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Research Paper

Analysis of energy consumption of room air conditioners: An approach using individual operation data from field measurements

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HIGHLIGHTS

- Operation of room air conditioners (RACs) was monitored in 87 households.
- Operation duration was reduced under mild-load conditions.
- A 20% reduction in operation duration led to a 40% energy reduction under mild load.
- Energy reduction was categorized as operation time- or physical efficiency-related.

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ABSTRACT

Room air conditioners (RACs) are heating/cooling appliances used widely in residential buildings. RAC seasonal or annual performance is strongly influenced by the user's operation schedule and by mechanical efficiency. In this paper, we address the energy consumption of RACs under different heat-load conditions and schedules. Individual operations were extracted from a series of energy consumption data for 87 RAC units. Individual operation data were divided into two groups, mild- and severe-load conditions, whose outdoor temperatures differed by 5 °C. Mild-load conditions tended to result in shorter individual operation durations than did severe-load conditions, suggesting a difference in user behavior. When individual operation durations were reduced by 20%, average energy reductions of 40% were observed. Part of this reduction resulted from duration reduction; the rest came from changes in RAC physical efficiency, which depends on outdoor temperature and heating/cooling load. The time-reduction effect exceeded the physical-efficiency effect when individual operation durations were shortened by >20% during heating, or by >26% during cooling.

1. Introduction

About one-third of global final energy is consumed in the building sector, which comprises residential and commercial sub-sectors [1]. Energy consumption in the building sector continues to increase in Japan [2]. Much of this consumption is in the form of thermal energy, such as for space heating and cooling plus hot water heating, in particular in the residential sub-sector. To produce thermal energy more efficiently, appliances with heat-pump technology have become widespread; more than 3.5 million units of heat-pump water heaters that use CO_2 as a refrigerant have been shipped and installed in buildings in Japan [3]. For space heating and cooling, ~90% of residential homes in Japan own one or more RAC units, defined as heat pump units with cooling capacities $\leqslant$10 kW [4]. Currently, nearly all RACs on the market in Japan are split-type units equipped with inverter-driven compressors both for heating and cooling [5]. The efficiency of Japanese heat pumps has improved each year after 2000 [6]. One of the reasons may be the introduction of heat pumps to the "top runner standard," which specifies energy performance requirements for appliances [2]. Shimoda et al. [7] reported that installation of RACs conforming to that standard was one of the most effective means of energy savings in Osaka.

In evaluating the efficiency of RACs, partial load characteristics are an important factor, because much of heat load is generally smaller than the rated capacity of RACs throughout a season. Laboratory performance test, in which energy output is measured under several different load conditions, is one way to obtain partial

Abbreviations: RAC, room air conditioner.
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Nomenclature

D_{op}	total operation days [day]
n	sample size [–]
n_{op}	daily number of individual operations [–]
N_{op}	total number of individual operations [–]
Q_{mld}	energy consumption for an individual operation under mild-load conditions [W h]
Q_{sev}	energy consumption for an individual operation under severe-load conditions [W h]
t_{rep}	representative time of an individual operation [–]
T_{op}	average outdoor temperature during an individual operation [°C]

Greek symbols

γ	time rate of change of an individual operation [–]
ΔQ_{phy}	physical efficiency-related energy reduction of an individual operation [W h]
ΔQ_{time}	time-related energy reduction of an individual operation [W h]
Δt_{op}	individual operation duration [h]
ε	energy reduction rate of an individual operation [–]
η	effect of reduction in operation duration [–]
ϕ_{op}	average power output in an individual operation [W]

load characteristics. Methods of testing are regulated by several standards, such as EN14825 [8], ASHRAE 116-2010 [9], and JIS C9612 [10]. Some researchers have conducted laboratory performance tests using various types of heat pumps, and have reported measured efficiencies under partial load conditions [11–15]. Computational methods to reproduce the mechanical behavior of inverter-driven heat pumps based on laboratory performance tests have been proposed [16–18].

To predict RAC seasonal performance using results of the laboratory performance test, it is necessary to assume operation schedule such as frequency and duration. There have been many studies on user behavior of RACs. For instance, a few reports are available on relationships between the control behavior of residents and the indoor thermal environment [19,20]. Some researchers have also estimated energy consumption in residential buildings using various user behavior models for end-use appliances (including air conditioners) in computer simulations [21–24]. However, few models focus on seasonal variation of user behavior depending on heat-load conditions. The bin method, in which the operation duration is classified within temperature intervals called bins, is well known for evaluating seasonal differences in operation frequency [25]. A few studies have used the bin method to calculate seasonal energy consumption of air conditioners [26,27]. Although the bin method provides relationships between ambient temperature, as representative parameter of heat-load, and operation duration, the characteristics of individual operations are not considered.

