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Interlaboratory verification of feed-forward compensation for enhanced reproducibility of emulator-type load-based tests – Case study of defrost operation –

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Abstract

Frost formation is among the main causes of performance degradation in heat pumps. As defrosting cycles are energy intensive and dynamic maneuvers programmed within the system control board, their characterization intensifies the challenges in reproducibility of dynamic performance tests and remains mostly unresolved. Emulator-type load-based tests respond to the necessity of performing representative yet reproducible performance evaluation of air conditioners and heat pumps. Core of this testing methodology is the use of a room emulator to mimic the response of a virtual building to the capacity supplied by the tested unit under given load conditions. Thereby allowing for tests conducted while operating the system with its native control and while defining representative thermal characteristics of the conditioned space, independently from the thermal and moisture inertia of the testing facility itself. The feed-forward compensation method (FFC) is a model predictive control technique developed to minimize information loss and discrepancies in the continuous data transfer between hardware and software side of such testing methodology. This study practically deploys the FFC in a feed-forward architecture during actual tests on a 10kW-ceiling-type unit operated in heating mode and exhibiting defrost dynamics. Maximum peak to peak delay during cycling on-off operation was limited to below 60 seconds. The benefit on results reproducibility was investigated and verified through interlaboratory tests conducted in two different facilities. Consequently, reached a level equivalent to current fixed-capacity tests, with maximum *COP* deviations of the same tested unit within 2% in the tested range of conditions. The proposed method does not require additional equipment and aims at enhancing the capability of current testing equipment in conducting reliable load-based and dynamic tests, opens to reliable and clear investigations of defrosting operation, and complementarily enables supports control optimization to minimize performance degradation due to frost formation.

Keywords: Frost formation; Emulator testing; Feed-forward control; Delay compensation; Dynamic performance evaluation.

1. Introduction

There are billions of air conditioning and heat pump installations worldwide. Moreover, demand is expected to multiply further in the coming decades [1]. Most of these unit are equipped with a variable-speed drive control, which enables expanding high efficiency operation over a broader range of conditions. However, the control response introduces complex dynamic interactions between the system and the surrounding thermal and humidity features of the conditioned environment. As a result, the actual performance of heat pumps not only is dynamic but also exhibit a possible variety of performance for the same unit when installed in different buildings at corresponding ambient and load conditions.

As the system hardware nears its thermodynamic efficiency limit, optimizing operation through advanced control becomes critical for reducing energy consumption. Among control manoeuvres, defrost cycles are particularly critical in defining the system performance during heating operation.

When evaporator surfaces cool below 0 °C in humid air, frost layers may accumulate, impeding heat transfer and increasing pressure drop. Periodic defrosting restores capacity but introduces severe thermal transients that challenge laboratory reproducibility as well as thermal comfort, or the quality of goods, in case of cold storage applications.

Conventional steady-state rating methods fix compressor speed and deactivate native control, yielding satisfactory result reproducibility at the expense of performance metrics that neglect real dynamic characteristics. Studies comparing rated and field performance consistently reveal large deviations [2]. On the other hand, one of the main reasons for the limited confidence in conducting active-control laboratory tests is the possibility of a different response and performance as a consequence of different thermal and control characteristics of the testing equipment across laboratory environments. In fact, active-control or load-based testing approaches were developed [3-5]; however, they often suffered from limited reproducibility because of the specific thermal inertia of the testing environment.

Recent progress introduced emulator-type load-based testing, where a virtual model defines the thermal response of a representative space [6-7]. Institutions such as BAM (Germany) [8] demonstrated promising reproducibility under steady conditions. Yet, at low load ratios and during heating, strongly unsteady behaviors such as defrost still induce delays between emulator and physical response [9–10].

Focusing on defrost operation as a demanding case study, this works applies a feed-forward compensation algorithm that minimizes delay, captures various operation characteristics during heating operation at low outdoor temperature, and demonstrates that levels of reproducibility comparable to steady-state measurements are achievable in of interlaboratory tests.

