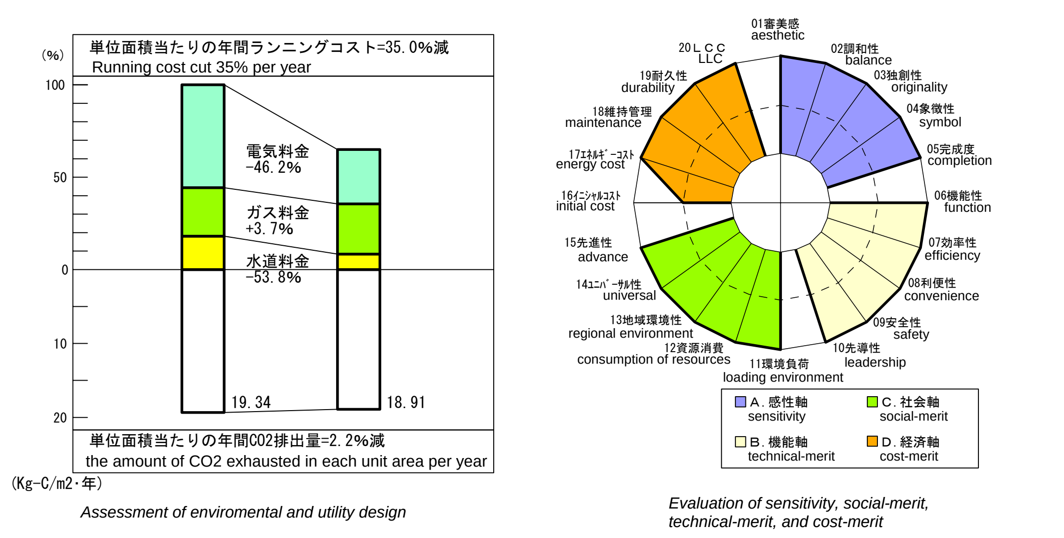
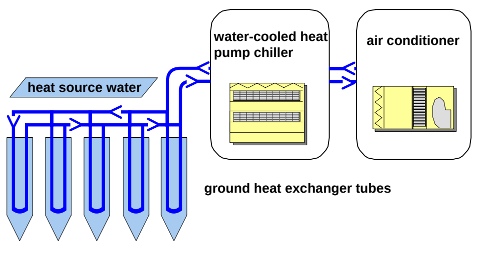


Fig.3 Assessment of environmental and utility design. (in eco-design for the Daito Bunka University)



Terrestrial water-cooled heat pump chiller using ground heat

Cooling capability: 53kw (15RT), Heating capability: 43kw

Hollow-pile insertion-type heat-exchange tube for use of ground heat

46 sets of high-density polyethylene tubing having a total length of 1,982m

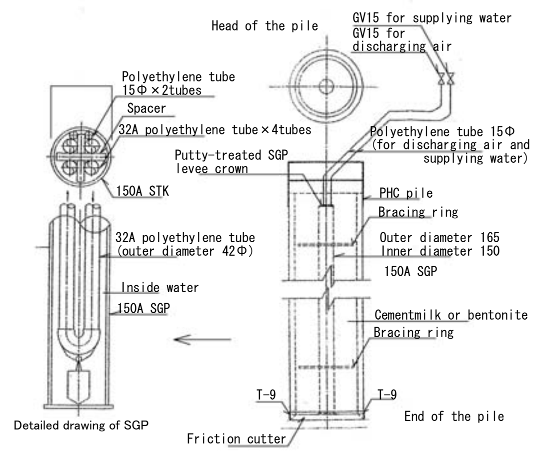


Fig.4 Layout of Ground Heat Tube Pile

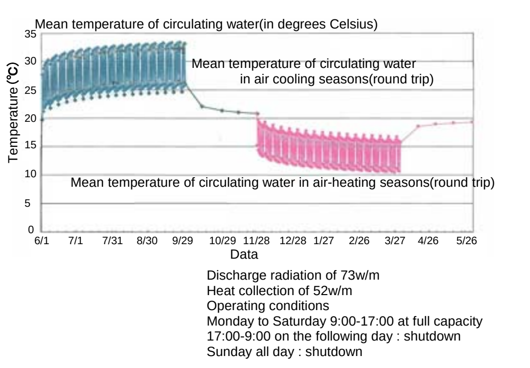


Fig.5 Estimated thermal transition of circulating ground water

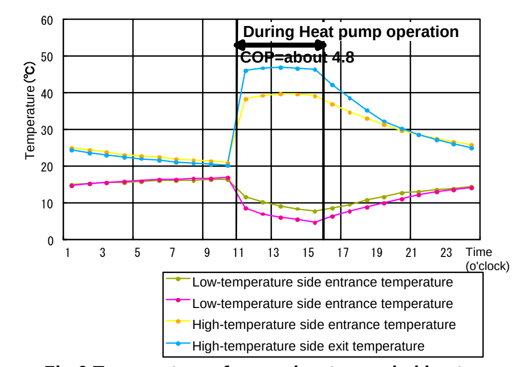


Fig.6 Temperature of ground water-cooled heat pump measured at the opening

Photo2 :left: Vertical cloth louver center : Curved ceiling of the library right : Light-shelfs, for Lecture halls

