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Energy efficiency evaluation of multiple split-system air conditioners with unbalanced load operation for building energy simulation

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Abstract. The number of buildings that adopt the multiple split-system air conditioners is increasing, especially for small and medium-sized buildings. Many researches have been done on the energy consumption performance of the multiple split-system, but there are still many unclear points about its actual performance, in particularly, with regard to performance under partial load condition. It is important to understand the partial load performance and set the reliable performance characteristics when we perform building energy simulation because it will have a significant influence on annual energy consumption of the system. In order to clarify the efficiency under partial load condition, we have analysed the measurement data of actual buildings and found that there is a range of the efficiency even at the same load ratio. We assume that the cause of this range is due to bias (unbalance) in the heat amount handled by multiple indoor units. The efficiency tends to be higher when the heat amount of all indoor units of the system are equal, which is same as the test condition specified by ISO 15042:2017, but the efficiency tends to be lower when the heat amount handled by the indoor units is highly unbalanced. This research clarifies the influence of the unbalanced heat load to the system energy efficiency. We measured fundamental data on the energy efficiency of the multiple split-system air-conditioner in an experimental facility that connects multiple constant temperature and humidity chambers. We found that the unbalanced load operation caused about 20% energy loss in maximum and concluded that the indoor units should be arranged so that extreme unbalanced heat load does not occur.

1. Introduction

The number of buildings that adopt the multiple split-system air conditioners is increasing, but there are still many unclear points about its actual performance, in particularly, with regard to performance under partial load condition [Goetzel, 2007], [Watanabe, 2007]. It is important to understand the partial load performance and set the reliable performance characteristics when we perform building energy simulation because it will have a significant influence on annual energy consumption of the system [Horie, 2012].

In order to clarify the efficiency under partial load condition, we have analysed the measurement data of actual buildings and found that there is a range of the efficiency even at the same load ratio as shown in Figure 1 [Enteria, 2016a, 2016b]. Figure 1 also shows the performance curve assumed in Japanese Building Energy Standard. This curve is expressed by the following formula [Building Energy Standard of Japan, 2013].



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$$COP_{ratio} = \frac{1}{(0.7823 L^2 + 0.0398 L + 0.1779)} \quad (1)$$

where L is heat load ratio [-].