A more reliable way to obtain RAC operation characteristics is to carry out field measurement. Field measurement can provide continuous variation of RAC energy consumption including unsteady operation, whereas laboratory performance tests are usually conducted at steady state. Baxter et al. [28] demonstrated RAC efficiencies during a heating and cooling season, using test houses. Ding et al. [29] proposed a statistical prediction method for partial load operation coefficients using monthly energy consumption data. However, there are few reports on the relationship between heat-load conditions and operation changes, and the effects of these changes on energy consumption of RACs in actual situations.

To assess the seasonal change of RAC operation by field measurement, we examined frequency and duration of individual operation data, which was extracted from continuous electric power consumption data in actual detached houses in the Hiroshima area during a heating/cooling season. Electric power consumptions of the individual operation data which had different heat-load conditions were compared for each unit so as to evaluate multiple RAC units which had various efficiencies in the same index. Reduction of electric power consumption under lower heat-load conditions was then addressed by separating the reduction associated with the time-reduction effect (i.e., behavior change), and the reduction associated with the physical characteristics of heat pumps.

2. Data analysis

2.1. Measurement objects

The measurement object was 100 detached houses around Hiroshima, western Japan, in which electricity was the only energy source. Fig. 1 shows properties of the target buildings and households obtained from a questionnaire survey conducted in 2008. Sample sizes were different among the items because of differences of number of nonresponse. All of these houses were built after 2000. Wooden structures accounted for >70% of the total. Many houses had a total floor area <140 m^2. On average, 3.63 people were living in each house.

2.2. Measurement conditions

Electric power consumption was measured in the detached houses continually at 30-min intervals beginning in autumn 2008. The heating season was defined as 1 November 2008 through 30 April 2009, and the cooling season as 1 June through 30 September 2009. Electric power use for up to 10 appliances was monitored in each household, along with the total electric power consumption. We analyzed data obtained independently from RACs, which were installed in main rooms, such as living rooms. A total of 87 RAC units, which provided continuous data over both heating and cooling seasons, were chosen for analysis.

2.3. Extraction of individual operation data

Individual operations, during which power output was greater than standby power (20 W/30 min), were extracted from a series of consumption data (Fig. 2). ϕ_{op} was defined as average power output during an individual operation, which was the measured average for the individual operation. A representative time t_{rep} was defined as half of the individual operation duration Δt_{op} from the start time of the individual operation.

Intermittent operation, in which heat source equipment including RACs works in response to requests from residents, is more common than continuous (24-h) operation for space heating or cooling in Japan, because many residential buildings have relatively lightweight. In this situation, we thought that lifestyle of the residents was one of the most important factors for evaluating differences of RAC user behavior among households. Therefore, we classified the households by occurrence time of individual opera-

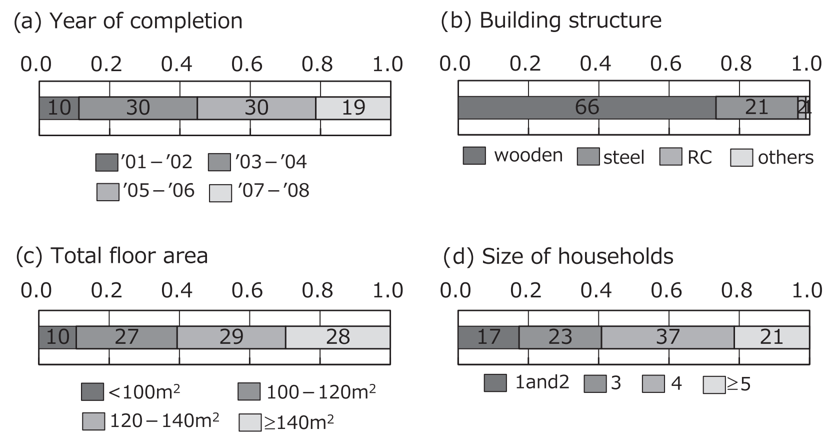

Fig. 1. Characteristics of monitored households.

