Analysis of Thermal Characteristics of Heat Source Equipment for HVAC Systems Installed in a Multi-functional Building and Improvement of Energy Efficiency

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Abstract

This paper investigates the energy efficiency of heat source equipment (gas-fired absorption chillers/heaters) for HVAC systems by using long-range data (including cooling and heating periods) of a multi-functional building mainly composed of office space, which had been put into operation one year previously. The main approach for improving energy efficiency is to estimate the impact on energy consumption of operating strategies for heat source equipment that are easily adopted on-site and variation in thermal capacity ratio of its two or more units, the selection of which is important at the stage of HVAC system design. The results show that the impact on energy consumption is most significant during the cooling period, and can realize energy savings of up to 13%.

Keywords: heat source equipment; commissioning; thermal performance; energy saving

1. Introduction

Seasonal performance of an HVAC system is a difficult index to determine at the time of commissioning. Although numerous location-specific studies have been conducted, to date few reports have been published, because of the requirement for long-term measurement and analysis. Heat source equipment is one of the main objects of concern regarding seasonal performance (Ishiguro, 2005), (Yoshioka, 2005). However, full information is not available regarding analysis of its operation with two or more units and with low thermal load characteristics.

An opportunity arose to investigate the seasonal performance of gas-fired absorption chillers/heaters installed in a multi-functional building. Based on its characteristics in the cooling and heating periods, simulations were conducted in order to determine how the following factors affect the period performance of the primary system:
1. Operating strategies of heat source equipment
2. Variation of cooling/heating capacity of a few units of heat source equipment (Maehara and Sagara, 2004, 2005).

2. Outline of Building and HVAC System

The 12-story multi-functional building, constructed in Oct. 2002, is located in Kitakyushu, Japan and consists of office space, main and sub-halls, and one plaza, with a total floor area of 37,000 m². Three gas-fired absorption chillers/heaters are installed as heat source equipment, two (R1 and R2) which are for cooling and heating with capacities of 1,407 kW (400USRT, 5.07 GJ/h) and 1,138 kW (4.09 GJ/h), respectively, while the remaining one (R3) is for cooling only and has a capacity of 880 kW (250USRT, 3.17 GJ/h). R1 and R2 are manually switched from heating mode to cooling mode in May, and are...
switched back in November.

The secondary air conditioning systems consist of makeup air units and fan coil units (FCUs) for both interior and perimeter zones in office spaces. The air supply temperatures of makeup air units were controlled at the set point, and room temperatures were kept constant by varying the water flow rate through FCUs to meet the thermal load. For the remaining areas, room temperatures are controlled by air handling units for each zone.

Fig.1. shows the piping system diagram for the HVAC system. The primary chilled/hot water pump and cooling water pump for each heat source machine can be operated independently. During the day in summer, all three machines are operated: R3 to cope with the loads for the chilled water system only, independent from R1 and R2 for the chilled/hot water systems. At night, only R3, having the lowest heat capacity, is operated and the other two (R1 and R2) are not operated. In winter, only R3 takes charge of cooling loads, and R1 and R2 are individually operated to deal with heating loads. The valves in Fig.1. are closed when R1 and R2 are operated in heating mode and R3 in cooling mode, and are closed when R1, R2 and R3 are operated in cooling mode and are open when only R3 is operated at night in cooling mode. The dotted lines indicate the bypass of the constant water flow through the heat source machines. The operation patterns of the three machines are shown in Table 1.

