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Development of model of heat source characteristics for home air conditioners: Extension of the model to both heating and cooling modes

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Abstract
The COP of home air conditioners greatly depends on the operating conditions and its actual values may largely deviate from the catalogue values. Therefore, the amount of energy saved by changing the type or improving the use of air conditioners cannot be accurately estimated from the catalogue values alone. To address this problem, we proposed a heat source characteristic model for estimating the COP and power consumption of home air conditioners under arbitrary operating conditions for cooling period. In this study, the model constructed in the previous study was applied to both cooling and heating operations to experimentally examine the estimation accuracy of the model with the aim of improving the practicality of the developed model.

Keywords – Home Air Conditioner; Heat Source Characteristic; Residential Building

1. Introduction

Home air conditioners are equipped with a heat pump as the heat source and can efficiently cool and heat a room using outdoor air. Recently, the coefficient of performance (COP) of air conditioners described in catalogues has markedly increased as a result of technological developments. However, the COP of air conditioners changes significantly depending on operating conditions, and its actual value may deviate considerably from the catalogue values. Therefore, the amount of energy saved by changing the type or improving the use of air conditioners cannot be accurately estimated from the catalogue values alone.

To address this problem, we simulated the characteristics of the heat source of home air conditioners and proposed a model for estimating the

COP and power consumption of home air conditioners under arbitrary operating conditions.[1]

The model has the following two features.

1) The COP and power consumption of the heat source under arbitrary conditions of indoor and outdoor temperatures and humidities and indoor heat load can be calculated.

2) The values in 1) can be calculated for various types of home air conditioners: that is, the heat source characteristics of target air conditioners can be modeled using data published in catalogues and technical specifications (e.g., [2][3]).

In a previous study,[1] we modeled the heat source characteristics of air conditioners in the cooling mode and compared the calculated values with the measured values for a highly functional air conditioner to examine the accuracy of the estimations.

In this study, the model constructed in the previous study was extended to the heating and cooling modes, and the accuracy of its estimations was experimentally examined with the aim of improving the practicality of the model.

In Section 2, the development of an extended model that can be applied to both the heating and cooling modes is described on the basis of the previous model. In Section 3, cooling and heating experiments using a highly functional air conditioner (the same type used in the previous study) and an ordinary air conditioner (newly adopted in this study) to examine the estimation accuracy of the extended model are described.

2. Extension of previous model of heat source characteristics to both heating and cooling modes

In this section, a model of heat source characteristics of air conditioners in the heating mode is constructed on the basis of the concept of the model in the cooling mode described in the previous report.[1] Figure 1 shows the outline of the construction and use of the model. The basic concept of the model for the heating mode is similar to that for the cooling mode. The characteristics of air conditioners, such as COP and power consumption, during the steady-state operation are simulated as follows. (1) The relationship between the heat transferred during a refrigeration cycle and the power consumed by a compressor and a fan is formulated. (2) The formula is solved under arbitrary operating conditions of the air conditioners. In the construction of the model, characteristic parameters specific to each air conditioner are determined using published data, including power consumption, described in the specifications of the target air conditioner. In a simulation using the model, arbitrary operating conditions including indoor and outdoor air temperatures are input to the model to obtain the outputs such as COP of the air conditioner under the given conditions.