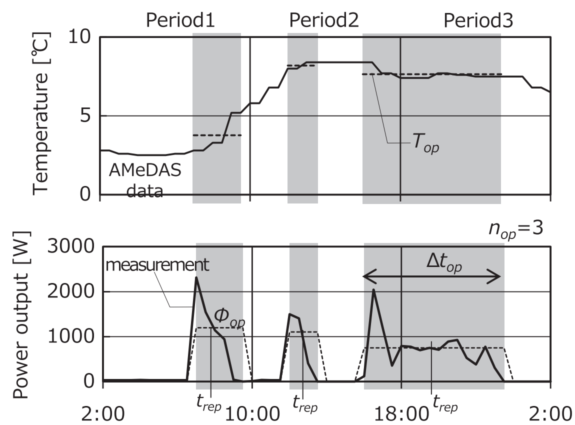

Fig. 2. Concept of extraction of individual operations.

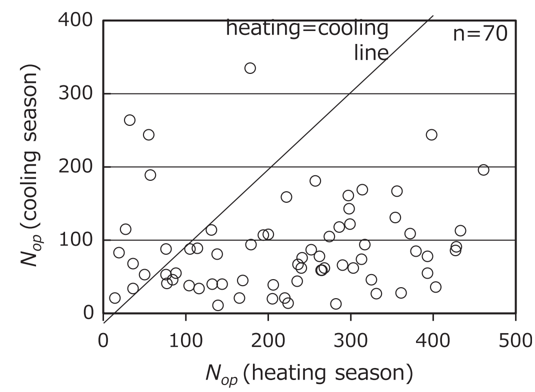

Fig. 3. Comparison of total number of individual operations between heating and cooling seasons for each household.

tions (t_{rep}) based on living activities: Period 1 (2:00–10:00, from waking to leaving home), Period 2 (10:00–18:00, diurnal activities at home), and Period 3 (18:00–2:00, from returning home to going to bed). We adopted these three classifications so that there were large enough samples in each cluster in the cluster analysis in Section 3.2 to provide significant results.

Mean outdoor temperature during an individual operation T_{op} was calculated using hourly weather data from the Automated Meteorological Data Acquisition System [30]. The daily number of individual operations n_{op} was determined if one or more individual operations were observed in a day.

3. Operation characteristics of RACs

3.1. Number of individual operations

Fig. 3 shows the relationship between the total number of individual operations N_{op} counted during the heating season and that during the cooling season, for each household. Sample size n was 70, for which one or more individual operations were observed in both seasons. The plots show a wide distribution, with a maximum of 461 in the heating season and 335 in the cooling season. Many households had a larger number of individual operations in the heating season than in the cooling season.

Relationships between $\overline{n_{op}}$ and N_{op} are plotted in Fig. 4, in which $\overline{n_{op}}$ is the seasonal mean value of n_{op}. Total operation days D_{op} were calculated by dividing N_{op} by $\overline{n_{op}}$. In the range with $\overline{n_{op}} > 2.0$ day^{-1}, N_{op} tended to follow lines of $D_{op} = 150$ days in the heating season and $D_{op} = 70$–80 days in the cooling season. These findings suggest that households operating the RAC multiple times per day had a similar behavior throughout the season. In contrast, for the range with $\overline{n_{op}} < 2.0$ day^{-1}, N_{op} had a wide distribution, even compared with those at the same $\overline{n_{op}}$. The difference of N_{op} was probably caused by the various operation behaviors in each household during the season.

3.2. Operation period

The measured households were classified into four clusters for the heating season and three for the cooling season, based on operation periods (Section 2.3) from cluster analysis using Ward's method with squared Euclidean distance. Fig. 5 shows average distribution ratios of periods 1, 2 and 3 and average $\overline{n_{op}}$ in each cluster. Heating season cluster A1, in which RACs were operated twice daily (mainly before and after waking up and at night), accounted for the most households, at 50. This is because that cluster had large rates of operation in periods 1 and 3 and an average $\overline{n_{op}}$ of nearly 2 day^{-1}. Cluster A2, comprising 15 households, had more operations in Period 2 than cluster A1, and indicated an $\overline{n_{op}} > 2$ day^{-1}. Thus, in this cluster, some households appeared to use RACs not only in the morning and at night, but also in the daytime. In contrast, clusters A3 and A4, with fewer households than the other clusters, had principal operations at night and in the morning, respectively, because each cluster indicated the largest ratios of operation in periods 3 or 1 and smaller values of $\overline{n_{op}}$ than the other clusters, ~1.3 day^{-1}.

