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Study on the smart operation approach of an air conditioner when occupants go out

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Abstract

This study demonstrates how to use an inverter air conditioner more effectively when a room is not occupied for a relatively short period of time (2 ~ 3 hours). We directly employed environmental changes (outdoor temperature, indoor building load) during daytime in a qualified test room with specific dimensions. The energy consumption of three behavioral cases was compared under several experimental simulation conditions. The first case involved turning on the air conditioner steadily using the same setting temperature without touching even if no occupants. The second involved turning off the air conditioner while occupants were out and restoring the set temperature rapidly after their return. The third case involved an artificial set temperature adjustment while occupants were out. Using several climate and building load data of Korea and the Middle East, the three air conditioner operation approaches were analyzed while occupants were out. Results showed that the first and third operating cases were energy saving depending on the environmental conditions. These results can be used for the design of smart air conditioners or policy guides for nationwide energy saving.

Keywords: Inverter air conditioner; Smart operation; Going out time operation; Energy saving; Smart home appliances

1. Introduction

According to IEA data [1], the number of air conditioners per population in homes is close to 90% in Japan, the United States, and Korea. Unexpectedly, however, the air conditioner penetration rate is presently low in many hot parts of the world (Saudi Arabia (~ 60%), China (~ 60%), Brazil (~ 15%), Mexico (~ 15%), Indonesia (~ 10%), South Africa (~ 10%), and India (~ 5%)). Therefore, this report predicts that energy consumption for space cooling will increase to nearly 40% by 2050 if no action is taken, due to the increase of air conditioners in the above developing countries.

In order to reduce the use of electricity caused by the increase of air conditioners, it is important for manufacturers to develop high-efficiency air conditioner products and for consumers to operate them efficiently. For some time, a lot of research has been undertaken to increase the efficiency of air conditioners. In particular, the efficiency of each component (e.g., compressor, heat exchanger, fan, valve, etc.) constituting an air conditioner can be improved to increase the efficiency of the final product [2,3]. Over the past 20 years, inverter compressors and vapor injection technology have been used to improve product efficiency [3,4]. In the future, technologies such as high-efficiency refrigerants, multi-stage cycles, and human recognition sensors are expected to be used widely [5–7].

Consumers are also required to take action to save air conditioner energy, such as by purchasing high-efficiency products referring to energy labels, refraining from open-door cooling, and maintaining proper room temperature. One of the important questions related to the third area is how to operate an air conditioner while occupants are out. Is it good to turn off an air conditioner when occupants go out? If the going out time is long enough, such as one day, cooling supply energy is not necessary, but if the going out time is short, as in a few

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hours, we need to worry about what to do with the air conditioner. This was not a problem in the past when air conditioner control technology was not very sophisticated and the thermal insulation of a typical home was poor. However, if it is possible to precisely control the part-load of the cooling capacity of an air conditioner and offer good insulation conditions such as in a zero-energy building, careful research on the approach to air conditioner operation is necessary. When operating an inverter compressor, in order to save energy by the efficient low-speed driven compressor, it may be better to set the temperature slightly higher than the ordinary set temperature while an occupant is out, rather than turning it off when going out and turning it on again rapidly after returning home. In particular, if IoT or AI technology is further developed, it will be driven automatically by using real-time weather status, weather forecast, and occupant status information without worrying about energy saving.

With this in mind, the present study experimented with various operation conditions to discover the energy saving effect of an inverter air conditioner according to the operation approach of an air conditioner during occupants' absence.

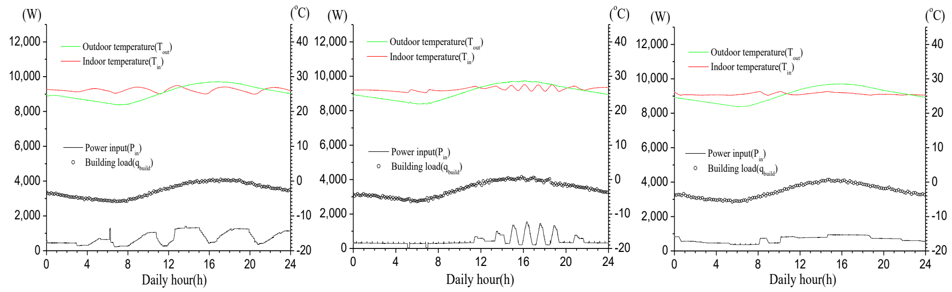
2. Experimental Approach

2.1. Preliminary work

It is well known that inverter air conditioners have a higher operating efficiency than constant speed air conditioners. However, even if an air conditioner uses inverter compressor technology, an efficiency difference between inverter products may occur due to the performance difference in an inverter compressor and control technology depending on the manufacturer and model of the product. Figure 1 shows the operation of three different inverter air conditioner models when the remote controller's set temperature is maintained at 26°C. Under the same time-dependent outdoor temperature and indoor building load condition during the day, the change in room temperature and power input shows different patterns.

