Development of air supplied ceiling radiant air conditioning system using the Coanda effect

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ABSTRACT

Air-supplied ceiling radiant air conditioning is expected to become more popular in Japan in the future because there is no leakage from pipes and no condensation on the surfaces of radiant panels. Coanda air conditioning, a type of air-supplied ceiling radiant air conditioning, uses the Coanda effect, which is the tendency a fluid passing near a wall to maintain contact with it. As used commonly, Coanda air conditioning cools the ceiling surface by blowing airflow horizontally along it from the top of the wall surface and cooling by radiation1). In contrast, the line-type Coanda air-conditioning system proposed in this study (Figure 1) blows airflow to the ceiling in both directions from the air outlet, thereby enabling uniform cooling of the ceiling surface at low air volumes. As an initial study, this paper presents a case study involving the use of computational fluid dynamics to optimise the outlet shapes. The effectiveness of the proposed method is verified by using air diffusion performance index/predicted mean vote environmental assessment for a typical office space, and it is confirmed that the proposed method provides a comfortable thermal environment by radiant heat transfer mainly on the ceiling surface around the air outlet.

KEYWORDS

Coanda effect, CFD analysis, air supplied systems, ADPI

1 INTRODUCTION

Recently, ceiling radiant air conditioning systems have attracted attention owing to their high levels of comfort and energy-saving, and such systems are increasingly being adopted in office buildings. In particular, air-supplied ceiling radiant air conditioning systems are expected to become more widespread in Japan in the future since there is no leakage from pipes and no condensation on the surfaces of radiant panels. However, although general air-supplied systems are easier to install compared with water systems, the initial costs are higher than for general air-conditioning systems. In addition, there is much need for a simpler system that can be installed in existing buildings without complications such as the need to re-cover ceiling surfaces. Coanda air conditioning, a type of air-supplied ceiling radiant air conditioning, uses the Coanda effect, which is the tendency a fluid passing near a wall to maintain contact with it. As used commonly, Coanda air conditioning cools the ceiling surface by blowing airflow horizontally along it from the top of the wall surface and cooling by radiation1). However, if the airflow is blown from the wall to the ceiling rapidly for a long time, a draft may occur where the blown airflow detaches from the ceiling. Therefore, this research aims to further improve the comfort of and ease of installing and retrofitting air-supplied radiant air-conditioning systems by developing a line-type Coanda air-conditioning system for installation in office spaces. The line-type Coanda air-conditioning system proposed in this study (Figure 1) blows airflow to the ceiling in both directions from the air outlet, thereby enabling uniform cooling of the ceiling surface at low air volumes. Also, air-supplied ceiling radiant air conditioning can be realised simply by installing a dedicated protrusion at the outlet of the line-type air conditioning commonly used in offices, which is expected to reduce costs and lead to considerably improved workability.

In this paper, as an initial study of the proposed system, the projection shape is optimised in a computational fluid dynamics (CFD) case study, and the optimised projection shape in a general office space is subjected to CFD analysis to verify the effectiveness of the proposed system.

2 OUTLINE OF LINE-TYPE COANDA AIR CONDITIONING SYSTEM

Figure 1 shows an overview of a line-type Coanda air-conditioning system. A typical air-conditioning system in an office space tends to cause discomfort due to drafts. Therefore, in this system, the airflow direction is changed by installing protrusions and plates at the air outlets and cooling the ceiling surface by the Coanda effect. The coldness creates a radiative air-conditioning area near the air outlet and a convection one away from it, the aim being to improve the comfort of the entire space.