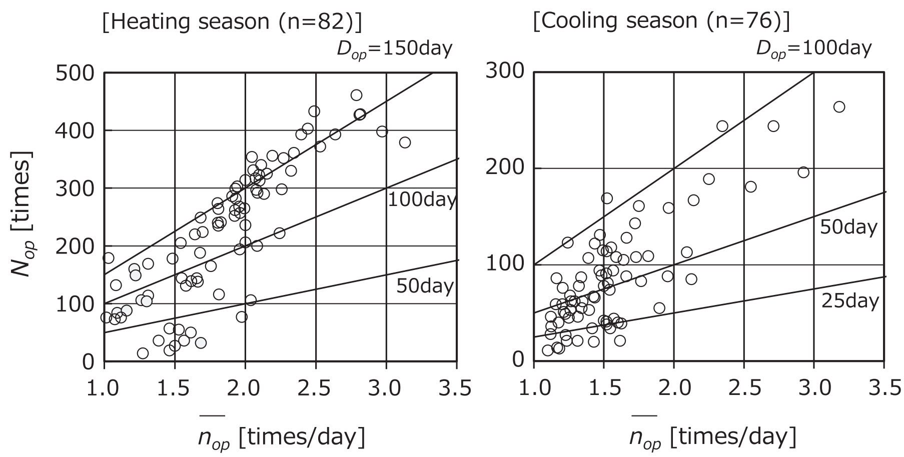

Fig. 4. Relationships between average number in a day and total number of individual operations in each household.

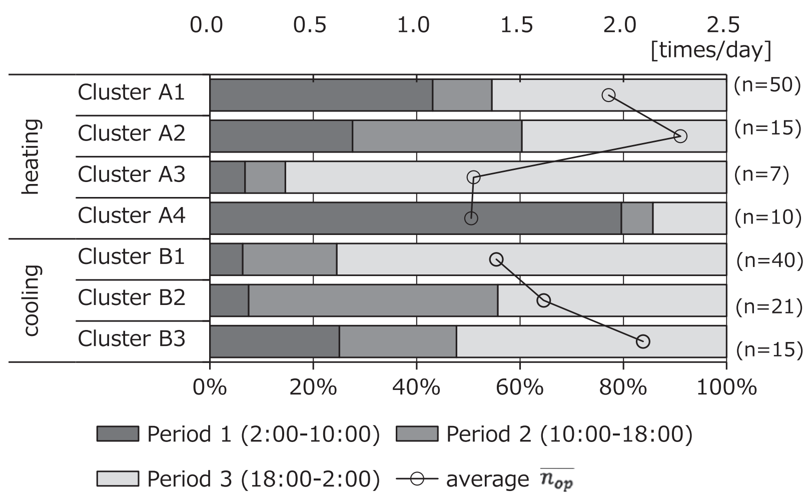

Fig. 5. Distribution ratios of operation period and average number of individual operations in a day for each cluster.

In the cooling season, operation was mainly at night because the operation ratio in Period 3 was 75% in cluster B1, accounting for 40 households. In comparison, cluster B2, comprising 21 households, showed a higher operation ratio in Period 2, with daytime operation similar to that at night. Cluster B3 had a larger $\overline{n_{op}}$ than the other clusters, 2.1 day^{-1}. This means that many households in this cluster operated RACs in the morning or daytime as well as at night.

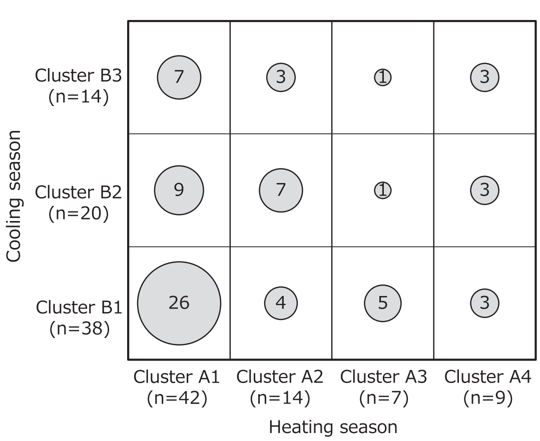

Fig. 6. Number of households belonging to each cluster.

The relationship between the number of households in the heating clusters and the number in the cooling clusters is shown in Fig. 6. Many households were found in the combination of clusters A1 and B1. This indicates that household behavior varied with season, because householders used RACs multiple times per day during the heating season and mainly at night during the cooling season. Conversely, a combination of clusters A1 and B3 was observed in seven households, which did not show such seasonal use variation, operating the RAC multiple times with similar frequency in both heating and cooling seasons. Five households, corresponding to a combination of clusters A3 and B1, operated RACs mainly at night, regardless of season. These results suggest that user behavior greatly depended on resident lifestyle, which varied with work schedules and home activity.

