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System Performance with Variation of Outdoor Unit Layouts at Building Re-entrants

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Abstract

Air-cooled split-type air conditioners (AC) are very popular in high-rise residential and commercial buildings in Korea. The performance of such AC systems varies significantly with system characteristics and environmental conditions. Particularly, the outdoor condensing unit of the system, if poorly cooled due to high density of AC distribution and restricted outdoor space, will result in large decrease of cooling efficiency and increase of electrical energy consumption and may further jeopardize the system reliability. This paper presents a numerical analysis on the thermal and energy performance of a group of air-cooled air conditioners installed at a courtyard of a high-rise building. The study introduces a series of new energy performance indices to assess the group performance of the AC condensers with different outdoor unit layouts. The results not only indicate the COP of the systems, but also quantify the system capacity and energy consumption. The evaluation method and indices developed are useful for guiding the design of the distribution plan of the AC units at building re-entrants.

Key words: Air conditioner; Building, Re-entrants; High-rise building; Outdoor unit

Nomenclature

P : electric power consumption [kW]
Q : cooling capacity [kW]
T : temperature [℃, K]

Subscript

Eff : effective value
s : standard (Outdoor condition)
o : on coil
α : atmosphere

Abbreviations

COP : Coefficient of performance
GCPR : Group Condenser Performance Rate
GCCR : Group Condenser Capacity Rate
GCER : Group Condenser Electric power consumption Rate

1. Introduction

Many residential and commercial buildings in Korea favor the usage of split-type individual air conditioning (AC) units instead of central systems because of the low capital cost, increasing energy efficiency, and high flexibility in installation and operation of individual air conditioning systems. Individual air conditioners usually have relatively small cooling capacities with air-cooled condensing units. To effectively remove the heat from the condensing unit requires installing the condenser at areas with low air temperature. High ambient air temperature will degrade the air conditioner performance, increase the electrical energy consumption, and further affect the reliability of the system.

Generally, for high-rise buildings, most condensing units of split-type AC systems are installed at restricted spaces inside the buildings. Recent trend in building and system design in Korea, especially for residential buildings, has been moving towards installing individual condensing units at local external locations (called "outdoor unit rooms"). This kind of

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arrangement can directly reach the outdoor fresh air for condenser cooling and also separate condenser noise from indoor spaces. However, the concentrated dispatch of massive AC condensers at building facades, especially within an isolated or restricted space, may lead to accumulated heat around external condensers and induce a buoyant air plume across the upper condenser locations. As a result, the overall performance of the group of individual air-conditioners will be largely impaired.

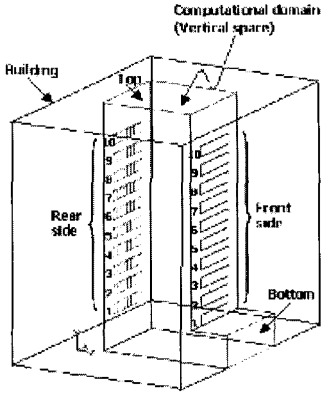
Chow et al.$^{(1\text{-}3)}$ investigated how the heat rejected from external condensers of split-type air conditioners would affect the air temperature distribution in the recessed spaces of high-rise buildings in Hong Kong. The AC capacity studied, however, was much smaller than those used in most tall buildings in Korea, which are usually more than 14kW per system. Ahn et al.$^{(4)}$ explored the thermal characteristics of 28kW split-type air conditioners with outdoor airflow re-entrant. Choi et al.$^{(5\text{-}6)}$ attempted to develop new air-conditioning systems that can avoid the condenser stack effect. This study investigates the group performance of air-cooled split-type air-conditioning systems with different condenser layouts in a courtyard of a high-rise building. A new energy evaluation method based on the computational fluid dynamics (CFD) analysis is presented.

