ENERGY MANAGEMENT IN HEATPUMP-BASED HVAC SYSTEM RENOVATION PROJECT

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Abstract: This paper describes that what effects could be gained by applying an energy simulation tool consistently to each phase of an air-conditioning equipment renewal project for an office building with heat pumps served as heat sources. As for the simulation tools, Life Cycle Energy Management (LCEM) tool that can evaluate energy throughout the life cycle of a building was used for application to phases from designing to test running.

In the design phase, the optimum air-conditioning system including heat pumps was selected, energy-saving effects were evaluated, and management targets were set. In the next phase of execution of work, it was confirmed that the air-conditioning system could clear the targets that were set in the design phase. Then, in the trial operation and adjustment phase, the difference between the results of simulation and actual operation was checked, and it was confirmed that actual operating characteristics could be reproduced by correction, and the management targets were adjusted in consideration of the characteristics of the real system. These were made possible by applying a single tool throughout the project.

The results of examination showed that the consistent application of the energy simulation tool to phases from designing to trial operating contributed to optimized design of air-conditioning system, optimized selection of equipment including heat pumps, and further to the optimum operation of the air-conditioning system as a whole.

Key Words: heat pumps, renovation, life cycle, LCEM tool

1 BACKGROUND AND PURPOSE

Reduction in CO_2 emissions is strongly required to cope with global warming issues. Of CO_2 emissions of energy origin, on the other hand, those from the commercial sectors tend to be large in proportion to the increase in total floor areas and the spread of office automation (OA), and measures against global warming in buildings for commercial use are regarded as important challenges to be addressed from now on. As for the breakdown of energy consumption in commercial buildings, air conditioning and hot water supply account for about half of the total energy consumption. To reduce CO_2 emissions, approaches such as the improvement of thermal insulation in buildings and introduction of highly efficient equipment are necessary.

Of the offices that account for a large share in buildings for commercial use, such approaches have not been progressed in an overwhelming number of existing buildings. Here, we introduce the effect of reduction in energy consumption by renovation of equipment mainly with the introduction of recent high-efficiency heat pumps, and an example where energy consumption could be reduced as targeted by making use of the LCEM tool as an effective management tool to decrease energy consumption throughout the life cycle.

2 OUTLINE OF LCEM TOOL

2.1 Outline of simulation tool

LCEM tool has a structure that is operated by Microsoft Excel and partly uses Visual Basic for Applications (VBA). LCEM tool provides "objects" that modularizes individual components of air-conditioning system. Users construct and simulate systems by linking them together and placing them in a line on a sheet of Excel as shown in Fig. 1. As each object is independent, users can conduct simulation in a limited area of system.

2.2 Outline of objects

Fig. 2 shows an outline of objects of air-source heat pump (hereinafter referred to as "AHP") unit. AHP unit is a model that allows for outside air dry-bulb temperatures (wet-bulb temperatures for some types), cold and hot water outlet temperatures (set values), and capacity and input characteristics with partial load factors.

Energy consumptions are calculated by using COP at the time of partial loads, which is calculated by correcting COP at the time of full-load operation under outside air conditions with load factors.