If it is an ideally designed product, the room temperature should remain constant at a set temperature of 26°C, and the instantaneous power input should have a smooth, cubic function curve with a peak at 16:00 and a minimum at 06:00, following the same building load or outdoor temperature variation patterns. The exact design specifications and technology of the products are unknown, but Fig. 1 shows the desirable control pattern toward the right in the order of (a), (b), and (c). In the case of (a), the power input and room temperature vary largely in all regions of the graph. In (b), there are large deviations of power input and room temperature under large building load and high outdoor temperature (12:00 – 14:00) regions. A near ideal product case is (c), which has a small variation in room temperature and the smoothest change in power consumption among the three cases.

Although it is difficult to state directly what the quantitative energy saving effects between the products are because of the different product specifications (such as the rated capacity and rated power consumption of the three products), it can be reckoned that case (c) is the most energy efficient case judging by the simple insight. Therefore, the product corresponding to Fig. 1(c), which allows precise control, was selected and experimented with throughout this paper. Details of the specifications are in Table 1.



(a) (b) (c)

Fig. 1. Improvements in the control aspects of an inverter air conditioner ((b) is reproduced from Yoon et al [8,9])

Table 1 Specifications of the tested inverter product

Contents	Specification
Electricity	220 V, 60 Hz
Rated cooling capacity	7 000 W
Rated power input	2 010 W
Middle cooling capacity	4 700 W
Middle power input	1 250 W
Minimum cooling capacity	1 600 W
Minimum power input	330 W
Refrigerant	R410a
Product type	Floor stand split type

2.2. Problem set up

In this study, three behavior cases of air conditioner operation while occupants were out were experimentally set up, as shown in Fig. 2. In the first case, the air conditioner was operated without being turned off regardless of occupants' going out for a few hours. In the second case, the air conditioner was turned off when occupants went out and was turned back on to the target temperature immediately after returning home. In the third case, the air conditioner's compressor ran at low speed at a slightly higher set temperature and was activated again to reach the target temperature just before occupants returned.

If we go out for a day or for a few days, turning off air conditioners in uninhabited spaces is a good thing. However, if we need to go out for a short time (a few hours), we should consider whether to turn on (case 1) an air conditioner or not (case 2). And if an air conditioner can automatically adjust the temperature, it is also possible to raise the set temperature slightly while occupants are absent and return the temperature before they come back (case 3). These three behavioral cases were experimented with under the various climate environments of Table 2.

