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# Load-based performance characterization of air conditioners using an emulator-type assessment technique

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## Abstract

The operation of air conditioning installations may respond to different thermal load scenarios with variable or intermittent modulations of the compressor speed and expansion valve opening, according to the native control system. Therefore, the representativeness of the standard performance rating procedures obtained at a fixed compressor speed is limited and may be misleading for the efficient development of this technology.
The emulator-type performance assessment technique was developed by combining the equipment of air-enthalpy testing facilities for real-time measurement of the cooling capacity supplied by the air conditioner and a room emulator to reproducibly generate arbitrary indoor load conditions. This study demonstrates the ability of the developed assessment approach to characterize the performance of air conditioners in response to variations in the indoor air state according to the native control system. Specifically, an R32 ceiling-type commercial unit was tested under the conditions necessary for the calculation of the annual performance factor over a load range between 25 and 100% of the nominal system capacity for a 147 $m^3$ virtual room with a total thermal capacity of 1470 kJ/K. The steady, fluctuating, and intermittent controllability of the system was captured. Finally, the efficiency of the system operating according to its native control system was compared with the results obtained according to the current standard procedure defined by the Japanese Industrial Standard at a fixed compressor speed.

*Keywords: Dynamic performance evaluation; Testing facility; Emulator; Cyclic operation; Load-based test;*

## 1. Introduction

The need to decarbonize the energy sector through efficient energy management has steadily become more relevant in recent years as policymakers and stakeholders, as well as manufacturers, are reacting to the rising climate threat. Air conditioners and heat pumps are among the most frequently deployed devices worldwide, with billions of operative installations. Although vapor compression air conditioning is generally recognized as a well-developed technology, the actual performance of these systems remains largely unknown. Specifically, standard testing and rating methods were conducted with a fixed compressor speed while deactivating system control. Therefore, the rated performances are not representative of the actual operation of air conditioners (AC). In addition, the sensors required by conventional measurement techniques are too costly and complex to capture the actual performance of a statistically meaningful number of AC installations. For example, air flow meters are too bulky, and the installation of refrigerant pressure sensors and flow meters requires cutting refrigerant pipelines. Consequently, owing to this gap in knowledge regarding the actual performance of ACs, optimal control strategies that are able to efficiently respond to different building structures, occupant lifestyles, and climates of different air conditioning installations are yet to be understood and developed. Sholahudin et al. 2021 [1] demonstrated the ability of machine learning techniques to deal with the latter issue through broadly applicable and cost-effective performance-monitoring techniques. Nonetheless, this monitoring approach requires training data to be collected with dedicated testing methodologies. However, standardized testing methodologies are conducted with a fixed compressor speed while deactivating the system

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control, thus deviating from the actual performance of operating installations. To overcome this challenge, an emulator-type testing facility was designed and built for load-based tests. Contextually, the time evolution of indoor conditions, such as temperature and humidity, is recreated by a condition generator to represent the dynamic thermal response of the conditioned room in accordance with the system capacity and building loads. The system reacts to deviations from the setpoint of the thermostat according to its native control with variable compressor speed and fan speed, allowing this testing method to capture actual field operation performance. Although standardization of such a methodology is yet to be conclusively defined, load-based testing methodologies have been recognized as an effective approach for capturing system controllability and representative performance [2-4]. Accordingly, load-based testing methodologies are being endorsed to form the basis for new rating standards (CSA [5]) and are being investigated to ensure test reproducibility [6-9]. In this study, the current Japanese standard testing methodology (JIS B 8615-1/2:2015) [10] was compared with the proposed emulator-type load-based testing methodology to clarify the difference between the two approaches and discuss the advantages of capturing the interdependencies between the controllability and system performance. The testing conditions were defined according to the requirements for calculating the seasonal performance index adopted in Japan (Annual Performance Factor, APF). Finally, the APF was evaluated with reference to the test results obtained from the testing facility and from the manufacturer.

## 2. JIS test methodology

JIS tests are conducted with reference to the JIS B 8615-1/2:2015 [10] regulations. The system is operated at a maximum volumetric air flow rate, constant outdoor conditions, and return conditions to the indoor unit while overriding the native control of the system to constantly maintain the prescribed compressor speed and valve opening. These tests adopt the air-enthalpy method for cooling and heating capacity measurement.

## 3. Testing Facility and Methodology

Load-based tests require a real-time evaluation of the supplied cooling capacity for the considered system operating under constant load conditions and the set value of the indoor temperature. During operation, the native control of the system is kept active, regulating both the valve opening and compressor speed. To perform load-based tests, it is necessary to calculate and reproduce the time variation of the indoor condition in its interaction with the variable-speed control of the air conditioner (Figure 1).