3. Energy Performance for Heat Source Equipment in Summer

3.1 Actual operation in summer

The period from June to August 2003 was analyzed. Monthly cooling loads are shown in Fig.2. In each month, R1 and R2 take almost equal charge of the greater part of the cooling load. Fig.3. shows the monthly operation time (hours) for each operation pattern. In June, the main operation patterns are D4 (R1+R3) and D5 (R2+R3), while N1 (R3 only) is scarcely used. As compared with June, in July, N2 and D6 (R1+R2+R3) are increased, and D4 and D5 are decreased. In August, the same tendencies become more pronounced. Because D4 is almost equal to D5 in each month, alternating operation of R1 and R2 is working as planned. Fig.4. shows the hourly cooling loads during the cooling season rearranged from the larger values to the smaller ones in the direction of the X-axis from the origin (i.e., in descending order). R1 and R2 take almost equal charge of the cooling loads, depending on their ratio of capacity. R3 is operated for a long time during the entire summer season. The maximum total cooling load for the three units is 68% of the designed load. The machine partial load ratio is defined by Equation 1.

\[ \eta_i = \frac{Q_i}{Q_{io}} \]  

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where

- $P_{ki}$: machine partial load ratio,
- subscript "i": machine,
- $Q_{i0}$ [GJ/h]: actual load for each machine.
- $Q_{i}$ [GJ/h]: designed cooling/heating capacity for each machine.

Fig. 5 shows $P_{ki}$ in descending order for each heat source machine. The maximum machine partial load ratios for R1, R2, and R3 are 115, 101, and 121%, and their seasonal averages are 46, 47, and 12%, respectively. R3 is operated under an extremely low thermal load condition for a long time. The average outlet chilled water temperatures of the heat source machines are 7.5, 7.3, and 8.2 deg C, which are about 0.5, and 1 deg C higher than the design values, and their standard deviations are 0.37, 0.45, and 0.59 deg C, respectively.

### 3.2 Heat performance in summer

The relationships between gas energy consumption (see Notes 1 and 2) and cooling load for each machine are shown in Figs. 6 and 7, and regression equations are shown as Equations 2 to 4 (see Notes 3 and 4).

$$Q_{c1} = 0.923G_1 - 0.112 \tag{2}$$
$$Q_{c2} = 0.965G_2 - 0.242 \tag{3}$$
$$Q_{c3} = 0.999G_3 - 0.165 \tag{4}$$

where

- $Q_{ci}$ [GJ/h]: cooling load for each machine,
- $G_i$ [GJ/h]: gas energy consumption for each machine.
- COP [-] for each machine is defined as Equation 5.

$$\text{COP}_i = Q_{ci}/G_i \tag{5}$$

Fig. 8 shows COP calculated from cooling loads and gas energy consumption for each machine, where the X axis plots machine partial load ratio $P_{ki}$ and the curves are drawn by transforming the regression equations to $\text{COP}_i=f(P_{ki})$. Each $P_{ki}$ for R1 and R2 is almost over 0.3 in actual operation, and the COPs range from 0.9 to 1.0. $P_{ki}$ for R3 approximately under 0.3 leads to low COP. The COP in design specifications for each machine is 1.01. Each actual COP over $P_{ki}$ of 0.3 is slightly lower than the designed COP.

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Fig. 6. Relation between Gas Energy Consumption and Cooling Load of Gas-fired Absorption Chiller R3 in Individual Operation

Fig. 7. Relation between Gas Energy Consumption and Cooling Load of Gas-fired Absorption Chiller R1 Operated with R3

Fig. 8. Relation between Estimated COP and Machine Partial Load Ratio for Each Gas-fired Absorption Chiller

Fig. 9. Monthly Heating Load of Each Piece of Heat Source Equipment

Fig. 10. Monthly Heating Operating Hours in Each Operation Pattern
4. Energy Performance for Heat Source Equipment in Winter

4.1 Actual operation in winter

The analysis period is from November 2003 to April 2004. Monthly heating loads are shown in Fig.9. In every month, R1 and R2 take almost equal charge of most of the heating load. The peak-heating load is about 2,100 GJ/month in January. The monthly operation time (hours) for every operation pattern is shown in Fig.10. D1 (R1 only) is almost equal to D2 (R2 only) from December to March, during which heating loads are huge. The operation time for D3 (R1+R2) shows a tendency equivalent to that of the heating load in Fig.9. In January, the pieces of heat source equipment are seldom stopped simultaneously, and at least one piece of heat source equipment is always operated substantially throughout the day. Hourly heating loads are shown in Fig.11. in descending order. The heating period is about 3,000 hours in winter; R1 and R2 are simultaneously operated for 600 hours, and R1 or R2 are operated alone for 2,400 hours. The heating loads of R1 and R2 are almost the same when the two units are operated together. Total peak load for the two units is 115% of the designed value. Fig.12. shows the machine partial load ratio in descending order for each heat source machine.

