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Multi-criteria Evaluation Of River Source Heat Pump Systems In Terms Of Life Cycle Performance

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ABSTRACT

In this study, the feasibility of thermal energy utilization in river source was investigated by evaluating the performance of a river source heat pump (RSHP) system. The performance of the RSHP system is evaluated with the validated WSHP model and the actual demand of an office building. The system performance is comprehensively analyzed in terms of the life cycle performance, considering energetic, environmental, and economic metrics. The energy consumption is converted to the primary energy consumption (PEC). The environmental impact is represented as CO2 emissions based on life cycle climate performance (LCCP). The economic feasibility is derived in terms of the net present value (NPV), internal rate of return (IRR), and payback period (PBP) based on the life cycle cost (LCC). When the RSHP system was applied to office building, the energy consumption and CO2 emissions were reduced by 6.9% and 10.5%, respectively. The results of the economic feasibility study presented a net present value of $10,587,848, an internal rate of return of 20.5%, and a payback period of 5.3 years. In addition, the WSHP system is evaluated under various water source temperature and utility rate conditions for further investigation. The parametric study showed the maximum improvement of the energy consumption, CO2 emissions, and economics are expected to be 16.4%, 19.6%, and 15.2%, respectively.

1. INTRODUCTION

In recent years, water heat pumps (WSHP) have emerged as one of the ways to reduce building energy consumption. The application of WSHP instead of ASHP may improve performance because the water temperature is relatively constant compared to the air temperature. Because of these advantages of the WSHP, they have been actively studied. In the literature review, it is found out that many studies have been conducted to investigate the performance of the WSHP systems under various water source conditions. However, performance evaluation of river source heat pump (RSHP) systems is rarely addressed. Most of the studies focused on seawater, and groundwater, and did not considered a real building model with validated energy system. Moreover, few studies have considered life cycle performance in terms of energy, environmental and economic metrics when evaluating the performance of RSHP systems. To fill this research gap, current research aims to evaluate the performance of the RSHP systems using validated WSHP models and the actual demand of office buildings. System performance is comprehensively analyzed in terms of lifecycle performance, taking into account energy, environmental, and economic metrics. Energy consumption is converted to Primary Energy Consumption (PEC). The environmental impact is represented by CO2 emissions based on Life Cycle Climate Performance (LCCP). Economic performance is derived in terms of Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) based on Life Cycle Cost (LCC). The WSHP system is also evaluated for further investigation under various water source temperatures and utility speed conditions.

2. SYSTEM DESCRIPTION

The performance of the RSHP system was evaluated by comparing it with the conventional system. Figure 1 shows a schematic diagram of the conventional and RSHP systems. The conventional system consists of an electric chiller, a cooling tower and a gas-fired boiler. The electric chiller and the cooling tower that handle the cooling demand of buildings operate as electricity, and gas-fired boilers that supply the heating demand of buildings operate as natural gas. This generated energy is transferred to the building via the heating and cooling coils of the air handling unit (AHU).

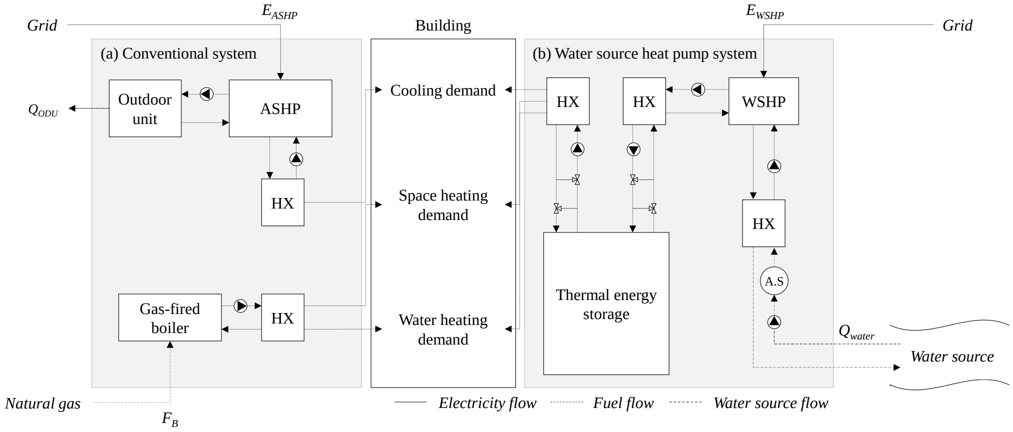

Figure 1: Schematic diagram of conventional system and RSHP system

2.1 Conventional System

The conventional and RSHP system components such as electric chillers, cooling towers, heat exchangers, pumps, heat pumps and thermal energy storage systems were developed as modules and integrated into the system.