The experimental setup was composed of two psychrometric rooms. Both rooms were equipped with a condition generator to reproduce the operational environment, and a measurement chamber instrumented for the measurement of the sensible and latent cooling capacities with dedicated temperature and humidity sensors. Other round-robin tests are in progress with other companies that possess calorimetric testing facilities to statistically confirm the conclusions of this study and spread the effectiveness of this methodology in capturing the controllability and dynamic performance of air conditioners.

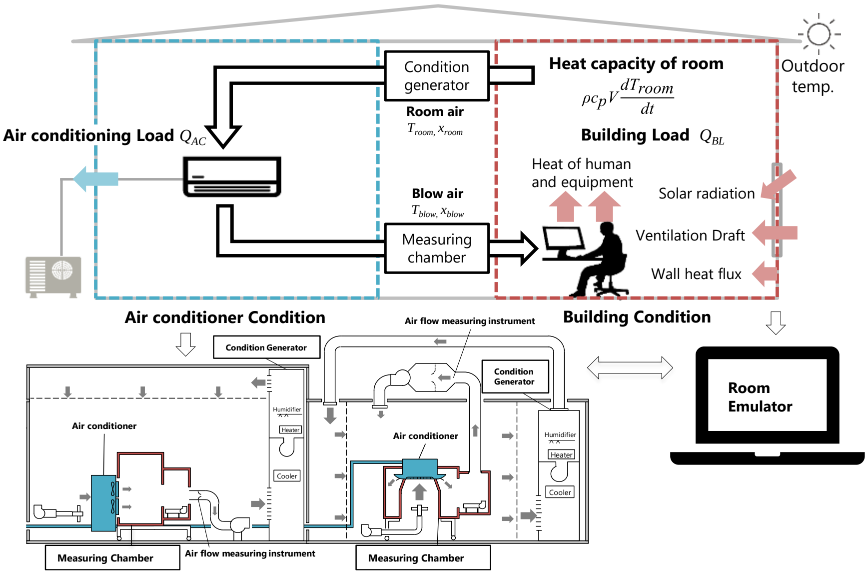

Fig. 1. Testing Facility schematic.

## 4. Emulator

The virtual room emulator is a central element for the reproducibility and representativeness of the time-dependent response resulting from the interaction of the system control with specific heat load conditions.

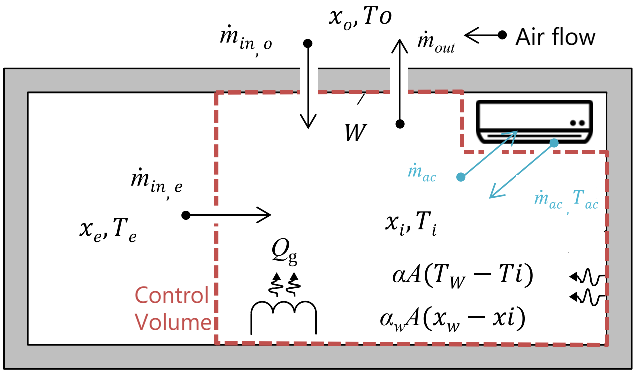

Fig. 2. Testing Facility Indoor room schematic.

The numerical model of the room (schematically represented in Figure 2) accounts for heat infiltration from the external environment, ventilation, and heat transfer from solar radiation through windows. Furthermore, the model considers the internal generation of sensible and latent heat from the occupants, lighting, and indoor equipment, in addition to heat and moisture accumulation owing to the heat and mass capacities of the volume of indoor air, fixtures, walls, and floors.

$$\dot{m}_{out} = \dot{m}_{in,o} + \dot{m}_{in,e} \tag{1}$$

$$C_{S,i}\frac{dT_i}{dt} = Q_{ac,S} + Q_{bld,S} \tag{2}$$

$$M_{L,i}\frac{dx_i}{dt} = \dot{m}_{ac}(x_{ch} - x_i) + L_g \tag{3}$$

$$Q_{ac,S} = \dot{m}_{ac}\, c_p(T_i - T_{ch}) + \alpha_{ch}A_{ch}(T_i - T_{ch}) \tag{4}$$

In the present study, the mathematical model was based on the continuity of indoor air (Eq. 1), energy balance (Eq. 2), moisture balance (Eq. 3), and the auxiliary relations for heat and mass transfer of walls and fixtures considering the thermal and moisture capacity of a 147 m$^3$ room (details of the present formulation can be found in [9]). In the following tests, the terms $Q_{bld,S}$ and $L_g$ summarize the combination of effects defining the sensible and latent load scenarios, respectively, and are kept constant during the load-based tests. The cooling capacity $Q_{ac,S}$ accounts for the sensible part of the overall system capacity and, in these preliminary tests, it is calculated as in Eq. (4). Accordingly, it accounts for the sensible heat transfer between the return air conditions and the supply air condition measured at the measurement chamber, plus the correction factor that represents heat infiltration through the chamber walls. Here the factor $\alpha_{ch}A_{ch}$ indicates the thermal conductance of the chamber, which is measured at standard conditions as in [10]. More detailed investigations on the influence of such measurement methodology for the supply air condition is referred to [7].