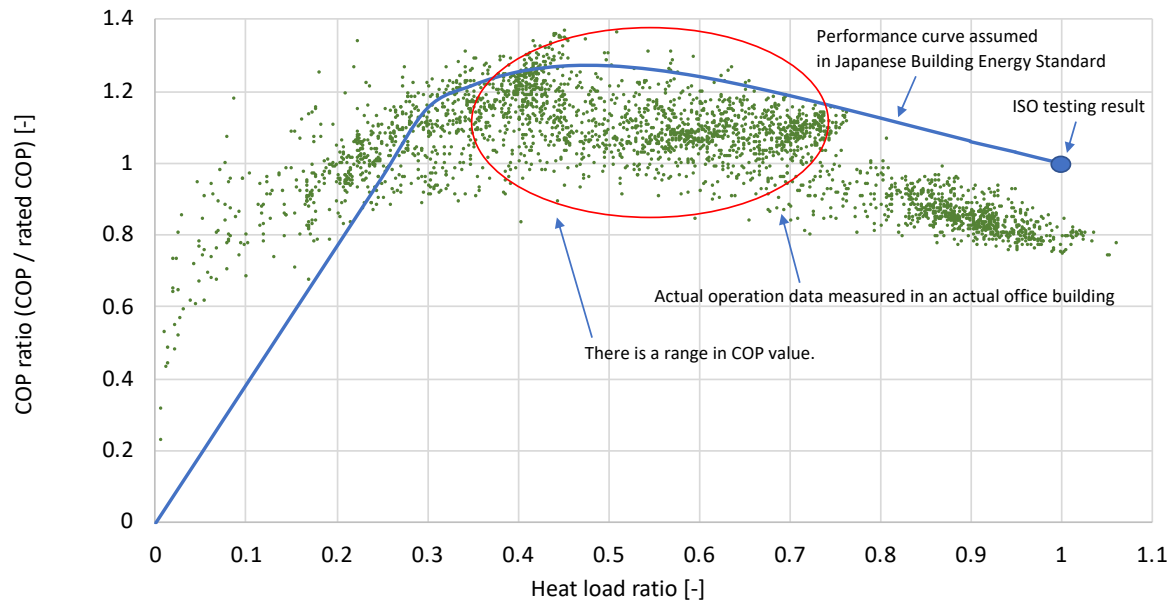


Figure 1. Performance characteristic of a multiple split-system air-conditioner.

We assume that the cause of this range is due to bias (unbalance) in the heat amount handled by multiple indoor units. The efficiency tends to be higher when the heat amount of all indoor units of the system are equal, which is the test condition specified by ISO 15042:2017, JIS B 8615-1:1999 and JIS B 8616:2015, but the efficiency tends to be lower when the heat amount handled by the indoor units is highly unbalanced. This point is generally not considered and ignored in the existing building energy simulations.

This research clarifies the influence of the unbalanced heat load to the system energy efficiency. We measured fundamental data on the energy efficiency of the multiple split-system in an experimental facility that connects multiple constant temperature and humidity chambers.

2. Test facilities

Figure 2 shows the technical diagram of the testing facilities used to make the performance evaluation of the multiple split-system air conditioners presented in this paper. Figure 3 shows the actual view of the testing facilities. The testing facilities consist of one outdoor chamber and three indoor chambers. The outdoor chamber can support the system with an outdoor capacity of from 0.33kW to 56kW. The outdoor chamber dry bulb (DB) temperature can be varied from -20°C to 45°C. The relative humidity range can be varied from 30% to 80%, controlled by using a wet bulb temperature sensor for the outdoor temperature when it is above the freezing point of water. The three indoor chambers can simulate both cooling and heating loads. The two smaller indoor chambers (Indoor Chamber 1 & 2) can support a heating load of up to 12kW with humidification capability while the bigger indoor chamber (Indoor Chamber 3) can support a heating load of up to 24kW with humidification capability. Both indoor chambers 1 and 2 can support a cooling load of up to 12.5kW, and indoor chamber 3 can support a cooling load of up to 25kW; the two indoor units can be installed in tandem for the case of indoor chamber 3. Control and monitoring devices are installed to gather the needed parameters.

3. Test specimen

The air conditioner to be tested in this research is an air conditioner made by a Japanese domestic manufacturer whose rated heating capacity is 22.4 kW (8 HP). We tested with four 5.6 kW indoor units connected (two for indoor chambers No.1 and No.2 and the other two for indoor chamber No.3).

Since the purpose of this research is to reveal the actual performance assumed to be installed in actual buildings, we did not fix the rotation speed of the compressors and the expansion valve opening degrees intentionally though it is usual in the case of the testing specified by ISO 15042:2017.