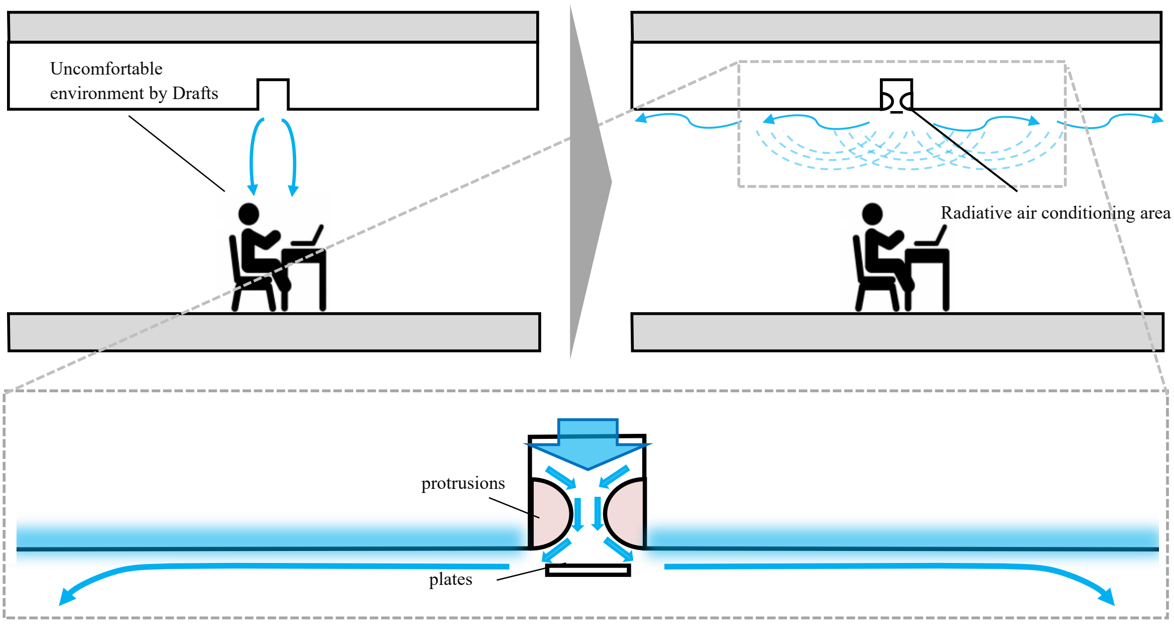
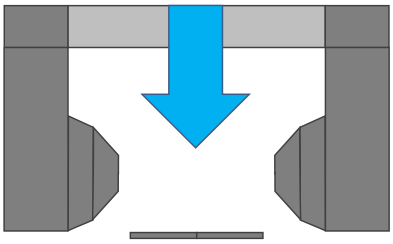
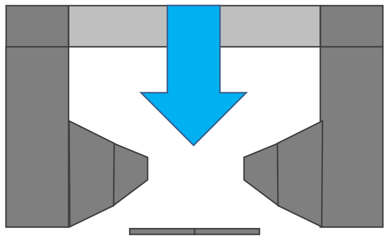
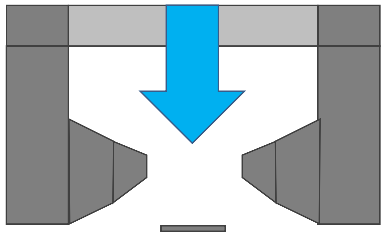


Figure1: Outline of line-type Coanda air-conditioning system

3 OPTIMIZATION OF OUTLET SHAPE (2D ANALYSIS)

The studied outlet shapes are described in Table 1, and to determine the case that gives the largest separation distance, the temperature, flow field, and radiation field are analysed here by means of steady-state CFD. In addition to determining the separation from the calculated streamlines, the distance until the blown airflow separates from the ceiling (hereafter the separation distance x_{max}) is calculated from how the distribution of wind velocity vectors varies along the z axis, and the shape that gives the largest separation distance is considered the optimal shape.

Table 1: Case table of outlet shape

Case1	Case2	Case3
		
Basic Case	A model with extended central projection	A model with half the plate width of Case 2

3.1 Analysis Model

Table 2 and Figure 2 show respectively the analytical conditions and model for optimising the outlet shape. The analysis is performed on a two-dimensional model for improved calculation accuracy and reduced calculation load. Although this system has a two-directional blowout, the centre of the outlet is the symmetry boundary and only one side is analysed. In addition, a heat load of 15.7 W/m^2 is given to the floor surface, and the exhaust is sufficiently far from the air outlet so that the airflow at the exhaust port affects neither the separation distance nor the entire wall surface. Since this analysis was performed at the design stage, comparison with experimental results to verify the validity of the analysis has not yet been performed. However, we have verified that the analytical model has sufficient grid resolution to analyze the flow and temperature fields.

Table 2: Analysis conditions for CFD analysis (2D Analysis)

Domain	10.00m(X)×3.35m(Z)	
Mesh	360(X)×199(Z)=71,640	
Outlet boundary conditions	Temperature: 18℃, Speed of moving fluid: 0.42m/s $k_{in}=(U_{in}/10)^2$, $\varepsilon_{in}=C_\mu^{3/4} \cdot k_{in}^{3/2}/l_{in}$	
Inlet boundary conditions	Speed of moving fluid: 0.42m/s	
Turbulence model	Linear Low Reynolds turbulence model	
Advection scheme	QUICK	
Wall boundary conditions	Velocity	Analytical wall function, Cutcell
	Temperature	above the ceiling: (28℃)External temperature, (9.0 W/m^{2}K) overall heat transfer coefficient Ceiling interior side: Logarithmic law
Heat generation	Floor heating: 15.7 W/m^2	