The maximum partial load ratios for R1 and R2 are 122 and 127%, and their seasonal averages are 41.8 and 42.8 % respectively. The average outlet hot water temperatures of the heat source machines are 55.6 and 55.5 deg C, which are about 0.5 deg C higher than the design values, and their standard deviations are 1.84 and 1.86 deg C, respectively.

4.2 Heat performance in winter

The relationships between gas energy consumption and heating load for R1 and R2 are shown in Fig.13., and regression equations by Equations 6 and 7.

\[
Q_{h1} = 0.856G_1 - 0.119 \quad [6]
\]
\[
Q_{h2} = 0.866G_2 - 0.0876 \quad [7]
\]

where

\[
Q_{hi} [\text{GJ/h}]: \text{heating load for each machine.}
\]

Heating efficiency \( \eta_i \) [-] is defined by Equation 8.

\[
\eta_i = \frac{Q_{hi}}{G_i} \quad [8]
\]

\( \eta_i \) calculated from heating load and gas energy consumption for each machine are shown in Fig.14. The curves in Fig.14. are drawn by transforming the regression equations to \( \eta_i = f(P_{ki}) \). Each \( \eta_i \) for R1 and R2 descends in low thermal load condition, and shows approximately constant values of over 0.8 over \( P_{ki} \) of
0.3. The design values of $\eta_i$ for R1 and R2 are both 0.85. Each actual $\eta_i$ in $P_{ki}$ of near 1 is almost equal to the design value.

5. Improvement of the Operation Mode and Capacity of Heat Source Equipment for Energy Savings

5.1 The influence of variation in operation mode in cooling on energy consumption

Table 2. shows two approaches for improving energy consumption efficiency in the real system. Both the operation mode A and B adopt a mode where R3 is operated only under high heating load conditions; specifically, when the system partial load ratio, defined by Equation 9, exceeds 80%, which R1 and R2 alone cannot deal with. Additionally, in mode A, R1 is operated when the system partial load ratio falls below 20%, and in mode B, R3 is operated.

$$P_{s} = \frac{(Q_{c1} + Q_{c2} + Q_{c3})}{(Q_{c1o} + Q_{c2o} + Q_{c3o})}$$  \[9\]

where

$P_{s}$ [-]: system partial load ratio,

$Q_{c}$ [GJ/h]: hourly cooling load for R1, R2 and R3,

$Q_{c0}$ [GJ/h]: maximum cooling capacity of R1, R2 and R3.

The calculation conditions are as follows. In view of the fact that R1 and R2 have the same capacity, R1 is operated by priority in one-machine operation. Under two-machine operation, R1 and R2 simultaneously deal with half of the total load each. The primary gas energy consumption is calculated from the measured hourly cooling loads and estimated COP of each machine. The electric power of the primary pumps for R1 and R2 is the same, at 22 kW each, and that for R3 is 11 kW. The electric power of the cooling water pumps is 45 kW for both R1 and R2, and 30 kW for R3, and those of the cooling tower fans are 5.5 kW×3 units for each of R1 and R2, and 7.5 kW×2 units for R3, which are operated depending on the cooling load. The cooling water pumps are operated under constant water flow volume.

