The Effects of the Physiological Response of the Human Body and the Human Sensation by using the Directional or the Diffusible Airflow of the Personal Air-conditioning System

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ABSTRACT

In recent years, energy consumption in office buildings is required to be reduced. It is important to satisfy worker's comfort to keep high productivity. However, it is difficult to keep a comfortable environment for all of the office workers. In many cases, thermal sensation of men and women is different. Workers who come in from outside tend to feel warmer than workers who have been inside. We developed a personal air-conditioning system that has two outlets for each person. These outlets can supply directional or diffusible airflow, which a person can select using a PC according to their physiological condition. The purpose of this study is to verify the influence of the physiological response of the human body and the human sensation when the directional airflow is blown to one part of the human body. A warm/cool feeling and the comfort sensations are investigated by a subjective questionnaire in a laboratory. The influences of the physiological amount (skin temperature and skin wettedness rate) to the human body and the human sensation are examined by using the subjective questionnaire and a mathematical human model for heat balance of the human body, the complex thermal environment comfort model (COM). COM takes into consideration the blood circulation throughout the human body involving the extremities of the arms and legs. The calculation accuracy is verified through the comparison of calculation results and measured skin temperature. Furthermore, the parametric simulation is performed to examine the effect of the physiological response of the human body by changes in metabolic rate, clothes, temperature and wind speed of local airflow.

KEYWORDS

Personal air-conditioning system, Local airflow, Heat balance of human body, Human sensation, Subjective experiment

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INTRODUCTION

The personal air-conditioning system to aim the energy conservation and the human comfortable have been developed (Kasuya A. et al., 2009). We have suggested a personal air-conditioning system as a way to meet individual comfort (Okamoto S., Chikamoto T. et al., 2012). This system is aimed at achieving reduction of the increased the metabolic rate at the time of returning to the office in summer. Figure 1 shows the conceptual diagram of the personal air-conditioning system. This system has two kinds of outlets of directional or diffusible on one ceiling panel. These outlets are able to be remote controlled with the individual PC depending on the personal comfort. In the previous report, thermal sensation of the test subject and the energy performance were evaluated by the experiments and CFD analysis. In these verifications, the efficacy of the system, as well as the human-comfort level, was improved by using a personal air-conditioning system (Kozaki M., Chikamoto T. et al.,2015).

However, the physiological reaction of the human body by the local airflow was not able to be grasped. So, the optimum operating conditions of this system have not been investigated. Thus, the test subject experiment that was supposed to be used for the local airflow of the personal air outlet at the time of return to the office can ascertain the physiological and the psychological response of the human by a questionnaire survey and measuring skin temperature. Furthermore, the influence that the physiological response of the human gives to a warm/cool feeling is verified by comparing the results of the calculation of skin temperature and skin wettedness of each body part by a mathematical human model and the test subject values of questionnaire of the physiological response.

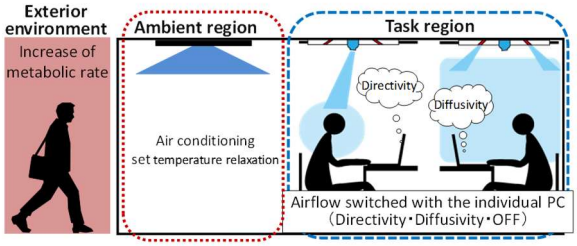
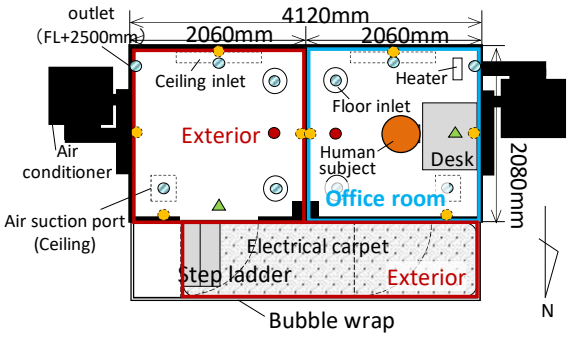