U_{in}: Outlet air wind speed [m/s], k_{in}: Outlet air turbulence energy [m^2/s^2], ε_{in}: Dissipation rate of k_{in} [m^2/s^3], C_μ: Model constant (=0.09) [-], l_{in}: Length scale [m]

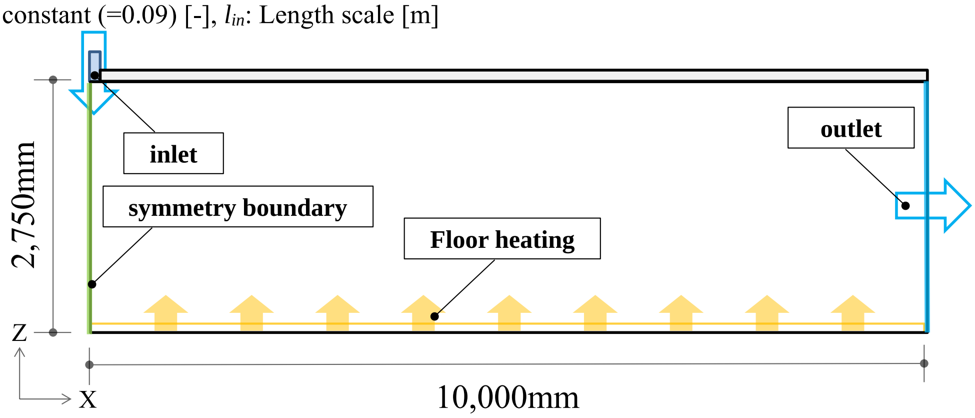


Figure 2: Analysis model (2D analysis)

3.2 Analysis case

The protrusion models are shown in Table 1. As the initial proposal, the cylindrical protrusion is Case 1. In Case 2, the protrusion is extended to the centre to increase the distance that the airflow travels along the surface of the protrusion just before it blows out into the occupied area. Finally, Case 3 has half the plate width of that in Case 2.

3.3 Analysis Results

Figure 3 shows the results of the streamline analysis for the three cases. As can be seen, Case 2 gives the longest separation distance, presumably because the separation distance is affected by the magnitude of the wind velocity vectors along the *x* axis between the protrusion and the plate. In the subsequent sections, the analysis is performed using Case 2 as the optimal shape.

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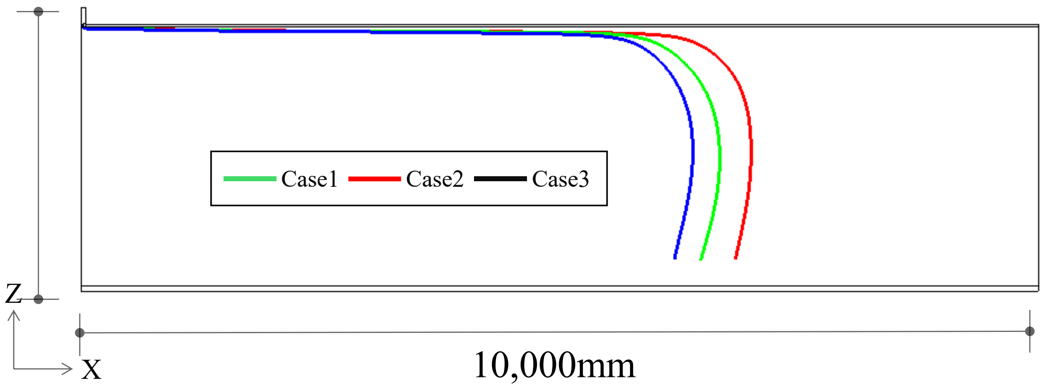


Figure 3: Streamlines analysis results

4 Validation using model office (3D analysis)

In this analysis, the temperature, airflow, and radiation fields are analysed by means of steady-state CFD to assess whether the proposed system forms a comfortable thermal environment.

4.1 Analysis model

Figure 4 and Table 3 show the three-dimensional analytical model and analytical conditions, respectively. A typical office span is assumed, and Case 2, which was the optimal shape from Section 3, is used for the outlet shape.