3.3. Individual operation duration

Fig. 7 shows distribution ratios of Δt_{op} in each period. All data were sampled from the dataset with $N_{op} > 10$ in a household for each season. In the heating season, the range 2–4 h accounted for the largest ratio in every period. Most individual operations were shorter than 4 h in Period 1, whereas periods 2 and 3 showed rates of 17–30% for the 4–6-h range and tended to have long operations. In the cooling season, Δt_{op} in Period 1 was even shorter than that in the heating season. More than 60% of the individual operations had

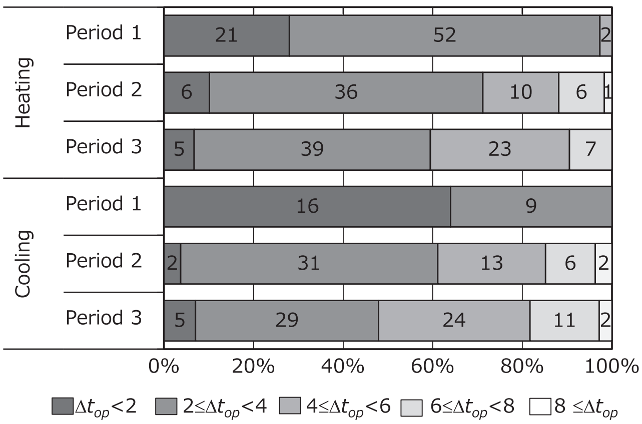

Fig. 7. Distribution ratios of individual operation duration in each operation period.

Δt_{op} < 2 h. In periods 2 and 3, Δt_{op} distributions skewed toward longer operations compared with Period 1, in which individual operations longer than 6 h accounted for ~15–18%.

3.4. Change of individual operation duration because of temperature change

To clarify the change of individual operation duration in a household with variation of heating/cooling load, individual operation data under two temperature conditions were selected using the following process. Fig. 8 shows frequencies of the individual operation data depending on T_{op} at intervals of 2.5 °C. 84% of the samples were included in the range from 2.5 to 12.5 °C in the heating season. Similarly, 95% of the samples were in the range from 22.5 to 32.5 °C in the cooling season. We divided them into severe- and mild-load conditions, which had T_{op} = 5 ± 2.5 °C and 10 ± 2.5 °C in the heating season, respectively, and 30 ± 2.5 °C and 25 ± 2.5 °C in the cooling season. Accordingly, we confirmed that the severe- and mild-load conditions accounted for 45% and 39% of the samples, respectively, in the heating season, and 37% and 58% of the samples, respectively, in the cooling season, showing relatively equal distributions.

Values of Δt_{op} were averaged for each load condition for the case in which >10 samples were collected from one household in each period. As shown in Fig. 9, most points were in ranges for which Δt_{op} under the severe load was longer than under the mild load, regardless of the period in both seasons. In other words, the individual operation duration tended to be shorter under the mild-load conditions. This suggests that users changed their behavior based on outdoor temperature or load conditions.

4. Influences of operation change caused by temperature variation on energy consumption

4.1. Concept of energy reduction for an individual operation

We investigated the effects of change in operation duration based on outdoor temperature, as mentioned above, on energy consumption, under actual RAC operation. Fig. 10 illustrates that energy consumption per individual operation under the severe-load condition Q_{sev} decreased to energy consumption under the mild-load condition Q_{mld}, for which each Q was calculated as the area multiplying Δt_{op} on the horizontal axis by ϕ_{op} on the vertical axis. Here, energy reduction under the mild-load condition may be caused by two factors: ΔQ_{phy}, which comes from an increase of RAC physical efficiency caused by a change of heat source temperature and heating/cooling load, and ΔQ_{time}, which is related to the effect of reduction in operation duration by the user. Actual energy reduction ΔQ including those two factors is obtained by the following equation from the measurements.

$$\Delta Q = Q_{sev} - Q_{mld} \tag{1}$$

Energy reduction rate ε is defined by

$$\varepsilon = 1 - Q_{mld}/Q_{sev} \tag{2}$$

The time rate of change of individual operation γ is defined by

$$\gamma = 1 - \Delta t_{op\_mld}/\Delta t_{op\_sev} \tag{3}$$

4.2. Relationships between operation duration reduction and energy reduction in an individual operation

Fig. 11 represents the relationship between γ and ε with approximate expressions and the coefficient of determination R^2 for all samples in each season. ε tended to increase with γ during both heating and cooling seasons. At γ = 0, i.e., $\Delta t_{op\_mld} = \Delta t_{op\_sev}$, values of ε were 0.0–0.35 during the heating season and 0.0–0.6 during the cooling season. This indicates that only differences of outdoor temperature and heat load between the two conditions caused energy reduction. On average, energy reduction from an increase of RAC efficiency because of differences of outdoor temperature and heat-load conditions was assumed to be 24% during the heating season and 28% during the cooling season, from values of intersections between the vertical axis and the approximate expressions.

