Ceiling fans are often used for improving thermal environment, and they consume low amount of energy in comparison with air-conditioners. This study aims to establish a design and operation method in the office for an air-conditioning system combined with ceiling fans, which can realize comfortable air-conditioning and energy conservation all year round. This paper shows the results of SET* obtained from CFD simulation under several positions for the indoor thermal environment controlled by the air-conditioner and the ceiling fans in summertime. From a result of CFD simulation for summer, it is confirmed that the ceiling fan is beneficial to reduce SET*, raising indoor air velocity. The rate inside the ASHRAE Standard 55 comfort zone increased when ceiling fans were operated. The CFD results of air velocity, temperature and SET* were compared between conditions by frequency distribution. For cooling, air velocity increases and SET* decreases as a result of ceiling fan effect.

Introduction
In recent years, use of ceiling fans (CF) is increasing to conserve energy by improving thermal environment and moderating room air temperature distribution through airflow control. Previous studies\textsuperscript{1}) have been examining the effects of ceiling fans in a large space, but no design method has been established. The purpose of this study is to establish air-conditioning design methods that use both air-conditioner and ceiling fans. In this paper, we report the effect of the position and number of ceiling fans on the airflow and thermal environment during cooling.

1. Conditions of Computational Fluid Dynamics (CFD) simulation in the basic space
1.1 Outline of simulation
Figure 1 shows the space of CFD simulation. Assuming an office interior space of 12,800 mm × 12,800 mm × 2,600 mm, we installed a 4-way outlet cassette-type air-conditioner on the center of the ceiling. Two or four ceiling fans were installed 3,200 mm away from the air-conditioner. The angles of ceiling fans were set at 0° or 45° against the outlet of the air-conditioner.

1.2 Calculation conditions
Calculation conditions are shown in Table 1. Using the standard k-ε model, we analyzed the flow field and temperature field. The air-conditioner had a 4-way outlet, and on the center of the space’s ceiling, we installed the air-conditioner inlet of 500 × 500 mm. Air velocity near the wall of the room followed the generalized log-law and the wall had thermal insulation. The heat flux of the ceiling was 7.5 W/m² and that of the floor was 22 W/m². Total heat generation is 4.8 kW.

1.3 Air-conditioner conditions
Boundary conditions of the air-conditioner are summarized in Table 2. The air-conditioner has a rated cooling capacity of 8.0kW and heating capacity of 9.0kW. The size of outlet area was determined in such a way that outlet air velocity and air volume matched with the actual object. The direction of outlet took depression angle (angle from the ceiling) of 25°, and the following air velocities were given to the 4 outlets: 2.4 m/s (2.18 m/s for horizontal direction and 1.00 m/s for vertical direction) in the summer setting. The air volume was 810 m³/h in the summer setting. As for turbulence parameters, we set the turbulence intensity at 10% and turbulence length scale at 100 mm. The outlet temperature for summer was set at 14.5 degrees Celsius so that outlet temperature would be 28 degrees Celsius based on load calculation. We have not taken into account automatic on-off operation and swing operation of the air-conditioner.

1.4 Operating mode of ceiling fans
Analysis cases are shown in Table 3. The air velocity and turbulent parameters for inputting into CFD as airflow model
of the ceiling fan are shown in Fig 2. Two kinds of models were considered. One is a ceiling fan model with 1100 mm in diameter, and another is a ceiling fan model with 1300 mm in diameter. The airflow direction of ceiling fans was downward for cooling. Also, assuming “soft” as operation condition of ceiling fans, the rotational speed was set at 160 rpm. For cooling, a hypothetical horizontal plane with 1,400 mm on a side at 200 mm below the ceiling fans was set and gave measurement value of 3-dimentional average air velocity and turbulence parameters.

2. CFD results for summer setting

2.1 Air velocity distribution

Figure 3 shows CFD results of the air velocity on the horizontal plane at 1,100 mm above the floor. When ceiling fans were being operated, a high air velocity area was created below the ceiling fans. At the 0° setting, the air velocity became higher between the wall and under the ceiling fans. This is because the distance between the ceiling fans and wall was closer for the 0° setting as compared with the 45° setting, and this has facilitated airflow circulation caused by airflow of ceiling fan that reached the floor.