2. Emulator-Type Load-Based Testing Facility

In emulator-type load-based testing, the tested unit operates in two psychrometric chambers, which control indoor and outdoor environmental conditions, while a *room emulator* mirrors the thermal and humidity response of a virtual building to the measured modulations of sensible and latent capacity from the tested air conditioner or heat pump. As represented schematically in Figure 1, software and hardware elements of this testing methodology continuously exchange data. Specifically, the measured capacity is converted in numerical parameters used as input to the room emulator, which accordingly calculates temperature and humidity variation of the indoor environment in response to the measured capacity for given load conditions. Consequently, the calculated indoor temperature and humidity conditions for the next time step are fed as a control signal to the condition generator and converted to actual test room conditions at the return port of the tested unit. Further details on the proposed testing procedure are referred to [6]. Such coupling implies unavoidable measurement and actuation delays that limits the accuracy of the recorded dynamic performance representation. These delays become particularly significant during heating mode, as the system might experience defrosting cycles superimposed to other dynamic operation characteristics. In fact, during such maneuvers, both the airflow and refrigerant-side control parameters vary abruptly.

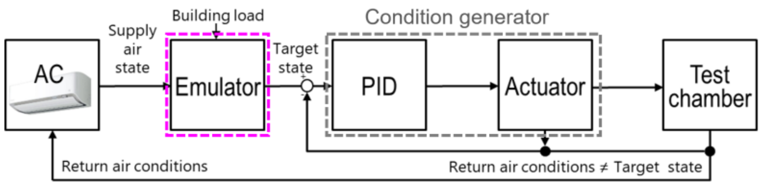

Figure 1. Block diagram of the emulator-type load-based tests.

3. Test Results

In this case study, the unit was tested under heating operation at low and intermediate thermal loads. Specifically, Figure 2 presents the results obtained at 25% of the design heating capacity, with the indoor temperature setpoint fixed at 20 °C and the outdoor environment maintained at a constant dry-bulb temperature of 7 °C. The data shown on the left-hand side indicate that the system undergoes recurrent defrost cycles, during which the compressor speed (green line) exhibits pronounced dynamic modulations within the intermittent on–off operation cycle. During these periods, the evaporator fan speed (blue line) drops to zero, and the supplied heating capacity (black line) quickly falls to zero. Correspondingly, the calculated emulator signal (dashed purple line) shows strong short-term oscillations, while the return-air temperature at the indoor unit (black markers), controlled by the testing facility, displays peak-to-peak delays of approximately 120–160 s and overshoot/undershoot amplitudes of about 0.15–0.20 K. Figure 3 illustrates the case of intermediate load operation (50% of the design capacity) with the same set point and outdoor temperature. In this condition, the variable speed drive compressor manages to stabilize around nearly steady operation, with indoor return temperature (red line) close to the set point temperature. However, such operation is regularly interrupted, every approximately 80 minutes, with defrosting cycles, which introduces dynamic compressor and fan speed modulations, resulting in noticeable deviations from the room setpoint temperature. Correspondingly, the calculated emulator signal (dashed purple line) represents the calculated deviation from the set point temperature for the defined virtual building features (147 m^3, with empirically assumed thermal inertia [11]. The actual return-air temperature at the indoor unit (represented by the black markers) is controlled by the condition generator of the testing environment and displays delays of approximately 140 s. It was demonstrated in a previous work [12] that such uncontrolled inaccuracies and delays may limit result reproducibility.