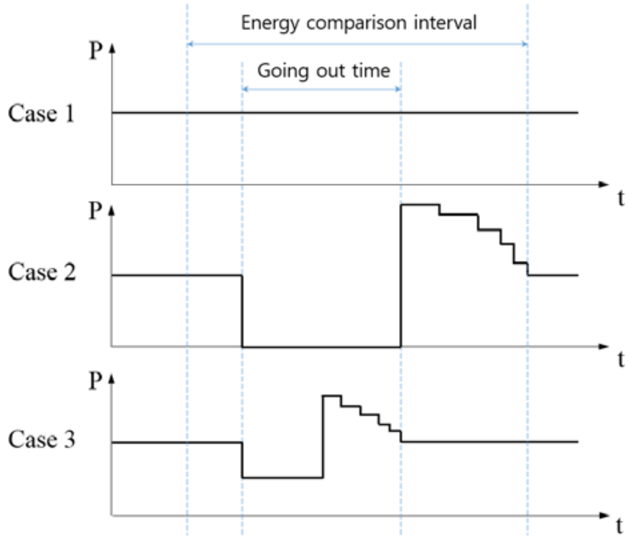


Fig. 2. Energy consumption comparison concept

Table 2 Comparison environments

	Climate condition	Behavioral case	Going out time	Total test time	Energy comparison interval	Remarks (Case 3 artificial T_{set} operation)
Env. 1	Middle East (October)	Case 1	12:00 ~ 14:30	10:00 ~ 23:00	12:00 ~ 22:00	~ 12:00 (T_{set} = 26°C)
		Case 2				12:00 ~ 14:00 (T_{set} =27°C)
		Case 3				14:00 ~ (T_{set} =26°C)
Env. 2	Seoul (August)	Case 1	12:00 ~ 15:30	Same as above	Same as above	~ 12:00 (T_{set} = 26°C)
		Case 2				12:00 ~ 14:30 (T_{set} =28°C)
		Case 3				14:30 ~ (T_{set} =26°C)
Env. 3	Seoul (August)	Case 1	12:00 ~ 15:30	Same as above	Same as above	~ 12:00 (T_{set} = 26°C)
		Case 2				12:00 ~ 15:00 (T_{set} =27°C)
		Case 3				15:00 ~ (T_{set} =26°C)
Env. 4	Middle East (April)	Case 1	12:00 ~ 15:30	Same as above	Same as above	~ 12:00 (T_{set} = 26°C)
		Case 2				12:00 ~ 15:00 (T_{set} =27°C)
		Case 3				15:00 ~ (T_{set} =26°C)
Env. 5	Middle East (October)	Case 1	14:00 ~ 16:30	Same as above	Same as above	~ 14:00 (T_{set} = 26°C)
		Case 2				14:00 ~ 16:00 (T_{set} =27°C)
		Case 3				16:00 ~ (T_{set} =26°C)

The going out time started at midday, except for Environment 5 (14:00), and the duration of the going out time was set to 2.5 (Env. 1 and 5) or 3.5 hours (Env. 2 ~ 4). Three climate conditions were used for the outdoor temperature and indoor building load, as in Fig. 3. The total test time during the day was 13 hours from 10 to 23 h, but the power consumption from 12 to 22 h was calculated to compare at the same room temperature conditions (26°C) of the start and the end between cases 1, 2, and 3 (energy comparison interval of Fig. 2).

Inverter air conditioner compressors improve efficiency at minimum operation [4], so it is important to identify what the effect is of increasing the remote control set temperature slightly during a short period of non-occupancy, as long as it has the 26°C room temperature again at the moment of occupants' return. Throughout the test environments of case 3, T_{set} was raised to 27 or 28°C during the going out period, and the T_{set} was adjusted again to 26°C a few minutes before occupants returned home (remarks of Table 3).

TRNSYS simulation was used to generate the test environments of the outdoor side temperature ($T_{out}(t)$) and indoor side building load ($q_{build}(t)$). The same methodology was used as previous studies [8,9]. In previous studies, the building load ($q_{build}(t)$) was determined under the condition that the interior room temperature was constant at 26°C. Although this hypothesis does not exactly fit behaviors 2 and 3 in this study, behavior 3 would not have a significant effect because the difference between the indoor target temperature and the instantaneous temperature is within 2°C.

Table 3 TRNSYS simulation conditions in Seoul and the Middle East [8,9]

Input variable	Seoul	Middle East
Space size (single zone)	10m × 8m × 2.5m	10m × 8m × 2.5m
Window	60% of the southern wall area – 15m^2	30% of the southern wall area – 7.5m^2
Floor of space	Located between floors – up and down insulations	Located between floors – up and down insulations
Glass	1.20 W/m^{2}K	1.720 W/m^{2}K
Wall	0.21 W/m^{2}K	0.345 W/m^{2}K
Room temperature & humidity	26°C & 60 %R.H.	26°C & 60 %R.H.
Heating & light element	25 W/m^2	25 W/m^2
Persons	4	4
Infiltration	0.4 (1/h)	0.4 (1/h)
Ventilation	0.6 (1/h)	0.6 (1/h)