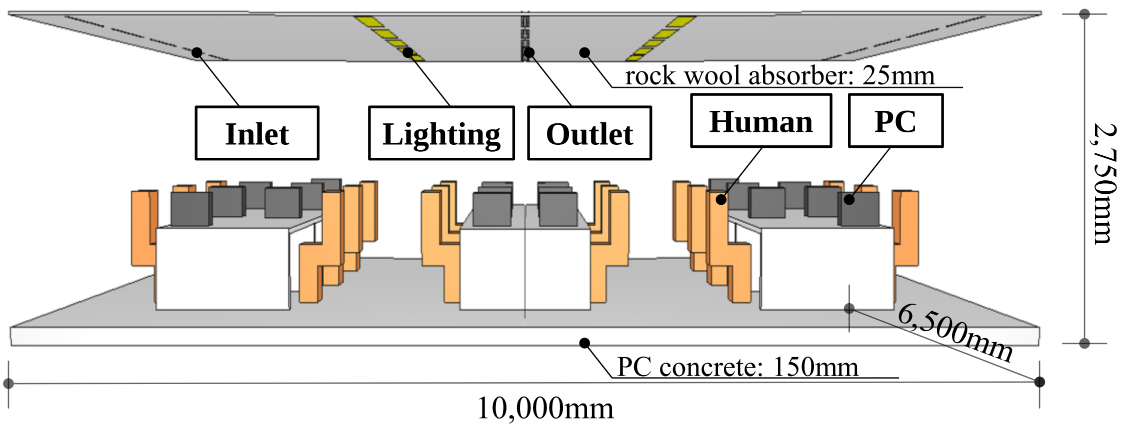


Figure 4: Analysis model (3D analysis)

Table 3: Analysis conditions for CFD analysis (3D Analysis)

Domain	10.00m(X)×6.5m(Y)×2.75m(Z)	
Mesh	127(X)×76(Y)×103(Z)=994,156	
Outlet boundary conditions	Temperature: 17.11℃, Velocity: 190m³/h $k_{in}=(U_{in}/10)^2$, $\varepsilon_{in}=C_{\mu}^{3/4} \cdot k_{in}^{3/2}/l_{in}$	
Inlet boundary conditions	Velocity (5units): 190m³/h/unit	
Turbulence model	Linear Low Reynolds turbulence model	
Advection scheme	QUICK	
Wall boundary conditions	Velocity	Analytical wall function, cutcell
	Temperature	above the ceiling: (28℃)External temperature, (9.0 W/m²K) overall heat transfer coefficient Ceiling interior side: Logarithmic law
Heat generation	Human (18 person): 69W/person, Lighting (10 lights): 40W/unit, PC (18 units): 32W/unit	

U_{in}: Outlet air wind speed [m/s], k_{in}: Outlet air turbulence energy [m²/s²], ε_{in}: Dissipation rate of k_{in} [m²/s³], C_{μ}: Model constant (=0.09) [-], l_{in}: Length scale [m]

4.2 Analysis case

Table 4 shows the analysis cases. To derive the optimal operating conditions for the proposed system, the cases were set up with a fixed air flow rate and different air temperatures at each outlet.

Table 4: Operating Conditions Case Table (Model Office Verification)

	flow rate [m³/h]	blowoff temperatures [℃]
Case2-1	190	19.11
Case2-2		18.11
Case2-3		17.11
Case2-4		16.11

4.3 EDT and ADPI

The effective draft temperature (EDT) is the temperature at which the human body is comfortable when exposed to a draft. If this temperature is between −1.7 and +1.1 and the air velocity does not exceed 0.35 m/s, then the majority of people in the room are considered to be comfortable. The EDT is calculated as given in (1).

$$\text{EDT} = (t_x - t_c)\text{-}7.66(V_x - 0.15) \tag{1}$$

t_x: Room local temperature [℃]

t_c: Average temperature of the living area [℃]

V_x: local wind speed [m/s]

The air diffusion performance index (ADPI) is an index for draftiness indoors and is calculated as given in (2).

$$\text{ADPI} = \eta/\eta' \times 100\% \tag{2}$$

η: Area where EDT values meet the comfort range(−1.7≤EDT≤1.1) [m2]

η′: Indoor floor area [m²]

4.4 Analysis Results

Figure 5 shows the ceiling surface temperature distribution, the predicted mean vote (PMV) distribution at 1.2 m from the floor, the horizontal surface EDT distribution, and the ADPI. The ceiling surface temperature distribution shows that the average ceiling surface temperature also decreases as the air temperature at the outlet decreases, and it is confirmed that the cooling range of the ceiling surface is generally constant. It seems that because the cooling is blocked by the lighting between the air outlet and the inlet, the cooling range is limited to the space between the air outlet and the lighting. The PMV distribution is within ±0.5 after Case 2-3, confirming the formation of a good indoor thermal environment. The horizontal EDT distribution and ADPI in Case 2-3 are confirmed to be more than 80% of ADPI, indicating a comfortable thermal environment with little draft and temperature irregularity. The above results confirm that a comfortable and good thermal environment forms at the present outlet air temperature of 17.11°C.