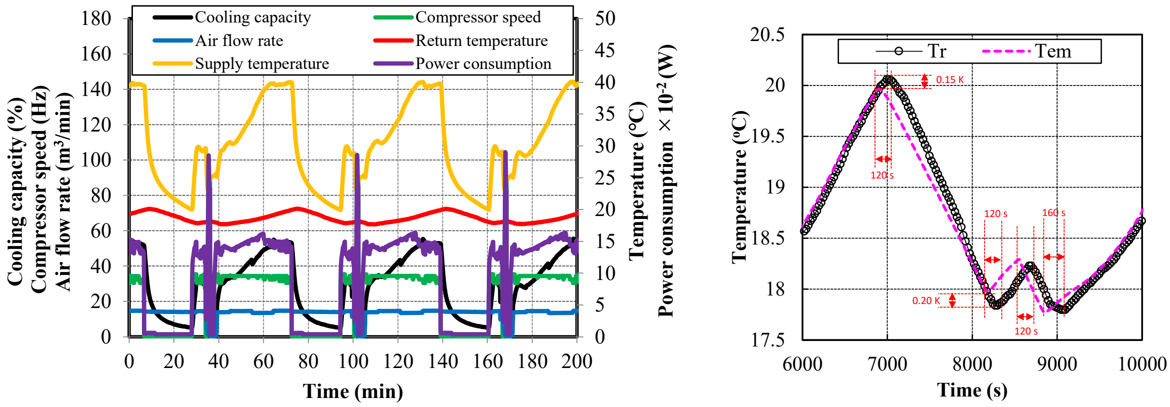

Figure 2. Data collected at 25% load (7 ºC outdoor temperature) during heating operation (left), and corresponding delay characteristics of the return air (right).

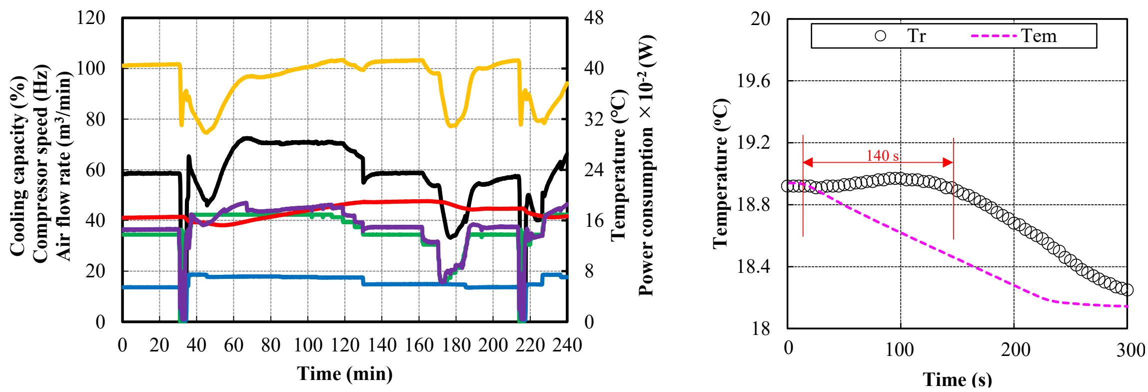

Figure 3. Data collected at 50% load (7 ºC outdoor temperature) during heating operation (left), and corresponding delay characteristics of the return air (right).

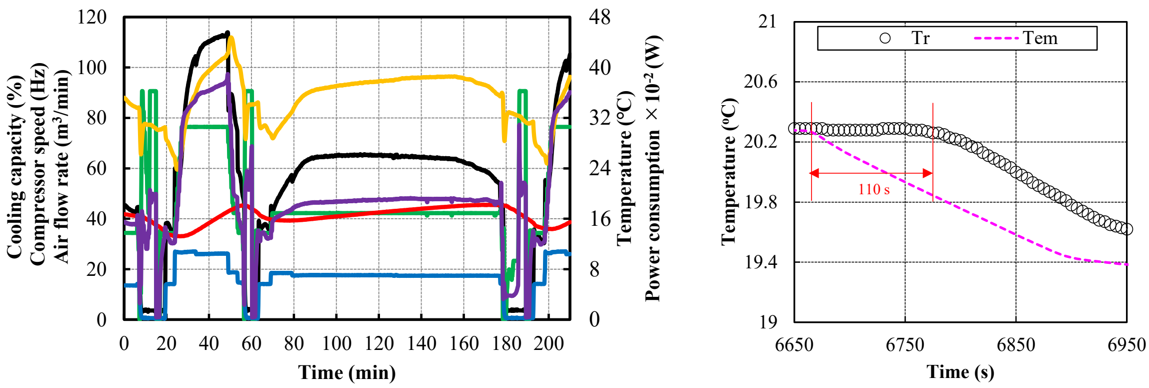

Figure 4. Data collected at 50% load (2 ºC outdoor temperature) during heating operation (left), and corresponding delay characteristics of the return air (right).