Figure 1. *Personal Air-Conditioning System with selectable airflow*

OUTLINE OF TEST SUBJECT EXPERIMENT

Figure 2 shows the floor plan of the experimental room that can keep the temperature and humidity constant. The experiment was conducted at a constant temperature and humidity in rooms within Ritsumeikan University in Japan. The experimental room was composed of two rooms (width 2,060 mm × depth 2,080 mm × height 2,700 mm per room). A single ceiling outlet and two floor outlets where the blowing air volume could be controlled were installed in each room. One room is assumed to be an office and other room an exterior space in summer. The migration path which is covered cushioning material recreated the exterior space using an electric carpet as the heating element. The environment was measured for the air temperature, humidity and surface temperature by using the amenity meter (2 points) and the thermocouple (17 points) (see Figure 2). Also, the skin surface temperature of the test subject was measured by



Legends	Items	Points	Instruments
●	Temperature distribution	8 points × 2 rooms (FL+0mm, 100mm, 600mm, 1100mm, 1600mm, 2100mm, 2600m, 2700m)	Thermocouple
●	Wall surface temperature	4 points × 2 rooms (FL+1100mm)	
▨	Outlet / inlet temperature	5 points × 2 rooms	
▲	Air temperature /humidity	2 points (FL+1100mm)	Amenity meter

Figure 2. *Floor plan and measurement point*

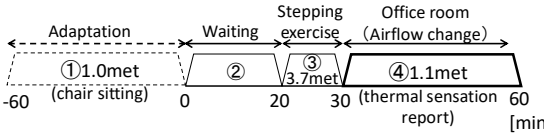


Figure 3. *Experimental procedure*

Table 1. *Questionnaire items*

Thermal sensation / Comfort sensation / Airflow feeling / sweating / Sweating parts / Free writing

Table 2. *Experiment cases*

Case	Airflow property	Temp. of the office [℃]	Inlet temp. [℃]	Velocity [m/s]	Airflow blowing part
A	Diffusible	28.0	22.0		-
B	Directional			1.0	Neck
C				0.4	L. Arm
D			24.0	1.0	Neck

Figure 4. *Local cooling device*

the thermocouple. The mean skin temperature was calculated using the three points of the Burton equation by measuring the skin temperature of the chest, the upper arm and the thigh.

Figure 3 shows the experimental procedure. The test subject was a healthy adult male student who had enough sleep and abstained from alcohol from the day before. The experiment was carried out for two days from December 21 to December 22, 2015. As the experimental procedure, ①complete rest in the office room at 28 ℃ in winter clothing in order to adapt to the summer environment (60 minutes), ②change of clothes to summer wear and fix the thermocouple sensor on the skin in the office room (20 minutes), ③stepping exercise in the exterior space (10 minutes), ④enter the office room again, change the blowing method of the airflow on a case-by-case basis (30 minutes). At that time, the thermal sensation questionnaire (See Table 1) was performed (④) every 1 minute for 10 minutes after entering the office room and every 5 minutes until the end of the experiment. In other to get detail declination, the questionnaire used the new scale which divides each scale of the seven-step evaluation of ASHRAE. Also, the test subject could declare referring the declaration of last time.

Table 2 shows the experiment cases. The experiment cases are as follows, Case A: applying the diffusible airflow, Case B: applying the directional airflow to the neck, Case C: applying the directional airflow to the arm, Case D: changing the temperature from Case B. The directional airflow was reproduced by fixing the flexible duct attached to the floor air outlet (See Figure 4). The clothing amount of the test subject was 0.7 clo which assumed the “Cool Biz” of without a tie and a jacket.

CALCULATION CONDITION OF MATHMATICAL HUMAN MODEL

The physiological response of the test subject in the experiment is reproduced by the mathematical human model as the thermal environment conditions are input at the time of the experiment. The mathematical human model called "COM" (Tanabe S. et al., 2006) is used for the analysis. COM can calculate the detailed heat balance of human body parts, taking into consideration the blood circulation (arterial and venous flow) throughout the body, and involving the extremities. By dividing the whole body into 17 segments, each with skin and a core layer, the temperature distribution of the skin and blood at 59 points over the whole body can be predicted. COM can subsequently calculate a detailed human physiological response under conditions such as those of a non-uniform thermal environment. The COM calculations are conducted by setting up the boundary conditions of the surrounding air temperature and humidity, airflow velocity (convective heat flux), radiant heat flux, the clothing amount, and the metabolic energy. The human model of COM can adapt the experimental conditions by blowing the directional air flow using a neck and arm part. Input data of the convective heat transfer coefficient is used in the equations for each body part at the middle wind speed (Kuwabara K. Mochida T. et al., 2001).

