Study on the Design and Operation of an Outdoor Air-Cooling System for a Computer Room

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Abstract: Due to the recent growth of the Internet and the rapid development of information and communications technology, the number of data centers and the amount of power consumed are expected to increase rapidly. However, these data centers consume large amounts of electric power throughout the year, regardless of working days or holidays; hence, measures to save energy at these facilities are urgently required. A numerical analysis was conducted in this study by changing various variables to examine the effects of various design and operating conditions on outdoor air-cooling systems and to derive some operating plans to minimize electric power consumption through the introduction of outside air into the computer room. When designing the system, it is desirable to select airflow considering various factors, such as the heat generated by the computer equipment, the efficiency of the fan, and the performance of the refrigerator, rather than the theoretical maximum outdoor airflow. As a result, the optimal design air volume was calculated according to the equipment load. Consequently, the optimal design air volume of the modeled computer system was obtained as 26,200 m$^3$/h. The application of this optimal design air volume is expected to yield an annual energy-saving effect of 56.1% compared with the power consumption in the air-conditioning period during which the application of outdoor air cooling is impossible.

Keywords: computer room; outdoor air cooling; design and operation; airflow ratio; energy saving; field application

1. Introduction

There are a total of 158 data centers in Korea, and the domestic data center market is expected to grow rapidly over the next five years, from 2019. There will be 32 additional data centers planned to be built by 2025 [1]. Apart from large commercial data centers, several public- and private-sector small- and medium-sized buildings have their own computer rooms. Considering the huge amount of electricity consumed by computer rooms when operating air conditioning throughout the year to maintain a constant and secure environment for information and communications technology (ICT) equipment, measures to save energy are urgently required. In a space with a high cooling energy demand, such as a computer room, a significant amount of energy may be saved by installing an outdoor air-cooling system in conjunction with a thermo-hygrostat that can cool the indoor space by introducing a relatively low outdoor air temperature.

As an instance of a data center that uses an outdoor air-cooling system, LG CNS’s Busan Global Cloud Data Center obtained the highest rating in Green Data Center Certification with the lowest power usage effectiveness (PUE) (1.39) [2]. PUE is the ratio of the total amount of energy used by a data center to the energy consumed by ICT equipment. Similarly, after installing an outdoor air-cooling system, Chuncheon Naver Data Center operated an air cooler for fewer than 30 days a year [3]. In countries located in geographically cold regions, several data centers actively use outdoor air-cooling systems,
with their PUE maintained below 1.25 (Google, Hamina, Finland) [4] through a control operation configured to maximize the use of outdoor air or even below 1.2 (Facebook, Dublin, Ireland) [4] by relying completely on the outdoor air-cooling system.

We analyze various research cases that achieved energy savings by applying an outdoor cooling system to the data center [5–20]. Among them, we provide an overview of the major studies conducted thus far. Soe et al. [21] performed an energy simulation and reported that an energy saving of 49% was achieved by employing an outdoor air conditioning system. Jeong et al. [22] performed energy simulations to compare the energy-saving performances of various methods and identified that the enthalpy control technique had the highest energy saving rate of 54.5% compared with the reference value. In addition, 10 data centers in Iran with various weather conditions analyzed the effectiveness of the application of a outdoor cooling system and found that the PUE index improved from 10% to 12% [23]. From the design perspective, the simulation of the energy saving effect of outdoor cooling due to changes in supply air temperature and design volume of an outdoor air-cooling system was evaluated. As a result, at the same supply-air temperature, the energy consumption was reduced as the design volume [24].

These studies focused on the prediction or analysis of the energy-saving effect expected or achieved by installing an outdoor cooling system in computer rooms. None of these studies, even those investigating actual installation cases, verified the energy-saving effect resulting from the use of an outdoor air-cooling system; consequently, they did not explore effective designs and operation methods of outdoor air-cooling systems.

Accordingly, we examined and analyzed the effects of relevant parameters on the energy consumption of cooling devices by installing an outdoor air-cooling system in a computer room. We also performed numerical analysis by varying the design and operating parameters to identify the operating strategies to minimize the power consumption of computer rooms by introducing outdoor air into the room. Additionally, by extending the results of a previous study that verified the energy-saving effect through field application of an outdoor air-cooling system to a computer room operated by a research complex in Korea [25], we verified through simulations, with the physical change in the facility system hardly attainable, the effect of an outdoor air-cooling system in conjunction with the design strategy of the cooling system.