Table 3. shows the simulation results. Because the estimated gas heat is almost the same as the measured value, the regression equations are assured as being highly accurate for the model. The gas heat is decreased by 3.1% in mode A and by 3.8% in mode B. This is attributable to the operation of R3 for as few hours as possible (mode A) or to operation of R3 only under high machine partial load ratio (mode B). Energy consumption of the primary pumps (see Note 5) declined greatly, by 26.6% in mode A and by 43% in mode B, while that of the cooling water pumps and cooling tower fans declined by 34.5% in mode A and by 41.8% in mode B, because of the elimination of long-term operation under low load for R3. Total energy consumption is reduced by 11% and 13%, respectively, due to the difference in the modes.

Figs.15. and 16. show primary energy consumption in descending order for the heat source equipment and pumps. As compared with the real operation shown in Fig.4., long-term low partial loads for R3 were eliminated.

5.2 Influence on energy consumption of the difference in operation mode and capacity of heat source equipment in heating

Fig.12. shows that, as compared with summertime operation, during winter both R1 and R2 were operated...
under low load for a long time. For improving low load operation to achieve energy savings, two energy saving approaches were proposed. One is the operation mode of heat source equipment, which is easy to adopt on-site. The other approach is selection of the capacities of R1 and R2 to deal with a maximum thermal load, which is important to review in the design phase. We investigated the effects of the approaches, and the results are as follows.

Table 4. shows the details of two approaches, and Table 5. presents two kinds of the operation mode. Selection of heat source equipment involves determining the ratio of heating capacities of R1 and R2 to cope with a maximum thermal load; for example r1:r2=0.7:0.3 (r1+r2=1). The primary pump specifications are determined according to the water flow rate fitting the heating capacities of R1 and R2 and the same total head of water as the real system, which are constant during operation. Table 6. shows the specifications of the pumps.

The simulation was conducted under the above conditions. The results are shown in Table 7. Fig.17. shows the primary energy consumption with r1:r2=0.7:0.3 in each operation mode.

First, the performance of two operation modes was estimated to reduce energy consumption. Mode C with the capacity ratio of r1:r2=0.5:0.5 is the operation mode adopted in the real building. Energy consumption was calculated under the condition of mode D, with the same capacity ratio as mode C, to find an effect in energy savings. The results show that Mode D is scarcely able to decrease primary energy consumption.

Next, selection of the capacity ratio of two heat source machines were evaluated to reduce primary energy consumption including the pumps, which is important during the design stage. The difference of three levels of capacity ratio of heat source machines exerts a small effect on period gas primary energy consumption, which fluctuates from -1.4 to 0.7% as compared with the standard value (r1:r2=0.5:0.5). In the case of a capacity ratio of r1:r2=0.7:0.3, gas

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**Table 4. Factor and Level for Heating Simulation**

| Factor                  | Level | Level 1 | Level 2 | Level 3 |
|-------------------------|-------|---------|---------|---------|
| Simulation mode         |       | Mode C  | Mode D  | -       |
| Ratio of capacity r1 : r2|       | 0.5 : 0.5 | 0.7 : 0.3 | 0.9 : 0.1 |

**Table 5. Heating Operation Mode for Gas-fired Absorption Chillers/Heaters**

| Mode C | Mode D |
|--------|--------|
| r1<Ps  | r1<Ps  |
| r1*Q_T | r1*Q_T |
| r2*Q_T | r2*Q_T |
| Q_T/2   | Q_T/2   |

Q_T, Q_s : hourly heating load for R1 and R2
Q_s : system heating load (= Q_T + Q_o)
Q_o : maximum heating capacity for R1 and R2
Q_T : total heating capacity (= Q_r1 + Q_r2)
r1, r2 : Ratio of maximum heating capacity for R1 and R2

**Table 6. Pump Specifications for Heating Simulation**

| Capacity ratio r1 : r2 | Piece of heating source equipment | Water flow rate [L/min] | Pump electric power [kW] |
|------------------------|----------------------------------|-------------------------|--------------------------|
| 0.5:0.5                | R1 R2 R1 R2 R1 R2                | 2520 2520 3528 1512      | 4536 504                 |
| 0.7:0.3                |                                  | 22 22 30 18.5 37 11      |                          |
| 0.9:0.1                |                                  |                          |                          |