Finally, Figure 4 presents the test results obtained at a corresponding intermediate load operation, but at lower outdoor temperature of 2 ºC. Here defrosting cycles became longer and more energy intensive with peak values of compressor speed and energy consumption. Additionally, large deviations from the target setpoint temperature are observed as a consequence of defrosting cycles. Corresponding delays were recorded to be within 110 s.

4. Feed-Forward Compensation

Accordingly, this study proposes a compensation technique to achieve enhanced reproducibility of the results. The proposed compensation technique relies on the concept of model predictive control, whereby delay and control inaccuracies of temperature and humidity in the testing environment are first modelled. The model is then reversed to recalibrate the control signal to define a new pseudo-target signal that minimizes deviations of the actual condition in the psychrometric room from the original target state (Figure 5). Several possible system identification approaches can be used, in this study a linearized thermal model of the main components is adopted, yielding a 2-poles/2-zeros transfer function with coefficients dependent on control gains of the condition generator and thermal/moisture inertia of the testing environment and virtual building (Eq. 1). The details of the derivation of the second-order transfer function are provided in [12].

$$G(s) \equiv \frac{output}{input} = \frac{T_r(s)}{T_{em}(s)} = \frac{b_2 s^2 + b_1 s + b_0}{s^2 + a_1 s + a_0} \tag{1}$$

As values of control gains of the condition generator and thermal and moisture inertia of the testing environment are not readily available, the transfer function identification is conducted through experimental fitting to test results that carry evidence of the delay and inaccuracy in the trackability of the condition generator.

The transfer function $G(s)$ consequently represents the response of the actual measured return air temperature (T_r) in the frequency domain, for certain modulations of the target temperature of the indoor test chamber (T_{em}) calculated by the emulator. Consequently, the inverse transfer function (Eq. 2) indicates the required input signal $T*_{\mathrm{em}}$ to the condition generator to compensate for trackability inaccuracies and delays from the target emulator state. This is done by mathematically imposing T_r=T_{em} (Eq. 3). It should also be verified that the obtained transfer function and the inverse transfer function have negative poles and zeros to minimize the risk of control instabilities.

$$\frac{1}{G(s)} = \frac{input}{output} = \frac{s^2 + a_1 s + a_0}{b_2 s^2 + b_1 s + b_0} \tag{2}$$

$$T_{em}^*(s) = \frac{1}{G(s)} \cdot T_{em}(s) \tag{3}$$

Equation (4) can be obtained by converting the expression in Eq. (3) to the corresponding differential equation in the time domain (t) using the properties of the Laplace Transform.

$$\frac{d^2 T_{em}(t)}{dt^2} + a_1 \frac{dT_{em}(t)}{dt} + a_0 T_{em} = b_2 \frac{d^2 T_{em}^*(t)}{dt^2} + b_1 \frac{dT_{em}^*(t)}{dt} + b_0 T_{em}^*(t) \tag{4}$$

Consequently, the pseudo-target temperature to be conveyed to the control of the condition generator can be generally expressed as an algebraic equation by discretizing time derivatives (Eq. 5) and solving for $T_{\mathrm{em}}^*(t$+d$t)$, as shown in Eq. (6).

$$\frac{T_{em}(t+dt) - 2T_{em}(t) + T_{em}(t-dt)}{dt^2} + a_1 \frac{T_{em}(t+dt) - T_{em}(t)}{dt} + a_0 T_{em}(t+dt) = b_2 \frac{T_{em}^*(t+dt) - 2T_{em}^*(t) + T_{em}^*(t-dt)}{dt^2} + b_1 \frac{T_{em}^*(t+dt) - T_{em}^*(t)}{dt} + b_0 T_{em}^*(t+dt) \tag{5}$$

$$T_{em}^*(t+dt) = \frac{\frac{T_{em}(t+dt) - 2T_{em}(t) + T_{em}(t-dt)}{dt^2} + a_1 \frac{T_{em}(t+dt) - T_{em}(t)}{dt} + a_0 T_{em}(t+dt)}{\frac{b_2}{dt^2} + \frac{b_1}{dt} + b_0} + \frac{b_2 \frac{2T_{em}^*(t) - T_{em}^*(t-dt)}{dt^2} + b_1 \frac{T_{em}^*(t)}{dt}}{\frac{b_2}{dt^2} + \frac{b_1}{dt} + b_0} \tag{6}$$