2. Analysis Models and Methods

2.1. Analysis Model

2.1.1. Cooling Load Model

We selected a computer room building located in the northern part of Gyeonggi for analysis and established the analysis model as illustrated in Figure 1 to calculate the heat load of the computer room based on the following assumptions:

1. Heat exchange occurs only through the wall and window in contact with the outdoor air, excluding all other parts.
2. Heat transmission occurs one-dimensionally.
3. The indoor temperature and humidity are maintained at the values set by the thermo-hygrostat throughout the year.
4. The heat release rate of the ICT equipment is a constant given value throughout the year.
5. The indoor heat release is included in the heat release of the ICT equipment because the former is negligible compared with the latter.

The heat load in this analysis model, considering the given climate conditions and the heat release of the ICT equipment, can be calculated using Equation (1).

\[ q = q_{\text{equip}} \pm q_{\text{th}} \pm q_{\text{inf}} + q_{\text{sol}} \]  

where \( q_{\text{equip}} \), \( q_{\text{th}} \), \( q_{\text{inf}} \), and \( q_{\text{sol}} \) are the sensible heat load elements affecting the indoor temperature, denoting the heat load released from the ICT equipment; the transmission
load determined by the outdoor air and building structure; the outdoor air infiltration load; and the solar load, respectively. The heat load released from the ICT equipment is assumed to be given, whereas the transmission and infiltration loads are calculated using Equations (2) and (3), respectively. Equation (2) is calculated as the difference between the heat transmission coefficient, the area, and the indoor and outdoor temperature, which is the resistance to heat transmission value calculated using the wall thickness and thermal conductance of the material, and the indoor and outdoor surface heat transfer coefficient. Equations (3) and (4) are calculated as the difference in volume, number of ventilating systems, and indoor and outdoor temperatures or humidity of the space. Equation (5), which can be used to calculate the solar load, consists of the insulation for each orientation and SHGC (solar heat gain coefficient). The latent heat load of the infiltration load obtained by converting the moisture content affecting indoor humidity into heat is expressed by Equation (5).

\[ q_{th} = K \times A \times (24 - T_o) \tag{2} \]
\[ q_{SH_{inf}} = 0.29 \times N \times V \times (24 - T_o) \tag{3} \]
\[ q_{LH_{inf}} = N \times V \times 597 \times (0.0093 - \phi_o) \tag{4} \]
\[ q_{sol} = q_{sol} \times \text{SHGC} \tag{5} \]

**Figure 1.** Analysis model for the computer room.

2.1.2. Fan Model

The heat load \( \dot{q} \) mentioned above should be removed by the thermo-hygrostat or outdoor air-cooling system. The capacity of the fan installed to perform outdoor air cooling, i.e., the airflow ratio \( \dot{Q} \), can be calculated using Equation (6).

\[ \dot{Q} = \frac{\dot{q}}{C \times \Delta t} \tag{6} \]

where \( C \) denotes the specific heat of air and \( \Delta T \) denotes the temperature difference between the outdoor air and indoor air. \( P_f \) and \( P_R \), which denote the power consumptions of the fan and thermo-hygrostat, respectively, are used to eliminate the heat load and can be calculated using Equations (7) and (8), respectively.

\[ P_f = \frac{\dot{Q} \times P_a}{102 \times 3600 \times \eta} \tag{7} \]
\[ P_R = \frac{\dot{q}}{\text{COP} \times 864} \tag{8} \]

2.2. Analysis Methods

We prepared an analysis tool to calculate the heat load and to perform numerical experiments for the analysis model, and we performed the annual cooling and heating load calculations at regular intervals. Table 1 outlines the physical properties applied to the
numerical experiments other than the parameter set for analysis. The total floor area of the building was 156.48 m², the ceiling height was 2.97 m, and the number of server racks was 32. The heat released by the operation of the ICT equipment was 22,560 W. The values of the parameters employed in the analysis were as follows: the heat transmission rate of the outer walls of the building = 0.64 W/m²·K, the heat transmission rate of the double-layered glass = 4.1 W/m²·K, and the heat transmission rate of the floor = 0.61 W/m²·K. Each heat transmission rate is referenced in the design drawings. The air infiltration rate (relative to the reference infiltration air per unit area) = 276 m³/h. The solar load was calculated by obtaining the insolation for each orientation and by applying the Sing class clear 6T solar heat gain coefficient of 0.67.