## 5. System

The system tested in this study is an R32 ceiling-type air conditioner that features a nominal cooling/heating capacity of 10 kW/11.2 kW with the main specifications summarized in Table 1.

Table 1. System characteristics

| Type | Cooling [W] | Heating [W] | Refrigerant | Mass Charge [kg] | Maximum air flow rate [m$^3$/min] |
|---|---|---|---|---|---|
| Ceiling | 10000 | 11200 | R32 | 3.3 | 32 |

## 6. Annual Performance Factor

The Annual Performance Factor (APF) is an index used in Japan to assess the seasonal efficiency of thermal systems such as air conditioners and heat pumps, accounting for both geographical and seasonal conditions. The tests conducted under the conditions listed in Table 2 were referenced for defining a COP value for each outdoor temperature and calculating the APF index as an overall value weighted on the annual hourly distribution of each temperature bin. During the JIS tests, the load condition was defined with reference to the maximum compressor speed, whereas for load-based tests, it refers to the nominal cooling/heating capacity of the system. In accordance with JIS B8615 [10] and JIS B8616 [11], the APF can only be obtained in the cooling mode, heat pump operation, or both. The temperature distribution used in the Tokyo area is shown in Fig. 3.

Table 2. Measurements required for APF calculations

| Cooling/Heating load (% of compressor speed at rated capacity) | Outdoor Temperature Dry/Wet bulb °C | Indoor Temperature setpoint Dry/Wet bulb °C | Operation Mode |
|---|---|---|---|
| Full Load (100) | 35/24 | 27/19 | Cooling |
| Half Load (50) | 35 /24 | 27/19 | Cooling |
| Half Load (50) | 29 /19 | 27/19 | Cooling |
| Low Load (25) | 29/19 | 27/19 | Cooling |
| Full Load (100) | 7 /6 | 20/15 | Heating |
| Half Load (50) | 7 /6 | 20/15 | Heating |
| Low Load (25) | 7 /6 | 20/15 | Heating |
| Full Load (100) | 2 /1 | 20/15 | Heating |

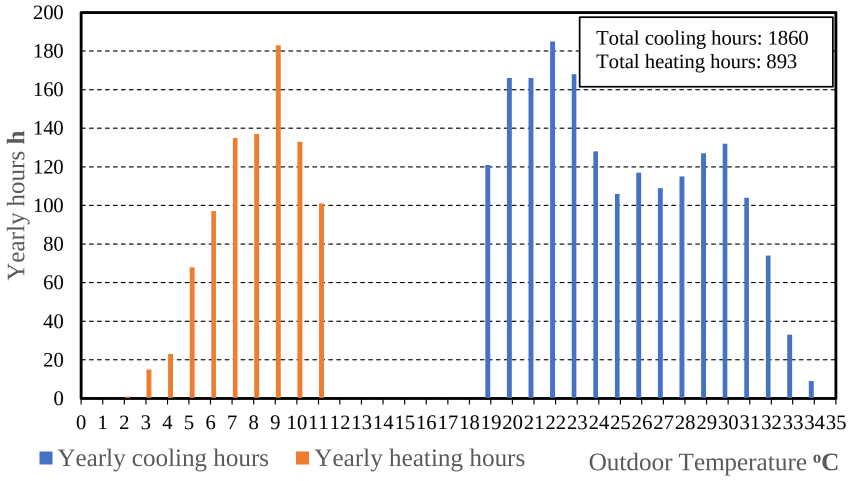

Fig. 3. Representative yearly heating and cooling hours distribution in the Tokyo prefecture

## 7. Data analysis

### *7.1. JIS tests*

The COP obtained under the aforementioned operating conditions for the JIS standard testing methodology is reported in Table 3, along with the load-based test results. Peak efficiency was demonstrated at low-load conditions for the cooling operation, whereas for the heating mode, the highest COP was achieved at half-load operation. JIS standard testing results reported in the study are obtained from the manufacturer catalogue of the specific system used in load-based tests. Because of the regulation on such performance tests [10-11], the test condition is set by fixing the compressor speed and setting the valve opening to achieve a safe degree of superheating at the compressor suction. Operating conditions set in this manner are not necessarily resulting in a cooling/heating capacity equivalent to the percentage of the rated value reported in Table 2.

