

Influence of Carbon Dioxide Fluctuation and Thermal Environment on Workability, Physiology and Psychology

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Abstract. Although carbon dioxide (CO_2) is a gas not perceived by human, extremely high concentration of CO_2 has an influence on the human's health. High concentration of CO_2 also leads to lowering concentration ability and promoting drowsiness. It may also have an influence on productivity and learning efficiency of human. We conducted experiments to measure the amount of workability and the physiological and psychological response of the subjects. In the experiment, the concentration of CO_2 was set at the constant level at each case. And then, the concentration of CO_2 was changed to examine the physiological and psychological response. In the result of the experiment, the CO_2 concentration had the influence on productivity and working efficiency of human. Even if the CO_2 concentration is not so high, physiological condition of the human would be also affected.

1 Introduction

Since Pettenkofer proposed that 700 – 1000 ppm is considered to be an allowable concentration of carbon dioxide (CO_2) [1], and other researchers started to suggest 1000 ppm of CO_2 as a limit value for an adequate ventilated room, many regulations of CO_2 density sets around 1000 ppm in office spaces etc.

Although CO_2 is a gas not perceived by human, extremely high concentration of CO_2 has an influence on the human's health. "Ventilation for Acceptable Indoor Air Quality" (ASHRAE Standard 62.-2016) notes CO_2 at very high concentrations (e.g. greater than 5000 ppm) can pose a health risk. It is also defined that 5000 ppm as the limits of the CO_2 density of time-weighted over five 8-hour work day average for industrial environments (TWA) to keep occupational safety and health (The Occupational Safety and Health Administration (OSHA)).

High concentration of CO_2 also leads to lowering concentration ability and promoting drowsiness. It may also have an influence on productivity and learning efficiency of human. Satish reported high indoor concentrations of CO_2 (2500 ppm) could significantly impair people's decision-making performance [2]. Allen analysed the cognitive function scores with various CO_2 density (about 500 - 1500 ppm) and other factors, to evaluate the impact of the CO_2 level on health and productivity [3].

We have focused on the relationship between CO_2 concentration and productivity of human.

We investigated the influence of the CO_2 concentration on productivity and learning efficiency of students using

the field experiment in the classroom of junior and senior high school [4]. By the results of the surveys, the relationship between the CO_2 concentration (500 – 1500 ppm) in the classroom and the productivity was observed statistically. However, the results were obtained by the field experiment, therefore temperature, humidity, illuminance and other factors have changed in the classroom and the influence of CO_2 was not caught in the independent event.

This time, we conducted experiments to measure the amount of workability and the physiological and psychological response of the subjects, by using a laboratory room in which not only the CO_2 concentration, but also temperature and humidity can be controlled. In the experiment, the concentration of CO_2 was set at the constant level at each case to verify the influence of the CO_2 concentration. And then, the concentration of CO_2 was changed to examine the physiological and psychological response to clarify the mechanism.

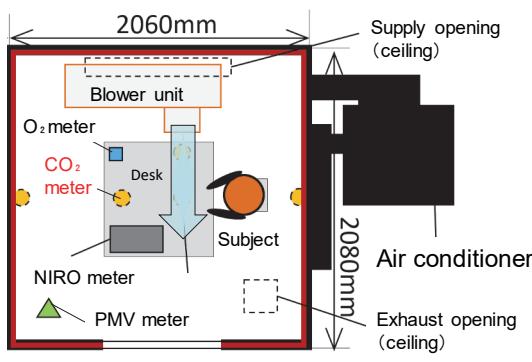
2 Outline of the Experiment

2.1. Chamber for the experiment

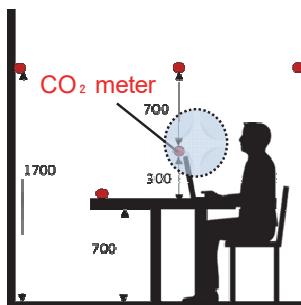
The experiments were conducted in a chamber in which both temperature and humidity would be controlled independently. The size of the space is 2060 mm in width, 2080 mm in depth and 2700 mm as the ceiling height. Inside the chamber, supply and exhaust openings were set at the ceiling, and temperature and humidity were kept constant at the target point. The subject sat on the seat. To control the CO_2 concentration which would be drawn in subject's breath, the blower unit, which

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would diffuse the air around the subject's nose, was installed as shown in Figures 1-2.