Table 1. Analysis model condition.

| Site modeling | Site: Koyang, Gyeonggi |
|---------------|-------------------------|
| Site modeling | Floor area: 156.48 m²   |
| Site modeling | Height: 2.97 m          |
| Site modeling | Heat transmission rate of the wall: 0.64 W/m²·K |
| Site modeling | Heat transmission rate of the window: 4.1 W/m²·K |
| Site modeling | Heat transmission rate of the floor: 0.61 W/m²·K |
| Site modeling | Infiltration: 276 m³/h  |
| Site modeling | SHGC (solar heat gain): 0.67 |

| Servers | Number of racks: 32 (600 × 1000 × 2000) |
|---------|-------------------------------------|
| Servers | Heat release rate from the servers: 22,560 W (Estimated) |

Figure 2 shows a schematic diagram of the modeled computer room. It was cooled though the air supply/exhaust duct installed in the high-temperature area and bottom discharge. To improve the total-air recirculation cooling method using a general thermo-hygrostat, the air supply and exhaust, and outdoor air damper were modeled, which was integrated into the modeling of an outdoor air-cooling system capable of controlling the air inlet rate. As cooling through an air inlet is impossible when the outdoor air temperature exceeds a certain threshold, the cooling operation was modeled according to the total-air recirculation method, in which the outdoor air was blocked and cooling was performed only with a thermo-hygrostat. Similarly, when the outdoor temperature fell below a certain degree relative to the indoor set temperature, the cooling system was stopped and cooling continued only with outdoor air. A mixed operation method was also modeled, in which the cold outdoor air in winter was mixed with the air recovered from indoor spaces to achieve the desired air temperature for supply.

Figure 2. Schematic diagram of the outdoor air-cooling system.

Table 2 lists the values obtained from the modeling of the outdoor air-cooling system and the capacity of the thermo-hygrostat. The cost and space for air supply could be
reduced by using both the thermo-hygrostat and the air supply fan. The total air volumes of the air supply fan and the exhaust fan were 20,000 m$^3$/h each, and a constant air volume was supplied to the air supply fan and a variable air volume was supplied to the exhaust fan.

**Table 2.** Capacity model of the outdoor air-cooling system and thermo-hygrostat.

| Equipment                         | Air Volume (m$^3$/h) | Electricity Consumption (kW) |
|----------------------------------|----------------------|------------------------------|
| SA Fan                           | 10,000 $\times$ 1 EA | 3.2 $\times$ 2 EA           |
| Thermo-hygrostat Compressor     | -                    | 7.2 $\times$ 4 EA           |
| Outdoor air cooling EA Fan, Inverter | 20,000 $\times$ 1 EA | 4.7 $\times$ 1 EA          |

Based on the indoor temperature and relative humidity of a computer room as recommended by the American Society of Heating, Refrigeration, and Air Conditioning (ASHRAE) in the flexible range of 18–27 °C and 20–80%, we set the indoor temperature and relative humidity at 24 °C and 60%, respectively. Figure 3 illustrates the fan model used for the calculation.

![Figure 3. Fan model used for the calculation (normalized).](image)

The decision to use the outdoor air-cooling system considered in this study depended on the indoor setting conditions, outdoor air condition, and the heat release level of the ICT equipment as well as on the capacity and performance of the fan and thermo-hygrostat. Among them, the outdoor air condition was the most decisive factor. That is, the application of the outdoor air-cooling system was greatly influenced by the outdoor air condition. In fact, while it can be used when the outdoor air temperature is significantly lower than the indoor temperature, its application is impossible when the outdoor air temperature exceeds a certain threshold and a thermo-hygrostat should be operated. Even when outdoor air cooling is applied under the same indoor set temperature and humidity conditions, the air volume and power consumption of the fan vary depending on the outdoor air condition.