1. The Potential of Ground Heat and Barriers to Its Promotion in Japan

1.1 Barriers to the Promotion of Ground-Source Air-Conditioning Systems in Japan

The increase in the number of installed Ground-Source heat pumps (GSHPs) has been remarkable in the United States, Sweden, Germany, Switzerland etc. In contrast, only a small number of the GSHPs have been used in Japan. The total number of the GSHPs functioning in Japan is estimated to be 120 to 200. Most of these are groundwater-source heat pumps. Thus, the utilization of ground heat has not been well promoted in Japan. The major reasons for this are as follows:

・High drilling costs

Unconsolidated and easily collapsible sedimentary formations are commonly distributed throughout inhabited areas of Japan. For this reason, drilling costs are approximately 10 and 5 times higher than those in the United States and Sweden, respectively. Hence, the total cost of the system is very high in comparison with that of conventional air conditioning systems.

・High electric power costs

It is said that the target COP (coefficient of performance) of the heat pump in GSHP systems is about 3 in countries which commonly use these systems. However, in Japan, the price of electric power per unit heat amount is 3.7 times higher than that of heating oil. If the COP of the heat pump were at the same level as those of above mentioned countries, it would be impossible to achieve cheaper running costs than the systems which burn oil.

・Low heat transfer performances in formations

Since unconsolidated sedimentary formations are widely distributed in Japan, the effective thermal conductivities of formations are generally small. The in-situ effective thermal conductivities of the formations measured by the authors range from 1.2 to 1.8W/m・k. They are quite small compared with those in Northern European countries and Switzerland where formations mainly consist of rock. For instance, in Sweden, formations of effective thermal conductivities ranging from 2.5 to 4.0W/m・k are widely distributed (Ohtani et al., 2003). Also, it is said that the effective thermal conductivities of formations are 2.0 to2.6W/m・k in Switzerland (Rybach, 1994). This indicates that longer ground heat exchangers, and thus higher construction costs, would be necessary in Japan as compared with these countries.

Conditions in Japan for applying ground-source air conditioning systems are much more severe than in countries where the GSHPs use has been rapidly increasing. In order to promote ground-source air conditioning systems in Japan, it is essential to reduce construction costs significantly and to achieve substantially higher energy efficiency with the system.

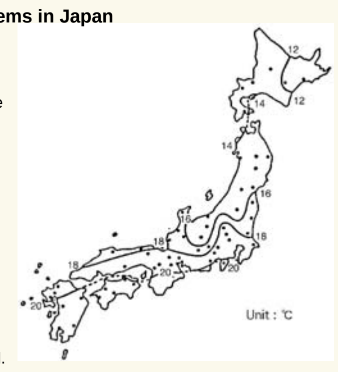


Fig. 1 Groundwater temperatures at 100m in depth in Japan (Yamamoto,1983)

3. Second Approach: Development of a Ground-Source Air Conditioning System for Single-family Houses

Despite high drilling costs and high electric power prices in Japan, our economical analysis of a 4,000m2 class building indicated that a ground-source air conditioning system was more economical than an oil-fired absorption chiller/heater system in the long term. This indicates that there is a greater possibility for the ground-source air conditioning system to be economical in relatively large buildings.

In regard to systems for single-family houses, the construction costs and energy efficiency of conventional ground-source systems have been far from economical, except for the case of groundwater-source systems. The authors have been developing a new air-conditioning system in cooperation with Kyushu University aiming at achieving a practical system. A prototype of the system was installed in December 2004 in Fukuoka City in a house built for experiments, and the operational data have been collected to evaluate performance of the system.

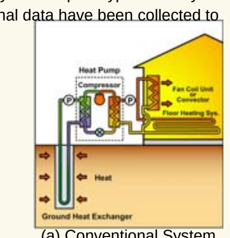
3.1 Concept of the Developed System

Schematic drawings of the conventional system and the newly developed system shown in Figure,55 can be applied up to 150m2 class single-family houses with up to 5 rooms.

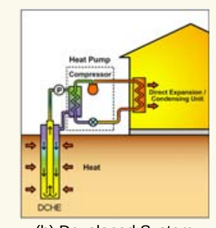
Single or double U-tube heat exchangers have been commonly employed in conventional systems in Japan as they have been abroad. In the developed system, **the Downhole Coaxial Heat Exchanger** (DCHE; Morita et al., 1985; Morita and Tago, 1995) proposed by the authors together with others is utilized. It is said that the specific heat extraction rate, i.e., heat extraction rate per unit length of the heat exchanger, of the single U-tube heat exchangers is around 20W/m and the double U-tube heat exchangers about 40W/m. On the other hand, a seasonal average specific heat extraction rate of about 90W/m has been obtained at 1.25 W/m・K of small effective thermal conductivity of the formation with the DCHEs in a snow-melting system (Morita and Tago, 2005).