Table 3 shows the calculation conditions. These conditions use the measured data for each experimental case. Temperature conditions are input by being divided into three parts of human body for each case from the measurement results of the temperature distribution of vertical.

Table 3. *Analysis cases and boundary conditions of mathematical human model*

Case	Division of human parts	All time	Adaptation (60min, 1.0met)		Sitting rest (20min, 1.0met)		Stepping exercise (10min, 3.7met)		Office room (30min, 1.1met)	
		Relative humidity [%]	Temp. [℃]	Airflow velocity [m/s]	Temp. [℃]	Airflow velocity [m/s]	Temp. [℃]	Airflow velocity [m/s]	Temp. [℃]	Airflow velocity [m/s]
A	Head, Neck	46.0	28.0	0.1	28.0	0.1	31.6	0.1	27.8	0.1
	Upper body				28.9				28.7	
	Lower body				28.2				27.9	
B	Head	43.3	28.0	0.1	27.9	0.1	31.8	0.1	29.6	0.1
	Neck				27.9				24.1	1.0
	Other				28.7				25.9	0.1
C	Head, Neck	43.3	28.0	0.1	28.3	0.1	31.3	0.1	28.4	0.1
	L. arm				28.5				25.4	0.4
	Other				28.5				25.8	0.1
D	Head	45.8	28.0	0.1	28.0	0.1	31.2	0.1	28.3	0.1
	Neck				28.0				26.4	1.0
	Other				28.2				26.4	0.1

CALCULATOION ACCURACY

The mean skin temperature of the measurement values of the test subject and the calculation values of the mathematical human model were compared for accuracy variation of COM. Figure 5 shows the mean skin temperatures from Case A to Case D. Although there was a difference in the temperature when waiting in the office, the calculated value could reproduce the trend of the measured value. However, the measurement value of the mean skin temperature in 3 minutes immediately after entering the office also increased in each case.