We selected the climate model for Incheon, located close to the study site, to consider the outdoor air condition, a determinant factor for the application of outdoor air cooling. Figure 4 plots the daily averaged outdoor air temperature using the 2019 data for Incheon provided by the Korea Meteorological Administration. We selected three daily outdoor temperature patterns considered representative of the season, i.e., when the daily averaged outdoor air temperature is the highest (summer, S), lowest (winter, W), and middle (mid-season, M), as listed in Table 3. Table 4 lists the design and operating parameters for the outdoor air-cooling system of the computer room used for the numerical analysis.
Figure 4. Annual daily averaged outdoor air temperature.

Table 3. Averaged outdoor air temperature for representative days.

| Types of Weather Conditions | Averaged Temperature (°C) |
|-----------------------------|----------------------------|
| S (summer)                  | 32.6                       |
| M (middle season)           | 11.9                       |
| W (winter)                  | −11.7                      |

Table 4. Design and operating parameters.

| Design Parameters | Operating Parameters |
|-------------------|----------------------|
| Outdoor Air-Cooling Air Volume (m³/h) | Equipment Heat Load (kW) | Indoor Temperature (°C) |
| 20,000            | 20                   | 15                         |
| 30,000            | 30                   | 17                         |
| 40,000            | 40                   | 19                         |
| 50,000            | 50                   | 21                         |
| 60,000            | 60                   | 23                         |
| 70,000            | 70                   | 26                         |
| 80,000            | 80                   | 28                         |
| 90,000            | 90                   | 100                        |
|                   |                      | 110                        |

Using the analysis model and tools developed in the previous section, we performed numerical analysis to analyze the outdoor air-cooling system application plan and its effect according to the design and operating parameters of the computer room. For numerical analysis, the heat load was first calculated by considering the climatic conditions given at regular intervals, the specifications of the building, and the heat load of the ICT equipment. Then, after choosing the mode of cooling between outdoor air cooling using the cool inlet air and apparatus cooling using the thermo-hygrostat, and by considering the indoor and outdoor conditions in the calculation time slot, design parameters (fan air volume and the heat load released from the equipment), and operating parameters (indoor temperature) with regard to the specified fan and thermo-hygrostat capacities, we calculated the fan air volume, the heat removed by outdoor air cooling, the power consumption of the fan, and the power consumption of the thermo-hygrostat for both cooling modes. In the case of outdoor air cooling using a fan, the air volume of the fan was variably controlled.
according to the heat load and outdoor air temperature, and the calculation was repeated, incrementing the time interval.

When the calculation results showed variations in the cooling load and rated air volume depending on the outdoor air temperature, we checked the air volume necessary for outdoor air cooling and analyzed the air volume of the fan required for cooling and the heat load removed by the fan according to the seasonal change of the representative days. In addition, the annual power consumption and removed heat load were compared and checked while varying the parameters. Based on the calculation results, we derived the design air volume according to the heat load released from the ICT equipment in the computer room studied and analyzed the effect of the indoor set temperature, which is an operating parameter. Finally, we predicted the annual energy-saving rates for the cases using the conventional cooling system and the thermo-hygrostat and applying the design air volumes and design air volume.

3. Results and Discussion

3.1. Verification of the Calculation Results

We compared the cooling load obtained from the analysis with the corresponding result of the experiment performed in the actual computer room modeled to verify the validity of the results obtained through the theoretical analysis. To obtain the experimental results, we performed outdoor air cooling using a fan in winter when air conditioning was not used. Thus, the cooling load was calculated using the fan air volume per hour and the temperatures of the inlet and outlet air.

Figure 5 and Table 5 present the results of the comparison between the theoretical and experimental results in time series. Among the Measurement and Verification calculation methods, we used the root mean square error (RMSE) method to calculate the error between the simulation and measurement values shown in Equation (9) to verify the error rate. The error between the theoretical and experimental results was 0.19%, which indicated that the results of the theoretical analysis may be used in this study.

\[
\text{Mean error of the predicted value} = \sqrt{\frac{\sum (P_1 - P_2)^2}{n-p-1}}
\]

\[
= \sqrt{\frac{(3.77)^2}{12-1-1}} = 0.19
\]

Figure 5. Predicted result of the daily cooling load compared with the measured one for a typical day.
Table 5. Comparison between the predicted and measured cooling loads.