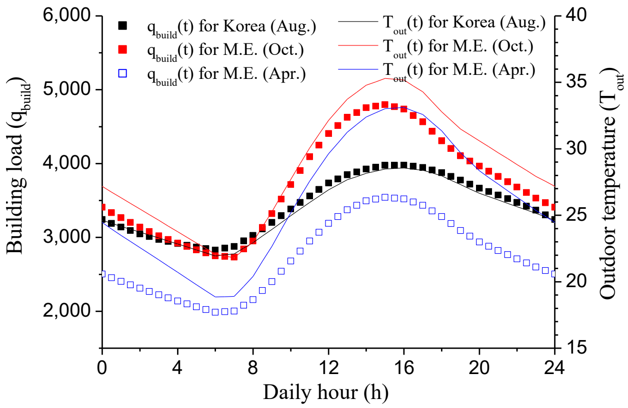


Fig. 3. Simulated building load and outdoor temperature

3. Results and Discussions

3.1. Environment 1 results

This is the climate case of October in the Middle East. For case 3, T_{set} was adjusted to 26 → 27 → 26 °C, as in the remarks of Table 2. For case 1 in Fig. 4, even if T_{set} is kept at 26°C, the power consumption of case 1 shows a parabolic shape from 12 h to 22 h with a maximum value at the vicinity of 16 h. This power input variation is due to the variations of the T_{out}(t) and q_{build}(t) during the day. In general, the instantaneous power input of the air conditioner is proportional to the compressor operation rate according to the outdoor side temperature and the internal building load (Figs. 1(c) and 4(a)). In case 2, the power input is zero during the going out time because the air conditioner is turned off, and the indoor temperature soars due to the heat of the building load. Even though the external outdoor temperature reaches up to 35°C (Fig. 3), the internal indoor temperature rise to close to 45°C is somewhat unrealistic and seems to be overestimated even when explained by radiative heat transfer through windows. This is due to the assumption of a constant indoor temperature of 26°C when simulating TRNSYS (Table 3). Because the heat intrusion from the outside of the building is qualitatively proportional to the temperature difference between the outside and the indoor temperature, that is, $q_{build} \sim (T_{out} - T_{in})$, the q_{build}(t) graph of Fig. 3 is overestimated when it assumes constant indoor temperature of 26°C. For accurate quantitative assessments in the future, instantaneous TRNSYS simulations are required to take into account changes in the indoor room temperature (T_{in}(t)) caused by the air conditioner test sample.

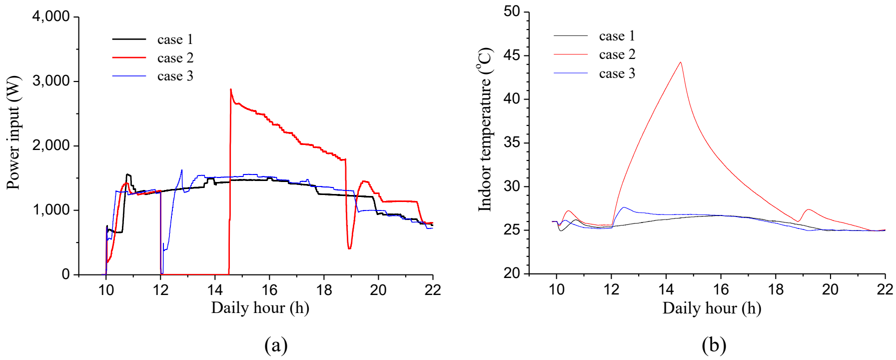


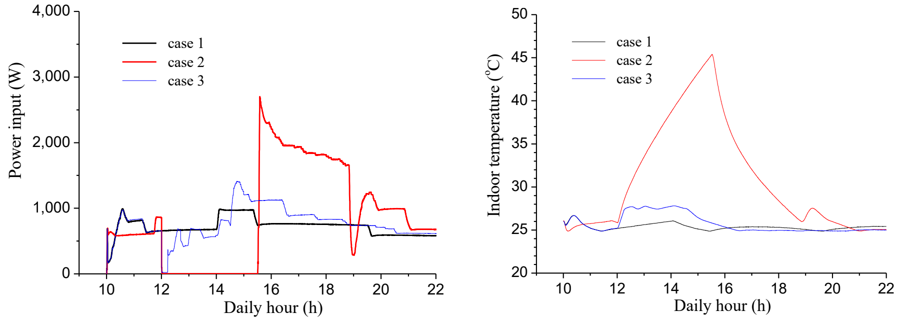
Fig. 4. Power consumption and indoor temperature variation (Environment 1)

In case 3 (blue line), during the non-occupancy period, less power is consumed than case 1 (black line), and the total final power consumption for the energy comparison interval is lowest in case 3 (12 474 Wh), as shown in Table 4. Considering the actual room temperature of 27 to 28°C, not 26°C when occupants are out, the power input of case 3 was also slightly overestimated. Therefore, an operation similar to case 3 seems to be more energy saving in practice (less than 12 474 Wh).