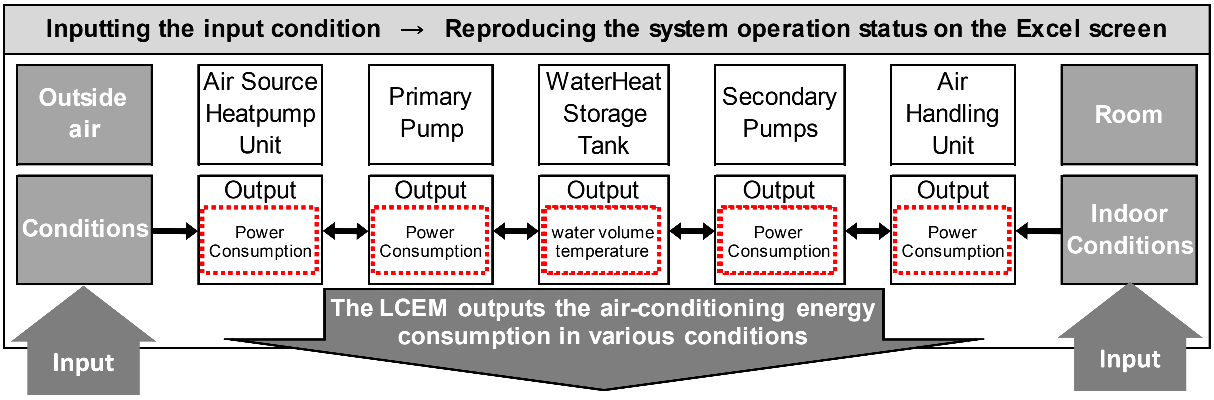

Figure 1: Conception diagram of LCEM tool

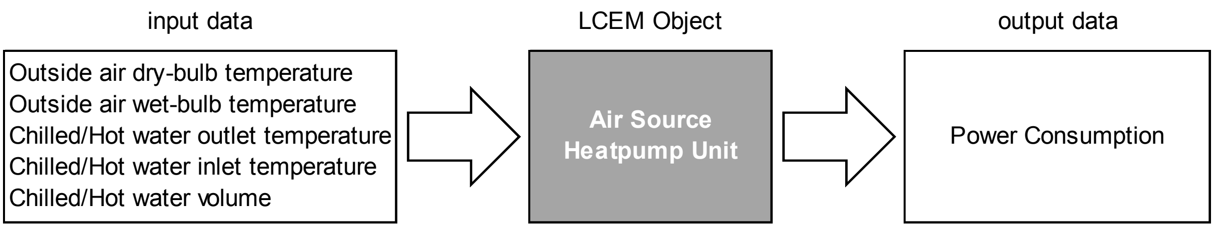

Figure 2: Outline of objects of AHP unit

3 GRASPING OF PRESENT CONDITIONS

3.1 Outline of applicable building and existing air-conditioning system

39 years have passed since the completion of the applicable office building and 20 years have passed since the last renovation of air-conditioning equipment. The equipment was quite aged. The air-conditioning equipment in the building was renewed as it became difficult to maintain necessary environment with the present air-conditioning system because of changes in room utilization patterns and increased loads of OA.

The air-conditioning system in the building is a centralized system that uses AHP units as heat sources and sends cold and hot water to an air conditioner on the secondary side by way of a thermal storage tank installed underground. The thermal storage tank is used for thermal storage operation from 10:00 p.m. to 8:00 a.m. next day, daytime follow-up operation at the time of shortage of the quantity of heat stored, and peak shaving operation. The 24-hour air-conditioning system is equipped with individual air-cooled package air conditioners, but they are excluded from the scope of examination on central heat sources. As for the existing system, moreover, there were only simple data because of remote monitoring. Therefore, spot measurements were conducted to work out renovation plans.

Table 1 shows the outlines of the building and the existing air-conditioning system, and Fig. 3 shows the outline of the air-conditioning system.

Table 1: Outlines of building and existing HVAC system

Building	Location:aichi prf. japan, completion:1970(Heat source repair:1989)
	Structure:Reinforced concrete, Floor:4F(Basement:1F)
	Total floor space:4,024m2
	Building use：office, showroom
Heat source	Air source heatpump unit × 2（symbol:R-1, R-2）
Water heat strage	Coupled completely mixed type, temperature:12-7℃
Air conditioner	Air conditioning system:CAV Secondary pumps···quantity control(CWV)
	Air handling unit:AHU-1···1F show room, AHU-2…1-3F south office AHU-3···1-3F north office, AHU-4…4F dining hall

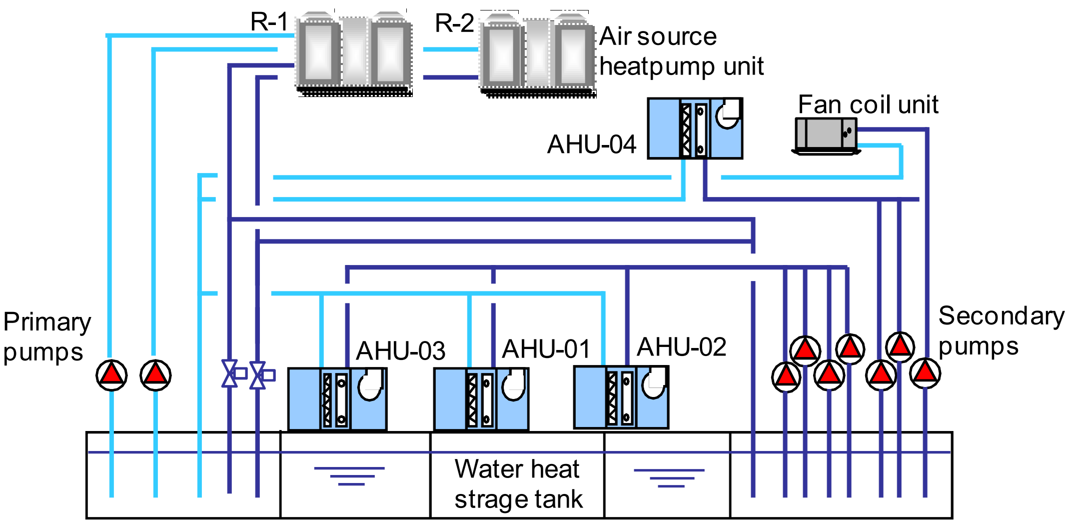

Figure 3: Outline of HVAC system diagram

3.2 Operating conditions of existing air-conditioning system

Spot measurements were conducted during a peak cooling period to check the operating conditions of the existing system.

The outside air temperatures during the measurement period ranged from 28℃ to 36℃ (38℃ at the highest) during daytime and 27℃ to 32℃ during nighttime. As shown in Fig. 4, on the other hand, heat source equipment was operated all day long, except at 7:00 a.m. when the thermal storage time zone ends and at 1:00 p.m. when the peak shaving time zone begins. Moreover, the AHP unit outlet temperature increased over time during daytime to about 5℃ to 11℃ compared with the set temperature of 7℃. It is estimated that this is because the capacity of the existing heat source equipment is not enough for assigned loads due to the increase in the loads of OA and the loads of personnel due to changes in room utilization patterns since the completion of the building.