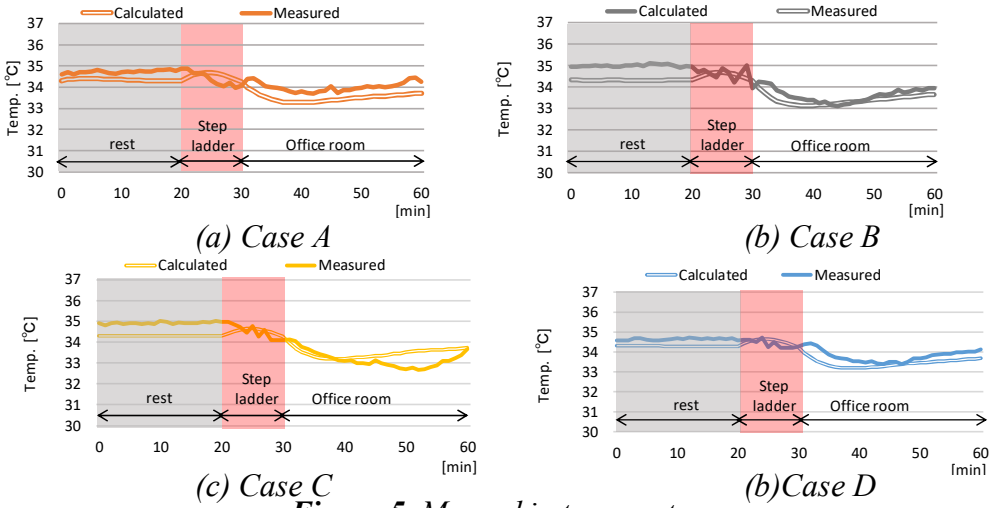


Figure 5. *Mean skin temperature*

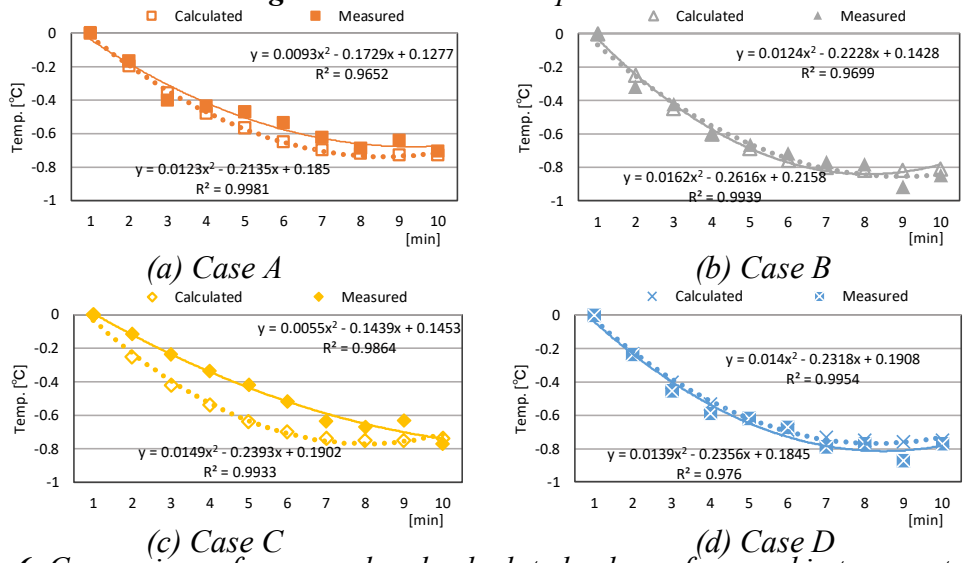


Figure 6. *Comparison of measured and calculated values of mean skin temperature for 10 minutes*

The metabolic rate during stepping exercise is believed not to decrease for a while in the cool environment. Therefore, the trend of decrease in the mean skin temperature for 10 minutes are compared using the measured value translated 3 minutes ahead and the calculated value (see Figure 6). The measurement value of Case C continues to be lower than the calculation value. The reasons of this is considered to be the effect of heat conduction from the desk to the arm in order to fix the arm on the desk to apply the directional airflow in the measurement of Case C. However, the calculation of Case C is not included the heat conduction. Case A, Case B, and Case D are generally in agreement, and high accuracy of calculation of the skin temperature by COM could be confirmed.

COMFORT EVALUATION BY TEST SUBJECT AND HUMAN ANALYSIS

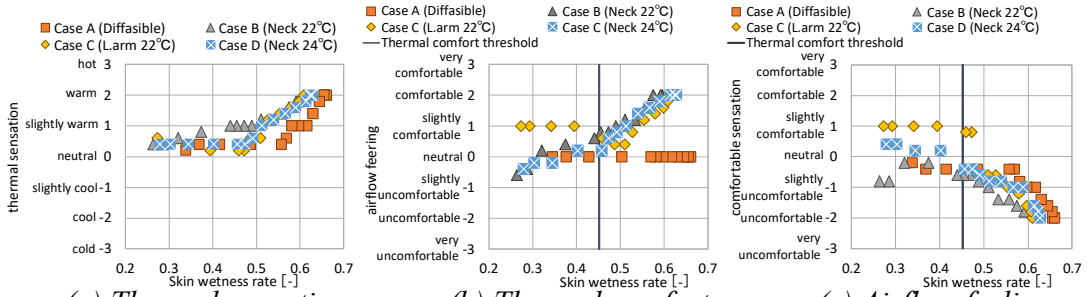
Figure 7 shows the correlation between the test subject declarations (thermal sensation / comfortable sensation / airflow feeling) for 30 minutes and skin wettedness rate by analysis. The graph of the comfortable sensation is written as a thermal comfort threshold (Fukazawa T., Qui E.,2014) line of skin wettedness rate. The thermal comfort

threshold is the threshold value of the skin wettedness as an indicator of the metabolic rate which begins to feel that the thermal temperature is uncomfortable.

The thermal sensations make a transition to the cool feeling side with a decrease of the skin wettedness rate in all cases. The differences for each case of the comfortable sensations appear when the skin wettedness rate is smaller than the thermal comfort threshold. Airflow feeling of the cases of blowing to the neck (Case B and Case D) changes to uncomfortable as skin wettedness rate reduces, but airflow feeling of the cases of blowing to the L. arm (Case C) becomes comfortable.