The electric chiller is used as a central air conditioning system. It removes heat energy from the building and delivers it to the cooling tower. The electric chiller uses water as a working fluid on the source and load sides. The chiller model was developed using Type 927. The performance map consists of four parameters: inlet source temperature, inlet load temperature, inlet source flow rate, inlet load flow, and inlet load flow. The heat extracted from the chiller is released through the cooling tower. The cooling tower has the advantage of improved cooling performance and stability due to fan use. This model is used to evaporate and cool the liquid flow from the chiller from the outside of the coil. Working fluids in the cooling tower are completely isolated from air and water, and evaporated water is sometimes replenished. This model was designed to the standard specifications of the cooling tower and was developed using Type 510.

Type 751 was used to simulate the transient behavior of gas-fired boilers. The phase change in the working fluid was ignored. The working fluids were assumed to be pure liquids, not vapors or liquid-steam mixtures. The performance of the boiler is defined by its overall efficiency and combustion efficiency. The overall efficiency is the ratio of the output to the input, and combustion efficiency is the ratio of the combustion energy to the input energy. The boiler performance data was obtained from an external data file consisting of inlet liquid temperature and PLR.

The air handling unit consisting of a central air conditioning system transfers the generated cooling and heating energy to the building. The energy generated is transferred to the cooling and heating coils via pumps and heat exchangers, which are supplied to the building via duct fans. The pump is controlled by an inverter. The pump power consumption was calculated taking into account static heads, friction losses and minor losses, and the loss from the equipment pressure in the heat exchanger was ignored. The duct fan is driven by inverter control, and the power consumption is calculated using a flow rate that meets the building demand. The supply air temperature and indoor return temperature were set at 28℃ and 22℃ respectively in winter and 16℃ and 26℃ in summer.

2.2 River Source Heat Pump System

A simulation model of WSHP has been developed. A mixture of water and antifreeze was used to prevent freezing in winter; 20% propylene glycol on the supply side and 10% methanol on the load side. The performance map of WSHP was modeled by three performance curves. The PLR in WSHP was designed as a function of water mass flow on each side of the system. The developed heat pump model was validated with experimental data on two parameters: capacity and power consumption. The heating and cooling capacities were validated within 0.98% and 0.39%, respectively, and heating and cooling power consumption within 0.27% and 0.09%. In the developed performance curve of WSHP, the heating COP is continuously increased as the inlet water source temperature increases or the inlet load temperature decreases. Similarly, the cooling COP increases as the inlet water temperature decreases or the inlet load temperature increases.

The transient behavior of thermal energy storage (TES) has been modeled as Type 534. This vertical cylindrical storage tank is a constant capacity storage tank filled with fluid without a submerged heat exchanger. The TES is assumed to be made from concrete under the building during the initial basic construction phase. The storage tank is insulated using a urethane foam. The internal temperature gradient of the storage tank was analyzed by dividing it into five temperature nodes to model the stratification of the storage tank. Each node has a fluid conduction and convection mechanism to interact with the nodes above and below. The convection is caused by forced flow from the inlet flow and natural de-stratification in the tank.

In addition, the energy consumption of the RSHP system was investigated according to the effect of the river water temperature to further improve the performance. The profile of the river water temperature was generated for four cases as shown in Figure 2. Case 1 is the actual river water temperature profile, and case 4 is the underground water temperature. Cases 2–3 denote an arbitrary water temperature having a temperature distribution between the river temperature.

