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Running Performance of Split-type Air Conditioning Systems Installed in School and Office Buildings in Tokyo

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ABSTRACT

Split-type air conditioning systems or heat pumps with multiple indoor and outdoor units are becoming popular for air conditioning and room heating of small or middle-sized non-residential buildings in Japan. However, their running performance is yet to be recognized due to difficulties of measuring actual amount of heat transferred by a system. Mixed irregular flow of vapor and liquid refrigerant has prevented building owners and engineers from obtaining accurate amount of heat transferred between units. This study introduces two alternative methods to calculate heat transfer by measuring air volume and enthalpy with simple sensors attached to indoor units as well as by measuring amount of heat exchanged by outdoor units. Results at a university and an office building in Tokyo showed unexpectedly low COP values caused both by their excess capacities and imbalance between summer and winter heat demand resulting in the operation under extremely low part load.

1. INTRODUCTION

Recent rise in environmental consciousness and deteriorating state of the earth combined with approaching deadline for public commitments to reduce CO2 emissions and increasing energy consumption at private sectors have intensified importance of developing and promoting methods for conservation and efficient use of energy. Somewhat irrelevant to these interests, multiple-unit electric and gas heat pumps (EHP/GHP) have been rapidly spreading from the aspect of cost saving and convenience and installed even in the buildings with several tens of thousand square meters of floor area in major Japanese cities. From the aspect of energy efficiency, however, it has been suspected that their high rated COP based on Japanese Industrial standards (JIS) does not necessarily represent its actual values in use. It has been also suggested that heat pumps may constitute a primary source of heat island, because unlike centralized air conditioning systems equipped with cooling towers which primary discharge latent heat, heat pumps exclusively discharge sensible heat directly into urban canyon contributing to the rise of temperature. Their efficiency therefore is also a primary interest from the aspect of urban environment. In order to obtain state of the art knowledge to these pending questions, series of researches have been conducted in cooperation with three Japanese universities and Tokyo Gas, a major GHP distributor, to measure energy efficiency of a typical EHP and GHP system under actual operating environment. The results will help us in designing and installing them in a better way.
2. INDOOR MEASUREMENT AT A UNIVERSITY CAMPUS BUILDING IN SUBURBAN TOKYO

A multiple type EHP system consisting of 7 indoor and 4 outdoor units installed on a national university campus in west suburb of Tokyo was the site of the first measurement. For this system, multiple points indoor measuring method was applied to examine its system efficiency (i.e. COP: Coefficient of Performance) in daily operation. Summer measurement was conducted from August 26 through September 5, 2005 with the indoor setting temperature of 27deg. and winter measurement from February 14 through 22, 2006 with the setting temperature of 24deg. (February 14 through 16), 22deg. (17 through 19) and 20deg. (February 20 through 22). Climate during summer measurement was average ranging between 21.9 and 33.1 degrees and warmer than average during winter between 22 and 18.5 degrees. Throughout measurement, airflow of the indoor units was set at strong mode while airflow direction was set no swing with middle low angle blowout position.

2.1 Measurement Specification

Measured units are specified in Table 1 and 2. The total cooling (i.e. air conditioning without humidity control) capacity of indoor units is 50.9kW (at 50Hz, same hereinafter) while heating capacity is 57.0 kW, 11% exceeding cooling capacity. Outdoor units consume 21.18kWh of electricity to remove 56kWh of heat for cooling and consume 18.3 kWh of electricity to provide 53kWh heat for room heating. Including small power consumed by indoor units, rated COP for the system is 56/(21.18+0.63) = 2.57 for cooling and 53/(18.3+0.63) = 2.80 for heating. Electricity consumption of all 7 indoor units, 4 outdoor units and their control systems were measured every minute by attaching clamp wattmeter to the power line.