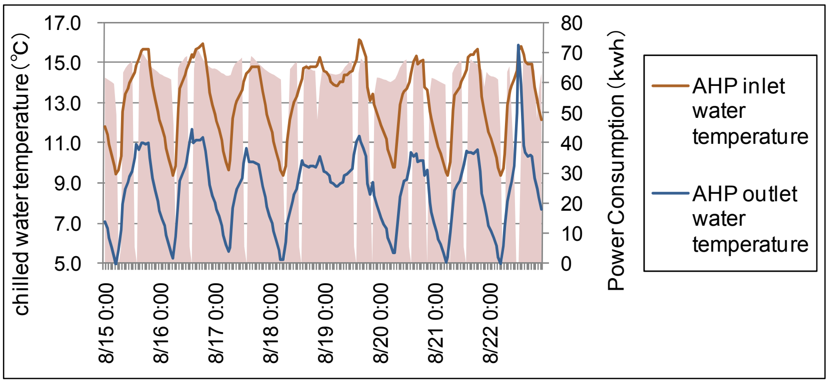

Figure 4: Power consumption and inlet/outlet water temperature of AHP unit

4 EXAMINATION IN DESIGN PHASE

4.1 Design concept of renovation

As the renovation work is conducted for the existing equipment in the applicable office building, the optimum system is constructed by making use of the existing equipment. The basic concepts of equipment renovation are the following four points:

①AHP units that have high part load performance should be used as heat sources.

②The system should effectively utilize the existing thermal storage tanks.

③The air-conditioning system should give consideration to energy conservation.

④The heat source equipment should have an appropriate capacity in consideration of load conditions in the future.

In addition, the following changes are made to solve malfunctions of the existing air-conditioning system:

①As the performance of heat source equipment is not enough to cope with the peak loads, the assigned area should be reduced.

②As the service of the air-conditioning system is divided into directions, temperatures and humidities cannot be controlled on each floor. Therefore, air-conditioning service should be provided on each floor.

As private rooms and others are individually air conditioned as the time period of the use of such room is different (outside the scope of examination).

4.2 Construction and modeling of existing system

In the design phase, the renovated system is examined with the amount of energy consumed by the existing air-conditioning system as an indicator. However, as the assigned area for central heat source and the air-conditioning system are changed, the renovated system was examined by using the simulation tool (LCEM tool) for comparison under the same conditions after the renovation. Moreover, management targets were set to calculate the performance of the selected air-conditioning system and confirm the effects of the renovation.

4.3 Identification of characteristics of existing equipment for simulation

As both the manufacturing year and equipment characteristics of the existing heat source equipment are different from those of the general-purpose objects provided for the LCEM tool, the validity of calculated values was checked by comparing the electricity consumption calculated by inputting actually measured values into the boundary conditions (outside air dry-bulb temperatures, wet-bulb temperatures, cold and hot water inlet temperatures and flow rates) of heat source equipment with the electricity consumption actually measured. If the deviance becomes large, the equipment characteristics must be identified by linear correction. Fig. 5 shows the results of correction of actually measured values and calculated values. The values after correction roughly agree with the actually measured values, and it could be confirmed that the above-mentioned correction was reasonable.

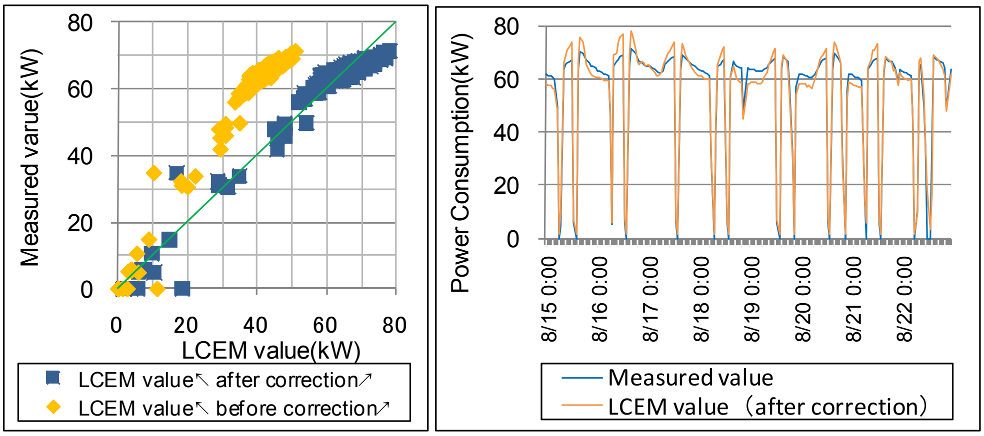

Figure 5: Results of correction of actually measured values and calculated values

4.4 Comparison of air-conditioning systems by LCEM tool

4.4.1 Conditions of comparison by LCEM tool

Based on the basic concept of design, AHP units that have high partial load efficiency are used as heat sources, and a combination of water thermal storage tank of complete mixing type and large temperature difference air conditioners for each floor is used as the basic system for effective use of the existing thermal storage tank. Moreover, it is necessary to give thermal loads when simulation is conducted by the LCEM tool. But as actually measured thermal loads cannot be given because the assigned area of central heat sources is reduced, the calculation results (sensible heat load in the room and latent heat load in the room) on the peak days due to micro-peaks and monthly representative days are given as boundary conditions. Fig. 6 shows the daily integrated values of total heat load in the room for respective air-conditioning systems (AHU-01 to 03).

For reference, the temperatures and humidities used in the calculations of micro-peaks are used as outside air conditions, and relative humidities are calculated from absolute humidities.

