

Peer Reviewed

Acceptability of Elevated Breathing Gas Temperature and Humidity in Relation to Ventilation Rate

Masayoshi Takahashi¹, Yoshihiro Mano², Masaharu Shibayama³, Nobuo Yamami²

¹ National Institute for Resources and Environment, 16-3 Onogawa,
Tsukuba, Ibaraki 305-8569, Japan

² Tokyo Medical and Dental University

³ Komazawa Women's University

Abstract

The purpose of the study was to determine the effects of elevated inhalation temperature, humidity and ventilation rate on the heat perception of users of closed-circuit breathing apparatus (CCBA). Two types of test were conducted and demonstrated that, at a moderate exercise level, the wet-bulb temperature was the controlling factor in the user's perception of heat, the dry-bulb temperature had no effect on the heat perception, and the maximum breathable temperature did not practically depend on the ventilation rate.

Introduction

Closed-circuit breathing apparatuses (CCBAs) are useful tools for escape and rescuer activities in an oxygen-deficient or toxic atmosphere. However, this type of apparatus does impose some physiological stressors due to necessary components. Elevated inhalation temperature is one of them and is caused by a chemical reaction removing the exhaled carbon dioxide or generating oxygen to compensate for the oxygen consumption of users. Many authors have investigated the effects of elevated inhalation temperature on the human body (Babb *et al.* 1989; Dahlback and Jorfeldt 1986; Gwosdow *et al.* 1989; Killick 1932; Lind 1955; McCutchan and Taylor 1951), and one of the most important findings was the close correlation between the inspired wet-bulb temperature and tissue temperatures in the respiratory tract (Gallagher *et al.* 1985; Gallagher and Vercruyssen 1986; Kyriazi 1988). They declared the advantage of using the wet-bulb temperature as an indicator for deciding the appropriateness of the apparatus as far

as the heat property was concerned. Considering the wet condition of the tissues in the mouth and the respiratory tract, it is reasonable to evaluate the thermal impact of the inhaled gas by its wet-bulb temperature. To the authors' knowledge, it is not yet clarified that the sensation of hotness is decided by only the wet-bulb temperature, especially in the case of hot and dry air possibly causing the respiratory tract to dry out. And another concern is the effect of ventilation rate. As suggested by Gallagher *et al.* (1985), higher ventilation caused the heat transfer from the gas to the body to increase and possibly raised tissue temperatures in the respiratory tract. So the purpose of the study was to determine the combined effects of temperature and humidity of inhaled air on the heat perception of human subjects, and clarify the effect of increased ventilation rate to the heat perception from the point of view of evaluating the heat property of CCBAs.

Method

Apparatus

Figure 1 shows the schematic diagram of the apparatus that provided hot and humid air to a subject for breathing. The subject inhaled the air through a breathing tube and a mouthpiece, and exhaled the air to ambient through a one-way valve near the mouthpiece. A blower delivered the ambient air to a wet chamber with the air bubbled through a water bath to add water vapor. The air was introduced to a dry chamber and heated to achieve the required temperatures and relative humidity. The accuracy of the controlled temperatures of the chambers was better than $\pm 0.1^\circ\text{C}$. The breathing tube was also heated to the same temperature as the dry chamber to avoid cooling by the

ambient air. The surface temperature of the hard palate of the subject was measured throughout the test by a thermocouple (CA) which was set in the mouthpiece and supported by a wire to contact with that surface during exercise. The temperature and humidity of the inhaled air were previously measured at the mouthpiece by an Assmann's psychrometer, and Table 1 shows the results. During the subject tests the inhaled dry- and wet-bulb temperatures were extrapolated from the controlled temperatures of the dry and wet chambers.

According to the required test conditions, carbon dioxide was added to the air from a compressed-gas cylinder and its concentration of the air was measured by a gas analyzer.

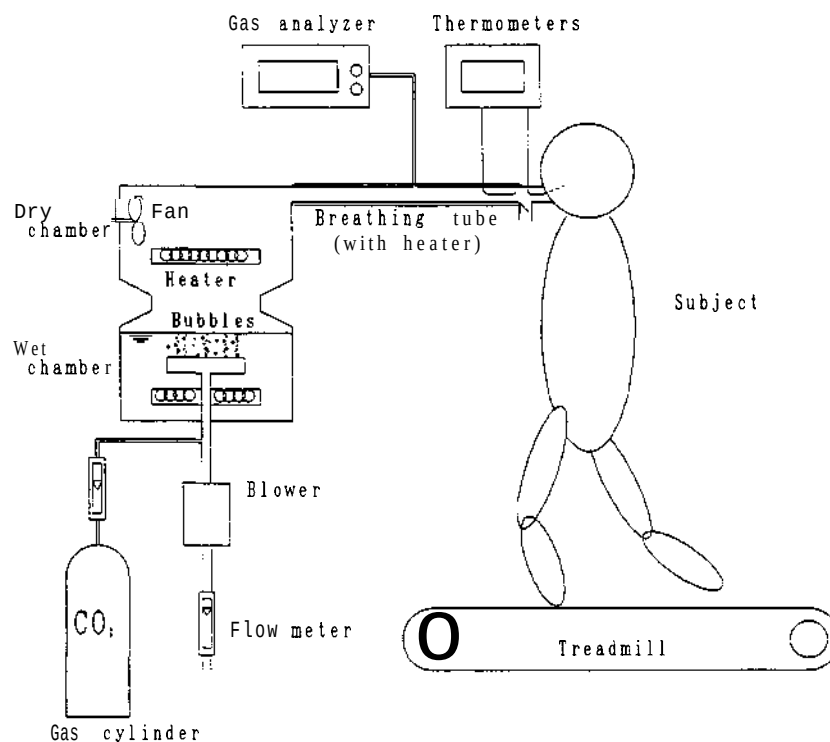


Figure 1. Schematic diagram of apparatus used in the tests.