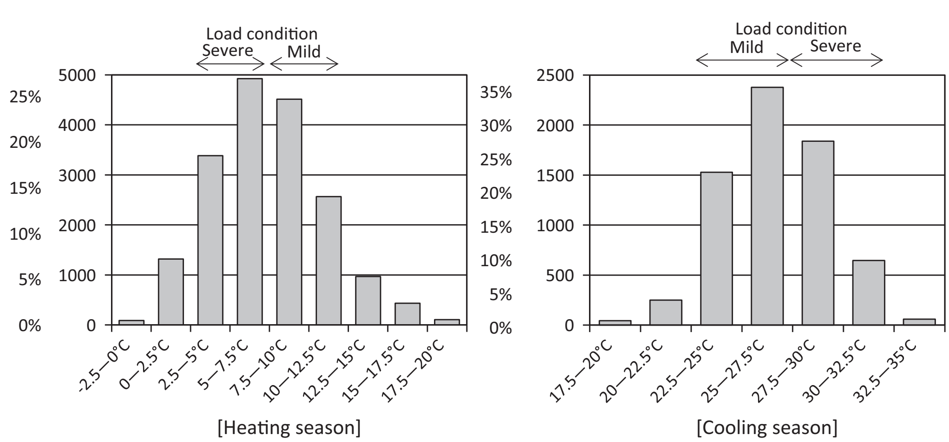

Fig. 8. Frequencies of individual operation data depending on T_{op}.

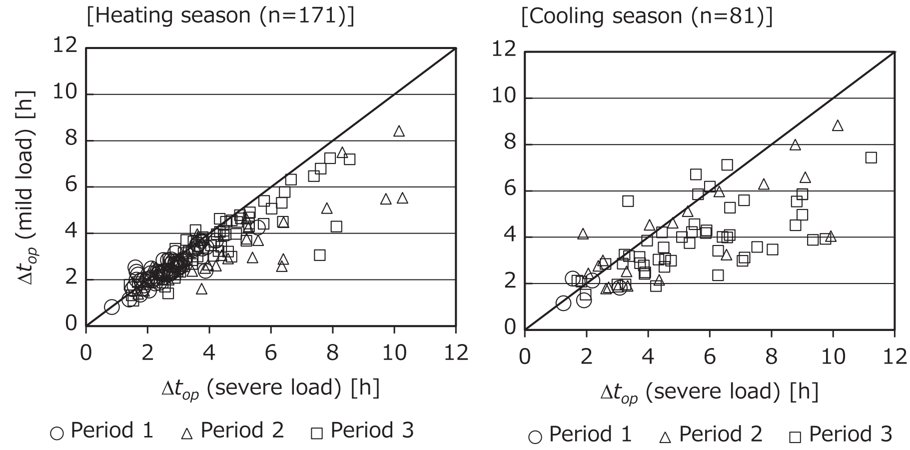

Fig. 9. Comparisons of individual operation durations between severe- and mild-load conditions.

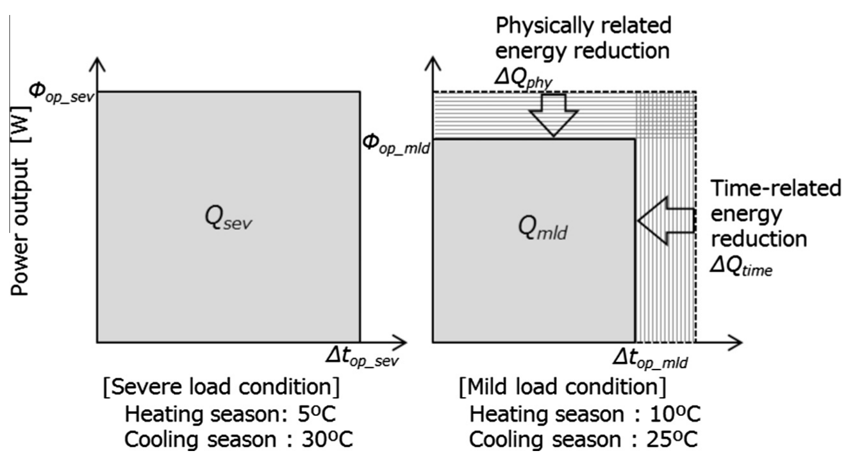

Fig. 10. Conceptual diagram representing energy reduction under mild-load condition compared with severe-load condition.