### *7.2. Load-based tests*

The following charts represent the four conditions used to measure the cooling performance of the system, as listed in Table 2. COP, power consumption, and cooling capacity were calculated with reference to the interval between the vertical dotted lines, representing an integer number of regular cycles.

Figure 4 Illustrates the results of a load-based test conducted for a load equivalent to 25% of the nominal cooling capacity at 29 °C outdoor temperature. In this operating condition, the control system is driving the air conditioner with on-off cycling operation. This type of regulation is required when the inverter is unable to stably maintain a low compressor speed, such as the one imposed during JIS tests. Such cycling operation, along with a lower air flow rate led to a 35% gap in COP when compared with steady operation JIS test.

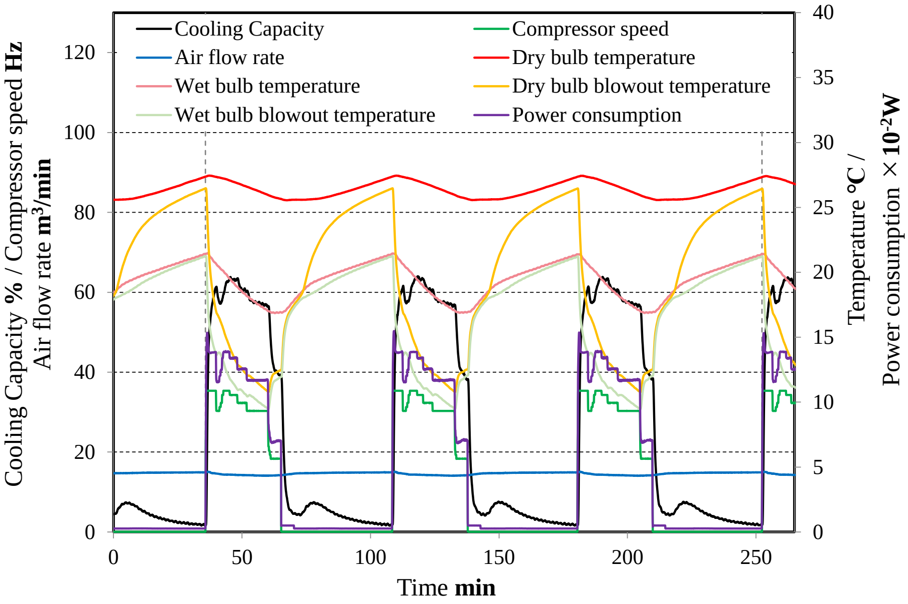

Fig. 4. 29 °C Outdoor Temperature, Low Load

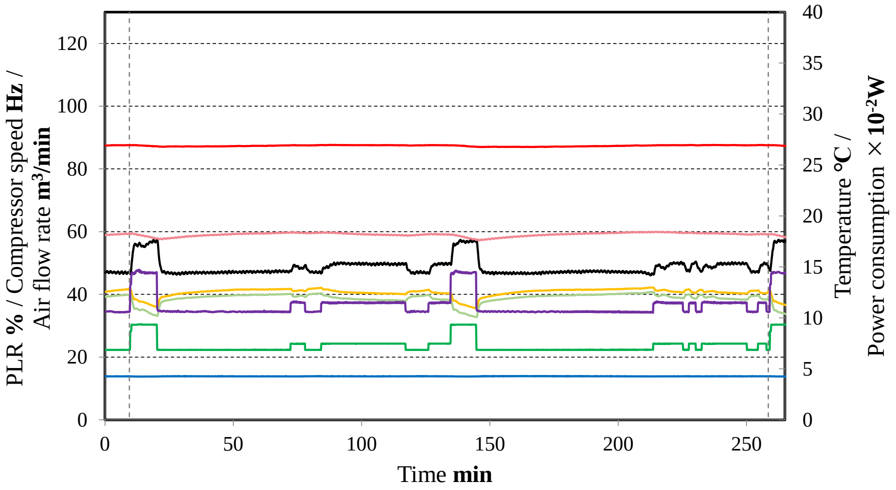

Fig. 5. 29 °C Outdoor Temperature, Half Load

The load-based test results reported in Figure 5 and 6 demonstrate the ability of the variable speed control to achieve a close-to-stationary operation (except for minor compressor speed adjustments owing to oil management processes), but a lower air flow rate than the corresponding JIS test results led to a lower COP value for load-based tests. Under this load condition, the control system operated the air conditioner with a supply airflow rate that was approximately half of the maximum value used during the JIS measurements. Accordingly, the compressor speed required to compensate for the less efficient heat exchange was approximately 20% higher, resulting in a higher power consumption to balance the same heat load and maintain the target indoor temperature.