2. Performance Evaluation Method for Split-Type Air-Conditioner

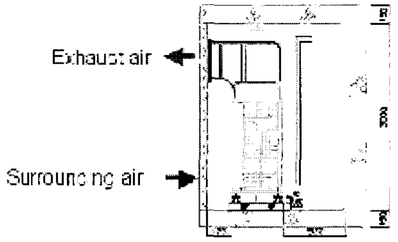
This study used a real building as an example to demonstrate the method and procedure for evaluating the energy performance of a group of air conditioners with different outdoor layouts. Fig. 1 shows the simplified model of an under-construction 10-story hotel building located at Pusan, Korea. The separate condensing units were installed on the glass facades in the open courtyard of the building. The scales of the courtyard are 17 m(width), 24 m(depth), 44 m(height) and the dimension of each condenser room is 2.5 m(width), 3 m(height). The ambient fresh air is continuously drawn into the courtyard through the ground-floor entrance (tunnel) and arises due to both wind pressure and thermal buoyancy effect.

Table 1. Case variations.

		Wind speed (m/s)			
		1.1	2.2	4.4	6.6
Condenser location	Front	CASE 1	CASE 2	CASE 3	CASE 4
	Rear	CASE 5	CASE 6	CASE 7	CASE 8



(a) CFD model



(b) Outdoor unit sketch

Fig. 1. Simplified building sketch (CFD model) and schematic drawing of outdoor unit layout.

2.1 *Thermal performance analysis*

In this building, each floor is served by eight air-conditioning units installed at either rear or front side of the courtyard, as shown in Fig. 1(a). The ambient air is drawn in and exhausted from the external side of the condensing unit as illustrated in Fig. 1(b). Each condensing unit has a heat extraction rate of 36 kW but not to exceed 45C, and the air discharge rate is 3.0 m^3/s.

This study investigated eight scenarios with combinations of different condenser locations and natural wind speeds, as listed in Table 1. In CASE 1~4, the condensing units were installed at the front façade, the same side as the wind inlet. In CASE 5~8, the condensing units were installed at the rear façade opposite to the wind inlet tunnel. Four representative wind speeds were evaluated according to the 30-year averaged typical meteorological year (TMY) data of Korea.

The study used the computational fluid dynamics technique to analyze the airflow and thermal characteristics in the courtyard and around the condensing units. The governing equations for three-dimensional steady-state turbulent airflow and heat transfer were solved by a commercial CFD program.(7) Boussinesq approximation for buoyancy was applied to correlate the energy equation with the momentum equations. The standard k-ε model(7) and no-slip wall condition were used for the turbulence simulation. The heat flux from the glass walls were assumed zero (adiabatic) to simplify the simulation. A total number of 350,000 non-uniform unstructured tetrahedral grids were used for the simulation with the compromise of both accuracy and computing cost. The predicted airflow velocity and temperature characteristics can be used for the next energy performance analysis.

2.2 Energy performance evaluation

Generally, the performance of an air conditioner can be quantified by using the COP, i.e., the ratio of cooling capacity to energy consumption. The COP value of an air conditioner heavily relies on the indoor and outdoor operating conditions. For a given indoor condition, the performance of an air conditioner can be expressed as a function of the standard on-coil temperature T_o. The measurement of the performance of the air conditioning units installed in the investigated building shows the correlations between COP, Q, P, and T_o (C) as shown in Figs. 2 and 3.(8) Fig 3 is compared the results based on 25℃ of the indoor design temperature. The polynomial regressions (1)~(3) apply fairly well for To ranging from 20~45℃. Because of the difference in system capacity range, these correlations are different from those developed by Chow(4-6).

$$COP = 700017 - 0.26969T_o + 0.00574T_o^2 - 0.00052442T_o^3 \tag{1}$$

$$Q = 24.3983 + 0.05852T_o + 0.0142T_o^2 - 0.00037972T_o^3 \tag{2}$$

$$P = 3.66483 + 0.12463T_o + 0.00786T_o^2 - 0.000138T_o^3 \tag{3}$$

$$GCPR = 1/n\sum\left[\frac{COP(T_o)}{COP(T_s)}\right]\times 100[\%] \tag{4}$$

$$GCCR = 1/n\sum\left[\frac{Q(T_o)}{Q(T_s)}\right]\times 100[\%] \tag{5}$$

$$GCER = 1/n\sum\left[\frac{P(T_o) - P(T_s)}{P(T_s)}\right]\times 100[\%] \tag{6}$$

where T_o is the actual on-coil temperature in C and T_s is the standard or design on-coil temperature in ℃.