<table>
<thead>
<tr>
<th>Name</th>
<th>ACM B-1 (1 Unit)</th>
<th>ACM B-2 (2 Unit)</th>
<th>ACM B-3 (4 Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric source</td>
<td></td>
<td>Single phase 200V, 50/60Hz</td>
<td></td>
</tr>
<tr>
<td>Capability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>4.5kW</td>
<td>9.0kW</td>
<td>7.1kW</td>
</tr>
<tr>
<td>Heating</td>
<td>5.0kW</td>
<td>10.0kW</td>
<td>8.0kW</td>
</tr>
<tr>
<td>Electric power consumption</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>0.07/0.08kW</td>
<td>0.11/0.12kW</td>
<td>0.085/0.09kW</td>
</tr>
<tr>
<td>Heating</td>
<td>0.07/0.08kW</td>
<td>0.11/0.12kW</td>
<td>0.085/0.09kW</td>
</tr>
<tr>
<td>Power current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>0.35/0.4A</td>
<td>0.55/0.6A</td>
<td>0.425/0.45A</td>
</tr>
<tr>
<td>Heating</td>
<td>0.35/0.4A</td>
<td>0.55/0.6A</td>
<td>0.425/0.45A</td>
</tr>
<tr>
<td>Air volume system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong(15m3/min),</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong(12), Week(10)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Specification of outdoor units (50Hz/60Hz)

<table>
<thead>
<tr>
<th>Name</th>
<th>ACM-6, 7, B1, 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Three phase 200V, 50/60Hz</td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>56.0kW</td>
</tr>
<tr>
<td>Heating</td>
<td>53.0kW</td>
</tr>
<tr>
<td>Electric power consumption</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>21.18/22.4kW</td>
</tr>
<tr>
<td>Heating</td>
<td>18.30/20.1kW</td>
</tr>
<tr>
<td>Power current</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>67.8/72.1A</td>
</tr>
<tr>
<td>Heating</td>
<td>69.3/66.1A</td>
</tr>
</tbody>
</table>

Table 3 Measurement specification of an indoor unit

During summer measurement, 9 dry and 3 wet bulb temperatures were measured at each air outlet while 5 dry and wet bulb temperatures were measured at the inlet for all indoor units with thermocouples and data loggers as shown in Figure 1. Airflow velocity at air inlets and outlets were pre-measured with a traverse unit reproducing the same airflow as during the measurement. Heat exchange quantity was calculated by multiplying inlet and outlet enthalpy difference and airflow volume calculated by the airflow velocity distribution described later. Measured items on indoor units are specified in Table 3.

In order to measure indoor temperature distribution, 15 representing points were designated each with three vertical measurements making up 45 altogether as shown in Figure 2. In addition, outdoor temperature, humidity, solar radiation, airflow direction, airflow velocity, atmospheric pressure and precipitation were measured with a portable weather station.

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2.2 Airflow Volume Calculation
Airflow velocities in and from an indoor unit were measured with a traverse unit designed by Professor Shigeki Kametani exclusively for the study (Figure 3). A scalar and a vector anemometer traverse across an indoor unit by a
tenth of an inch precisely measuring three dimensional airflow velocities in and from the unit creating accurate airflow velocity distribution curve (line graphs of Figure 4). Airflow velocity at each measuring point was calculated by modeling these curves (bar graphs of Figure 4). Outlet airflow volume at each measuring point was calculated from modeled airflow velocities. Inlet airflow volume was calculated according to the representing area of each measured point (Figure 5). A sum of calculated airflow volume was adjusted to match the rated airflow volume for strong airflow mode and distributed to each measuring point.

![Airflow velocities distribution of air outlet and inlet with approximation at each measuring point](image1)

![Figure 4](image2)

![Air inlet volume distribution at each measuring point](image3)

![Figure 5](image4)

### 2.3 Results

#### 2.3.1 Summer Measurement:
Outdoor air temperature and room temperatures at three vertical measuring points are shown in Figure 6. During most of the operating time (10am-9pm), room temperatures stayed well around the preset temperature or a little below identifying cooling was properly functioned. The change of COP during operating time in summer measurement is shown in Figure 7. Average COP calculated by formula (1) was considerably lower than the rated COP of 2.57. Figure 8 and 9 show distribution of load factor. Since most of the load is concentrated under 30% of the capacity, it can be assumed that the system has an excess capacity.

\[
\text{COP} = \frac{\text{Quantity of heat exchanged by the indoor units}}{\text{Electric power consumption by indoor and outdoor units}} \\
= 715.806 \text{ [kWh]} / 411.382 \text{ [kWh]} = 1.74 \quad (10am-9pm, August 26-September 5, 2005)
\]