The test results obtained at full capacity at 35 ºC outdoor temperature are shown in Figure 7. Under this limiting condition, it was necessary to override the air flow rate of the native control system during load-based tests to achieve the target room air temperature. Figure 7 demonstrates that the system control manages this load with a variable speed and results in a lower COP than that obtained during the JIS tests at a constant compressor speed.

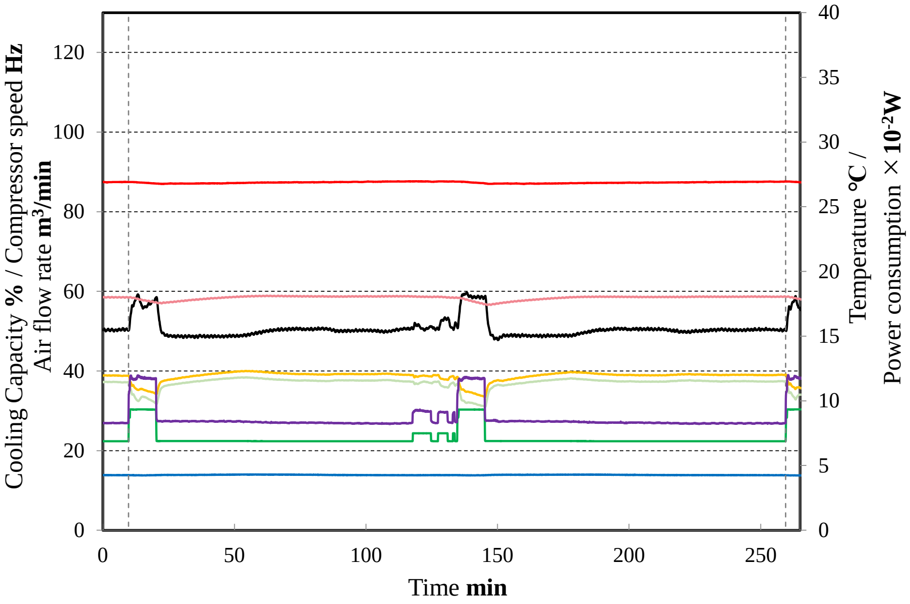

Fig. 6. 35ºC Outdoor Temperature, Half Load

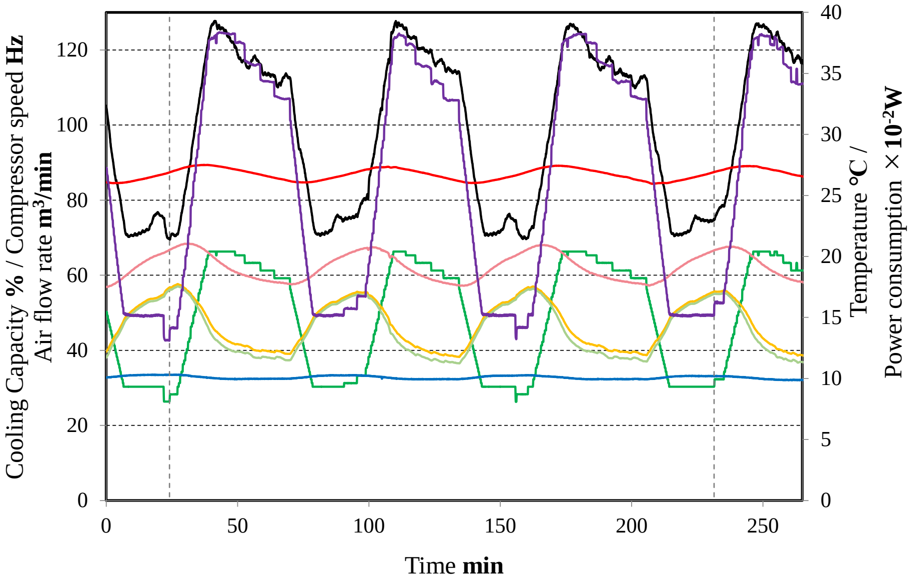

Fig. 7. 35ºC Outdoor Temperature, High Load

Consequently, the heating performance of the system was evaluated with reference to the four representative conditions listed in Table 2. Correspondingly, COP, power consumption, and cooling capacity, were evaluated in the time interval between the vertical dotted lines, representing an integer number of regular cycles. In accordance with the cooling case, in the heating mode, the on-off operation is performed at low loads (Figure 8), and to ensure a comfortable temperature for blowout air flow, a further adjustment of the compressor speed is performed between cycles.