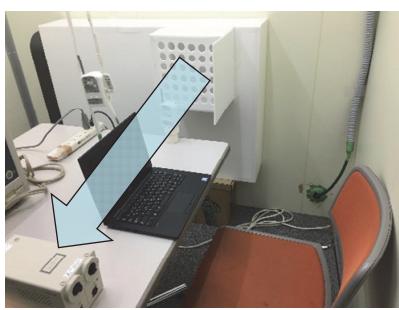


(a) Plan of the chamber.



By using the blower unit to diffuse the air around the subject's nose, we assumed that the CO₂ concentration of the CO₂ meter is the same as the inhaled air of the subject.

(b) Section of the chamber.
Fig. 1. Outline of the chamber.



(a) Inside view of the chamber.



(b) View of the blower unit to diffuse the air.
Fig. 2. View of the chamber.

2.2. Measurement items

Temperature, humidity, and the CO₂ concentration was measured inside the chamber. The blood pressure, the pulse and the salivary amylase of the subject were measured as a physiological condition. And total oxygen

index (TOI), change in concentration of oxygenated haemoglobin ($\Delta \text{O}_2\text{H}_b$), deoxygenated haemoglobin (ΔHH_b) and total haemoglobin (ΔcH_b) of the subject's blood flow in the brain were also measured using tissue oxygenation monitor (NIRO meter) that uses near infrared spectroscopy.

2.3. Outline of the experimental cases

2.3.1 Cases analysed

Table 1. Cases analysed.

	CO ₂ condition		Thermal condition		Lighting condition			
	CO ₂ concentration (ppm)	Wearing a mask	Tempera-ture (°C)	Relative humidity (%RH)				
Case.1	600	Not wearing	25	50	750			
Case.2	1500							
Case.3	3500							
Case.4	600	Wearing	27	50	750			
Case.5	600	Not wearing						
Case.6	600 -> 1500							
Case.7	600 -> 3500	25						

7 cases of experiment were conducted as shown in Table 1.

2.3.2 Steady CO₂ concentration

In cases from Case.1 to Case.5, CO₂ concentration was set steady in each case. These cases were conducted to verify the fundamental properties of human with different CO₂ concentration.

Indoor CO₂ concentration was set at 600 ppm (Case.1), 1500 ppm (Case.2) and 3500 ppm (Case.3). The experiment in which the subject had worn the mask was also executed (Case.4). In Case.4, CO₂ concentration which would be drawn in subject's breath was assumed 5000 ppm, when calculating on the condition that the amount of air between the mask and the face was 150 ml, the CO₂ concentration of vomited breath was 3.5 %, the CO₂ concentration of room was 600 ppm and the air leakage rate of mask was 50 %.

Indoor air temperature and humidity were kept constant in each case (25 °C, 50% RH). However, effects of the changing room temperature to 27 °C were also investigated (Case.5).

It is considered that high concentration of CO₂ leads to lowering concentration ability and promoting drowsiness. It might also have an influence on productivity and learning efficiency of human. Therefore, the amount of workability, and the physiological and psychological response of the subjects were also measured in these cases.

5 healthy male students were selected for the subjects. The experiment was executed by 25 cases with 5 cases a person in total during October 3 - November 6 in 2017.

The experiment procedure is shown in Figure 3. First of all, subject stayed for 30 minutes for the adaptation. Then the typing work was done for 60 minutes. Finally, subject rested for 15 minutes. At the measurement A, B and C, the blood pressure, the pulse and the salivary amylase of the subject were measured. TOI, $\Delta O_2 H_b$, ΔHH_b and ΔcH_b of the subject's blood flow were measured from A to C. At B and C, questionnaire survey had done.

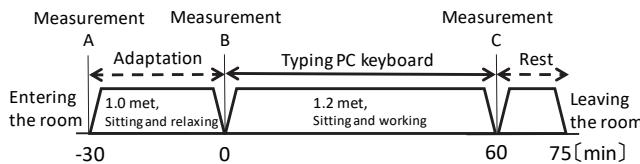


Fig. 3. Time table of the steady CO₂ concentration cases.