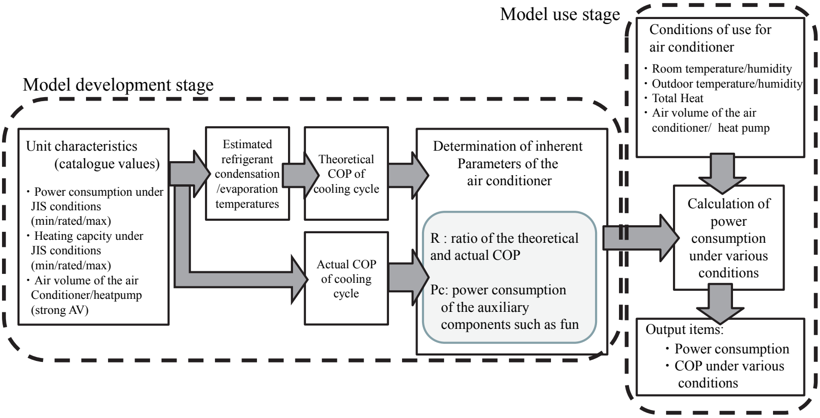


Fig. 1 Outline of of the construction and use of the model during heating period

3. Verification experiments for accuracy of model

3.1 Outline of experiments

We carried out a heating experiment using a highly functional air conditioner and cooling and heating experiments using an ordinary air conditioner to examine the accuracy of the model whose construction was described in Section 1. Table 1 shows a summary of the purpose of each experiment and the type of air conditioner used. The information on the cooling experiment using the highly functional air conditioner described in the previous report[1] is also provided.

Table 1. Summary of the purpose of each experiment and the type of air conditioner used

Target Appliance	Operational Mode	Experimental Period	Purpose of Experiments	Ambient Status of Outdoor Unit
Highly Functional Air Conditioner	Cooling[1]	Aug. 2009	Accuracy Verification of Cooling Model	Not Controlled
	Heating	Dec. 2009	Accuracy Verification of Cooling and Heating Model	
Ordinary Air Conditioner	Cooling	Jun. 2012		Controlled
	Heating	Nov. 2012		

In these experiments, the air conditioners were operated under different conditions, such as sensible and latent heat loads (in the heating mode, sensible heat load only), preset temperature (indoor), and inlet air temperature and humidity of the outdoor unit, to measure various parameters, including outlet and inlet air temperatures, air volume, power consumption, and temperature of the refrigerant pipe. On the basis of the measured values, the performance characteristics of the air conditioners, such as the relationship between the cooling and heating capacities and the power consumption under different conditions, are determined.

The experiments were carried out in a dedicated room, all sides of which were covered with extruded polystyrene foam plates with a thickness of 200 mm [3.94 (L) × 3.94 (W) × 2.4 (H) m3; hereafter, called the adiabatic room), similar to the experiment described in the previous report.[1] This room has no windows and THE ceiling, floor, and door were also covered with extruded polystyrene foam plates. We confirmed that the transfer of heat from/to the outside was minimized before the experiments.

In the heating experiment using the highly functional air conditioner, the outdoor unit was placed outside and the ambient temperature and humidity were not controlled, similar to the previous cooling experiment. In the heating and cooling experiments using the ordinary air conditioner, the outdoor unit was placed in a system that controls the inlet temperature and humidity of the unit. This system was placed in an adiabatic prefabricated building [2.69 (L) × 5.03 (W) × 2.44 (H) m3] and comprised the outdoor unit of the target air conditioner, air conditioners for cooling and dehumidification, duct heaters, and a humidifier. The air conditioners for cooling and dehumidification, the duct heaters, and the humidifier were controlled using a proportional-integral (PI) controller to maintain the inlet air temperature and humidity of the target air conditioners.

Table 2 shows the specifications of the air conditioners used in the experiments. Figure 2 shows the experimental setup (ordinary air conditioner, heating experiment). As measured in the previous experiment,[1] the power consumption of the air conditioner, the outlet and inlet air temperatures and humidities of the indoor and outdoor units, and their outlet air velocity were measured. In addition, the surface temperature of the refrigerant pipe and the number of revolutions of a compressor and the fans of the indoor and outdoor units were measured. To measure the surface temperature of the refrigerant pipe, an insulated thermocouple was attached to the refrigerant pipe, which was covered with an adiabatic material. In the measurement of the outlet air velocity of the indoor unit, a flap and a louver were removed from the air conditioner and an anemometer was installed inside the outlet to prevent the effect of the inclusion of indoor air.