The five cases shown in Table 2 are used for the examination on system comparison. Case 01 represents the standards of comparison, and is the case where only the reduction of assigned area for central heat sources and change of zoning for air conditioners are conducted and the existing heat source equipment is continuously used. In Cases 02 to 05, heat source equipment is renewed, and an inverter-controlled secondary pump and an inverter-controlled fan of air conditioner are compared with each other.

In the case where the “inverter-controlled secondary pump” is ○, the number of revolutions is controlled by constantly controlling water supply pressure control. In the case where the “inverter-controlled fan of air conditioner” is ○, the number of revolutions is controlled by variable static pressure control.

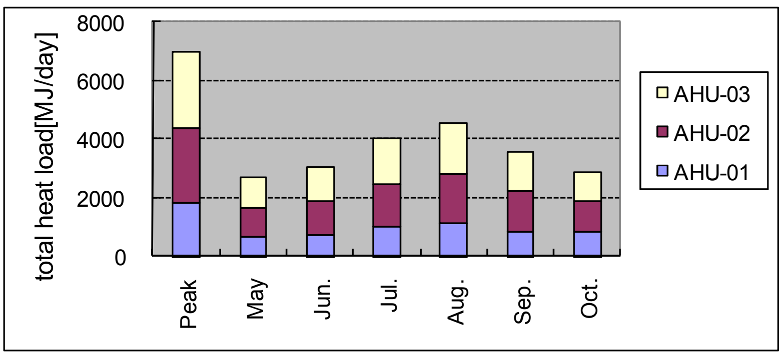

Figure 6: Daily integrated values of total heat load in the room

Table 2: Comparison cases

Case	Heat source equipment	Secondary pumps		Air handling unit-fan	
	update	update (CWV)	inverter (VWV)	update (CAV)	inverter (VAV)
Case01	×	○	×	○	×
Case02	○	○	×	○	×
Case03	○	○	○	○	×
Case04	○	○	×	○	○
Case05	○	○	○	○	○

4.4.2 Results of comparison of air-conditioning systems by LCEM tool

Fig. 7 shows the results of comparison of electricity consumptions in the period when air-conditioning service is provided. The periodical integration was calculated by multiplying the results in representative day by the number of days in each month, and by adding them up. For reference, calculations were conducted considering three days in August as peak days.

As a result of comparison between Case 01 and Case 02, the amount of electricity consumed for air conditioning is expected to be reduced by about 25% by the renewal of heat sources. Such reduction is considered attributable to the improvement of heat source efficiency, solution of aging degradation and improvement of load efficiency due to optimization of heat source capacity. As a result of comparison between Case 02 and Case 04, the energy-saving effect of the fans controlled by inverters is found to be high. In the case of inverter-controlled secondary pumps, on the other hand, the ratio of reduction in electricity consumption of secondary pumps is large, but the impact on the overall amount of electricity is not much large. This is because it is a large temperature difference system on the secondary side, and the ratio of power for secondary pumps to the overall amount of electricity is small.

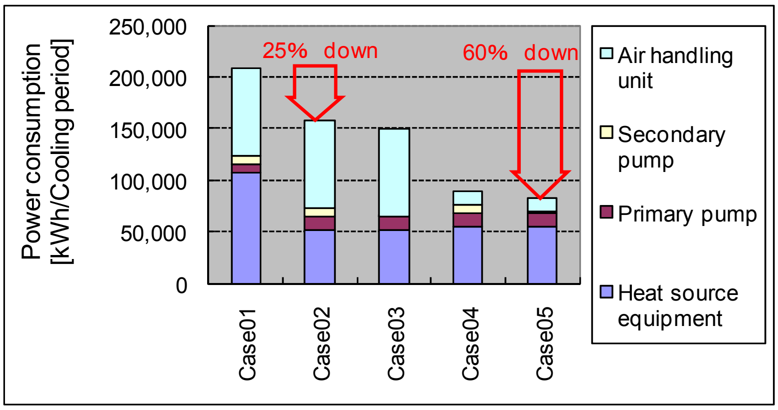

Figure 7: Comparison results of the period power consumption of each case

4.5 Performance verification of the system adopted

Judging from the results mentioned above, the renewal of heat source equipment and inverter-controlled fans are expected to yield a large effect of reducing electricity consumptions during the cooling period by more than half compared with Case 01 (the fans and pumps of the existing heat sources are renewed but they are not controlled by inverters). For reference, though the secondary pumps controlled by inverters do not much contribute to the reduction of overall amount of electricity, they yield an effect of reduction by about 7,000 kWh during the cooling period compared with a non-inverter-control case. Therefore, the system of Case 05 is adopted in a sense of aiming at achieving a higher energy-saving performance.

4.6 Setting of renovation target

Coefficient of Energy Consumption for Air Conditioning (CEC/AC) that shows the efficiency of an overall air-conditioning system is used as a management indicator throughout the life cycle of the renovated system. This is stipulated in the Act on the Rational Use of Energy as the criteria of judgment for owners and others concerning the rationalization of energy use in buildings. The smaller the figure is, the higher the energy saving performance is. Though the standard value of offices is set at 1.5, the target value is set at 1.1 that is about 30% smaller than the standard value with the aim of becoming the top runner under the conditions of renovation of the existing equipment (see Table 3).