Similar considerations and mathematical developments can be directly applied to compensate for the delays and discrepancies encountered in controlling the return air humidity. Therefore, the FFC module constitutes an additional software element, represented by two algebraic equations, implemented in a feed-forward arrangement in between the emulator and the condition generator (Figure 5) to minimize the loss of information between the emulator and the psychrometric chamber.

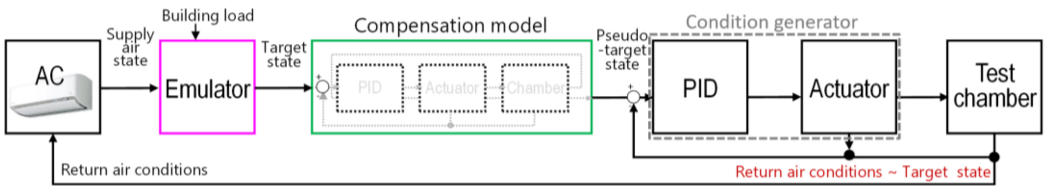

Figure 5. Block diagram of the testing procedure with feed-forward compensation.

The implementation of the FFC compensation technique was conducted in the same operating condition as the results illustrated in Figures 2-4. Figures 6-8 compare the delay characteristics of corresponding results obtained without (left) and with (right) the developed compensation technique in the testing laboratory of Waseda University. Delays as well as over- and under-shooting in the trackability of the return air condition to the indoor unit were effectively compensated by the pseudo target signal to the condition generator (green dashed lines).

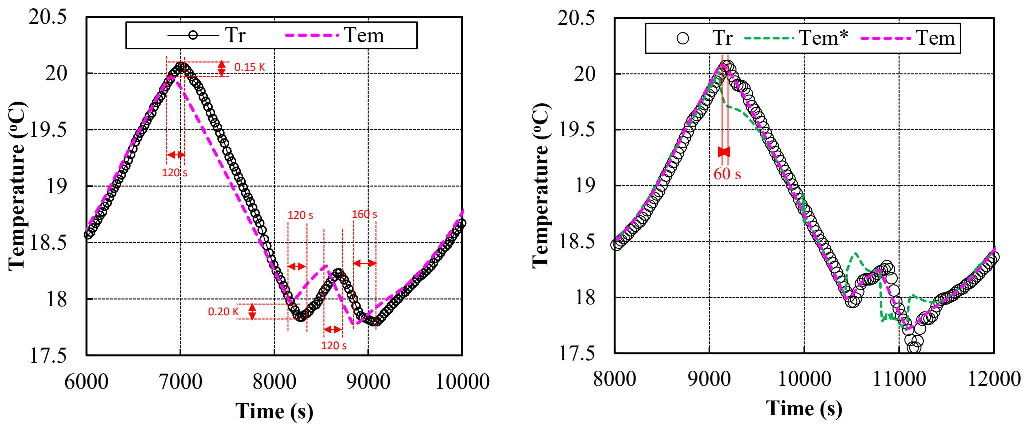

Figure 6. Feed-forward compensation (right) of the dry-bulb emulator signal from the room emulator at a 25% load (7ºC outdoor temperature).