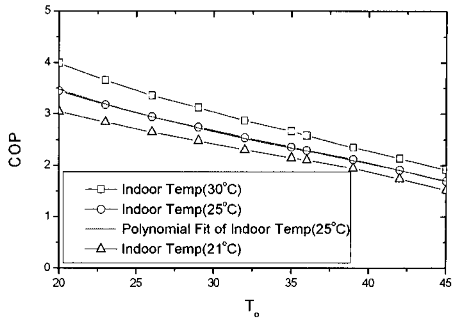


Fig. 2. COP of the air conditioner.

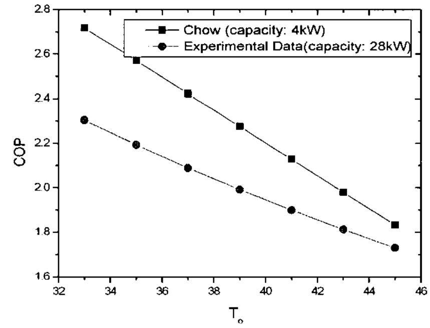


Fig. 3. COP differences of air conditioner.

In order to have a comprehensive evaluation of AC systems, Chow et al.(4-6) presented a new energy performance index, CGPI. The index allows the comparison of system performance on the base of computer simulation results. This study extended the concept and proposed three new indices that can be used to evaluate the systematic performance of group condensers. These indices are: GCPR, GCCR and GCER, which are, respectively, defined as (4)~(6).

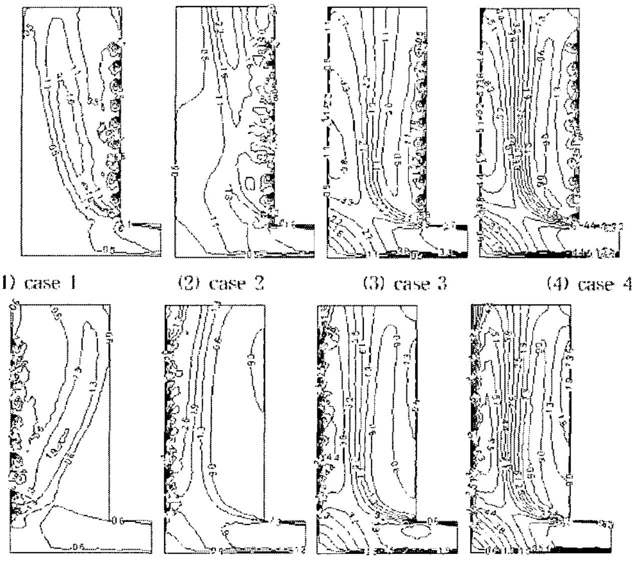
GCPR is an important index for evaluating the system efficiency of N condensing units operating together as a group. The index represents the ratio of the actual COP value of a group of condensers (e.g., at the same floor) to the COP at design conditions (or ideal conditions). When the index approaches 100%, the actual system performance approaches the designed performance. In this study, the outdoor and indoor design temperatures are, respectively, 33℃ and 25℃.

GCCR evaluates the cooling capacity of the group condensers by comparing the system performance under actual operating conditions to that under design conditions. On the same token, GCER quantifies the performance of electricity consumption of the group condensers. GCER usually will be less than 100%. GCER has to influence for properly sizing the overall capacity of electric facilities during the building design stage.