Table 3: Calculation results of management indicator (Design phase)

Management indicator	targeted value	Design phase	remarks
CEC/AC	1.10	1.00	primary energy equivalent （AHP unit ＋ Pumps ＋ Air handling unit） [MJ]／Secondary heat demand[MJ]
Heat source system COP	—	3.88	Production heat capacity of Heat source[MJ]／3.6 ／electoric energy （AHP unit＋Primary pump） [kWh]

5 EXAMINATION IN EQUIPMENT APPROVAL PHASE

5.1 LCEM simulation in equipment approval phase

Whether the management targets set in the design phase are satisfied or not by the air-conditioning system as a whole is confirmed in simulations by the LCEM tool at the stage where the specification of the equipment ordered is decided.

Major changes from the design phase are shown below for the simulations:

1) Heat source equipment: Replacement to objects compatible with the selected equipment
2) Primary pump: The rated flow rate is changed in accordance with pieces of heat source equipment. Though the pump performance curve is unchanged, the operating point is slightly changed.
3) Air conditioner coil: General coil specifications are changed to coil objects for compact air conditioners.
4) Air conditioner fan: The static pressure characteristic curve is changed to the specifications of the selected equipment. The capacity of motor is reviewed.

5.2 Performance validation in equipment approval phase

According to the results of calculation and the changes to the specifications of the equipment ordered, the following points could be confirmed:

①COP of heat source equipment decreases at the time of rated operation, but it tends to rise when the outside air temperature is low, and the seasonal electricity consumption decreased. This is considered attributable to the difference in the characteristics of electricity consumption in proportion to outside air temperatures.

②The air conditioners showed a tendency that the temperature difference between the inlet and outlet is larger on the water side due to the changes in coil characteristics.

③The decrease in the power for air conditioner fans of is considered attributable to the review to make the fan motors smaller.

According to the results of calculation in the equipment approval phase, the total electricity consumptions become smaller than those in the design phase. CEC/AC during the cooling period also declines to 0.94 (see Table 4), satisfying the management target of (1.1).

As mentioned above, as the equipment ordered satisfies the management targets, it is judged that there is no problem.

Table 4: Calculation results of management indicator (Equipment approval phase)

Management indicator	targeted value	Design phase	Equipment approval phase	remarks
CEC/AC	1.10	1.00	0.94	primary energy equivalent （AHP unit＋Pumps＋Air handling unit）[MJ]／Secondary heat demand[MJ]
Heat source system COP	–	3.88	4.04	Production heat capacity of Heat source[MJ]／3.6／electoric energy （AHP unit＋Primary pump） [kWh]

6 EXAMINATION IN THE TRIAL OPERATION AND ADJUSTMEN PHASE

6.1 LCEM simulation in the trial operation and adjustment phase

The trial operation and adjustment phase is aimed at confirming that the calculation results of LCEM can reproduce the actual system with a certain accuracy, clarifying the items of insufficient adjustment at the time of test running, and setting the “management targets in the trial operation and adjustment phase” that should be the management targets of the next phase of operation management.

In the trial operation and adjustment phase, those characteristics and others that were unclear in the designing and equipment approval phases can be matched to actual characteristics with high accuracy at the completion of installation. For example, pipe resistance, duct resistance, control parameters of higher and lower cut-off frequencies by test running adjustment, pump efficiency, fan efficiency and others.

6.2 Confirmation of reproducibility of system operation conditions

LCEM calculations were conducted based on the data of actual operation at the thermal load peak of cooling on Wednesday, August 5, 2009, and the calculation results were compared with actually measured values.

As for the boundary conditions of LCEM calculations, the actually measured values for outside air intake were given as outside air temperatures, and VAV-based indoor sensible heat and latent heat loads were given as indoor loads based on the amount of treated heat of the air conditioner on the air side. As these data are instantaneous data of every ten minute, they are provided as one-hour average values.

Figs. 8 and 9 show the actual values and the results of LCEM calculations. From an overall point of view, LCEM calculation values for temperature, flow rate and air volume well agree with the actually measured values thereof. As for the amount of electricity, on the other hand, there were some differences found in heat sources, secondary pumps and air conditioners.