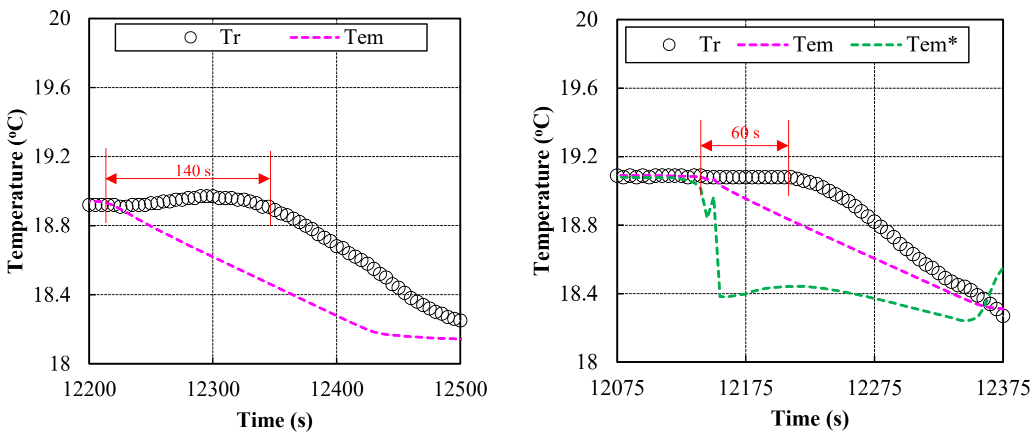

Figure 7. Feed-forward compensation (right) of the dry-bulb emulator signal from the room emulator at a 50% load (7ºC outdoor temperature).

Specifically, as shown in Figure 6, the peak-to-peak delays of approximately 120 s (left) were reduced to values within 60 s (right), and overshooting characteristics larger than 0.15 K were limited to 0.1 K. Evidence for corresponding delay compensations are reported in Figures 7 and 8, where it is shown that during mid load defrost operation at 7 and 2 ºC outdoor temperature, delays larger than 140 s and 110 s, respectively, from the beginning of the defrost cycle were limited to below 60s. Such enhanced trackability was achieved though the pseudo-target control signal (green dashed line), which suitable compensated for the delay and control inaccuracies modelled by the transfer function calibrated for the low load operation condition (25% PLR at 7 ºC outdoor temperature).

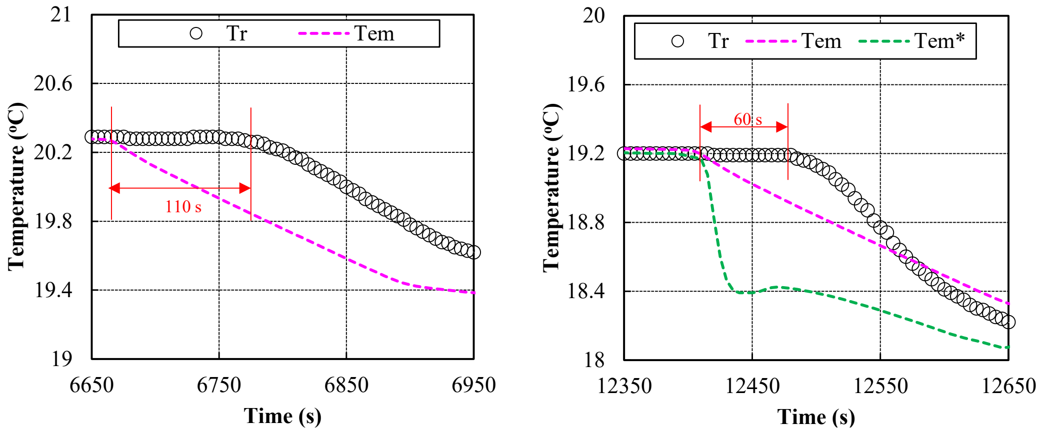

Figure 8. Feed-forward compensation (right) of the dry-bulb emulator signal from the room emulator at a 50% load (2 ºC outdoor temperature).

5. Interlaboratory tests

To verify the effectiveness and applicability of the proposed FFC methodology in reproducibly capturing operation performance during heating operation characterized by defrosting cycles, interlaboratory measurements were performed on the same unit, in two independent laboratory equipment.

5.1. Tested unit

The tested unit is a reversible R32 ceiling-cassette-type unit featuring a rated capacity of 11.2 kW heating, with a rated *COP* of 4.77 for heating.