2.3.3 Non-steady CO₂ concentration

In cases of Case.6 and Case.7, CO₂ concentration was set non-steady condition in each case. These cases were conducted to assume the actual work environment. In Case.6, the situation when a person entered the office space without enough ventilation was assumed. In Case.7, the situation when several persons entered the meeting room without enough ventilation was assumed. Indoor CO₂ concentration was changed from 600 ppm to 1500 ppm (Case.6), from 600 ppm to 3500 ppm (Case.7) in 30 minutes.

3 healthy male students were selected for the subjects. The experiment was executed by 6 cases with 2 cases a person in total during November 10 - 20 in 2017.

The experiment procedure is shown in Figure 4. First of all, subject stayed for 30 minutes for the adaptation. Then the typing work was done for 30 minutes, and during it, CO₂ concentration was changed. Finally, subject rested for 30 minutes. Measurement items were the same as steady CO₂ concentration cases.

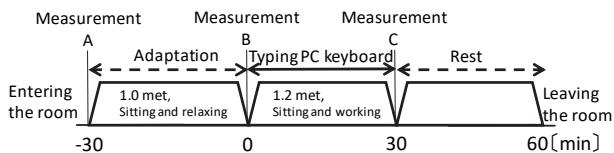


Fig. 4. Time table of the non-steady CO₂ concentration cases.

2.3.4 CO₂ concentration of each case

Figure 5 shows the CO₂ concentration of each time in each case. CO₂ concentration of Case.1, Case.2 and Case.3 was controlled constantly during the experiment. And CO₂ concentration was changed from 600 ppm to 1500 ppm (Case.6), from 600 ppm to 3500 ppm (Case.7) gradually from "B" to "C" in 30 minutes. Then, CO₂ concentration of Case.6 and Case.7 was returned to 600 ppm after "B" in 30 minutes.

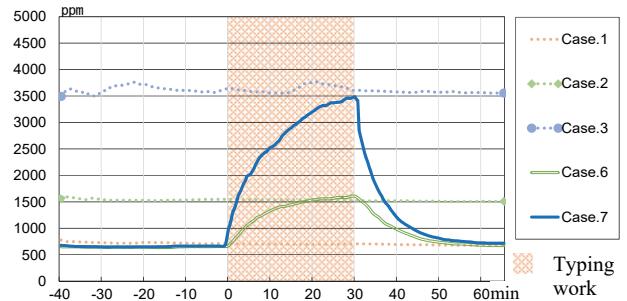


Fig. 5. CO₂ concentration in each case.

3 Results of steady CO₂ concentration

3.1 Subject declaration

Because CO₂ was a gas not perceived, a significant difference of subject declaration of satisfaction to air quality was not seen between cases in Figure 6 ("B" and "C" in the figures mean the survey done at the measurement B and C shown in the timetable Figure 3).

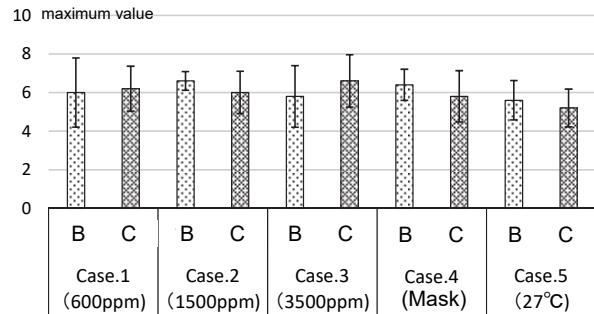


Fig. 6. Subject declaration of satisfaction to air quality.

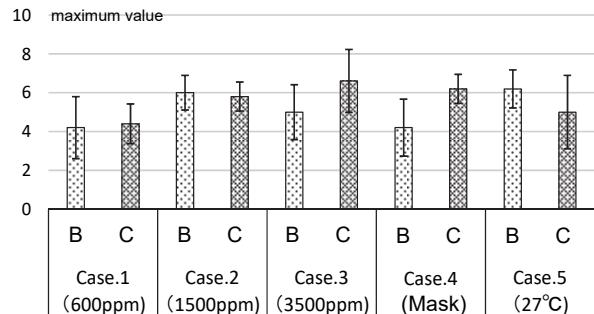


Fig. 7. Subject declaration of drowsiness degree.