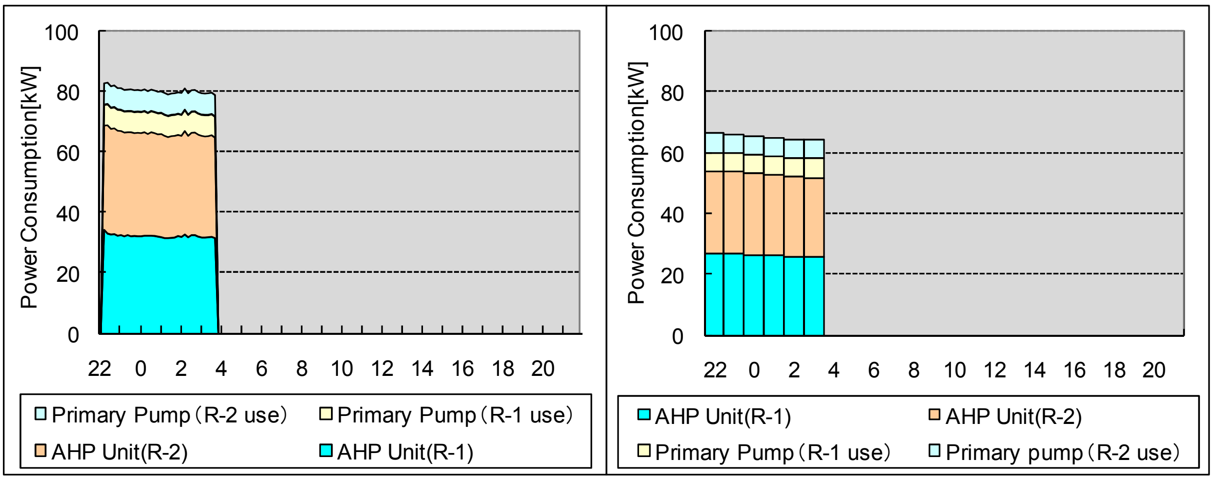

Figure 8: Power consumption of the heat source (left: measured, right: calculation)

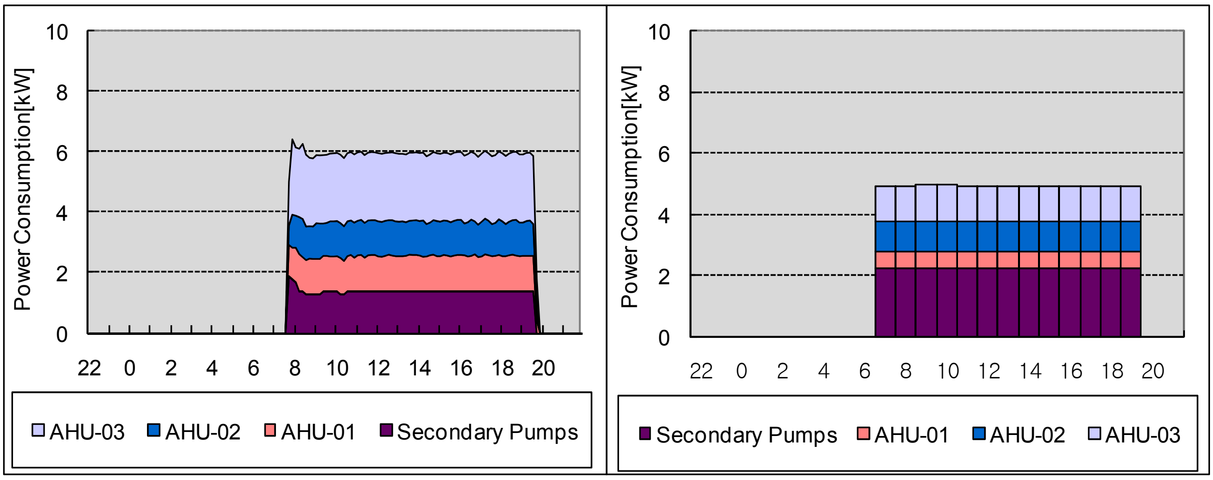

Figure 9: Power consumption of the secondary (left: measured, right: calculation)

6.3 Correction of LCEM calculation values for electricity amount

The differences in electricity consumptions are assumed to be caused by the following reasons:

①Heat source equipment :There are some differences in the inlet and outlet temperatures of heat sources between the actually measured values and calculated values.
The effect of hunting of absorption three-way valve control of heat sources
The effect of installation conditions of heat sources

②Secondary pump :The pipe resistance curve of actual system is different from that of calculation.
The pump efficiency of actual pump is different from the calculated value.

③Air conditioner fan :The duct resistance curve of actual system is different from that of calculation.
The actual system has fans controlled by inverters in accordance with the request for VAV-based air volume, but the calculation is conducted by taking variable static pressure control as an alternative because there is no similar control method for calculation.

Therefore, the following corrections were made:

①Heat source equipment :Actually measured values were inputted into inlet and outlet temperatures and flow rate of heat sources, and the power was corrected by linear regression.

②Secondary pump :"Overall pump efficiency" was calculated by dividing the product of actually measured flow rate and differential pressure by electricity, and it was used as the efficiency for calculation.

③Air conditioner fan :The power was corrected by linear regression to correct the efficiency of fan motor after the duct resistance curve is set based on test running data.

6.4 Validation of correction methods

The results on the representative day of August 5 were recalculated by using the correction methods mentioned above. The daily integral electricity consumptions recalculated roughly agree with the actually measured values.

To validate the correction methods by taking the day other than the representative day of August 5, LCEM calculations were applied to the results on Wednesday, September 2, 2009, and compared with the actually measured values.

The calculation results are shown in Figs. 10 and 11 and Table 5. The error of daily integral electricity consumptions is less than 5%. As they well agree with each other, it was judged that the correction methods mentioned above were valid.