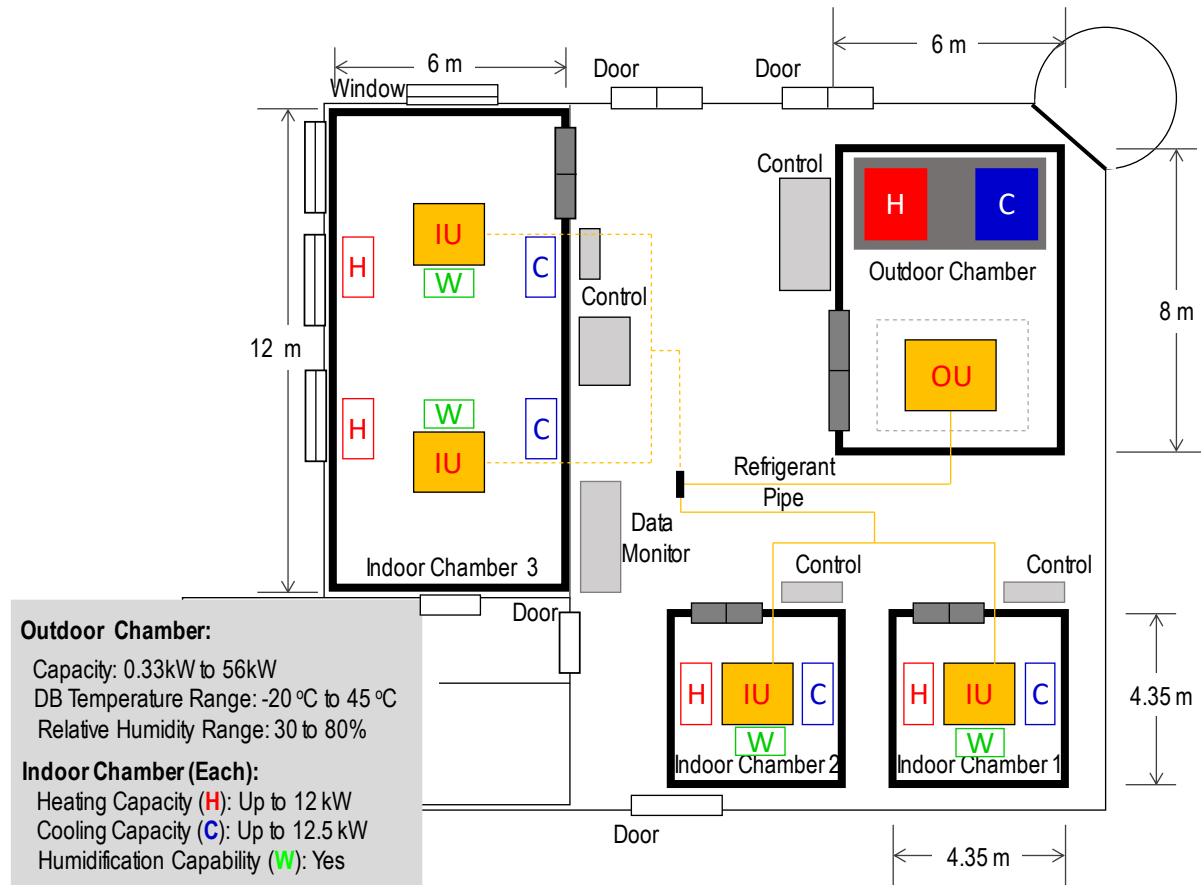


Figure 2. Outline of the testing facilities.
(located in Building Research Institute Japan)



Figure 3. Actual views of testing facilities.

(left: Indoor Chamber 1, right: Indoor Chamber 3)

4. Measurement

The heat load amount of each indoor unit was estimated by measuring the air enthalpy difference of the indoor unit. The total heat load amount of the air-conditioning system is obtained as the sum of the heat load amount of all the indoor units. The inlet and outlet air temperature and humidity of the indoor unit were measured with temperature and humidity sensors and the air volume of the indoor unit was estimated by measured fan rotation speeds. In addition, in order to measure the refrigerant pressure, pressure sensors were installed in the outdoor unit and watt meters were installed in order to measure the energy consumption of the indoor units and the outdoor unit. The sampling time of the energy consumption was set to 1 second, and the sampling time of the others was set to 5 seconds.

5. Experimental cases and methods

The experiment was conducted from September 2017 to February 2018. Table 1 shows the experimental cases carried out. As shown in Table 1, we classified the test cases into the following three groups;

- High load range cases (Case-H series, the total heat load ratio is 75% or more),
- Medium load range cases (Case-M series, the total heat load ratio is about 50%),
- Low load range cases (Case-L series, the total heat load ratio is 25% or less).