| Time (h) | Outdoor Air Temperature (°C) | Cooling Load (kWh) | (Y₁ - Y₂)² |
|----------|-----------------------------|-------------------|------------|
|          |                             | Y₁-Predicted      | Y₂-Measured|            |
| 0:00     | 2.5                         | 16.0              | 15.2       | 0.64       |
| 2:00     | 1.8                         | 15.7              | 15.4       | 0.09       |
| 4:00     | 1.5                         | 15.5              | 14.9       | 0.36       |
| 6:00     | 0.3                         | 15.0              | 14.7       | 0.09       |
| 8:00     | 0.7                         | 16.0              | 15.8       | 0.04       |
| 10:00    | 5.1                         | 19.6              | 19.2       | 0.16       |
| 12:00    | 7.5                         | 20.7              | 20.2       | 0.25       |
| 14:00    | 9                           | 21.1              | 20.2       | 0.81       |
| 16:00    | 8.6                         | 19.6              | 19.4       | 0.04       |
| 18:00    | 6.1                         | 17.5              | 16.7       | 0.64       |
| 20:00    | 2.1                         | 15.8              | 15.2       | 0.36       |
| 22:00    | 0.4                         | 15.1              | 14.9       | 0.04       |
| 24:00    | -0.1                        | 14.9              | 14.4       | 0.25       |
| Total    |                             |                   |            | 3.77       |

3.2. Changing Characteristics of Cooling Load

First, Figure 6 shows the cooling load of the ICT equipment and outside air for one year and the combined total load of the two according to the daily average outside air temperature in the area where the computer room is located. As the cooling load is directly affected by the state of the outside air, it has a large positive value when the outdoor air temperature is high, whereas it may have a negative value when the outdoor air temperature is low. This generally indicates that heating, not cooling, is needed at this time. On the other hand, the cooling load of the ICT equipment is constant throughout the year regardless of the condition of the outside air. Depending on the operating conditions of the ICT equipment, the power consumption or the amount of heat generated may vary and the cooling load may vary accordingly. Finally, the sum of these two cooling loads is the total cooling load, and as the load of the ICT equipment has a constant value, the total load is shifted upward by the amount of the external air load plus the load of the ICT equipment.

![Figure 6](image-url) Variations of several related loads with the daily averaged outdoor air temperature.

Figure 7 plots the fan air volume for outdoor air cooling applied to maintain the space temperature at the set value of 24 °C. The graph shows that only a small amount of air is necessary to remove the heat load released from the ICT equipment in the winter months. This is because the load caused by the outside air is negative or has little effect owing to the low outdoor air temperature. In contrast, as the air temperature gradually rises toward...
the middle period, the air volume increases as the cooling load increases. Except for some transient periods during which the outdoor air temperature is relatively low, outdoor air cooling is no longer possible and cooling must be performed by the thermo-hygrostat installed additionally for hot seasons.

Figure 7. Annual variation of outdoor air volume with fan used for cooling.

Based on the above results, the air volume required to remove the heat generated indoors including the heat released from the ICT equipment can be plotted according to the variations in outdoor air temperature, as shown in Figure 8. As the outdoor air temperature increases, a general tendency of increasing fan air volume is observed, tending toward an exponential increase with a further increase in the outdoor air temperature. That is, while the heat released from the ICT equipment can be removed even with a relatively small air volume in areas with low outdoor air temperature, the fan air volume required for offsetting the heat load increases drastically. Outdoor air cooling is possible only up to the rated capacity of the fan (20,000 m³/h) and an outdoor air temperature of 20.4 °C, as applied to the analysis model.

Figure 8. Variation in design air volume used for outdoor air cooling according to outdoor air temperature.

In other words, when an outdoor air-cooling system is installed in a computer room, the period of outdoor air cooling can be extended by increasing the fan air volume; however, excessive use of the fan sharply increases the power consumption, offsetting the cost-saving effect compared with air conditioning. Therefore, instead of choosing the maximum air
volume to perform outdoor air cooling as long as possible, an optimal air volume should be selected by considering the heat released from the ICT equipment, the rated capacity of the fan, and the performance of the thermo-hygrostat.