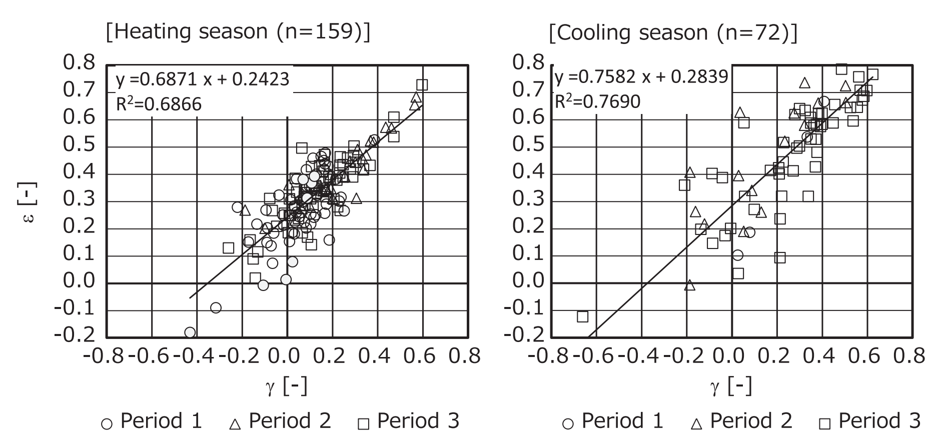

Fig. 11. Energy reduction rate ε as function of change rates γ of individual operation duration.

Some of the points corresponding with $\gamma \leqslant 0$, for which Δt_{op_mld} was longer than Δt_{op_sev}, showed negative values of ε and did not produce any energy reduction, whereas most of the points were on the positive side of the vertical axis in both heating and cooling seasons. Intersection points between the horizontal axis and approximate expressions were seen at $\gamma = -0.35$ during the heating season and $\gamma = -0.37$ during the cooling season. On average, energy reduction effects were generated in ranges with larger values of γ than at the intersections.

In this analysis, the rate of energy reduction is usually lower than that of operation duration reduction, in part because the startup load is included in energy consumption Q_{sev} and Q_{mld}. Never-

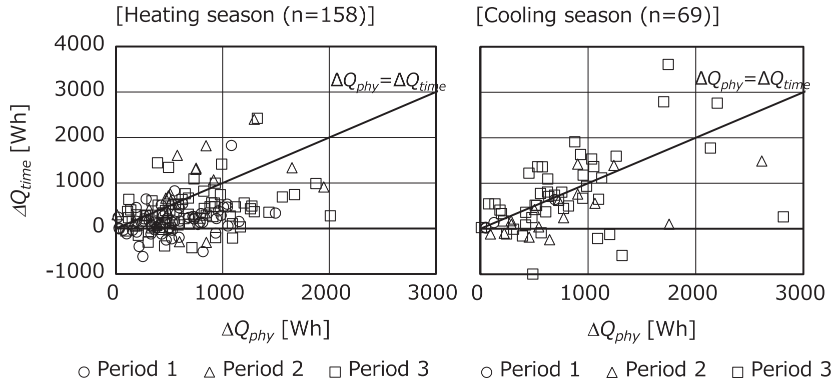

Fig. 12. Comparison between physical efficiency-related and time-related energy reductions.

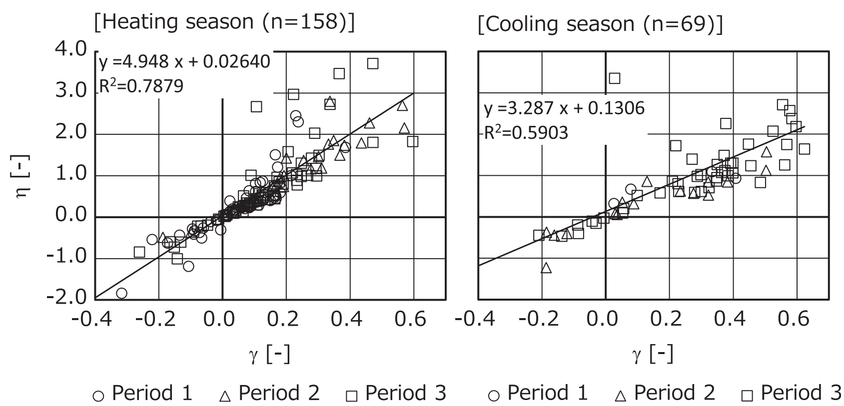

Fig. 13. Time-reduction effect η as function of γ.

theless, it is reasonable to stop RACs early under mild-load conditions to prevent excess heating or cooling caused by the relatively large capacity of the RAC.

