論文の内容の要旨

論文題目　Operation Strategy Optimization and Exergy Evaluation of HVAC System
(空調システムの運用方法の最適化とそのエクセルギー分析に関する研究)

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Buildings account for 30–40% of final energy consumption and 70% of total electricity use in Japan, EU and USA. The mitigation of energy consumption and CO2 emissions from buildings is important to combat energy shortage and climate change issues. As in many other countries in the world, Japan has witnessed an increased focus on low-energy buildings. The Japanese government is aiming to improve its building energy efficiency by at least 30% compared with the 2003 data by 2030.

For testing different engineering innovation and solutions for energy-efficient buildings, a low-energy building (21KOMCEE) was built at the University of Tokyo as an experimental pilot project. In this building, many innovative technologies are used, such as, ground source heat pump, air source heat pump, heat storage tank, desiccant dehumidifier and radiant heating/cooling ceiling panel system.

The research purpose is to evaluate the innovative technologies that are used in this nZEB and then, based on the field evaluation results, to apply theoretical analysis to find solutions for performance improvement. By performance measurement and evaluation of the nZEB the problems and challenges were uncovered. To improve the operation performance of HVAC system, optimization by genetic algorithm was applied to find good operation strategies. Furthermore, exergy analysis was applied to heat pump systems in order to determine the exergy flow and exergy consumption at all the points and to clarify the potential for improvement.

In this research, first, the building energy performance, the HVAC systems performance and indoor thermal environment have been evaluated. The annual energy consumption of the building was 67 kWh/m^2 during last two years. Primary energy consumption of the pilot nZEB is 35.4% of the average value of the University of Tokyo. This indicates that the nZEB is available by improving the operation strategy. The heat supply systems consumed almost half of the total electricity use. Combined with pumps & fans and the air conditioners energy use, the HVAC system consumed 77% of the annual electricity consumption of the building. For most days the indoor CO2 concentration was lower than 1200 ppm which is under ASHREA's acceptable level of less than 700 ppm above the outdoor CO2 concentration. However, the CO2 control strategy could increase the risk for high humidity levels. Field experiment measurements and evaluation results of the air-conditioning system have been carried out. The experiment evaluated the dependence of the cooling energy on the chilled water temperature. We found that by changing the temperature of chilled water from 4.5ºC to 8.7 ºC, the system's coefficient of performance improved by 13%, while the cooling capacity was found to be sufficiently high. The performance of the radiant heating/cooling ceiling panel system in relation to its heating/cooling capacity and thermal comfort has been evaluated. The heat flux between the ceiling panels and the room was measured with sensors and calculated based on the recommended models by ISO 11855-2. Good agreement between the results of these two methods was found, which indicated that the measurements were accurate. The heat transfer coefficient were 3.7 W/(m^2K) and 4.8 W/(m^2K) for heating and cooling cases, respectively. The upward heat flux was found to be as large as 30%–40% of the water heating/cooling capacity. Several proposals for reducing the upward heat flux were discussed. The thermal comfort measurement showed that the air and operative temperature distributions in the room were highly uniform.

Second, exergetic characteristics of both ground source heat pump systems (GSHPs) and air source heat pump systems (ASHPs) based on the concepts of "cool exergy" and "warm exergy" was presented. Quantitative example followed by theoretical analysis shows that GSHPs consume less exergy than ASHPs do. This is because firstly "cool exergy" is obtained from the ground in GSHPs, whereas no "cool exergy" is extracted from the environment by the ASHPs. Secondly, temperature difference between refrigerant via cooling water and ground in GSHPs is smaller than that between refrigerant and air in ASHPs. In the GSHP, cool exergy flows into the cooling water from the ground and then enters the indoor air through the refrigerant cycle. In the ASHP, the refrigerant cycle separates the electricity input of the compressor into "cool exergy" and "warm exergy." The "cool exergy" enters the indoor air and the "warm exergy" is exhausted to the ambient environment. The analysis also shows that compressor requires largest exergy input among the total exergy inputs, and the exergy consumption in the refrigerant cycle is the highest. Thus, the improvement of the compressor performance to reduce its electricity consumption was confirmed to be of vital in minimizing unnecessary exergy consumption.

Last, a system consisting of borehole heat exchangers, a water-to-water heat pump and a fan coil unit was modeled and simulated using MATLAB. A multi-variable evolutionary computation algorithm was proposed for generating optimal parameters for the system. As a result, an optimal system was designed with parameters that were calculated by minimizing system energy consumption. The case study shows the system operating with a higher supply cold water temperature of 13°C reduced by about 10% energy consumption compared to the system operated with a supply cold water temperature of 7°C. Exergy analysis of the ground source heat pump system was implemented in order to clarify the effect of supply water temperature to the system performance. The results show that the system operating with the optimal set point of the supply cold water temperature setting at 13°C had smaller exergy consumption, higher exergy efficiency and higher natural exergy ratio.

The research shows that the building is a low energy consumption building with 35% energy consumption of the average level of the buildings in the university. The theoretical analysis and the simulations show improvement potential in the HVAC systems, particularly heat pumps, pumps, desiccant dehumidifier, etc. In the future more research is required on system commissioning and tuning to realize the goal of an nZEB.