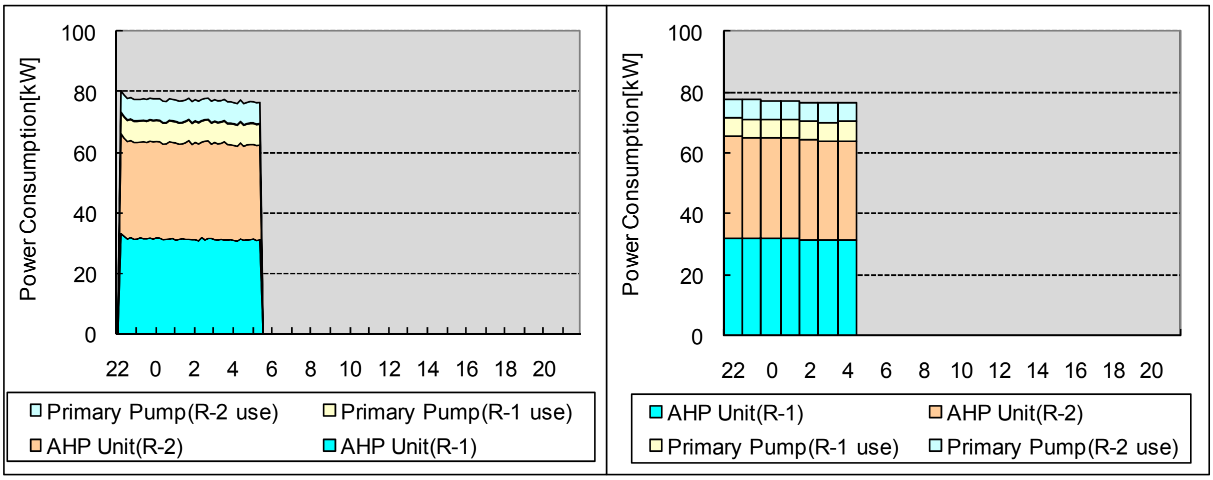

Figure 10: Power consumption of the heat source (left: measured, right: calculation)

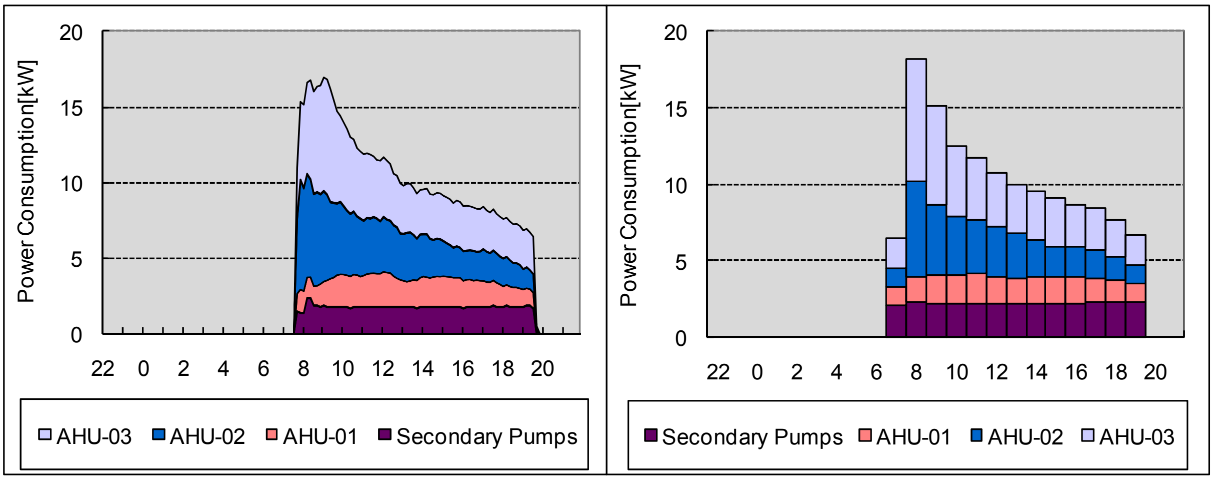

Figure 11: Power consumption of the secondary (left: measured, right: calculation)

Table 5: Comparison results of day multiplication electric energy （after correction）

Item	unit	Measured value	LCEM value
AHP unit(R-1)	kWh	231	222
AHP unit(R-2)	kWh	237	231
Primary pumps	kWh	104	87
Secondary pumps	kWh	23	29
Air handling unit(AHU-01)	kWh	21	21
Air handling unit(AHU-02)	kWh	39	37
Air handling unit(AHU-03)	kWh	46	48
Total	kWh	701	675

6.5 Confirmation of management targets in trial operation and adjustment phase

As the reproducibility of actually measured values by LCEM calculations could be confirmed, the management index values were recalculated by the models that adopted these correction methods. The results are shown in Fig. 12 and Table 6.

According to Fig. 3.3.1.40, the electricity consumptions in the trial operation and adjustment phase were overall larger than the values calculated in the designing and equipment approval phases.

As for heat sources, the cause is considered attributable to a slight deviation from the set values of cold water inlet and outlet temperatures, the effect of hunting of heat source absorption three-way valve control, and the effect of installation conditions of heat source equipment.

As for secondary pumps, it was made clear that the state of low-load operation was very frequent, and the value of efficiency in such operation was much lower than the efficiency (constant value) provided in the designing and equipment approval phases. As a result of correction in consideration of the efficiency characteristics of actual pumps, the amount of electricity became larger in the trial operation and adjustment phase.

As for air conditioners, the actually measured value of electricity tends to be larger than ideal electricity amount (LCEM calculated value) because of VAV reduction operation where the actual control is different from the variable static pressure control. As a result of power correction in consideration of this tendency, it is considered that the amount of electricity became larger than that in the equipment approval phase.