3.2 Experimental methods and conditions

The inlet and outlet air temperatures and humidities and the outlet air velocities of the indoor and outdoor units of the air conditioners were measured while they were operated under a predetermined heat load and preset temperature and air volume. Assuming that the air volume described in the specifications under the setting of “High” is proportional to the outlet air velocity, the air volumes of the indoor and outdoor units were calculated from their maximum measured outlet air velocities.

Table 2. Specifications of the air conditioners used in the experiments

		Ordinary Air Conditioner, Cooling	Ordinary Air Conditioner, Heating	Highly Functional Air Conditioner, Heating	Unit
Capacity	Rated	2.2	2.2	2.5	[kW]
	Min	0.9	0.9	0.7	
	Max	2.8	3.6	5.4	
Power consumption	Rated	0.455	0.385	0.390	[kW]
	Min	0.170	0.135	0.095	
	Max	0.745	1.070	1.360	
Air volume of indoor unit	High	12.0	12.0	13.1	[m³/min]
	Middle	9.4	9.9	10.4	
	Low	6.9	7.8	7.7	
AV of outdoor unit	High	27.6	22.5	25.5	[m³/min]

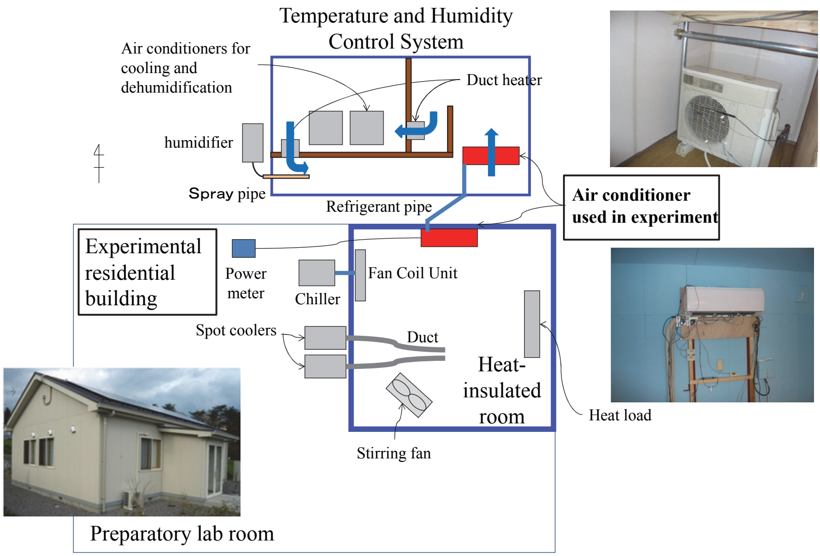


Fig. 2. Experimental setup (ordinary air conditioner, heating experiment)

The amount of sensible heat treated by the air conditioner was calculated from the difference between the outlet and inlet air temperatures of the indoor unit, air density, air specific heat, and air volume. The amount of latent heat treated by the air conditioner was calculated from the difference between absolute humidities of the outlet and inlet air of the indoor unit, air density, vaporization latent heat, and air volume (in the heating mode, sensible heat only).

Table 3 shows the settings for the experiment. For the parameters including sensible and latent heat loads, standard values were set as the basic experimental conditions. Measurements were carried out by varying each of the parameters in turn. As mentioned, only indoor conditions were changed in the heating experiment using the highly functional air conditioner because outdoor conditions were not controlled.

Table 3. Settings for the experiment

(a) Cooling Period(Ordinary Air Conditioner)

Setting Item		Base Case	Other Cases
Outside	Temperature[deg-C]	35	15, 20, 25, 30, 37, 40
	Humidity[%]	40	30, 50, 60, 70, 80
Inside	Setting Temperature[deg-C]	27	18, 21,24, 30
	Air Volume	5(High)	0(Slight),1(Low), 2,3(Middle),4,Auto
	Sensible Heat[kW]	2.0	0.5, 0.8, 1.1, 1.4, 1.7, 2.3, 2.6, 2.9
	Latent Heat[kW]	0.2	0.0, 0.4, 0.6, 0.8, 1.0