Figure 9 plots the fan air volume required for cooling and the heat removed by the fan when the indoor set temperature is maintained at 24 °C for the three models indicated in Table 3, viz. for the three days representative of winter (W), summer (S), and midseason (M). In Model S, outdoor air cooling was impossible because the outdoor air temperature was higher than the indoor temperature, whereas in Model M, outdoor air cooling was observed to be possible except for two hours (15:00–17:00) when the outdoor air temperature was higher than the indoor temperature. This suggests that the air volume required for cooling tends to change in proportion to the outdoor air temperature and that outdoor air cooling is impossible when the rated capacity of the fan is exceeded or when the outdoor air temperature is higher than the indoor set temperature. In the case of Model W, outdoor air cooling could be performed throughout the day owing to the low outdoor air temperature. This is because the lower the outdoor air temperature, the higher the cost-saving effect because indoor heat can be removed with smaller air volume.

The daily variations in heat removed by the fan show a general tendency similar to the variations in the air volume. Model S, which did not perform outdoor air cooling, did not incur any power consumption. In Models W and M, 100% and 90% of indoor heat, respectively, were removed by outdoor air cooling. Thus, the performance characteristic of the fan is reflected in the correlation between the air volume used for cooling and the power consumption.

3.3. Effects of Design Parameters

The design parameters to be considered when installing an optimal outdoor air-cooling system in a computer room are the equipment capacity and load, the capacity of the fan for outdoor air inlet, the capacity and performance of the thermo-hygrostat, and the insulation level of the building. We performed a range of numerical experiments using the analysis model to identify the capacity of the fan capable of performing the required cooling while consuming the least amount of energy by performing outdoor air cooling according to the heat release level of the ICT equipment.

Figure 10 plots the variations in the power consumption of the fan and the cooling load removed by the outdoor air depending on the design air volume of the fan with respect to the equipment capacity, i.e., the equipment load, to investigate the effect of the design air volume on the operating characteristics of the outdoor air-cooling system. As expected, the equipment capacity was positively related to the annual power consumption and the cooling load removed by the outdoor air. In addition, for any ICT equipment
capacity, an increase in the design air volume was associated with a decrease in the annual power consumption, followed by an inverse trend of increasing again. This suggests that, under the given circumstances, including the ICT equipment capacity or heat release rate, there is an optimal fan capacity for the most efficient execution of outdoor air cooling. It was also observed that, as the ICT equipment capacity or heat release rate increases, the optimal design air volume tends to increase as well.

Figure 10. Variations in the annual electricity consumption with the design air volume by equipment load.

Based on these results, Figure 11 plots the design air volumes when the annual power consumption reaches the minimum value with respect to the capacity and load of the ICT equipment, i.e., when the highest cost-saving effect is achieved. Table 6 lists the annual power consumption corresponding to each optimal design air volume. As the load of the ICT equipment increases, the power consumption and design air volume tend to increase. Notably, however, the design air volume increases more rapidly when the capacity of the ICT equipment is smaller but decreases after the capacity reaches a certain level.

Figure 11. Design outdoor air volume and electricity consumption according to the equipment load.
Table 6. Electricity consumption according to the design outdoor air volume by equipment load.

| Equipment Load (kW) | Design Outdoor Air Volume (m³/h) | Electricity Consumption (MWh) |
|---------------------|----------------------------------|------------------------------|
| 20                  | 25,000                           | 115                          |
| 30                  | 30,000                           | 122                          |
| 40                  | 35,000                           | 129                          |
| 50                  | 42,000                           | 135                          |
| 60                  | 50,000                           | 141                          |
| 70                  | 60,000                           | 145                          |
| 80                  | 69,000                           | 149                          |
| 90                  | 75,000                           | 153                          |
| 100                 | 79,000                           | 157                          |
| 110                 | 80,000                           | 158                          |

3.4. Effects of Operating Parameters

Once the outdoor air-cooling system is installed, the indoor temperature and the design outdoor air temperature switching to outdoor air cooling are considered crucial operating parameters. It is necessary to select an outdoor air temperature capable of outdoor air cooling at the indoor set temperature. Particular care should be given to the selection of outdoor air, especially because it is closely associated with the capacity of the fan that executes outdoor air cooling.

Figure 12 plots the variations in annual power consumption for outdoor air cooling according to the indoor set temperature. A linear inverse correlation is observed between the indoor set temperature and the power consumption. Our analysis revealed that each increase of 1 °C in the indoor set temperature results in a power-saving effect amounting to 441 kWh per year, which is tantamount to 0.4% less power consumed every year.