**Table 7. Simulation Outputs during Heating Period**

| Operating hour | Gas primary energy | Pump primary energy | Gas and pump primary energy |
|----------------|--------------------|---------------------|-----------------------------|
| Machine partial load ratio of each unit | Total | Percentage [%] | Machine partial load ratio of each unit | Total | Percentage [%] | [GJ] | Percentage [%] | [GJ] | Percentage [%] |
| Pk<0.3 | Pk≥0.3 | - | - | Pk<0.3 | Pk≥0.3 | - | - |

Simulation mode C

| Capacity ratio r1 : r2 | [hour] | [hour] | [hour] |
|------------------------|-------|-------|-------|
| r1=0.5                |       |       |       |
| 0                    | 630   | 630   | -     | 0     | 2047 | 2047 | -     | -     | -     |
| 1387                 | 1657  | 3044  | 954   | 4553 | 6208 | -     | -     | -     | -     |
| Total                | 1387  | 2287  | 3674  | 100.0 | 954  | 7300  | 8254  | 100.0 | 761  | 100.0  | 9016  | 100.0  |
| Percentage (%)       | 38    | 62    | 100   | -     | 12   | 88    | 100   | -     | -     | -     | -     | -     | -     |
| r1=0.3               |       |       |       |
| 0                    | 1142  | 1142  | -     | 0     | 4354 | 4354 | -     | -     | -     | -     | -     | -     | -     |
| 1001                 | 2043  | 3044  | 403   | 3462 | 3966 | -     | -     | -     | -     | -     | -     | -     | -     |
| Total                | 1001  | 3185  | 4186  | 113.9 | 403  | 7816  | 8220  | 99.6  | 853  | 112.1  | 9073  | 100.6  |
| Percentage (%)       | 24    | 76    | 100   | -     | 5    | 95    | 100   | -     | -     | -     | -     | -     | -     | -     |
| r2=0.1               |       |       |       |
| 807                  | 1142  | 1949  | 1492  | 5598 | 7090 | -     | -     | -     | -     | -     | -     | -     | -     |
| 1393                 | 1661  | 2044  | 286   | 940  | 1226 | -     | -     | -     | -     | -     | -     | -     | -     |
| Total                | 2190  | 2803  | 4993  | 135.9 | 1778 | 6538  | 8316  | 100.7 | 995  | 130.7  | 9311  | 103.3  |
| Percentage (%)       | 44    | 55    | 100   | -     | 21   | 79    | 100   | -     | -     | -     | -     | -     | -     | -     |

