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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 ⩽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-