3.2. Environment 2 results

In order to increase the energy saving, the test conditions were changed by allowing the compressor to be in minimum load operation while occupants were out. The climate condition was set as August in Korean, which has a lower heat load than the Middle East, and T_{set} was adjusted to 26 → 28 → 26 °C for the behavior 3 case. In addition, in order to observe the energy saving effect over a longer period, we increased the going out time (total 3.5 hours).

Contrary to expectations, however, case 3 consumed more electricity energy (7 814 Wh) than case 1 (7 258 Wh) in Environment 2. This is evident in the case 3 graph of Fig. 5(a). When returning the set temperature from 28°C to 26°C in advance in preparation for an occupant returning at 15:30, it consumes more electricity than case 1 as a side effect. In other words, raising and lowering the temperature by 2°C may consume more electricity than adjusting by 1°C.

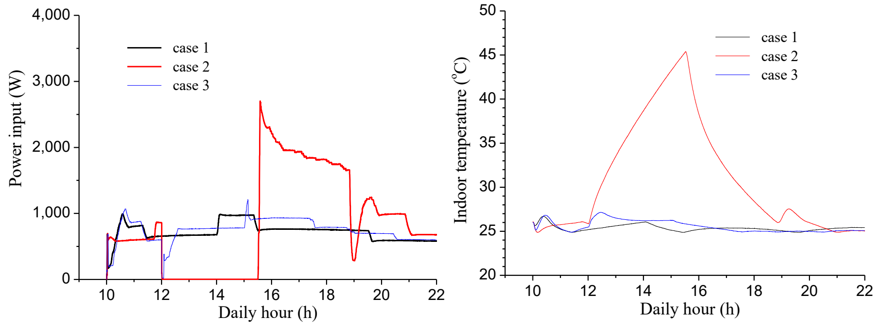


(a) (b)

Fig. 5. Power consumption and indoor temperature variation (Environment 2)

3.3. Environment 3 results

This time, to eliminate the adverse effect of the suspect 2°C adjustment in Environment 2 – case 3, the temperature adjustment in Environment 3 – case 3 was limited to 1°C, and it was restored to 26°C, 30 minutes before the occupants' return.



(a) (b)

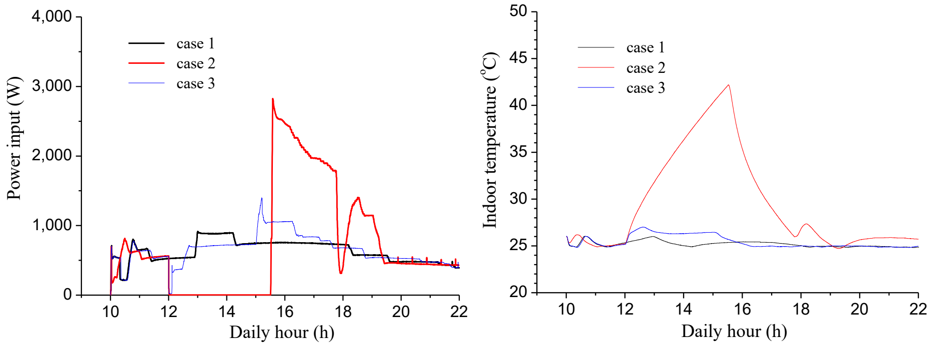
Fig. 6. Power consumption and indoor temperature variation (Environment 3)

Environment 3 – case 3 recorded energy consumption of 7 562 Wh, which is less than Environment 2 – case 3 of 7 814 Wh, but still more than the energy consumption of case 1 (7 258 Wh). This shows that 1 °C of temperature adjustment is somewhat effective, but not the main point of the energy saving as in Environment 1 – case 3. Environments 4 and 5 impose Middle East climate conditions where energy saving in case 3 occurred (Environment 1).