5.2. Test equipment

The tests were conducted at two testing facilities, one owned by Waseda University and the other by an independent third-party facility, hereafter identified as Facility A. Facility A's test room features a larger structure than Waseda University's, which may exhibit different delays and trackability characteristics. Table 1 lists the general specifications of the two test setups. Additional details of the experimental equipment and procedures refer to [13] for Waseda's facility and for Facility A.

Table 1. Specification of indoor test rooms

Characteristic	Waseda	Facility A
Dimensions (mm)	W3800×D6800×H3000	W5900×D4950×H3000
Volume (m^3)	77.5	87.6
Capacity (kW)	~12.5	~15.0

5.3. Test conditions

The results were evaluated in terms of reproducibility, that is, it was observed whether under corresponding conditions, the tested unit would produce consistent *COP*s in different testing environments. The *COP* was evaluated following JIS standards [14], which define it as the ratio of the average cooling capacity to the average power consumption, measured over a 35-minute period for stable operation or over three operational cycles for intermittent cycling operation. Partial load ratio (PLR) is defined as the ratio of the cooling load to the rated heating capacity. In this case, a *PLR* of 25.0% corresponded to a test performed at a load of 2.5 kW. The test conditions covered heating operations over a range of partial loads represented by 25% and 50% *PLR* (Table 2). Therefore, both cycling and stable near-steady operations were observed during the tests. Tests were conducted while integrating the FFC method.

Table 2. Test conditions

Operation	Outdoor temp. DB/WB (°C)	Indoor set temp. (°C)	PLR (%)	Virtual room volume (m^3)
Heating	7/6	20	25.0	147
			50.0	147

5.4. Results

In a previous publication [12], it was demonstrated that settlement to nearly stationary operation at 50% *PLR* condition exhibited a result reproducibility of approximately 2.2% in terms of recorded *COP*, provided that the sources of thermal delay in the measuring chamber [6] were properly compensated for.

The heating operation at 25% *PLR* exhibited a cycling on-off operation, often incurring in defrosting sub-cycles, in which the fan of the indoor unit was turned off and the minimum capacity was supplied. The same type of defrosting cycle, superimposed on a nearly stationary compressor operation, was observed when testing the system at 50% *PLR*, where the variable-speed unit stabilized the indoor temperature around the set-point with minor modulations of the compressor and fan speed. Additionally, during the heating operation, the recorded performance at 25% *PLR* was approximately 20% lower than that at 50% *PLR*. Performance result consistency within 2% was demonstrated across the two laboratory environments (Table 3).

Table 3. Test results

Operation	Outdoor temp. (°C)	*PLR* (%)	*COP* (-)		
			Waseda	Facility A	Max deviation (%)
Heating	7	25.0	3.47	3.51	**1.16**
		50.0	4.35	4.42	**1.53**

6. Conclusions

In order to improve the reproducibility of emulator-type load-based test method, a feedforward compensation (FFC) control that uses a linear space model to compensate for the delay of the test equipment was developed and implemented in actual tests. By adopting the proposed compensation technology, the reproducibility level of the performance test results was within 2% in *COP* under heating test conditions, demonstrating a significant improvement in the reproducibility of the test results from previous literature.

The proposed FFC can be set retroactively without changing the existing hardware in the test room or software such as the control system of the condition generator, so it is a software tool that can be applied without increasing test burden in terms of time or cost. Consequently, it facilitates the introduction of highly reliable emulator-type load-based tests and can contribute to the future spread of dynamic test methods.

Contextually, the proposed technology and analysis of the test results open to reliable and clear investigations of control performance, including defrost operation, and complementarily enables control optimization to minimize the performance degradation due to frost formation.

Nomenclature

Symbol	**Definition**	**Unit**
G	Transfer function	-
Ns	Compressor rotational speed	Hz
s	Complex variable	-
T	Temperature	°C
t	Time	s
Subscripts		
em	emulator	
r	indoor return air	

Superscripts		
*	recalibrated target	
Acronyms		
AC	Air conditioner	
COP	Coefficient of Performance	
DB	Dry bulb temperature	
FFC	Feed-Forward Compensation	
PLR	Partial Load Ratio	
WB	Wet bulb temperature	

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