3. Results of CFD analysis

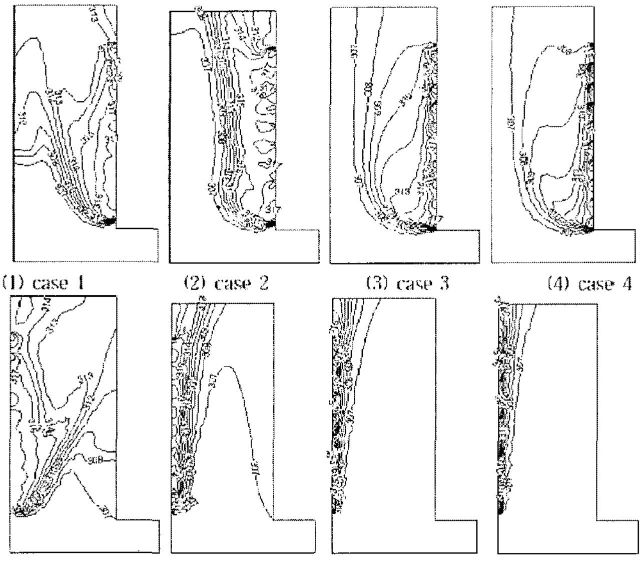
Fig. 4 presents the predicted velocity distribution contours at the middle vertical plane of the courtyard across the condenser array. In the cases of 1, 2, 5 and 6 with inlet air velocity of 1.1~2.2 m/s, the airflow pattern inside the courtyard is dependent on the locations of condensing units since the exhaust hot air from the condensing units have a significant impact on the uprising flows. However, in the cases of 3, 4, 7 and 8 with strong inlet air velocity of 4.4~6.6 m/s, the buoyancy effect is less significant compared to the strong forced convection from the inlet tunnel. The incoming fresh air from the ground-floor entrance causes a large vortex after it reaches the rear wall.

Fig. 5 shows the temperature contours on the same


(1) case 1 (2) case 2 (3) case 3 (4) case 4

(5) case 5 (6) case 6 (7) case 7 (8) case 8

Fig. 4. Predicted velocity contours at x=9 m (center plane) (all velocities are given in m/s).


(1) case 1 (2) case 2 (3) case 3 (4) case 4

(5) case 5 (6) case 6 (7) case 7 (8) case 8

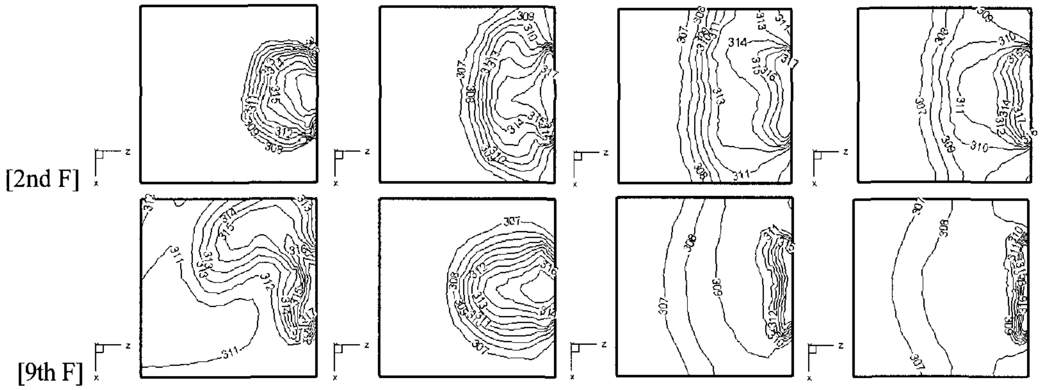
Fig. 5. Predicted temperature contours at x=9 m (center plane) (all temperatures are given in K).

plane. For all the cases, a hot air region is observed around the outdoor units, implying the effective exchange of heat between the condensers and environment. In the cases of 5~8 with condensing units installed at the rear façade, when increasing the inlet velocity, a thinner hot air plume layer arises near the rear facade. In the case of 1~4 with condensing units installed at the front façade, the exhaust air arises only with small wind speeds (1.1 and 2.2 m/s). For high wind speeds, the exhaust hot air is trapped in the condenser locations due to the strong air circulation. Fig. 8 presents the predicted average condenser on-coil temperatures at different floors. The results show that the temperature dramatically increases from the second floor but keeps fairly flat afterwards.

Fig. 6 further exhibits the predicted temperature contours on the 2nd floor and 9th floor at a horizontal plane across the condensing units. Fig. 7 shows the predicted velocity distributions on the same floors. Fig. 6 and 7 reveal that the air can flow through the entire courtyard channel for Cases 1, 2, 5 and 6, while there are some restricted areas in Cases 3, 4, 7 and 8. For the cases with the rear side unit installation, the near-surface air temperatures along the vertical direction linearly increases with the floor height due to the combined buoyancy and wind effect, which help improve the system performance. However, for the cases with front side unit installation, it is difficult to estimate the influence of air inlet velocity on the condensing unit performance. Fig. 8 indicates that the average condenser on-coil temperature is higher for the upper floors than that for the lower floors.