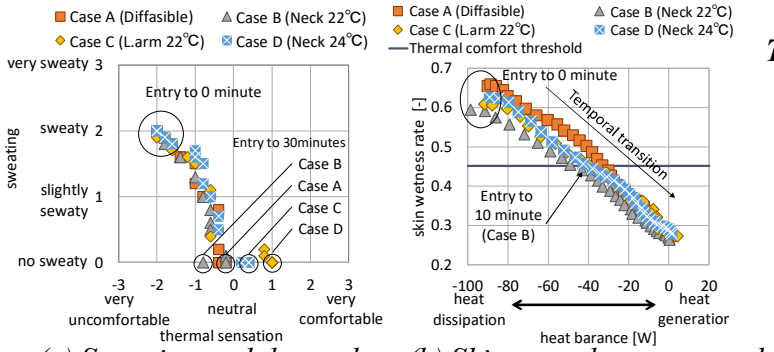
Figure 8 (a) shows correlation with comfortable sensation and sweating of the test subject. Table 4 shows the skin wettedness rate of calculation values when the test subject is declaring no sweating. The comfort after no sweating declaration is improved, except for Case B. The calculation value of the skin wettedness rate using the COM has a valid limit value in order to include a thermal comfort threshold, except for Case B. Because the temperature in the office of Case B was higher than the other cases, the sweat which had adhered to the clothes did not evaporate well, and the COM does not account for the moisture stored in the clothes.

Figure 8 (b) shows the correlation between the skin wettedness rate and the thermal balance. Case B promotes the most heat dissipation. However, the airflow feeling in Case B after reaching a thermal comfort threshold continues to be uncomfortable (see Figure 7 (b)). Therefore, the method of this system utilization is recommended so that the users cool the neck for 10 minutes to reach the thermal comfort threshold, and after to change the airflow site in the arm or to switch to the diffusible airflow.



(a) Thermal sensation *(b) Thermal comfort* *(c) Airflow feeling*

Figure 7. *Correlation between questionnaire results and calculated skin wettedness rate*



(a) Sweating and thermal comfort (questionnaire results) *(b) Skin wettedness rate and thermal balance (calculation results)*

Figure 8. *Correlation diagram*

Table 4. *Thermal comfort threshold and skin wettedness rate*

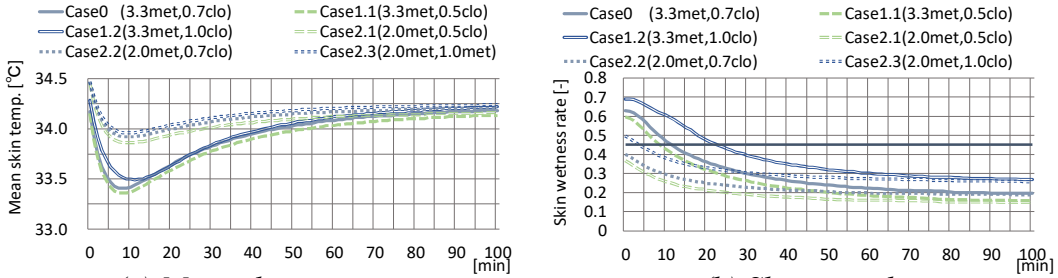
Case	Skin wettedness rate without sweating	Thermal comfort threshold
A	0.43 to 0.49	0.45
B	0.32 to 0.37	
C	0.40 to 0.46	
D	0.41 to 0.46	

Table 5. *Calculation conditions*

	Adaptation	Exterior	Office room
Hour [min]	60	10	100
Temperature [℃]	28.0	32.7	28.0
Relative humidity [%]	50	50	50
Velocity [m/s]	0.1	0.1	0.1
Metabolic rate [met]	1.0	See Tab. 6	1.1