Case-H1, Case-H3, Case-M1, Case-M2, Case-L1 and Case-L4 are the cases where the heat load ratios of all the indoor units are the same and there is no unbalanced load condition. In all the other cases, the heat load ratio of each indoor unit is not same but unbalanced. Case-M1 and Case-M2 are exactly the same conditions. The purpose of the same two experiments is to confirm the reproducibility of this experiment.

The operation mode of the system is "heating". The outdoor chamber was maintained at a dry-bulb temperature of 7 °C and a wet-bulb temperature of 6 °C. The set point of the indoor room air temperature is 20 °C. The air volume setting is "Maximum".

For each case, we adjusted the output of the load generators (fan coil units) installed in the indoor chambers so that the heat load ration of each indoor unit is maintained at the target load ratio shown in Table 1. Because this experimental facility does not have a function to stably and strictly control the heat load ratio of the indoor unit, the load ratio shown in Table 1 is just a "target" value, and the actual achieved load ratio is somewhat different from the target value.

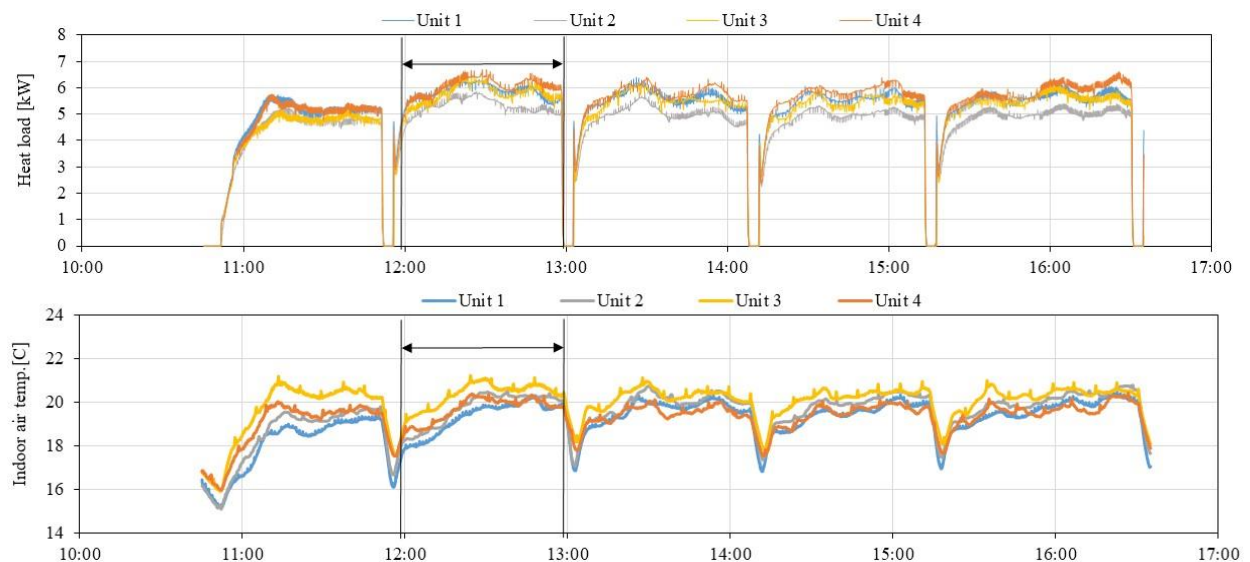
Table 1. Experimental cases carried out.