Figure 6 shows the temperature and mean radiant temperature (MRT) distributions of the line-type Coanda air-conditioning system under the air conditions of Case 2-3, that is, the optimal operating conditions. In the line-type Coanda air-conditioning system, the air temperatures at both ends of the room and the MRT at the centre of the room are low, seemingly because of the formation of convection and radiation air-conditioning zones as intended in the design.

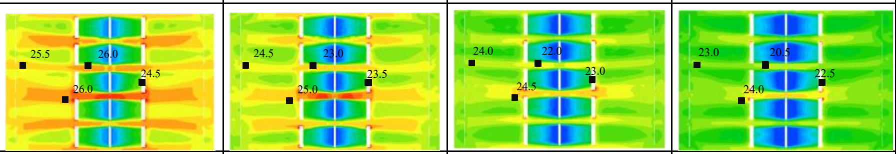
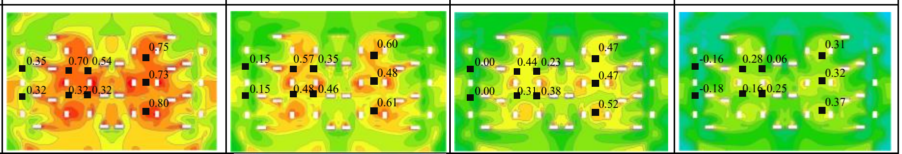
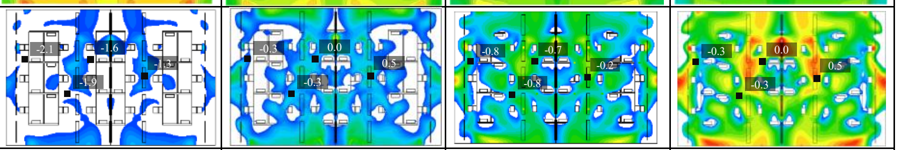
	Case2-1	Case2-2	Case2-3	Case2-4
Ceiling surface temperature				
Average ceiling surface temperature	24.7℃	24.1℃	23.4℃	22.8℃
PMV (Z=1.2m)				
EDT (Z=1.2m)				
ADPI	27.4%	70.2%	81.1%	94.7%

Figure 5: Ceiling surface temperature, MRT, PMV vertical distribution and 1.2m horizontal EDT distribution for each case

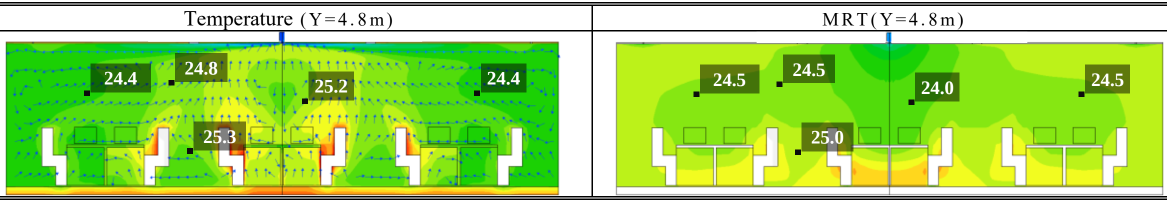


Figure 6: Case2-3Temperature and MRT distributions of line type Coanda air conditioning and convection type air conditioning (Anemo type) under blowout conditions

5 CONCLUSION

In this study, as an initial investigation of a line-type Coanda air-conditioning system, the shape of the air outlet was optimized through a CFD analysis case study. Furthermore, CFD analysis was conducted for a typical three-dimensional office space to clarify the characteristics of a line-type Coanda air-conditioning system.

The followings are the findings of this study.

1) We proposed an outlet shape that efficiently cools the ceiling surface. Case 2, which has the shortest distance between the projection and the plate, was confirmed to have the longest separation distance. This is presumably because the separation distance is affected by the magnitude of the wind velocity vectors along the x axis between the protrusion and the plate.
2) It was confirmed that installing a line-type Coanda air-conditioning system in the model office formed a radiative and a convection air-conditioning area and a comfortable thermal environment with little draft and uneven temperature.
3) Comparison with general air-conditioning systems, the proposal of design conditions using Archimedes number, and confirmation of ventilation performance using Age of air and other indices are future issues to be considered.

6 REFERENCES

1) Igarashi H et al. (2022). Study of Coanda air-conditioning system compatible with variable air volume- Thermal comfort evaluation by full-scale experiments-, Architectural Institute of Japan (in Japanese)

ACKNOWLEDGMENT

This work was supported by JSPSKAKENHI Grant Number 22H01653.