As shown in Figure 9, the same observations for the half-load cooling conditions could be made. Despite relatively steady functioning, the lower air flow rate led to a less efficient heat exchange and compression ratio; thus, the COP values obtained were 36% lower.

In Figure 10, it is possible to notice an unsteady operation performed by the native control system aimed at maintaining a comfortable blowout air flow rate and temperature, lowering the airflow when the blowout temperature is low, and increasing the compressor speed between peaks to avoid relatively colder air blows that may result in discomfort for users.

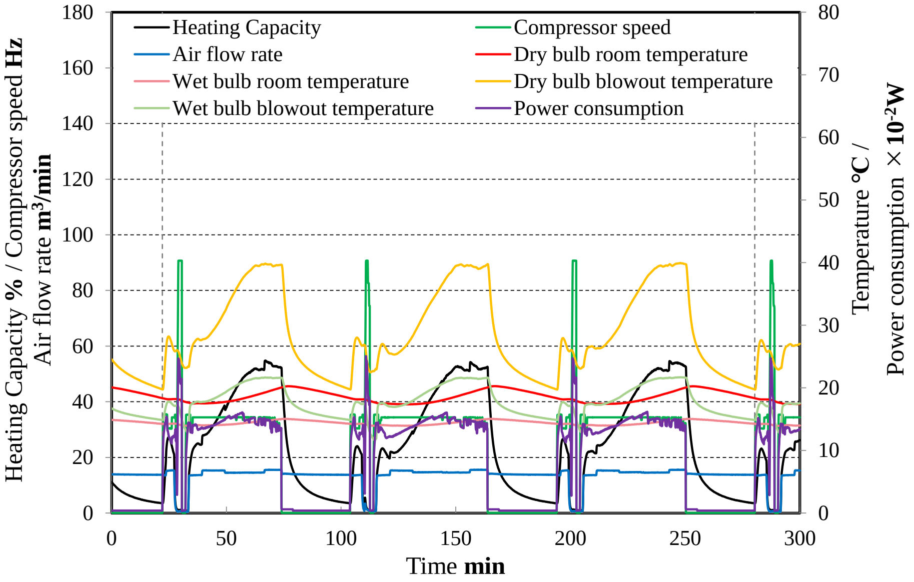

Fig. 8. 7 °C Outdoor Temperature, Low Load

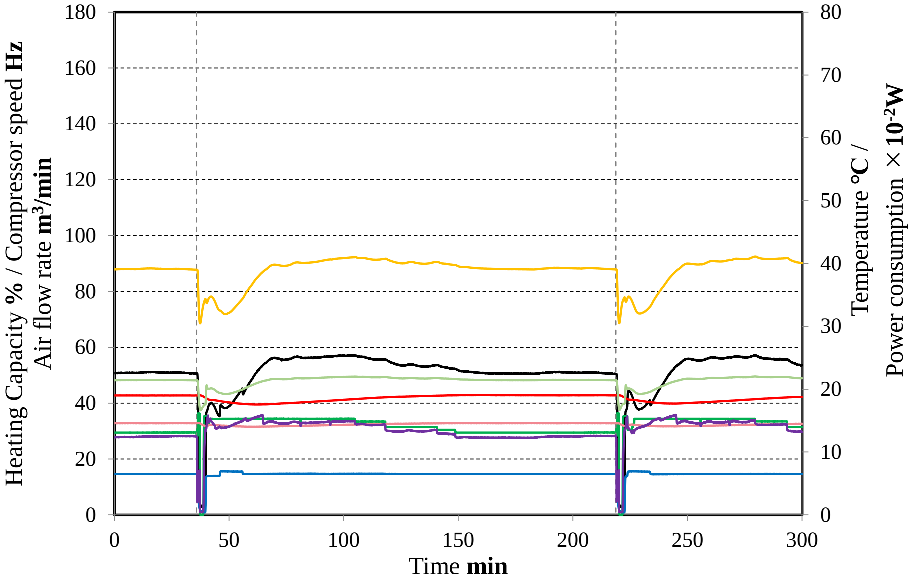

Fig. 9. 7 °C Outdoor Temperature, Half Load

In Figure 11, the full-load and low outdoor temperatures represent the most demanding operating conditions for the system. They present the overall lowest COP in both the load-based and fixed compressor speed rating methods. Moreover, this is the only condition where the load-based COP value is higher than the steady-state counterpart, and the ability of the control system to maintain the room temperature around the set point value of 20 °C with cyclic operation and a high air flow rate, along with a relatively broad dead band of the thermostat around the set value, results in a higher system COP when compared to the full load JIS test where the compressor speed is maintained at its maximum value.