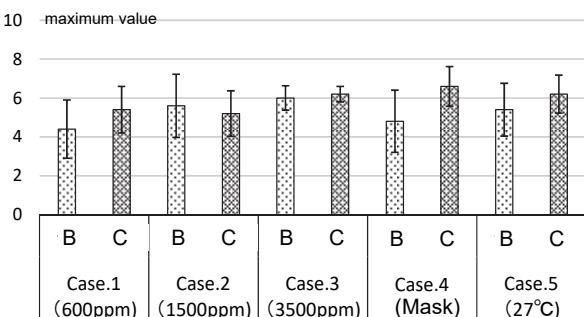


Fig. 8. Subject declaration of worthlessness feeling.

However, as the CO₂ concentration rose, the decreasing tendency was seen in concentration ability and work efficiency, on the other hand increasing tendency was seen in the drowsiness degree and the worthlessness feeling in Figures 7 and 8.

The subject declaration change rates from “B” to “C” from Case.1 to Case.5 of 4 items (air quality, drowsiness degree, worthlessness feeling and concentrated level) is shown in Figure 9. The difference is seen in Case.3 and Case.4, and the drowsiness feeling is increased with Case.4 by 48%, and it has increased with Case.3 by 32%. The difference of the worthlessness feeling is seen in Case.4 and the worthlessness feeling of Case.4 has increased by 38%. As for the concentrated level, Case.4 has decreased most greatly by 24%.

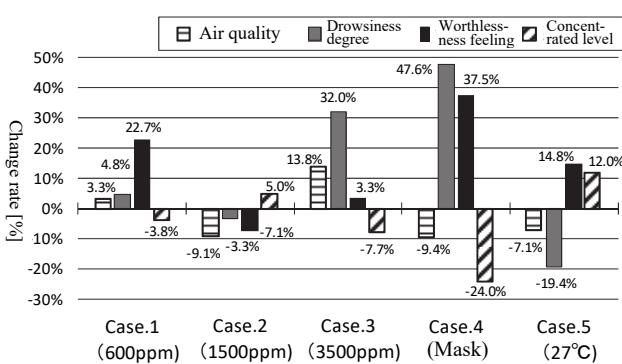


Fig. 9. Subject declaration change.

3.2 Subject productivity

Relations between the number of total input characters, correct input characters, ratio of error input characters of the typing test, and the CO₂ concentration are shown in Figures 10 -13. The number of total input characters and the number of correct input characters had the decreasing tendency as the CO₂ density rose (Figures 10 and 11). The error input rate had the increasing tendency as the CO₂ density rose (Figures 12 and 13). However, the temperature change had the little influence on the error input rate (Figure 13).

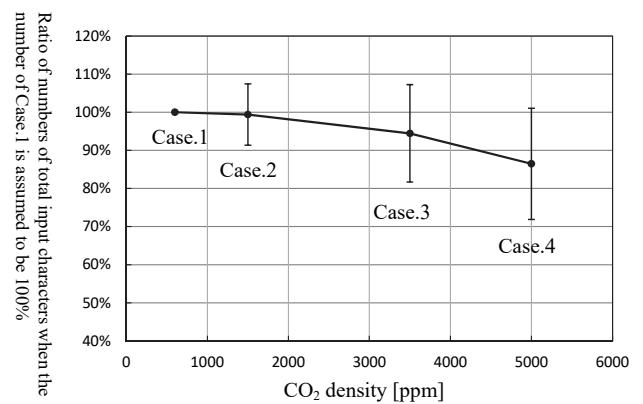


Fig. 10. Relation between the number of total input characters and the CO₂ density.

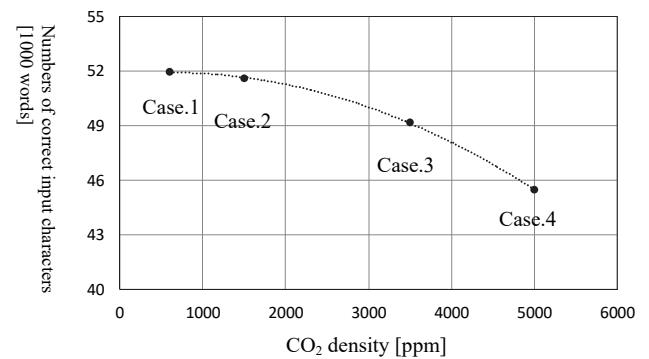


Fig. 11. Relation between the number of correct input characters and the CO₂ density.