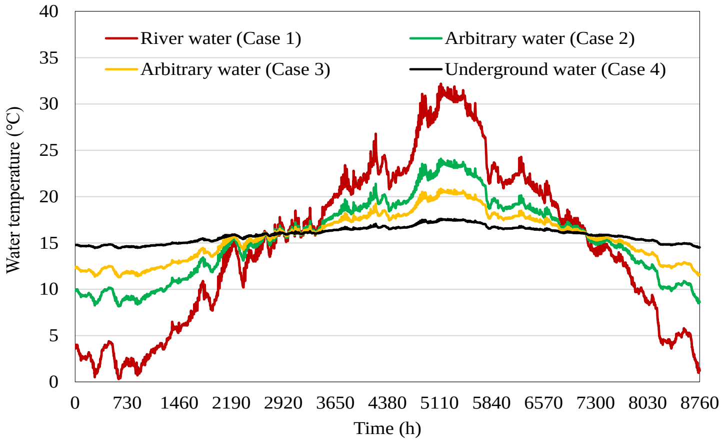

Figure 2: Various water temperature profile

3. RESULTS

The system's energy consumption is calculated from simulations, and performance evaluation is performed in terms of energy, environmental and economic metrics. Figure 3 shows the results of annual energy consumption. The energy consumption of the conventional and RSHP systems was analyzed in three parts: main components, AHU, and additional components. The main components are energy components that can generate cooling and heating energy directly, including electric coolers, gas-fired boilers, and WSHP. The AHU represents the pumps and fans that transfer energy generated from the main components to the building. The additional components include the cooling tower of the conventional system and the water pumping system of the RSHP system. When the RSHP system was compared with the conventional system, the energy consumption of the main component of the former was lower by 9.5%, whereas that of the AHU was nearly equivalent. The energy consumption of the additional component was higher by 24.7% in the open-loop system and 20.1% in the closed-loop system. As a result, the annual energy consumption was lower by 3.4% in the open-loop RSHP system and 6.9% in the closed-loop RSHP system. In the case of the open-loop system, the energy saving effect was not significant compared to what was expected. This is mainly owing to the insufficient energy savings of main component and the energy consumption increase of the additional component.

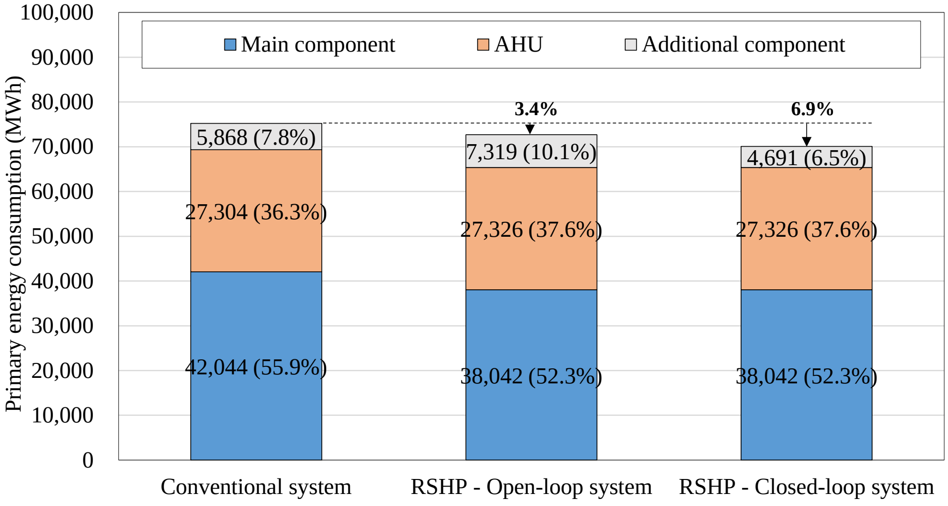

Figure 3: Comparison of annual primary energy consumption

The LCCP evaluation was performed by calculating the annual energy consumption of conventional and RSHP systems. The results of the LCCP evaluation are shown in Figure 4. As the river water temperature approaches to case 4, the total CO2 emissions of the RSHP system were reduced by up to 19.6% compared to the conventional system. Most of the CO2 emissions come from indirect emissions, especially the energy consumption of the system. The direct emission due to direct leakage of refrigerant accounts for less than 1%. The direct emissions from the RSHP system increased due to increased refrigerant charge in the RSHP. However, the indirect emissions have decreased significantly due to reduced energy consumption. This has resulted in a significant reduction in total CO2 emissions due to reduced energy consumption. Therefore, the total CO2 emissions significantly decreased because of the carbon emission reduction from the energy consumption.

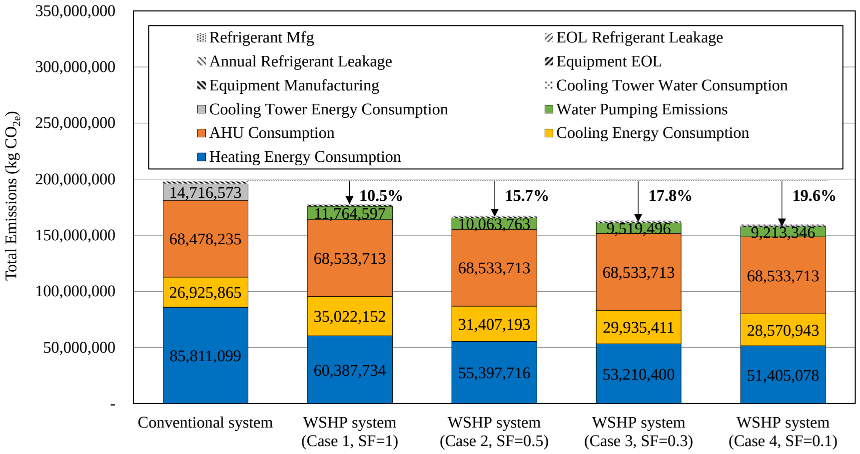

Figure 4: Environmental impact based on LCCP: annual CO_2 emission reduction of closed loop system