3.4. Environments 4 and 5 results

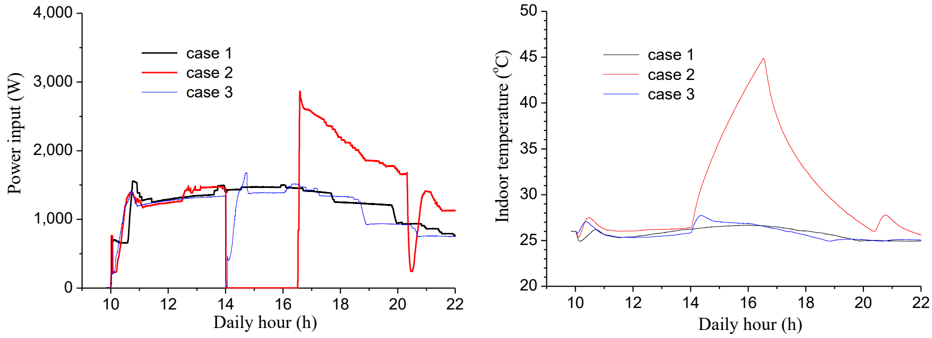
Figures 7 (Env. 4) and 8 (Env. 5) show the test results for the April and October climate and building load conditions in the Middle East, respectively. Because the Middle East's April condition (Env. 4) is similar to Seoul's August condition, the energy saving aspect is similar to Environments 2 or 3. In the case of Environment 5, the test conditions of Environment 1 were slightly modified to change the going out time from 14:00 to 16:30 when the $T_{out}(t)$ and $q_{build}(t)$ are relatively higher than the going out time of Environment 1 – case 3 (from 12:00 to 14:30). Then, the energy consumption of Environment 3 – case 3 (11 735 Wh) becomes smaller than Environment 1 – case 3 (12 474 Wh). These results indirectly show that in order for inverter air conditioners to achieve energy saving with minimal operation, the product must be operated in a partial cooling load range where inverter compressor efficiency can be achieved to some extent.

The part-load operation rate of Environment 5 – case 3 is approximately 67% (= building load, 4 700 W / product rating, 7 000 W). As future work, it will be necessary to further verify the energy saving effect under various conditions in terms of part-load operation rate.



(a) (b)

Fig. 7. Power consumption and indoor temperature variation (Environment 4)



(a) (b)

Fig. 8. Power consumption and indoor temperature variation (Environment 5)

3.5. Summary

The summarized energy consumptions (Wh) for the energy comparison interval (12:00 ~ 22:00) are shown in Table 4. There exist obviously smart operational approaches of an air conditioner that can save energy for a short period of non-occupancy of 2.5 or 3.5 hours at special environment conditions. Environments 1 and 5 could reduce the energy consumption when occupants were out by 139 Wh and 878 Wh, respectively, during 2.5 hours without occupancy. This amount is replaced by 56 W and 351 W per hour, respectively.

Table 4 Summary of the energy consumption for each test case

	Climate condition	Behavioral case	Energy consumption (Wh) between 12:00 ~ 22:00
Env. 1	Middle East (October)	Case 1	12 613
		Case 2	12 963
		Case 3	12 474
Env. 2	Seoul (August)	Case 1	7 258
		Case 2	9 118
		Case 3	7 814
Env. 3	Seoul (August)	Case 1	7 258
		Case 2	9 118
		Case 3	7 562
Env. 4	Middle East (April)	Case 1	6 521
		Case 2	7 592
		Case 3	6 770
Env. 5	Middle East (October)	Case 1	12 613
		Case 2	12 557
		Case 3	11 735

4. Conclusion and Future Work

Considering that inverter air conditioners are highly efficient at low-speed operation, energy consumption was compared for three behavioral cases: turned on (behavior case 1), turned off (behavior case 2), or the set temperature was adjusted to minimal operation (behavior case 3) while occupants were out for a short time. If air conditioner technology is further improved, it will be developed to save energy by inputting the outdoor condition, building load condition, and a user's usage pattern by combining with IoT and AI technology. In order to evolve in this direction, it is necessary to pre-study under what conditions an inverter air conditioner can be operated in an energy saving manner and whether current products have the hardware capability to perform such selective operation. With several arbitrary environmental conditions, we found that inverter air conditioners can save electricity by adjusting the set temperature when occupants go out. Assuming 2.5 or 3.5 hours of going out time in Korea and the Middle East climates, three air conditioner operational behaviors during non-occupancy were examined. Under certain conditions when the part-load operation rate was near 65%, the electrical energy consumption order was case 3 < case 1 < case 2, and under some conditions the order was case 1 < case 3 < case 2 when the part-load operation rate had small values under 65%.

In future work, however, TRNSYS analysis is needed to reflect the temperature change ($T_{in}(t)$) inside a building by the test product instead of assuming constant T_{in} (= 26°C). This will yield more accurate and realistic results for case 2. In addition, a wider investigation of the part-load operation rate and going out time environmental conditions is required for various types of inverter air conditioners.

Acknowledgements

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