In the developed system, direct expansion/condensing units are utilized. Because of this, the system is greatly simplified and the number of component parts can be reduced significantly. Installation of the air-conditioning refrigerant pipes is significantly easier than with conventional systems that circulate water or anti-freeze. These factors make the installation of the total system much easier. Hence, equipment and installation costs can be reduced considerably.

Moreover, the necessary pumping power might be less than one half that of the conventional system. This leads to a higher COP of the system. In the developed system, only one stage of heat exchange is necessary to transfer heat from the refrigerant gas to the ground heat exchanger. Meanwhile, two stage heat exchanges are necessary in conventional systems. Thus, the temperature loss in the indoor-side heat transfer circuit is smaller than with conventional systems. This leads to a higher COP of the heat pump.



(a) Conventional System



(b) Developed System

Fig.7 Comparison of conventional and developed ground-source air-conditioning systems for single-family houses

3.2 Estimated Required Length of the Ground Heat Exchanger and Performances

An investigation of the developed system was performed by carrying out numerical simulations to estimate the required length of the ground heat exchanger and to obtain knowledge on the operational performance of the developed system in four major cities in Japan, Sapporo, Sendai, Tokyo and Fukuoka.

In this investigation, a 150m2 class standardized single-family house which meets the Japanese next-generation energy saving standard was assumed. The hourly base air-conditioning loads calculated based on the standard weather data in each city were used in the simulations. Assumed temperature profiles in the ground for each city are shown in Figure 8. A 1.3 W/m・K of effective thermal conductivity of the ground was assumed in each city.

Table 1 shows the required length of the ground heat exchanger for a single-family house, and the estimated COPs of the heat pump system. These estimated lengths are significantly shorter than those of conventional systems. This indicates that the construction costs of the heat exchanger can be reduced substantially compared with conventional systems.

The estimated length for Tokyo is the shortest. This means that construction costs for the system would be cheapest in Tokyo. Until now, it has been considered that the ground-source air conditioning system is more practical in colder areas such as Northern Honshu and Hokkaido. However, this indicates that there is no less of a possibility of realizing practical ground-source air-conditioning in warmer cities such as Tokyo.

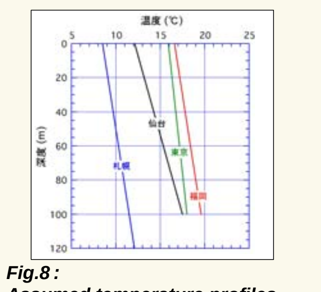


Fig.8 : Assumed temperature profiles in the ground at the major cities.

Table 1 Estimated required length of the heat exchanger and COPs.

City	Sapporo	Sendai	Tokyo	Fukuoka
Required Length of DCHE (m)	105	60	55	65
COP of Heat Pump in Heating (-)	4.5	4.9	5.3	5.5
COP of System in Heating (-)	4.1	4.5	4.8	4.9
COP of Heat Pump in Cooling (-)	9.2	6.1	4.3	4.3
COP of System in Cooling (-)	7.2	5.4	4.0	4.0
Overall COP of System (-)	4.4	4.7	4.4	4.3

The estimated COPs of the system, which include power consumption of auxiliary equipment such as a circulation pump and a control system, range from 4.1 to 4.9 for space heating. These COPs are higher by 1 compared with the conventional systems. Thus, the developed system might be much more competitive with the systems burning oil in terms of running costs. The overall COPs of the system which include space heating and cooling were estimated to be 4.3 to 4.7.

3.3 Discussion

Construction costs for conventional ground-source air-conditioning systems are estimated to be about 5 million Yen for a single-family house. On the other hand, construction costs for the developed system are estimated to be about 3 to 3.5 million Yen in Sendai, Tokyo and Fukuoka. These construction costs could become even cheaper if the system is promoted. It seems that the possibility for the promotion of the developed system is not small.

This investigation indicates that the heat charged into the ground is 2.16 times as great as the heat extracted from the ground in Fukuoka. This suggests that it is desirable to develop a system which can also supply hot water to improve the annual heat balance in the ground in warmer areas in Japan. Such a system might also improve the economic competitiveness of the system. The authors are planning to develop such a system.

This project has been carried out with the aim of developing an air-conditioning system for single-family houses. However, it might also be realistic to apply the same concept to bigger buildings using greater heat pumps.

4. Conclusions

The utilization of ground heat for air-conditioning should contribute to realise green buildings. In this report, a ground-source air conditioning system using energy piles installed at the Itabashi campus of Daito Bunka University and a newly developed ground-source air-conditioning system for single-family houses were introduced.

These two systems might be effective in reducing construction costs of the ground source air-conditioning systems. Also, an investigation of the developed ground-source air-conditioning system for single-family houses indicated that substantially higher COPs than that of conventional ground source air-conditioning system can be achieved with the developed system.

For further development of the design method, more data of temperature profiles and thermo physical properties of formations should be collected in many areas.

These approaches may leads to the future promotion of the ground heat utilisation to a popular system.