Simulation mode D

| Capacity ratio r1 : r2 | [hour] | [hour] | [hour] |
|------------------------|-------|-------|-------|
| r1=0.5                |       |       |       |
| 0                    | 630   | 630   | -     | 0     | 3111 | 3111 | -     | -     | -     | -     | -     | -     | -     |
| 1747                 | 1297  | 3044  | 1221  | 3922 | 5143 | -     | -     | -     | -     | -     | -     | -     | -     |
| Total                | 1747  | 1927  | 3614  | 100.0 | 1221 | 7034  | 8254  | 100.0 | 761  | 100.0  | 9015  | 100.0  |
| Percentage (%)       | 48    | 52    | 100   | -     | 15   | 95    | 100   | -     | -     | -     | -     | -     | -     | -     |
| r1=0.7               |       |       |       |
| 0                    | 1142  | 1142  | -     | 0     | 5942 | 5942 | -     | -     | -     | -     | -     | -     | -     | -     |
| 1089                 | 979   | 2068  | 446   | 750  | 2196 | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| Total                | 1089  | 2121  | 3210  | 87.4  | 446  | 7693  | 8139  | 98.6  | 663  | 89.8  | 8821  | 97.8  |
| Percentage (%)       | 34    | 66    | 100   | -     | 5    | 95    | 100   | -     | -     | -     | -     | -     | -     | -     | -     |
| r1=0.9               |       |       |       |
| 733                  | 1216  | 1949  | 1414  | 6378 | 7792 | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| 581                  | 540   | 1121  | 121   | 349  | 471  | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| Total                | 1314  | 1756  | 3070  | 83.6  | 1556 | 6278  | 8293  | 100.1 | 795  | 104.5  | 9058  | 100.5  |
| Percentage (%)       | 43    | 57    | 100   | -     | 19   | 81    | 100   | -     | -     | -     | -     | -     | -     | -     | -     |
primary energy consumption is minimized in both mode C and mode D. The reason is that the operation time in $P_{ki}<0.3$ is short compared with the other cases and avoids an increase in energy consumption. However, on the whole, the shortening of operation time does not lead to a sharp reduction in total energy consumption. As shown in Fig. 14., the machine heating efficiency rapidly changes for the worse under extremely low loads of $P_{ki}<0.1$. Avoidance of low-load operation brings improved energy efficiency, but does not effectively contribute to reduction in period energy consumption, because it is very small under low-load operation. Although pump energy consumption decreases following the decrease in operation time for heat source equipment, it does not appreciably contribute to the reduction of total energy consumption, because it represents approximately one-tenth of gas energy consumption. These results suggest that selection of the capacity ratio of two heat source machines is not an effective means for seasonal energy savings.

6. Conclusions

In evaluating the energy performance of heat source equipment for HVAC systems in a multi-functional building about one year after completion, we proposed two approaches towards energy savings; the operation mode of heat source equipment, which is easily adopted at the site, and selection of the capacity of each chiller to deal with a maximum thermal load. The results of our investigations can be summarized as follows.

1) For each of three gas-fired absorption chiller/heaters, regression equations were shown with gas energy consumption as an output variable and partial thermal load as an input variable. 
2) The operation mode of heat source equipment for annual cooling only was proposed to improve operational efficiency over the long term and its maximum advantage was quantitatively estimated as an energy saving of 13%.
3) Variation of heating capacity of two units of heat source equipment is not effective for energy savings.

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Notes

1) Measured gas volume (100 mmH2O (0.9807 kPa) and 15 deg C) is converted into normal cubic meters (101.325 kPa and 273.15 deg C) as follows.

$$ \text{1} \text{ m}^3 / h = \frac{101.325 + 0.9807}{101.325 + 0} \times 273.15 + 0 \times 0.957 \text{ [Nm}^3 / h] $$

2) Conversion from gas volume into primary energy: 46.046 [MJ/Nm$^3$].

3) Gas energy consumption theoretically depends on outdoor wet-bulb temperature, outlet chilled water temperature of gas fired absorption chiller, and machine partial load ratio. Therefore, we first conducted regression analysis on the correlation of above three factors for the cooling period. As a result, machine partial load ratio was found to have a significant effect on gas energy consumption, but wet-bulb temperature and outlet chilled water temperature were rejected at a significance level of 1%.

4) The outlet and inlet water temperatures of each heat source machine were measured, and the total gas volume $G_t$ of three machines was measured. Chilled water flow rate is not measured continuously and automatically. Secondary thermal loads are measured for two systems; one is thermal load $Q_{cl,w}$ [GJ/h] for the chilled water system throughout the year, and the other is thermal load $Q_{hs,w}$ [GJ/h] for chilled/hot water system with chilled water in summer and hot water in winter. Thermal load and gas volume are not measured for each heat source machine. Then, by using the measured data and operation pattern, we estimated the thermal loads and gas energy consumption, and showed the estimation flow of regression equations in Fig.18.

5) Conversion from electric power into primary energy: 9.4185 [MJ/kWh].

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Fig.18. Estimation Flow of Regression Equation for Cooling/Heating Load and Gas Primary Energy Consumption

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