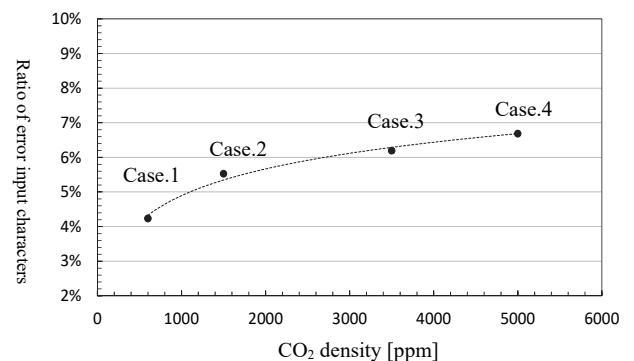


Fig. 12. Relation between the ratio of error input characters and the CO₂ density.

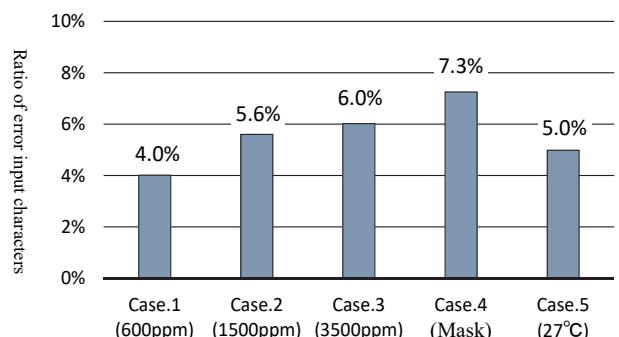


Fig. 13. Relation between the ratio of error input characters and the CO₂ density.

3.3 Physiological condition

To verify the physiological condition, tissue oxygenation index (TOI) of the blood in the brain was monitored. Change in concentration of oxygenated haemoglobin (ΔO_2H_b), deoxygenated haemoglobin (ΔHH_b) and total haemoglobin (ΔcH_b) of the subject's blood flow were also measured, however the result of TOI was shown as a representative. TOI shows the oxygen saturation of the hemoglobin of the blood. The relation between the number of total input characters, the TOI value and the CO₂ density is shown in Figure 14. TOI also rose as the typing work. Therefore, Figure 14 shows the averaged TOI value during typing work. As the CO₂ concentration rose, similar tendency between the number of characters and TOI was seen.

This time, we did not obtain clear difference of the blood pressure, the pulse and the salivary amylase of the subject.

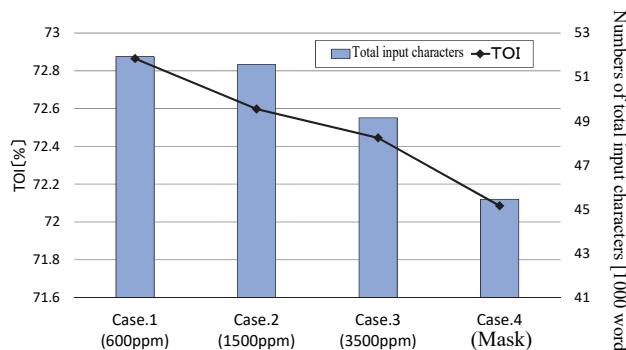


Fig. 14. Relation between the number of total input characters, the TOI value and the CO₂ density.

4 Non-steady CO₂ concentration

4.1 Subject declaration

The subject declaration change rates from "B" to "C" of Case.6 and Case.7 of 6 items (air quality, relaxation level, drowsiness degree, worthlessness feeling, concentrated level and productivity) is shown in Figure 15. The increasing tendency was seen in the drowsiness degree and the worthlessness feeling. And decreasing tendency was seen in the concentrated level and the productivity.

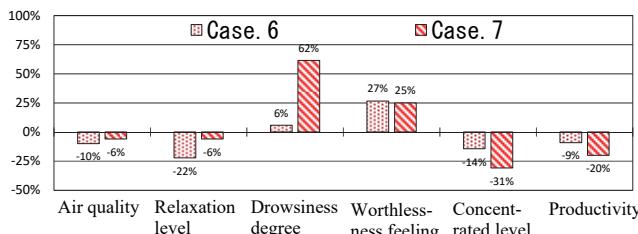


Fig. 15. Subject declaration change rates.

