論 文 の 内 容 の 要 旨

論文題目 Study on Development of Distributed Water Source Heat Pump System Using Renewable Energy
（再生可能エネルギーを利用する水循環・分散型ヒートポンプシステムの開発に関する研究）

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In a modern city where energy is becoming more precious, the use of renewable energy and the vitality and transformation of energy systems has become an inevitable trend of the future energy system. In this thesis, this study proposed a heat pump system designed to utilize multiple renewable energy sources, providing an idea and possibility for the next generation building or district energy or heat supply systems. The purpose is to verify the feasibility and performance of this system through field testing and to build a suitable system model, which can optimize the system composition and control strategy for further explore the performance under different conditions. This thesis reports the detailed system development process and field testing based verification, as well as the modeling of the heat pump system.

Firstly, we reviewed several heat pump systems widely used in the building/industries and analyzed their characteristics based on the review of previous research. In the field of building heating and cooling, heat pump technology has significant advantages over traditional heating and cooling systems. For example, renewable energy can be introduced into the building's energy supply system to improve overall operating efficiency and reduce dependence on non-renewable fossil energy. On the other hand, with the proposal and development plan of the

fifth-generation heat supply network, the realization of low heating temperature and the integration of renewable energy have become the future trend. These trends require the use of systems that can cope with such low-temperature heat sources, and heat pumps are the best choice that can meet the requirements. However, as mentioned above, each renewable energy has its advantages and disadvantages. The energy supply system that relies on a single heat source cannot efficiently and stably meet the heat demand of buildings that may change at any time. The heat pump system will become an optimal solution. Therefore, this research is also from this aspect; the goal is to build a heat pump system that can utilize a variety of renewable energy, can provide a stable and high efficiency building heat supply.

For the development of distributed heat pump system using renewable energy, we started with the basics and explained the concept and composition of this system. These include the development of sky source heat pumps, floor heating heat pumps, air conditioning heat pumps and hot water heat pumps. The concept, structure, and performance test of each machine are also explained in detail. The development and improvement of each device are to cooperate with the design and operation concept of the system, that is, the integrated use of multiple renewable energy sources, including solar radiation, air heat, and geothermal heat. Also, the soil is used as a heat storage body to achieve peak shaving operation.

In order to evaluate the system performance of each heat pump and the entire system for heating or cooling supply, a test building (RE house) was constructed in Chiba for the field testing of the proposed heat pump system. The heating and cooling operation performance evaluations obtained by the field testing are summarized below.

We have developed a sky source heat pump that collects and radiates heat using solar heat, air heat, and nighttime radiation. It was confirmed by the field testing that the performance of the heat collection operation of the sky source heat pump considerably changed, mainly depending on the amount of solar radiation and the ambient temperature. A good performance was achieved in winter operation. Also, the performance of heat dissipation operation in summer and interim period were evaluated by field testing and achieved a good result. Consequently, it was confirmed by a long-term continuous operation test that the daily cycle operation method combined with ground heat exchanger and sky source heat pump could help eliminates the temporal disagreement between the cold heat demand and the hot heat demand and the non-equilibrium of the heat quantity. It can expect a stable and efficient long-term system operation based on this system.

We also have developed water source heat pumps for floor heating and air conditioning. After satisfying the thermal comfort range, a stable coefficient of performance (COP) of about 11 of the floor heating heat pump was obtained based on the continuous operation in March. In a space cooling experiment conducted in July, the COP of the air conditioning heat pump was stable and achieved a value of 12.5. In a space heating experiment conducted in November, the COP of the air conditioning heat pump attained a value of 6.5.

A prototype water source heat pump for hot water supply was developed based on commercial EcoCute. The performance of the heat pump for hot water supply was evaluated based on field testing in summer. The result shows an average COP of around 4 due to the limitation of the basic EcoCute machine.

Then, we created a dimensional model of the target piping system and conduct simulation to predict the pressure loss and temperature, based on the experimental piping system of the RE house by the CFD method for two operating states. There are two case settings in the simulation, which is a heat collection operation period using the sky source heat pump and a heating operation period utilizing the heat pump for floor heating. By comparing with the experimental data, the prediction accuracy of pressure loss and temperature in this piping system model was confirmed based on the result. For the prediction of pressure loss, the maximum relative error is 23.3%, with an absolute error of 0.7 kPa. Regarding the cause of the difference, in this simulation, since there is no average roughness information corresponding to ground heat exchanger using a PVC corrugated pipe, the calculation was performed using an average roughness of 1 mm assuming that ground heat exchanger is a circular pipe. For the prediction of temperature, the maximum relative error is 14.3%, with an absolute error of 2 °C. The temperature distribution different from the actual temperature distribution taken as the surface temperature of the ground heat exchanger is considered to be the cause of the error.

Finally, for the modeling of the proposed heat pump system, we firstly analyze the characteristics and advantages and disadvantages of the tools and methods used in modeling and simulation of building energy systems and review the relevant research literature in recent years. According to the research needs and goals, it explains why Modelica was chosen as a modeling tool. We briefly introduce the Modelica language and its application in the field of architecture. Next, we demonstrated the modeling of the distributed heat pump system proposed earlier, including the description of each model and the whole system description.

The validity and accuracy of the model are verified by comparing the experiment results, including a sunny day and a cloudy day in winter. In the comparison, we compared the changes in the water loop (such as temperature and flow rate), and the performance (mainly coefficient of performance) of the floor heating heat pump and sky source heat pump. According to the comparison with the experiment results, the validity of the system model built by Modelica is proved. Also, the constructed system model has acceptable accuracy and can well reproduce the performance changes and dynamic characteristics of the system.

As a model of the distributed heat pump system built using Modelica, various control methods can be developed and verified based on this model, as well as verification of further system design and optimization.