(b) Heating Period(Ordinary Air Conditioner)

Setting Item		Base Case	Other Cases
Outside	Temperature[deg-C]	7	6, 10, 15, 20, 25
	Humidity[%]	80	60, 70, 87, 95, 99
Inside	Setting Temperature[deg-C]	20	14, 17,23, 27, 30
	Air Volume	5	0, 1, 2, 3, 4, Auto
	Sensible Heat[kW]	2.5	0.7, 1.0, 1.3, 1.6, 1.9, 2.2, 2.8, 3.1

(c) Heating Period(Highly functional Air Conditioner)

Setting Item		Base Case	Other Cases
Inside	Setting Temperature[deg-C]	20	24, 28, 30
	Air Volume	5	0, 1, 3
	Sensible Heat[kW]	2.5	0.7-5.6

Figure 3 shows the time course of the amount of treated heat, power consumption, and the inlet air temperature of the indoor unit in the heating experiments using the highly functional air conditioner [cooling load, 2.5 kW; air volume, 5 (High); preset indoor temperature, 20 deg-C; outdoor conditions, uncontrolled]. Approximately 30 min after the start of the experiment, the amount of treated heat and power consumption stabilized and began to fluctuate periodically.

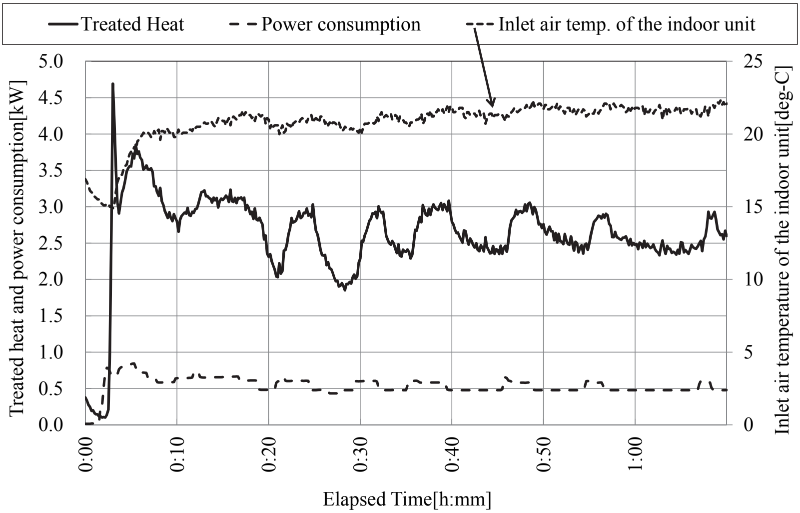


Fig. 3. Example of the results of experiment

3.3 Comparison between experimental and simulated results

In this section, the characteristic parameters [the ratio of the actual efficiency to the theoretical efficiency of the freezer (R) and the power consumption of the auxiliary component (Pc)] specific to highly functional and ordinary air conditioners are calculated using the developed model for the heating and cooling modes. The power consumptions of the two air conditioners were estimated under different conditions and compared with experimental data to verify the accuracy of the model. The results of the cooling experiment using the highly functional air conditioner, which were described in the previous report, are also shown.

As mentioned in the previous section, the experiments were carried out for different operating conditions, such as outdoor air temperature and humidity and indoor heat load. After the elapse of a certain period of time from the start of the operation, the air conditioners reached a steady state or a periodic steady state in which the operating state periodically changed. In this section, data obtained for approximately 5–30 min (depending on the conditions) after the air conditioner reached the (periodic) steady state are regarded as an experimental result. The mean values of power consumption and cooling and heating capacities were analyzed as representative values for the experiment. The numbers of experiments using the highly functional air conditioner were 192 and 432 for the cooling and heating modes, respectively. The numbers of experiments using the ordinary air conditioner were 59 and 68 for the cooling and heating modes, respectively. The experiments using the highly functional air conditioner were conducted many times under the same conditions because the outdoor air temperature and humidity were not controlled. However, these parameters were controlled when the ordinary air conditioner was used; hence, the number of experiments using the ordinary air conditioner was smaller than that using the highly functional air conditioner.