4.2 Physiological condition

Tissue oxygenation index (TOI) and the change in concentration of the oxy- hemoglobin (ΔO_2H_b) of the blood also rose as the typing work. Therefore, to analyse the change of the TOI and ΔO_2H_b , and to examine the physiological mechanism, the added experiments without typing work were conducted.

Figure 16 shows the TOI and ΔO_2H_b of Case.6, and Figure 17 shows them of Case.7.

In Case.6, CO₂ concentration is changed from 600 ppm to 1500 ppm gradually after 0-minute point (Figure 5). At the beginning of the change of the CO₂ concentration, it seems to be little difference in the TOI and ΔO_2H_b . However, after the CO₂ concentration reached to 1500 ppm (at 15 minutes' point), both TOI and ΔO_2H_b increased rapidly. Even if the CO₂ concentration is not so high, physiological condition of the human would be affected by the change of CO₂ concentration.

In Case.7, CO₂ concentration is changed from 600 ppm to 3500 ppm rapidly after 0-minute point (Figure 5). As increasing the CO₂ concentration, both TOI and ΔO_2H_b increased, different from Case.6. However, after a while, they fell. It is thought that it is because of the physiological response of the human body and we will analyse the physiological mechanism further.

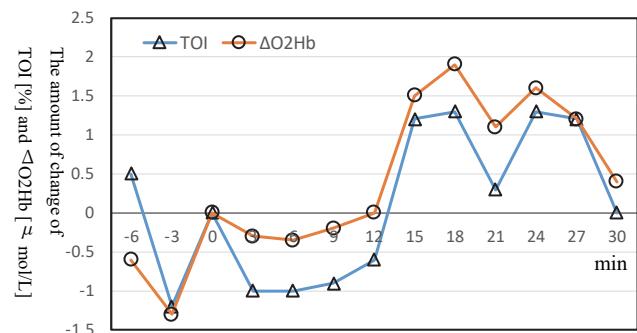


Fig. 16. TOI and the oxy- hemoglobin (ΔO_2H_b) of the blood (Case.6).

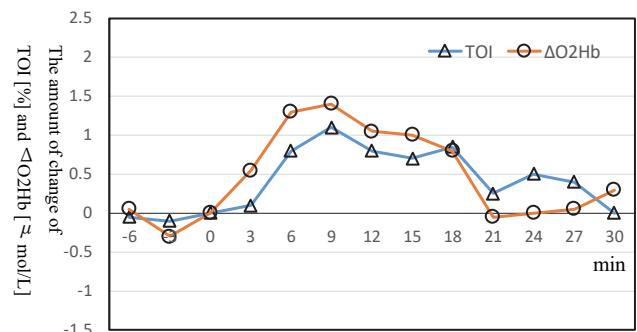


Fig. 17. TOI and the oxy- hemoglobin (ΔO_2H_b) of the blood (Case.7).

5 Conclusion and discussion

We conducted experiments to measure the amount of workability and the physiological and psychological response of the subjects. We used a laboratory room in which not only the CO₂ concentration, but also temperature and humidity can be controlled. In the experiment, the concentration of CO₂ was set at the constant level at each case to verify the influence of the CO₂ concentration. And then, the concentration of CO₂ was changed to examine the physiological and psychological response to clarify the mechanism.

The following results were obtained.

The tendency that the drowsiness feeling and the worthlessness feeling grew by high CO₂ concentration, was seen from the result of the subjective assessment. In the result of the typing work, it was suggested that it became a decreasing tendency as the CO₂ concentration rose, and the CO₂ concentration had the influence on productivity and working efficiency of human.

It has been understood that there is a possibility that the productivity is related to the tissue oxygenation index (TOI) and the change in concentration of the oxy-hemoglobin (ΔO_2H_b) of the blood.

It has also been suggested that the change of the CO₂ concentration affects the change of the TOI and ΔO_2H_b of the blood. Even if the CO₂ concentration is not so high, physiological condition of the human would be affected by the change of CO₂ concentration.

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