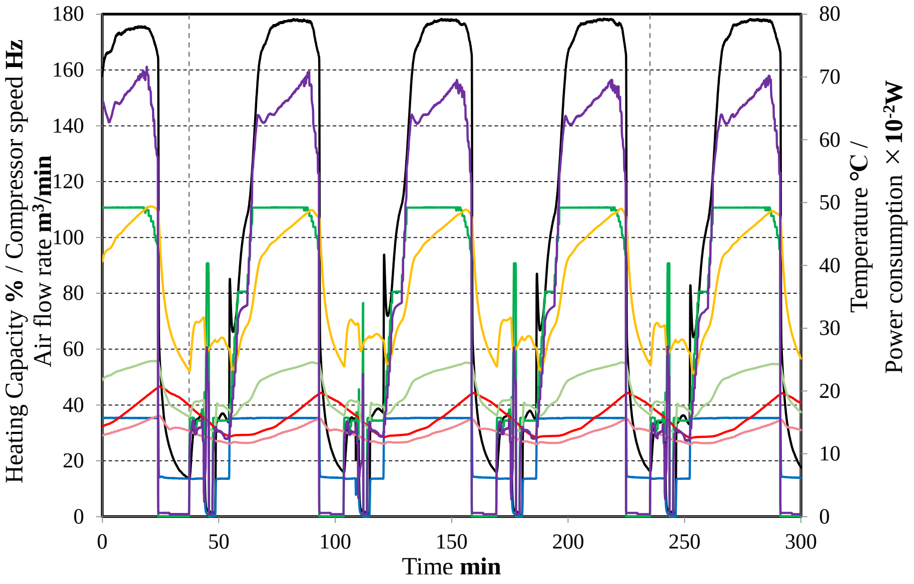

Fig. 10. 7 °C Outdoor Temperature, High Load

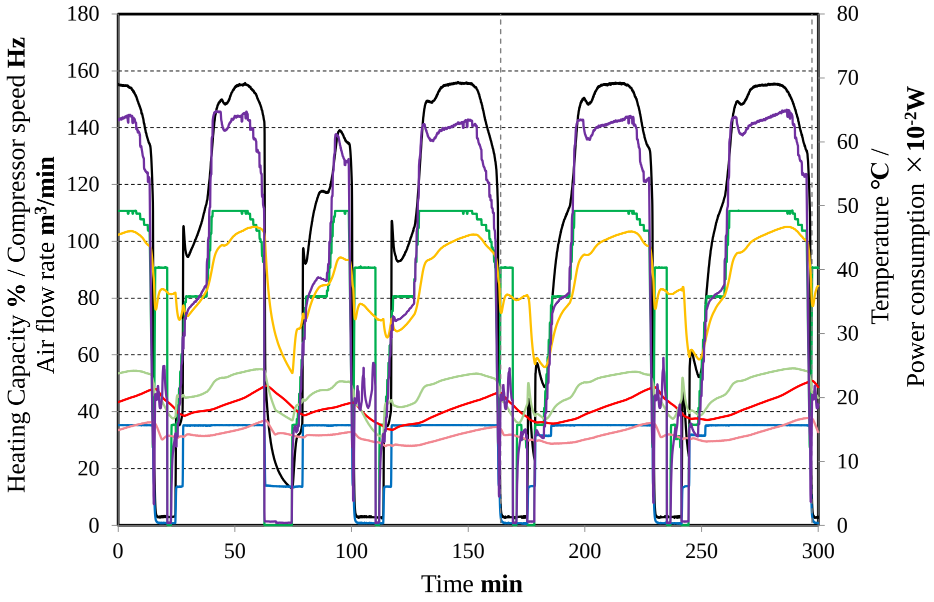

Fig.11. 2 °C Outdoor Temperature, Full Load

Table 3. Measurement results required for APF calculation

| Cooling/Heating Condition | Load-based test* Capacity/Power Consumption **kW** | Load-based test COP | JIS test Capacity/Power Consumption **kW** | JIS test COP | COP % Difference |
|---|---|---|---|---|---|
| Full 35ºC | 9.88 / 2.66 | 3.70** | 10.00 / 2.41 | 4.15 | 10.8 |
| Half 35 ºC | 4.86 / 1.12 | 4.34 | 4.50 / 0.79 | 5.66 | 23.3 |
| Half 29 ºC | 5.06 / 0.86 | 5.85 | 4.70 / 0.61 | 7.70 | 24.0 |
| Low 29 ºC | 2.53 / 0.49 | 5.15 | 3.30 / 0.41 | 7.97 | 35.4 |
| Full 7 ºC | 11.15 / 3.56 | 3.13 | 11.20 / 2.35 | 4.77 | 34.4 |
| Half 7 ºC | 5.70 / 1.33 | 4.28 | 5.10 / 0.76 | 6.67 | 35.8 |
| Low 7 ºC | 2.85 / 0.91 | 3.13 | 2.80 / 0.50 | 5.60 | 44.1 |
| Full 2 ºC | 11.22 / 4.12 | 2.72 | 13.50 / 5.30 | 2.55 | -6.7 |

*Average values, ** Air flow rate manually managed

As shown in Table 3., the results of the measurement process in the testing facilities lead to 10–44% lower COP values compared with the data reported in the manufacturer catalogue, obtained through fixed compressor speed testing following the JIS guidelines.