Cases		Target load ratio [%]				Average heat load ratio [%]
		Unit 1	Unit 2	Unit 3	Unit 4	
High load range	Case-H1	100	100	100	100	100
	Case-H2	25	100	100	100	81.25
	Case-H3	75	75	75	75	75
	Case-H4	100	100	50	50	75
	Case-H5	100	0	100	100	75
Midium load range	Case-M1	50	50	50	50	50
	Case-M2	50	50	50	50	50
	Case-M3	100	50	50	50	62.5
	Case-M4	25	25	100	100	62.5
	Case-M5	67	0	67	67	50.25
	Case-M6	0	0	100	100	50
Low load range	Case-L1	25	25	25	25	25
	Case-L2	33	0	33	33	24.75
	Case-L3	0	0	50	50	25
	Case-L4	15	15	15	15	15
	Case-L5	20	0	20	20	15
	Case-L6	0	0	30	30	15

6. Data analysis

With respect to the experimental data of each case, we selected the data that the heat load ratio and the outlet air temperature of each indoor unit are close to the target values and are stable, and we averaged the data for one hour during this stable period. Among the data for this one hour, the state in which the air-conditioner intermittently repeats ON and OFF (intermittent operation) is also included.

Although there is still room for discussion on how to extract this one-hour data, we have checked the graph with our eyes and arbitrarily extracted the data of the time span judged to be stable. As an example, the experimental data of Case-H1 is shown in Figure 4. For the Case-H1, operational data from 11:58 to 12:58 was extracted as a stable data.



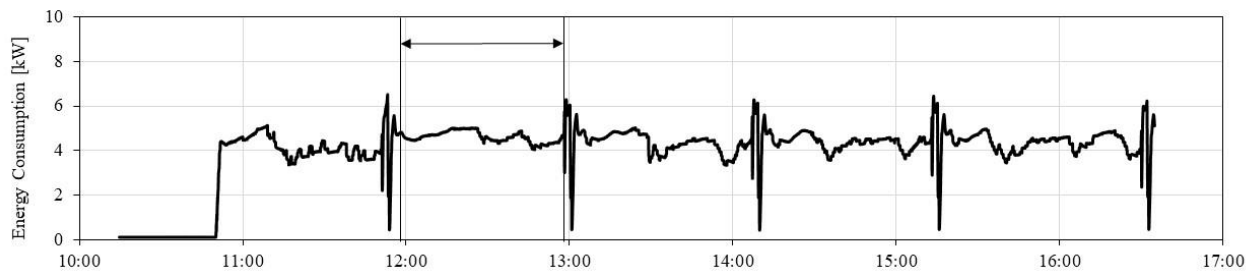


Figure 4. An example of measured data (Case-H1).