2.3.2 Winter Measurement:
Outdoor air temperature and room temperatures at three vertical measuring points are shown in Figure 10. During operating time (10am-9pm), room temperature stayed well around the preset temperature identifying heating was properly functioned. The change of COP during operating time in winter measurement is shown in Figure 11. Measured COP calculated by formula (1) was much lower than the rated COP of 2.80. One of the reasons for such low COP is the use of oil heaters to heat refrigerant adding to the stand-by power consumption in winter.

\[
\text{COP} = 92.700 \text{ [kWh]} / 153.898 \text{ [kWh]} = 0.60 \quad (10am-9pm, February 14 - 22, 2006)
\]
Figure 6  Outdoor and room temperature  
(Summer measurement)

Figure 7  Change of COP (Summer measurement)

Figure 8  Frequency distribution of load factor  
(summer measurement)

Figure 9  Relation between outdoor temperature and 
load factor (summer measurement)

Figure 10  Outdoor and room temperature  
(winter measurement)

Figure 11 Change of COP (winter measurement)

Figure 12  Frequency distribution of load factor  
(winter measurement)

Figure 13  Relation between outdoor temperature and 
load factor (winter measurement)
Load factor distribution during winter measurement is shown in Figure 12 and 13. Most of the load is concentrated under 20% of EHP’s capacity. Load Factor was lower in winter than in summer because relatively high outdoor air temperature prevailed during the measurement had worsened imbalance of summer and winter heat demand in addition to its excess capacity. It is observed from the measurement that for a building with more daytime and less night time use, load factor can stay very low for the most of winter except for a few snowy cold days because in Tokyo metropolitan area heating demand maximizes during night and early morning hours when outdoor temperature falls and stays at the bottom.

3. OUTDOOR MEASUREMENT AT AN OFFICE BUILDING IN TOKYO

A multiple type packaged gas heat pump (GHP) unit installed in an office building in central Tokyo was the outdoor unit measurement site. The measured system consists of an outdoor unit driven by a 30HP gas engine fueled by city gas and 11 indoor units each with 7.1kW of cooling and 8.0 kW of heating capacity. Rated COP of this unit is 1.25 for cooling and 1.37 for heating at primary energy basis. Referring to an EHP, its secondary-energy based COP is 3.39 for cooling and 3.71 for heating.

Probing sensors insertion method exclusively developed for this measurement was applied for the first time to measure the amount of heat exchanged through heat exchange chambers of outdoor units in daily operation. The measured system placed on the rooftop of three stories building provides primary heat source of cooling and heating of 384 m$^2$ of office floor. Measurement was conducted from July 11, 2007 through February 13, 2008 without interruption. Neither indoor measurement was conducted nor measurement informed to workers on the object floor.

3.1 Measurement Specification

Figure 14 shows how probing sensors as well as airflow velocity sensors were fitted on the outdoor unit. Each probing sensor is equipped with two T type thermocouples, one of which is put on the exterior of heat exchange fins and the other penetrates through fins into exhaust air chambers so that temperature of before and after heat exchange could be measured at one time. Figure 15 shows fitting of sensors through heat exchange fins (a), a penetrated sensor appeared in an exhaust chamber (c), CPU fans for PCs were placed over the exhaust air fans to measure velocity of exhaust air (b). To make good representation of the heat exchanged by the entire system, a total of 27 probing sensors were fitted on three sides of the outdoor unit (shown in round dots in Figure 14). Velocity of exhaust airflow was measured on each fan unit (shown in oval dots in Figure 14) so that volume of air through heat exchange fins can be calculated with a fan’s performance curve supplied by the manufacturer. Assuming heat was exchanged only as sensible heat, amount of exchanged heat was simply calculated by multiplying temperature difference between exterior and interior sensors and volume of air came through heat exchanging fins.

Electricity consumption of both outdoor and indoor units was measured with cramp watt meters not disturbing their daily operation. To measure gas consumption, however, an additional gas meter had to be installed halting the operation for half a day. Measurement was conducted at 10 minutes interval throughout the term. All the measured data were automatically sent wireless by cellular phone radio wave to a data center and accumulated for later analysis. Climatic condition throughout the measurement was observed by a portable weather station.