CEC/AC as a management target was 1.07 in the trial operation and adjustment phase, which was slightly higher than the values in the designing and equipment approval phases. This value is corrected in consideration of the characteristics, behaviors and installation conditions of actual equipment as mentioned above, and the result of correction made by confirming that the difference is not attributable to malfunction of actual system. Moreover, CEC/AC = 1.1 as a management target value is also satisfied. Therefore, the management target value of CEC/AC = 1.1 is also set as the “management target value in consideration of characteristics of the actual system,” which should be used also as a standard in the operation management phase in the future.

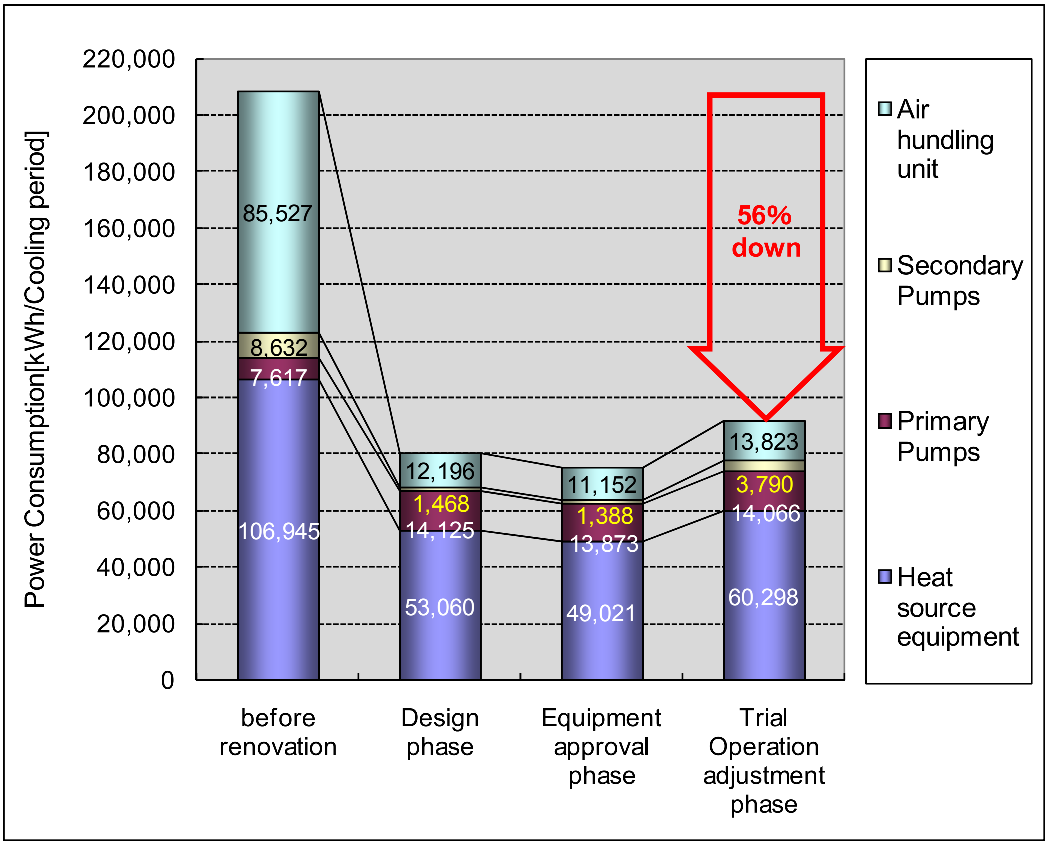

Figure 12: Calculation results of the period power consumption in each stage

Table 6: Calculation results of management indicator

Management indicator	targeted value	Design phase	Equipment approval phase	Trial operation adjustment phase	remarks
CEC/AC	1.10	1.00	0.94	1.07	primary energy equivalent （AHP unit ＋ Pumps ＋ Air handling unit）[MJ]／Secondary heat demand[MJ]
Heat source system COP	―	3.88	4.04	3.48	Production heat capacity of Heat source[MJ]／3.6 ／electoric energy（AHP unit＋Primary pump）[kWh]

7 CONCLUSION

For renovation of the existing air-conditioning system, an example of replacement of heat sources with the latest air-source heat pump units is introduced. As the latest air-source heat pump units have not only higher rated performance but also much higher efficiency at the time of partial load, the amount of energy consumed for air conditioning could be reduced by about 25% as a result of heat source renewal. Moreover, the existing system could be renovated into a highly energy-saving system whose Coefficient of Energy Consumption for Air Conditioning (CEC/AC) is 1.1 or lower as a result of combination with inverter-controlled air conditioners and inverter-controlled secondary pumps, and it was also confirmed that the energy consumption could be reduced by more than half.

Additionally, the targeted energy performance can be made clear from the design phase by applying the LCEM tool as an energy management tool throughout the life cycle, and the targeted energy performance can be ensured by the performance checking at the time of finalizing the specification of equipment to be ordered and by the performance checking in the trial operation and adjustment phase where the system is actually operated.

In LCEM calculations, the equipment characteristics of the existing heat source equipment are identified based on actually measured values to reflect the former equipment performance and the effect of aging degradation. In the trial operation and adjustment phase, it could be confirmed that actual operation could be reproduced with high accuracy by correction in consideration of characteristics and behaviors of the actual equipment. In the next operation management phase, therefore, it is possible to try to optimize operation with the management target values set in the trial operation and adjustment phase as the targets, and to promote the operation that is aimed at further lowering CEC/AC by conducting case studies with operating conditions changed by LCEM calculations.

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