We found that the energy consumption of an individual operation can be reduced by ~40% when each operation duration was shortened under mild-load conditions by ~20% compared with that of severe-load conditions.

4.3. Discussion of physical efficiency-related and time-related energy reductions

ΔQ_{phy} and ΔQ_{time}, the components of ΔQ, can be defined by the following expressions using Eqs. (2) and (3). Three cases in which ΔQ_{phy} became negative in Eq. (4), resulting in ΔQ_{time} being larger than ΔQ were excepted in the following analysis. In these cases, the decrease in power output was smaller than the reduction in operation duration in the mild-load condition. This might be a result of low efficiency of RAC appliances under partial load.

$$\Delta Q_{phy} = \Delta t_{op\_sev}(\Phi_{sev} - \Phi_{mld}) = \frac{\varepsilon - \gamma}{1 - \gamma} Q_{sev} \tag{4}$$

$$\Delta Q_{time} = (\Delta t_{op\_sev} - \Delta t_{op\_mld})\Phi_{sev} = \gamma Q_{sev} \tag{5}$$

Fig. 12 shows the relationship between ΔQ_{phy} and ΔQ_{time} for each sample. Some of the points have negative values of ΔQ_{time} for $\gamma < 0$, which means no reduction of operation duration under the mild-load condition. Many samples showed $\Delta Q_{phy} > \Delta Q_{time}$ regardless of period in the heating season, whereas samples were equally distributed for both $\Delta Q_{phy} > \Delta Q_{time}$ and $\Delta Q_{phy} < \Delta Q_{time}$ in the cooling season.

To compare the intensities of ΔQ_{phy} and ΔQ_{time} more quantitatively, the effect of operation duration reduction η was defined as

$$\eta = \Delta Q_{time} / \Delta Q_{phy} \tag{6}$$

The variations of η indicate positive correlations with γ in both seasons, as shown in Fig. 13. This means that the relative contribution of ΔQ_{time} became greater than that of ΔQ_{phy} as the individual operation duration was reduced under mild-load conditions. If we compare values of η at the same γ between seasons, those in the heating season were larger than those in the cooling season, which resulted in a larger gradient of the approximate expressions for the heating season. It appears that the difference of 5 °C in outdoor temperature had a relatively weak influence on reduction of the heating load, and therefore on ΔQ_{phy} relative to ΔQ_{time} in the heating season. Intersections between η = 1.0 and the approximate expressions were obtained at γ = 0.20 in the heating season and γ = 0.26 in the cooling season. This result suggests that the time-related energy reduction exceeded the physical efficiency-related energy reduction in the range with larger γ than that of the intersections.

5. Conclusions

We investigated the influence of the operation schedule of inverter-driven RACs on energy consumption based on individual operation data that were extracted from continual measurements at 30-min intervals.

Many households used RACs for both heating and cooling. More frequent individual operations were observed in the heating season than in the cooling season in 85% of the households. Individual operation duration tended to be shorter in the morning than in other periods. Also, we found that individual operation durations were reduced by the user under mild-load conditions.

An energy reduction ~40% was obtained under the mild-load conditions when the individual operation duration was reduced by 20%. No change in operation resulted in energy reductions of 24% during the heating season and of 28% during the cooling season, because of the lower heating/cooling load in mild-load conditions. Thus, voluntary shutdown behavior is a potential energy-saving solution in RAC use on the assumption that occupants are thermally satisfied.

The energy reduction effect under the mild-load condition was divided by the effect related to user behavior, based on the change in individual operation duration and the effect related to physical efficiency-related conditions. We found that the time-related effect was stronger than the physical efficiency-related effects when individual operation duration was reduced by >20% during the heating season and >26% during the cooling season. This result suggests that, although power output (in watts) tends to be emphasized in laboratory performance tests, the operation schedule is an important factor for evaluating the RAC seasonal energy consumption.

In conclusion, this study shows that consideration of operation changes depending on load conditions might improve RAC user behavior models and may lead to increased prediction accuracy of seasonal energy consumption of RACs in future works.

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