![Figure 12. Variation in the annual electricity consumption with the indoor set temperature.](image)

Figure 13 plots the variations in the limit in outdoor air temperature allowed for outdoor air cooling according to the design fan capacity with respect to the capacity of the ICT equipment, i.e., equipment load. The graphs show that the outdoor air temperature allowing outdoor air cooling increases with the increase in design fan air volume but that the increase rate decreases asymptotically. Moreover, in areas with lower design air volume, the difference caused by the difference in equipment load is larger, but the difference decreases with an increase in the design air volume. This result can be used
when setting the outdoor air-cooling switching time (outdoor air temperature value) for efficient operation of the selected system.

![Figure 13. Outdoor air-cooling temperature according to the design outdoor air volume by equipment load.](image)

3.5. Outdoor Air-Cooling Operation Time

As examined above, the most determinant factor for the outdoor air-cooling system is the outdoor air condition, which also determines the time periods of the day during which the operation of the outdoor air-cooling system is allowed. For example, the system can be operated throughout the day in winter and cannot be operated during the summer months.

Figure 14 shows the results of the analysis of the time periods of the day during which outdoor air cooling is allowed depending on the annual daily average outdoor air temperature under the given circumstances, as described in the previous section. As the daily average outdoor air temperature becomes lower, the period of outdoor air cooling becomes longer. In one of the experimental models of this study, it was estimated that outdoor air cooling was possible in an area with the daily average outdoor air temperature at 11 °C or lower; however, in an area with the temperature at 20.4 °C or higher, outdoor air cooling was not possible. In the temperature range of 11–19.9 °C, outdoor air temperature and outdoor air-cooling time displayed an inversely proportional relationship.

![Figure 14. Outdoor air-cooling operating time according to the average outdoor air temperature.](image)

3.6. Analysis of the Effects of Outdoor Air Cooling

The equipment load of the modeled computer room was 22,560 W, and the design air volume of the outdoor air-cooling system was 20,000 m³/h. The optimal design air
volume with respect to the equipment load, which was estimated in the previous section, was observed to be 26,200 m$^3$/h. Figure 15, Table 7 presents the results of the monthly comparison of power consumption and cost-saving ratio among three outdoor air-cooling application models: (i) pre-application (conventional), (ii) post-application (design air volume), and (iii) optimized application (optimal design air volume). The applications of the design air volume (20,000 m$^3$/h) and optimal design air volume (26,200 m$^3$/h) yielded the annual cost-saving ratios of 55.1% and 56.1%, respectively, relative to the power consumption in the air-conditioning period during which the application of outdoor air cooling is impossible.

![Figure 15](image_url)

**Figure 15.** Comparison of the monthly electricity consumption and saving ratio by cooling method.

| Month | Conventional (kWh) | Outdoor Air-Cooling System (kWh) | Saving Ratio (%) | Optimal Design Air Volume Applied (kWh) | Saving Ratio (%) |
|-------|--------------------|---------------------------------|------------------|----------------------------------------|------------------|
| 1     | 21,193             | 5240                            | 75.3             | 5639                                   | 73.4             |
| 2     | 19,254             | 4718                            | 75.5             | 5067                                   | 73.7             |
| 3     | 21,828             | 5180                            | 76.3             | 5535                                   | 74.6             |
| 4     | 22,030             | 5264                            | 75.7             | 5447                                   | 75.3             |
| 5     | 23,281             | 7144                            | 69.3             | 6772                                   | 70.9             |
| 6     | 22,847             | 14,699                          | 35.7             | 13,339                                 | 41.6             |
| 7     | 23,783             | 21,509                          | 9.6              | 20,446                                 | 14.0             |
| 8     | 23,857             | 23,749                          | 0.5              | 23,030                                 | 3.5              |
| 9     | 22,859             | 15,995                          | 30.0             | 14,871                                 | 34.9             |
| 10    | 23,136             | 6321                            | 72.7             | 6164                                   | 73.4             |
| 11    | 21,591             | 5012                            | 76.8             | 5326                                   | 75.3             |
| 12    | 21,515             | 5213                            | 75.8             | 5592                                   | 74.0             |
| Total | 267,174            | 120,044                         | 55.1             | 117,228                                | 56.1             |