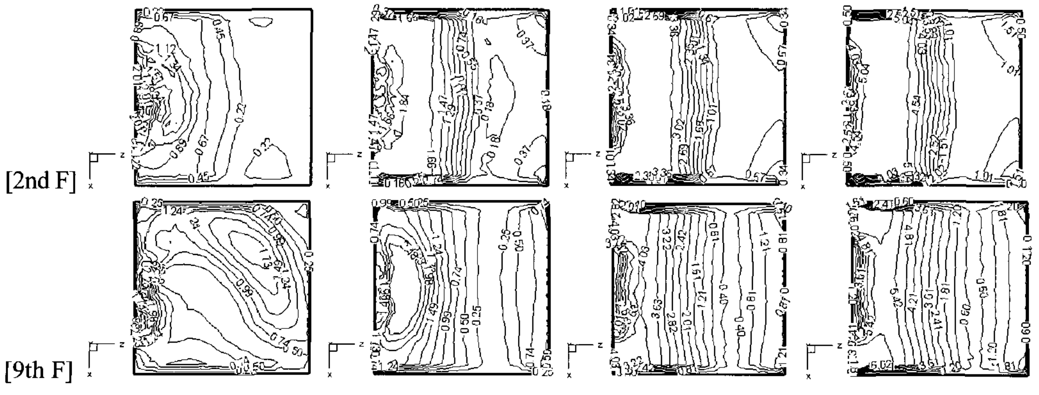
4. Results of energy evaluation

Figs. 9, 10 and 11 present the energy performance of the air conditioning units by using the new performance indices. For GCCR in Figs. 9, the cooling



case 1 case 2 case 3 case 4

Fig. 6. Predicted temperature contours at the planes of different floors (all temperatures are given in K).



case 5 case 6 case 7 case 8

Fig. 7. Predicted velocity contours at the planes of different floors (all velocities are given in m/s).

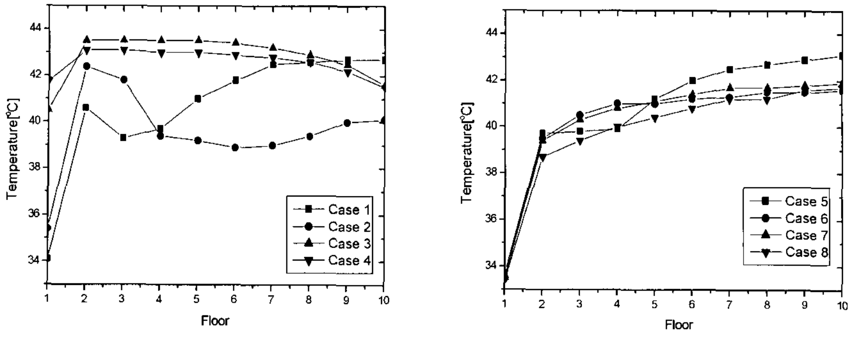


Fig. 8. Predicted average on coil temperature of condensers at different floors.

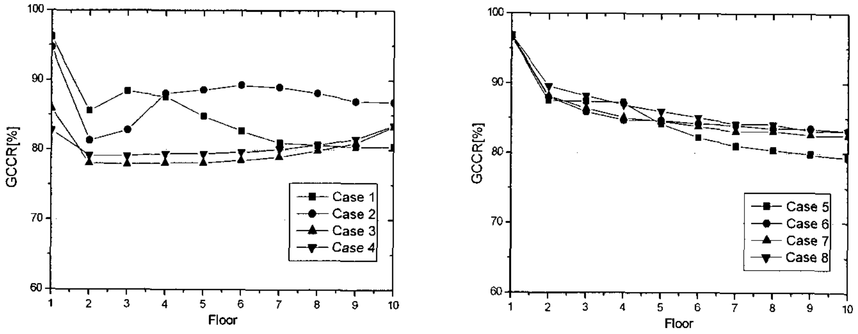


Fig. 9. GCCR at different floors.