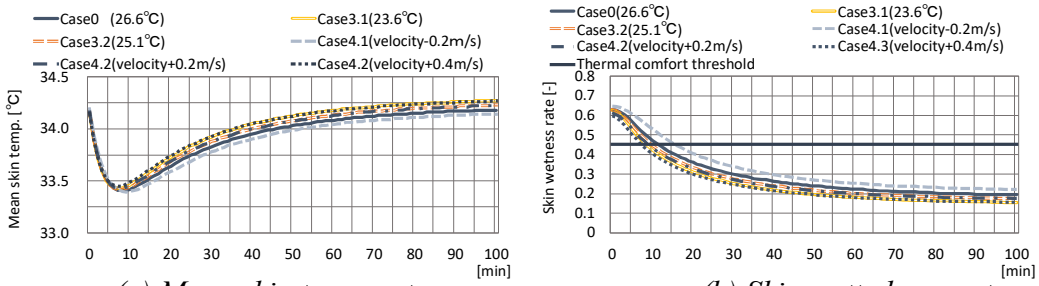
Table 6. *Analysis cases*

Case	Metabolic rate of exterior [met]	Clothing amount [clo]	Local airflow temperature [℃]	Local airflow velocity [m/s] Head	Neck	Back
0	3.3	0.7	26.6	0.6	0.5	0.4
1.1		0.5				
1.2		1.0				
2.1	2.2	0.7	26.6	0.6	0.5	0.4
2.2		0.5				
2.3		1.0				
3.1	3.3	0.5	23.6	0.6	0.5	0.4
3.2			25.1			
4.1	3.3	0.5	26.6	0.4	0.3	0.2
4.2				0.8	0.7	0.6
4.3				1.0	0.9	0.8



(a) Mean skin temperature *(b) Skin wettedness rate*

Figure 9. *The cases of changing metabolic rate and clothing amount*



(a) Mean skin temperature *(b) Skin wettedness rate*

Figure 10. *The cases of changing the airflow temperature and velocity*

EFFECT OF LOCAL AIRFLOW BY PARAMETRIC ANALYSIS

The influence of the directional airflow at the time of changing the human metabolic rate and the clothing amount in the office are confirmed. Tabel 5 shows the calculation conditions. The reference condition is the condition of blowing the directional airflow of 26.6 ℃in the surrounding neck (head, neck, back) by calculation of CFD analysis. The analysis makes the assumption that the subject is returning to the office from a hot external environment. Table 6 shows the analyzed cases. The change parameters are the metabolic rate (3.3 met or 2.0 met), the clothing amount (0.5 clo, 0.7 clo or 1.0 clo), the airflow temperature, and the airflow velocity.

Figure 9 and Figure 10 show the mean skin temperature and the skin wettedness rate due to differences in the metabolic rate and the clothing amount or the airflow temperature and the airflow velocity. The thermal comfort threshold is shown as the skin wettednedd rate on Figure 9 (b) and Figure 10 (b). The mean skin temperature has received significant influence from the metabolic rate. Also, in the case of changing the clothing amount, the skin temperature immediately after entering the office is drastically reduced, because the smaller the clothing amount, the more heat is dispersed. In the case of the high metabolic rate (Case 0～1.2), the skin wettedness rate immediately after entering the office was high. Especially, the case of the high clothing amount (Case 1.2) was required to have about 20 minutes of cooling. On the other hand,

the mean skin temperature and the skin wettedness rate are less affected by the temperature and the velocity changing. However, the change in airflow can obtain the similar results with the temperature changing, such as Case 3.1 and Case 4.3, and Case 3.2 and Case 4.2. In the case of the low metabolic rate, the airflow method with the diffusible airflow is more suitable than the directional airflow. Also, the case of wearing the light clothing is able to decrease the skin wettedness of the directional airflow.

RESULTS

In this paper, the influence of the human body of the physiological response and the thermal sensation is confirmed by the test subject experiment and a mathematical human model analysis. The calculation accuracy of a mathematical human model is verified by comparing the mean skin temperature with measured and calculated values. In addition, the method of optimal blowing airflow has become clear to cool the neck by the directional airflow for 10 minutes to reach the thermal comfort threshold, and then to change airflow to the arm or the diffusible airflow. Furthermore, the effect of conditions such as the metabolic rate or the clothing amount of the user is clarified by parametric analysis of airflow properties of the personal air-conditioning system and heat properties of human body with the mathematical human model. However, this study is not taken into account the personal error, because test subject is one person. In the future, more than one person of test subject experimental data should be accumulated.

ACKNOWLEDGEMENTS

This study was supported by a Grant-in-aid for Scientific Research (B) No.26289207 and a Grant-in-Aid for Young Scientists (B) No.15K18170 from the Japan Society for the Promotion of Science (JSPS)

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