Table 7 outlines the results of the analysis of the time periods during which the application of outdoor air cooling was allowed under the conditions of design air volume and optimal design air volume. The total durations of application of outdoor air cooling were estimated to be 5545 h and 6739 h, respectively, out of 8760 h for the design air volume (20,000 m$^3$/h) and optimal design air volume (26,200 m$^3$/h).
Table 8. Expected monthly operation time of the outdoor air-cooling system.

| Month | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | Total |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|-------|
| Outdoor air-cooling system operating time (h) | 743 | 672 | 744 | 676 | 492 | 82 | 0  | 0  | 95 | 576 | 720 | 745 | 5545 |
| Optimal design air volume applied operating time (h) | 743 | 672 | 744 | 716 | 704 | 422 | 155 | 42 | 351 | 725 | 720 | 745 | 6739 |

4. Conclusions

We examined the effects of various factors on the energy consumption of cooling equipment in the context of installing an outdoor air-cooling system in a computer room. We also performed numerical analysis by considering various design and operating parameters to identify the optimal operational strategy to minimize power consumption in computer rooms by integrating an outdoor air-cooling system into an existing HVAC system. The analysis results can be summarized as follows:

1. A computer room has high cooling load throughout the year because of high equipment load. When an air volume of 20,000 m$^3$/h was applied, which is the rated capacity of the fan used for the analysis model of outdoor air cooling, outdoor air cooling could be allowed only up to the outdoor air temperature limit of 20.4 °C. An analysis of the fan air volume required for cooling and the heat removed by the fan on the representative days of three seasons (summer, winter, and midseason) indicated that, the lower the outdoor air temperature, the greater is the efficiency of outdoor air cooling because indoor heat could be removed with smaller air volume.

2. While an increase in air volume can prolong the operation period of outdoor air cooling, it also results in an increase in the power consumption of the fan. Therefore, at the system design stage, it is recommended to select the optimal air volume by considering the theoretically possible maximum air volume along with the equipment load, the efficiency of the fan, and the performance of the thermo-hygrostat. We performed numerical analysis and identified the design air volume when the annual power consumption reached the minimum value with respect to the capacity and load of the ICT equipment, i.e., when the highest cost-saving effect was achieved.

3. Once the outdoor air-cooling system is installed, the indoor temperature and the design outdoor air temperature switching to outdoor air cooling are considered crucial operating parameters. Our analysis revealed that each increase of 1 °C in the indoor set temperature results in a power-saving effect amounting to 441 kWh per year, which is tantamount to 0.4% less power consumed every year.

4. The results of the analysis of the time periods during which the application of outdoor air cooling was allowed under the conditions of design air volume and optimal design air volume are as follows. The total durations for application of outdoor air cooling were estimated to be 5545 h and 6739 h, respectively, out of 8760 h for the design air volume (20,000 m$^3$/h) and optimal design air volume (26,200 m$^3$/h).

5. The optimal design air volume was calculated according to the equipment load. Consequently, the optimal design air volume of the modeled computer system was obtained as 26,200 m$^3$/h. Application of this optimal design air volume is expected to yield an annual energy-saving effect of 56.1% compared with power consumption in the air-conditioning period during which application of outdoor air cooling is impossible.
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Abbreviations

A  Area of the space (m²)
C  Specific heat of air (kcal/kg·°C)
ICT Information and Communications Technology
K  Heat transmission rate (W/m²·K)
N  Ventilation rate (m³/h)
P_f Fan power consumption (kW)
P_s Fan static pressure (mmAq)
P_R Power consumption of thermo-hygrostat (kW)
Q  Airflow ratio (m³/h)
q  HVAC load (kal/h)
q_equip ICT equipment heat load (kal/h)
q_th Transmission load (kal/h)
q_{SH\cdot inf} (Sensible heat) infiltration load (kal/h)
q_{LH\cdot inf} (Latent heat) infiltration load (kal/h)
q_{sol} Solar radiation load (kal/h)
SHGC Solar heat gain coefficient
T_o Outdoor air temperature (°C)
ΔT Difference between the indoor and outdoor temperatures (°C)
V  Volume of the space (m³)
η  Fan efficiency (%)
ϕ  Absolute humidity (kg/kg)

Subscript
equip ICT equipment
f Fan
inf Infiltration
LH Latent heat load
o Outdoor air
R Thermo-hygrostat
s Static pressure
SH Sensible heat load
sol Solar radiation load
th Heat transmission rate

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