The corresponding APF values are listed in Table 4 for a standard office in the Tokyo area. This result provides evidence for a difference of approximately 27% between standard and load-based tests, which is sensitively related to the number of hours of functioning encounter cycling on-off or modulating variable speed mode when driven by the native control system. Further, this may sensitively depend on the interactions with the specific building characteristics and load scenarios of different installations.

Table 4. APF calculation

| APF Load-based tests | APF JIS tests |
|---|---|
| 4.76 | 6.40 |

## 8. Conclusions

In this study, an emulator-type load-based testing methodology was proposed to overcome the limitations of the current JIS testing procedures conducted at constant compressor and fan speeds by disabling the native control system of the air conditioner. The proposed method allows the system to respond to the dynamic variation in the return air condition according to its native control system, as it responds during field operation. This was made possible by combining an emulator simulating the time variation of the room condition during its interaction with arbitrary load scenarios and air-enthalpy testing equipment for the real-time measurement of the output capacity.

The ability of this testing methodology to capture the controllability and dynamic response of air conditioners to constant load and set indoor temperature conditions is presented and discussed herein. The heating and cooling operation performance of an R32 ceiling-type air-conditioning unit was investigated under the prescribed conditions required for the characterization of the annual performance factor. A qualitative and quantitative comparison between the results of the JIS constant-speed tests and emulator-type load-based tests was conducted to clarify the differences and connotations of the two approaches.

During the cooling mode operation at high loads, the COP difference between the JIS and load-based tests was approximately 10% and it increased with decreasing cooling load, showing no substantial difference for the two different conditions at half load (23 and 24% COP difference) despite the different outdoor temperatures, reaching the maximum gap for the low-load condition (35% COP difference). For heat pump operation, the efficiency comparison follows the same trend, but with higher discrepancies of up to 44% for lower loads. These results, even though affected by the aforementioned discrepancies of cooling/heating capacities between JIS and load-based, show a substantial performance difference between the fixed compressor speed and native control-driven functioning, especially at lower loads, where the divergences between the on and off cyclic operation and steady operation are significant and closely related to the specific control method integrated in the system.

Accordingly, the results suggest the importance of accounting for the system controllability, load scenario, and room characteristics to improve current standard rating procedures and demonstrate the ability of the proposed emulator-type load-based testing methodology to capture these operating characteristics. The use of such an emulator-type load-based testing approach is critical for effectively developing high-efficiency control methods for air conditioners and heat pumps.

## Nomenclature

Symbol:

| | |
|---|---|
| $A$ | Area [m$^2$] |
| $C$ | Heat [J/K] |
| $c_p$ | Constant pressure specific heat [J/(kg・K)] |
| $d$ | Thickness [m] |
| $H$ | Internal heating of the walls [W/m$^2$] |
| $h$ | Specific enthalpy [kJ/kg] |
| $L$ | Vapor generation rate [kg/s] |
| $\dot{m}$ | Mass flow rate [kg/s] |
| $Q$ | Heat transfer rate (load/capacity) [W] |
| $T$ | temperature [K] |

| | |
|---|---|
| $t$ | Time [s] |
| $V$ | Volume [m$^3$] |
| $W$ | Wall |
| $x$ | Specific humidity [kg/kg$_a$] |

Greek symbols:

| | |
|---|---|
| $\alpha$ | Heat transfer coefficient [W/(m$^2$・K)] |
| $\alpha_L$ | Moisture transfer coefficient [(kg/s)/(kg/kg$_a$・m$^2$)] |
| $\lambda$ | Thermal conductivity [W/(m・K)] |
| $\rho$ | Density [kg/m$^3$] |

Subscript:

| | |
|---|---|
| *ac* | Supply |
| *bld* | Overall building coefficient |
| *ch* | Measuring chamber |
| *e* | Exterior |
| *g* | Internal generation |
| *i* | Indoor |
| *in* | Inflow |
| *L* | Latent heat |
| *o* | Outdoor |
| *out* | Outflow |
| *S* | Sensible heat |
| *w* | Water |
| *W* | Wall |

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