7. Analysis of performance

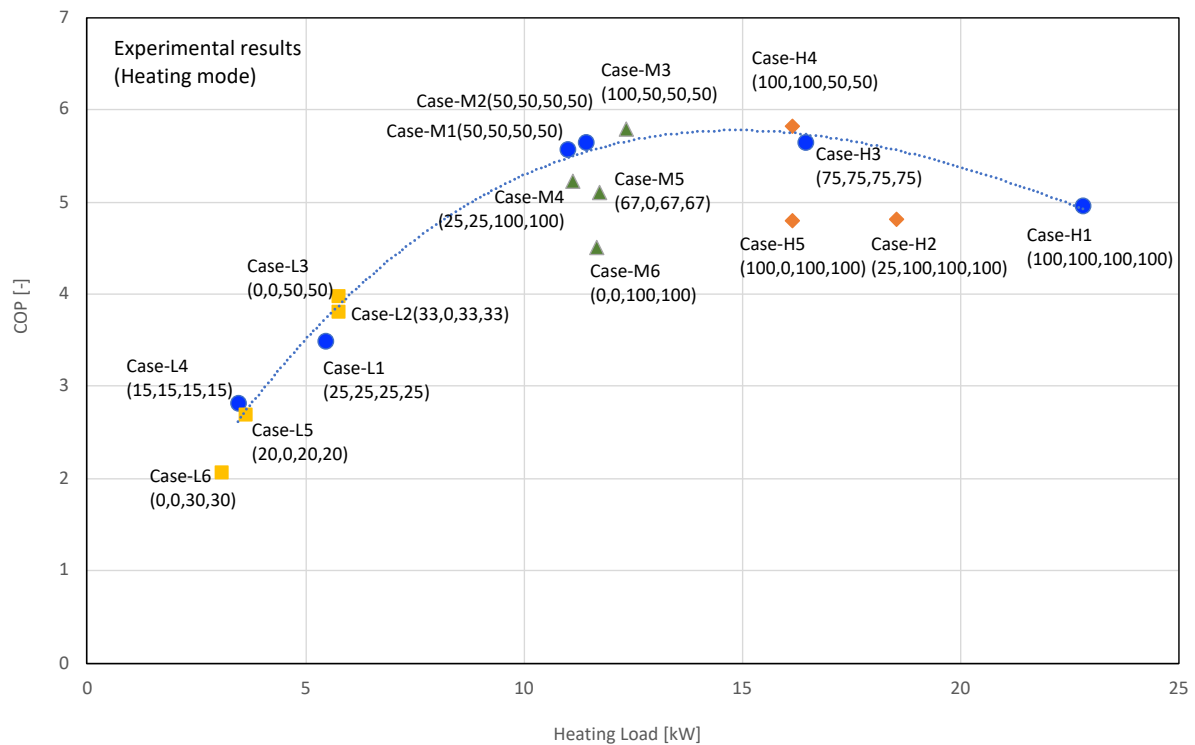
For each case, the average heat load amount of the outdoor unit (the sum of the heat load amount of the indoor units) and the average energy consumption are calculated using the measured data. Using these two values, the average operation efficiency of the system can be calculated (The average heat load amount / the average energy consumption).

Table 2 shows the results of the experiment. This table also shows the state of the indoor unit and the refrigerant pressure. Figure 5 shows the relationship between the average heat load amount of the outdoor unit and the average operation efficiency. Here, for Case-H4, Case-M3 and Case-M4, the room air temperature was significantly lower than the set value of 20 °C. Further studies are needed in order to know why these cases couldn't maintain the room air temperature at the set value.

For Case-M1 and Case-M2, experiments with exactly the same conditions were conducted on different days with the purpose of confirming the reproducibility of the experiment. As shown in Table 2, the results of both cases are almost the same. In this experiment, intentional fixation of the compressor rotation speed and the expansion valve opening degree was not conducted, but it was confirmed that there was to some extent the reproducibility.

Table 2. Experiment results for all cases.

Cases		Outdoor unit			Heat load of indoor units [kW]				Indoor temperature [°C]				Refrigerant pressure [MPa]	
		Heat load [kW]	Energy consumption [kW]	Efficiency [-]	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	High	Low
High load range	Case-H1	22.81	4.62	4.94	5.83	5.26	5.72	6.00	19.27	19.71	20.33	19.68	1.80	2.33
	Case-H2	18.53	3.86	4.81	0.98	5.28	6.01	6.27	21.77	19.72	19.10	18.67	1.79	2.33
	Case-H3	16.47	2.92	5.64	4.17	3.82	4.03	4.45	19.73	19.82	19.95	20.38	1.64	2.11
	Case-H4	16.13	2.77	5.82	5.42	5.02	2.71	2.98	14.73	15.10	20.86	20.74	1.53	2.01
	Case-H5	16.13	3.36	4.80	5.38	-	5.81	4.94	20.19	-	19.80	20.13	1.82	2.32
Medium load range	Case-M1	11.00	1.98	5.56	2.78	2.52	2.99	2.71	20.49	19.97	20.44	19.86	1.55	2.01
	Case-M2	11.42	2.03	5.63	2.75	2.69	2.79	3.18	20.95	20.34	21.40	21.26	1.55	2.07
	Case-M3	12.32	2.13	5.78	5.07	1.87	2.77	2.61	14.24	20.56	20.52	20.32	1.50	1.96
	Case-M4	11.11	2.13	5.22	1.03	0.76	4.58	4.74	21.21	21.18	16.10	15.74	1.63	2.13
	Case-M5	11.73	2.30	5.10	3.93	-	4.10	3.70	19.17	-	20.26	19.94	1.67	2.17
	Case-M6	11.65	2.59	4.50	-	-	5.60	6.05	-	-	19.95	19.38	1.82	2.36
Low load range	Case-L1	5.47	1.57	3.48	1.42	1.04	1.22	1.79	20.36	20.43	21.34	21.27	1.75	2.02
	Case-L2	5.77	1.52	3.80	2.03	-	1.48	2.26	20.01	-	21.34	21.14	1.82	2.06
	Case-L3	5.75	1.45	3.97	-	-	2.42	3.33	-	-	20.82	20.53	1.82	2.13
	Case-L4	3.45	1.23	2.80	0.96	0.83	0.85	0.76	20.65	21.23	21.15	21.07	1.82	1.89
	Case-L5	3.64	1.36	2.68	0.94	-	1.58	1.12	20.70	-	21.15	21.21	1.91	2.00
	Case-L6	3.09	1.51	2.05	-	-	1.45	1.64	-	-	21.50	21.35	1.89	2.05