Figure 14 Location of sensors set on the outdoor unit
Figure 15 Sensors fit into (a) and penetrate through (c) heat exchange fins and placed on exhaust air fans (b)

Table 4 Measurement specification of the outdoor unit

<table>
<thead>
<tr>
<th>Measured Item</th>
<th>Sensor or sensor method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchanged heat through outdoor unit</td>
<td>Probing sensor insertion method</td>
</tr>
<tr>
<td>Power consumption</td>
<td></td>
</tr>
<tr>
<td>Indoor units</td>
<td>Cramp power meter</td>
</tr>
<tr>
<td>Outdoor units</td>
<td>Cramp power meter</td>
</tr>
<tr>
<td>Gas consumption</td>
<td>Gas meter, Pressure gauge</td>
</tr>
<tr>
<td>Exhaust gas heat value</td>
<td>T type thermocouple</td>
</tr>
<tr>
<td>Outdoor climate</td>
<td>Weather Station</td>
</tr>
</tbody>
</table>

3.2 Results

Upper part of Figure 16 shows amount of heat exchanged daily both for cooling (left half) and heating (right half). It is easy to recognize that there is a big difference between cooling and heating demand presumably due to worsening heat island in central Tokyo and to the global warming. It is also easy to understand that if we decide the capacity of the system by cooling demand, then in winter we must operate it under lower part load because all heat pumps have structurally more than 10% larger heating capacity than cooling as was the case on measured GHP: 7.1 kW for cooling and 8.0 kW for heating per indoor unit. Lower part of Figure 16 shows primary energy use, which is a sum of gas and electricity consumption. By simply dividing amount of heat exchanged by total amount of primary energy consumed, COP of the GHP unit was calculated and shown in line graphs. It is clear that COP for heating is much lower than the rated value staying between 0.6 and 1.0. Although these values were much higher in comparison with indoor units measurement, where COP was calculated on the secondary energy basis, it is likely that low part load was preventing the unit from running at expected efficiency not only at a university campus but also at an office building.

Figure 16 Daily heat exchange, primary energy consumption and COP
It has been observed that efficiency of heat pumps varies much with the change in outdoor temperature. Thanks to continuous measurement over seasons, relation between climate and COP has been clearly disclosed in this measurement. Bar graphs of Figure 17 show accumulated time length of operation classified by outdoor temperature, the left bars show total heating and the right bars show total cooling hours. Line graphs with colored background show part load factors for corresponding temperature. Line graphs with dots and numbers are the average primary-energy based COP at corresponding outdoor temperature. It has become clear from figure 17 that during peak cooling days, COP did not rise as high as expected because the unit has an excess capacity and never runs over 50% of the capacity even on summer peak days. It has to be investigated how far COP can rise if a system with proper capacity and better part load is installed. For heating season, fall of COP by outdoor temperature drop is moderate for GHP because it can choose operation between heat pump cycle and direct heating by burning gas. EHP without such an alternative should demonstrate lower performance. Change of COP can be explained not only by part load but also by outdoor climate. COP varies with the inlet air temperature much greater than our recognition. For example, cooling COP drops as the outdoor temperature becomes 30 degrees centigrade or above and 25 degrees or below. Therefore more attention must be paid not only to its capacity but also to the climate of the site all year around before installation of a heat pump.

![Figure 17 Change of primary-energy based COP classified by outdoor temperature](image)

### 4. CONCLUSION

Running performance of split-type electric and gas-engine multiple-unit heat pump systems were measured under actual operating environment at a university campus building and at an office building in metropolitan Tokyo. For the measurements, classic indoor measuring method and probing sensors insertion method for outdoor units originally developed for the study were applied respectively. Both results showed considerably low COP compared to the rated values of the systems because cooling and heating capacities were far exceeding actual load resulting in operation under low part load throughout measured period. Fall of COP values were also explained by the difference of air temperature from that of peak COP. Therefore more attention should be taken to the operating climate all year around especially to the cooling at 30 degrees centigrade or above and 25 degrees or below. COP was lower for heating than for cooling because imbalance of summer and winter heat demand is increasing probably due to urban heat island and global warming. To solve these problems, more accurate load calculation and proper designing with reliable data and software must be conducted. And also, a technological breakthrough to integrate heat load into fewer outdoor units to operate them at higher part load is expected.

### REFERENCES

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