Regarding each experimental result, the power consumption was calculated using the model. The set conditions input to the model were the inlet air temperature and relative humidity of the indoor unit, those of the outdoor unit, the measured air volumes of the indoor and outdoor units, and the calculated amounts of sensible and latent heats treated by the air conditioner. Here, data obtained during defrosting were excluded from the experimental results because the operation during defrosting that occurred in the heating mode was not modeled.

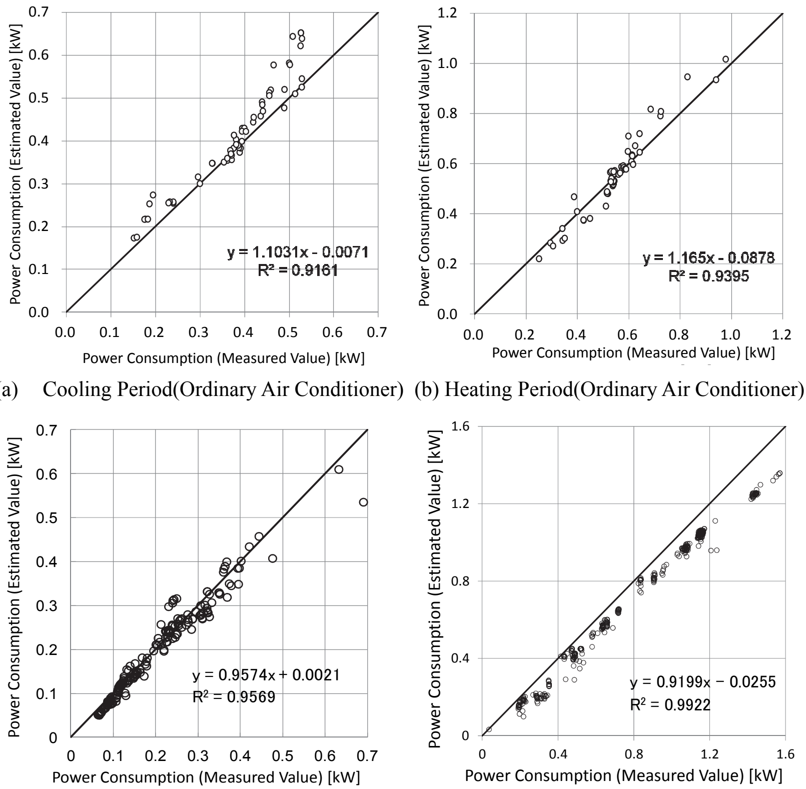
Figure 4 shows the relationship between the measured and estimated values of power consumption. These values were in good agreement for both the highly functional and ordinary air conditioners in the cooling and heating modes. This suggests that the model is applicable to the heating mode of the highly functional air conditioner and the cooling and heating modes of the ordinary air conditioner.

4. Conclusions

In this report, we extended the model of heat source characteristics in the cooling mode constructed in the previous study[1] to the heating mode and experimentally verified the accuracy of estimations by the model with the aim of improving the practicality of the model. The following are the results obtained.

1) The model of heat source characteristics of air conditioners was extended to both the heating and cooling modes for calculating the power consumption of air conditioners under arbitrary conditions of indoor and outdoor temperatures and humidities and indoor heat load.

2) The power consumptions measured by the heating experiment using the highly functional air conditioner and the cooling and heating experiments using the ordinary air conditioner were compared with the power consumptions estimated using the model. The measured and estimated values were in good agreement, confirming that the power consumption of the air conditioners was accurately estimated using the model.



(a) Cooling Period(Ordinary Air Conditioner) (b) Heating Period(Ordinary Air Conditioner)

(c) Cooling Period(Highly Functional Air Conditioner)[1] (d) Heating Period(Highly Functional Air Conditioner)

Fig. 4. Relationship between the measured and estimated values of power consumption

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