**Figure 5.** Experimental results plotted on the performance curve.

Regarding the experimental results in the high load range cases, when comparing Case-H3 (without load unbalanced) and Case-H5 (load ratio is 100% for 3 units and the other is stopped), it is clear that the efficiency of Case-H5 is about 15% lower even though the outdoor unit load is almost the same (about 16 kW). When comparing Case-H3 and Case-H2 (load ratio is 100% for 3 units and 25% for 1 unit), Case-H2 is also about 15% less efficient. Compared to Case-H3 in Case-H5 and Case-H2, the refrigerant pressure of Case-H3 and Case-H5 is higher, which seems to cause the performance deterioration.

Regarding the experimental results in the medium load range cases, Case-M1 (without load unbalanced) and Case-M3 (load ratio is 50% for 3 units and 50% for 1 unit) have nearly the same operation efficiency, but Case-M5 (load ratio is 67% for 3 units and the other is stopped) is also about 8% less efficient than Case-M1. Furthermore, Case-M6 (load ratio is 100% for 2 units and the others are stopped) is about 20% less efficient.

Regarding the experimental results in the low load range cases, Case-L2 (load ratio is 33% for 3 units and the other is stopped) and Case-L3 (load ratio is 50% for 2 units and the others are stopped) are more efficient than Case-L1 (without load unbalanced). This is because Case-L1 intermittently repeats ON and OFF at a total load factor of 25%, which causes energy loss, but Case-L2 and Case-L3 are continuously operating.

8. Discussion and conclusion

This paper shows the experiment results on the energy performance of the multiple split-system air conditioners to clarify the influence of the unbalanced heat load of indoor units. The testing method specified in ISO 15042:2017 is assumed to be conducted under the condition that the heat load amount of all the indoor units is equal, but in actual buildings, the heat load amount of all the indoor units is not equal due to the following reasons.

- a) difference in heat load between the perimeter zone and the interior zone. Especially for buildings with poor thermal insulation performance and air tight performance, the difference may be larger.
- b) difference in heat load from appliances in the room (for example, there is a place where heat generation is locally higher because many copy machines are located at the place).
- c) difference in how the rooms are used (for example, the office room and the meeting room are air-conditioned with the same outdoor unit).

The experimental results show that the unbalanced load operation caused about 20% energy loss in maximum. Because this paper just clarified the trend by limited experiments only for limited air-conditioner, we should carry out more detailed experiments in the future and clarify the mechanism by which the unbalanced heat load influences energy consumption efficiency. In order to accurately calculate annual energy consumption of buildings, it is necessary to incorporate this mechanism into building energy simulation.

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Acknowledgments

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