The economic feasibility of the RSHP system was evaluated with three economic parameters: NPV, IRR, and PBP. Lifecycle performance was considered in the calculations, which were performed based on the differences between the cost of initial investment, operation, maintenance and disposal in conventional and RSHP systems. In the future, late-night electricity charges may increase if the RSHP system is actively used. Therefore, the economic feasibility was analyzed in various scenarios, including scenario 1: current late night electricity rate, scenario 2: 10% increase, scenario 3: 20% increase, scenario 4: 30% increase. The economic assessment results are shown in Figure 5. The gray bar graph represents the current value, which is the sum of annual expenditure and revenue. The present value of Scenario 1 has been consistently positive, with the exception of initial investment costs, due to reduced energy costs. Annual depreciation has reduced energy cost savings slightly every year. The line graph shows the change in NPV. NPV, which start at the initial investment point, follows an incremental curve. The payback period, which represents the time required to recover the total expenditure, is where the NPV curve meets the x-axis. Consequently, for scenario 1, for current utility rate plans, it is clear that the RSHP system provides sufficient benefits compared to conventional systems as a result of NPV of $10,587,848, IRR of 20.5%, and PBP of 5.3 years. For other scenarios in which utility rates increase, the economic feasibility was derived as follows: NPV of $9,020,429, IRR of 18.5%, and PBP of 5.8 years for scenario 2; NPV of $7,453,009, IRR of 16.4%, and PBP of 6.5 years for scenario 3; and NPV of $5,885,589, IRR of 14.2%, and PBP of 7.3 years for scenario 4. Therefore, the economic feasibility can be maintained even if the utility rates increase in the future.

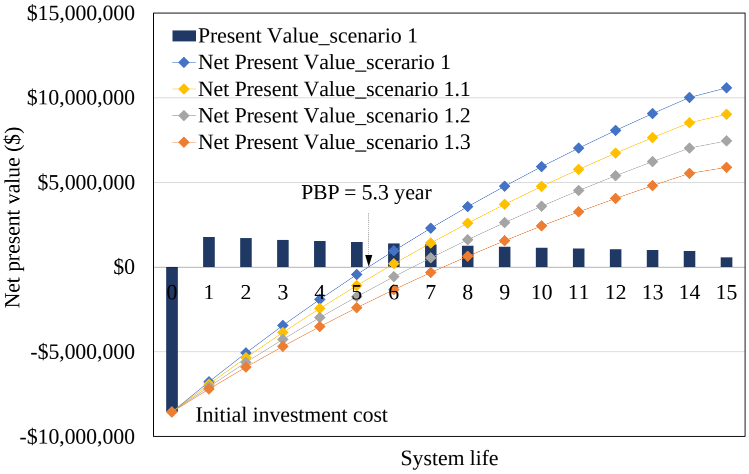

Figure 5: Economic evaluation results based on electricity rate increase scenarios: NPV and PBP

6. CONCLUSIONS

In this study, a comprehensive feasibility study on the RSHP was conducted in terms of life cycle performance evaluation. The remarkable research results are summarized as follows:

- When the closed-loop RSHP systems were used instead of conventional systems, energy savings increased from 6.9% to 16.4% due to changes in water temperature. The open-loop RSHP system has relatively low energy savings due to the power consumption of the primary pump.

- Reducing the power consumption of the hydronics is the first important factor in improving the performance of the RSHP system, as it accounts for a significant portion of the total energy consumption.

- The performance of the RSHP system depends heavily on the energy consumption of the main components and the water pumping system. Therefore, various surrounding conditions that affect the main component and water pumping system should be carefully examined before applying the RSHP system.

- From an environmental perspective, CO2 emissions from the RSHP system decrease from 10.5% to 19.6% as water temperature changes.

- Since the CO2 emissions are mainly due to energy consumption, analysis of energy consumption without complicated methods can lead to a suitable environmental impact assessment.

- From an economic perspective, the economic feasibility is characterized by the following values: NPV of $10,587,848, IRR of 20.49%, and PBP 5.3 years. In addition, the economic feasibility may be maintained even if the applicable temperature changes or utility charges increase in the future.

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