2.2 Air Temperature distribution

Figure 4 shows air temperature distribution at A-A’ section and horizontal cross-section 1,100 mm above the floor. In the CF0 (no ceiling fun was used) condition, temperature under the air-conditioner decreased due to downward airflow of cool air released from the air-conditioner. In the CF2 (2 ceiling fans were used) condition, wide area recorded the temperature above 28.5 degrees Celsius, and the overall temperature was higher as compared with the CF0 condition. The temperature of the occupied zone became higher probably as a result of air agitation and braking temperature stratification. It is also possible that cool air from the air-conditioner was blocked by air stream circulation around the ceiling fans. In the CF4 (4 ceiling fans were used) condition, the cool air from the air-conditioner spread across the residential area, and temperature distribution was dissolved for both vertical and horizontal planes.

2.3 Calculation of SET*

SET*(Standard New Effective Temperature) of the horizontal section 1,100 mm above the floor was calculated, given that clothing insulation was 0.5 clo and metabolic rate was 1.0 met. The convective heat transfer coefficient of human body surface was calculated using Mitchell’s equation2),
Figure 3  Air velocity horizontal distribution (FL+1100)

Figure 4  Temperature horizontal distribution (FL+1100)

Figure 5  SET* horizontal distribution (FL+1100)

Figure 6  SET* frequency distribution (FL+1100)

Figure 7  Relation between CFD results of air velocity and temperature and comfort range of SET*
assuming the seating situation under airflow. We used the radiative heat transfer coefficient of 4.65W/m²K.

(1) Horizontal distribution of SET*

Figure 5 shows horizontal distribution of SET*. In the CF0 condition, although SET* became lower where the downward airflow was blown out from the air-conditioner, its distribution range was small (25.5 to 27 degrees Celsius). In the CF2 condition, decrease of SET* up to 24 degrees Celsius was observed around the ceiling fans. It seems that SET* decreased due to increase of airflow velocity, while indoor air was agitated and the temperature of residential area increased. In the CF4 condition, SET* decreased further because the temperature became lower than the CF2 condition. At CF4-45, the temperature decreased up to approximately 23 degrees Celsius. Furthermore, SET* was slightly lower at the 45° setting as compared to the 0°setting. These findings suggest that operation of ceiling fans would provide possibility of allowing lower preset temperature of air-conditioner, which would lead to energy saving.

(2) SET* frequency distribution

Figure 6 shows relative frequency distribution and accumulation frequency of air velocity, temperature and SET*. In the CF0 condition, 90% was within the range of 26.0-27.0 degrees Celsius. Meanwhile when ceiling fans were used (CF2 and CF4), the frequency distribution became larger. Furthermore, the average SET* values were 0.5 degrees Celsius lower at CF2-00 and 0.6 degrees Celsius lower at CF2-45 as compared with CF0-00.

(3) Examination of comfort range by SET*

In Figure 7, the horizontal axis is temperature and vertical axis is air velocity. The equivalent SET* line was overlaid. The thick line represents the comfort range based on the ANSI/ASHRAE Standard 55 3) (-0.5 < PMV < 0.5) within the range of equivalent SET* (SET* = 23.31 - 26.68 degrees Celsius) (calculation was conducted using clothing insulation of 0.5clo, metabolic rate of 1.1met, air velocity of 0.15m/s, and relative humidity of 50%). The left bottom outside of the Figure shows the ratio within comfort range. We can see that SET* is lower under conditions of using ceiling fans as compared to the CF0 condition. The ratio of SET* within the comfort range was the highest for the CF4 condition. When the preset temperature of the air-conditioning was increased, the frequency of high temperature became higher. Therefore it is possible that the ratio of SET* within the comfort range would become lower in the CF0 condition.

2.4 Effect of ceiling fan’s diameter on air velocity, temperature and SET*

Figure 8 shows relative frequency distribution and accumulation frequency of air velocity and temperature in φ1300 and φ1100 of ceiling fan’s diameter and SET* in φ1100. In φ1100 conditions, the frequency of high wind velocity is falling in an occupied zone. When averaged air velocity is compared, CF2 and CF4 of φ1100 are about 1/2 of φ1300. Averaged SET* of CF2-φ1100 increased by 0.91 °C as compared with that of CF2-φ1300, and increased by 0.27 °C as compared with that of CF0. Moreover, Averaged SET* of CF4-φ1100 increased by 0.49 °C as compared with that of CF4-φ1300, and decreased by 0.53 °C as compared with that of CF0. It can be said that the effect of decreasing SET* in CF4-φ1100 is comparable as CF2-φ1300.

3. Conclusions

This report conducted CFD simulation under various numbers and position of ceiling fans with a use of one air-conditioner. For cooling, air velocity increases and SET* decreases as a result of ceiling fan effect. By setting higher preset temperature of the air-conditioner, we can expect energy conservation effect.

References

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