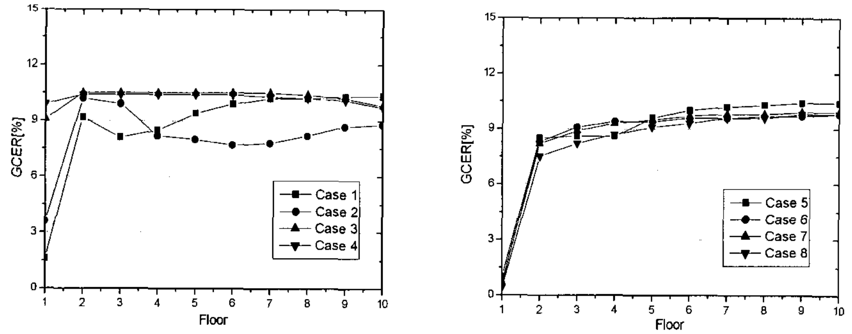


Fig. 10. GCER at different floors.

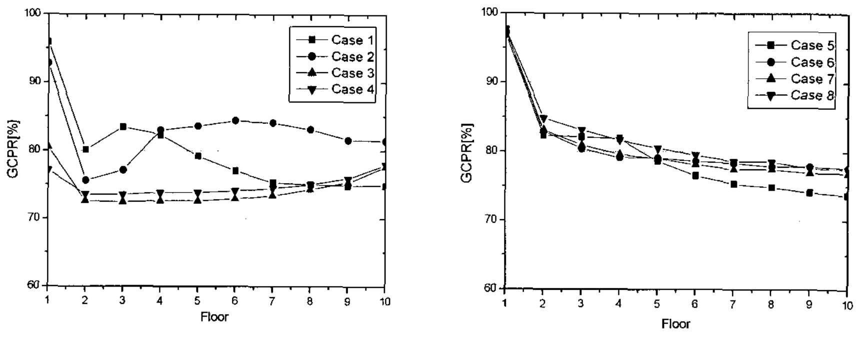


Fig. 11. GCPR at different floors.

capacity is reduced by 10~22% compared to the design condition. The performance of an air conditioner is evaluated not only by the cooling capacity of its condensing unit but also its total energy consumption.

Fig. 10 shows that the electricity consumption increases for the second floor and above in CASES 5~8 due to the observed rising thermal plume. The electricity consumption increasing rate for CASE 2 is relatively lower than those for the other cases. This implies that a critical air circulating condition may exist between low and high wind velocity. Case 2 exhibits the best performance than the other cases. GCER is a convenient index that can be used for factoring the electric facility scale. The results indicate that the designed electric facility capacity of the building should be increased by 10~12% to accommodate the need with actual operating conditions.

Fig. 11 shows the GCPR calculated based on the standard indoor temperature of 25℃ and the variant condenser on-coil temperatures. According to Fig. 10, it is obvious that the installations at the front side have a disadvantage of more operating cost. For most rear side installation cases as well as the front side installation cases with high air velocity, the system performance is degraded. The condensers at the front side show an abnormal change of efficiency in that the efficiency of condensers at lower floors is less than that at upper floors. This may be attributed to the air circulation caused by wind effect. The efficiency of condensers at the rear side is linearly decreased from the second floor to the upper floors, and the performance is improved somehow as the inlet velocity increases.

5. Conclusions

This study investigated the group performance of air-cooled split-type air conditioners installed at the external facades of a hotel building. The study introduced three new indices that can help evaluate the comprehensive performance of a group of air conditioning systems on the base of CFD predictions of the thermal characteristics around the condensing units.

The research reveals that AC condensing units located at restricted spaces within sufficient air circulation will decrease the overall system performance, including cooling efficiency, capacity and total energy consumption. In the particular case studied, for the condensing units installed at the rear facade opposite to the wind inlet, the efficiency of air conditioning units deceases with the floor story increases and the wind effect may slightly help improve the system performance. For the condensing units installed at the front facade and with large wind effect, the system performance largely reduces due to the hot air trapped at the upper floors. For sustainable air-conditioning operations, the placement of condensing units should avoid the low COP areas. This study presents a practical evaluation method that can help HVAC engineers and designers to evaluate and optimize the design.

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