Table 1. The relationship between the temperatures in the chambers and at the mouthpiece.

Test no.	Laying temp. in the chambers (°C)		Measured temp. at the mouthpiece(°C)	
	The dry chamber	The wet chamber	Dry-bulb	Wet-bulb
1	60.0	52.0	59.9	53.2
2	60.0	54.2	60.0	55.0
3	70.0	50.0	69.9	52.7
4	70.0	53.3	70.0	55.5
5	80.0	49.0	79.8	52.5
6	80.0	52.5	79.7	55.5
7	90.0	51.0	89.6	55.0
8	90.0	51.5	89.6	55.5

Test I: Acceptability of Increased Dry- and Wet-Bulb Temperature of Inhaled Air

The purpose of this test was to reveal the combined effect of increased dry- and wet-bulb temperature on human heat perception. Three male subjects volunteered to participate in the tests with knowledge of the possible risks related to the tests. The characteristics of the subjects are shown in Table 2 as subject 1 to 3. Each subject worked on a treadmill horizontally for 5 minutes at the speed of 5 km/h while breathing hot and humid air supplied from the apparatus. A series of tests was conducted with given dry- and wet-bulb temperatures of the inhaled

air, and the limit of breathable condition were decided on the basis of the results. Initially, the dry-bulb temperature was set to be 60°C and the wet-bulb temperature was increased from 50°C in steps of 0.5°C. The highest wet-bulb temperature at which a subject was able to breathe for 5 minutes was noted as the tolerance limit at that dry-bulb temperature. One subject repeated for dry-bulb temperatures of 70°C, 80°C, and 90°C, and the others repeated for 80°C.

Test II: Effect of Increased Ventilation Rate on Acceptability

This test was performed to determine the effect of ventilation rate on 11 male subjects (Table 2) who volunteered to participate in the tests with knowledge of the possible risks related to the test. Each subject breathed hot and humid air through the mouthpiece as long as he could. The dry-bulb temperature of the supplied gas was fixed at 60°C and the wet-bulb temperature was increased continuously from 50°C at the rate of 0.6°C per minute. The wet-bulb temperature at which the subject stopped the test was noted as the tolerance limit at that ventilation rate. Each test was performed at one of the following test conditions. The reason of change in work rate and addition of carbon dioxide in inhaled air was to expand the range of ventilation rate:

- A: Breathing ambient air while walking on the treadmill horizontally.
- B: Breathing air containing 3% CO₂ while walking on the treadmill horizontally.
- C: Breathing ambient air while walking on the treadmill with an inclination of 5%.

The walking speed for each test was 5 km/h. Each subject performed 2 tests with one at test condition A and the other at either B or C, depending on the subject. As shown in Table 2, the ventilation rates at each test conditions were previously measured with a metabolic analyzer (AIC Co. SYSTEM-5).

Table 2. Individual subject characteristics.

Subject	Age	Height (cm)	Weight (kg)	Ventilation rate (L/min:BTPS) at each test condition		
				A	B	C
1	33	169	69	28.3	36.3	—
2	31	174	67	28.4	51.0	—
3	31	172	75	27.6	40.3	—
4	31	175	65	27.9	43.9	42.6
5	57	162	57	20.8	—	26.0
6	34	181	72	27.6	31.7	—
7	26	180	70	26.4	45.8	—
8	42	171	64	25.5	28.5	—
9	25	175	57	25.0	—	35.7
10	37	172	70	23.0	—	31.8
11	30	182	65	30.6	—	36.2
Mean	34.3	174.0	66.5	—	—	—
S.D.	8.5	5.5	5.4	—	—	—

The values in column A were the ventilation rates while the subjects walked on a treadmill at 5 km/h horizontally breathing ambient air. The test condition of B was same with that of A except the inhaled air contained 3% carbon dioxide. In the case of C, the subjects inhaled ambient air while walking on the treadmill with an inclination of 5%.

Results

Test I: Combined effect of increasing dry- and wet-bulb temperature

Figure 2 shows the results of the testing. Each data point corresponds to the highest tolerable wet-bulb temperature at a particular dry-bulb temperature with each test subject denoted by a different symbol. The solid line was drawn using the method of least squares and indicates the upper limit of breathable air conditions. The line is almost parallel to the horizontal in the range of dry-bulb temperatures we examined. This means that the wet-bulb temperature is the primary factor determining whether the gas is breathable or not and that dry-bulb temperature is irrelevant in that determination. The highest tolerable wet-bulb temperature of inhaled air was between 52 and 54°C.

Test II: Effect of increased ventilation rate on acceptability

Figure 3 shows the upper limit of breathable wet-bulb temperature as a function of ventilation

rate. When these values are compared with those of test at almost the same ventilation rate, the former are a little higher than the latter. The reason for the discrepancy must be attributed to the difference in the test methods. The solid line was obtained from the acquired data by using the method of least squares. This line is described by the following equation:

$$T_{WB} = 55.4 - 0.057V_E$$

where T_{WB} is the highest tolerable wet-bulb temperature(°C), V_E is the ventilation rate (L/min) expressed by BTPS (body temperature and pressure saturated with water vapor). The standard estimate of error is 0.53(°C) for this linear regression.

Figure 4 shows the heat transfer from the inhaled gas to the mouth and respiratory tract per minute at the breathable limit. The heat transfer is an isobaric process, so the acquired heats were obtained by the calculation of the difference in enthalpies between

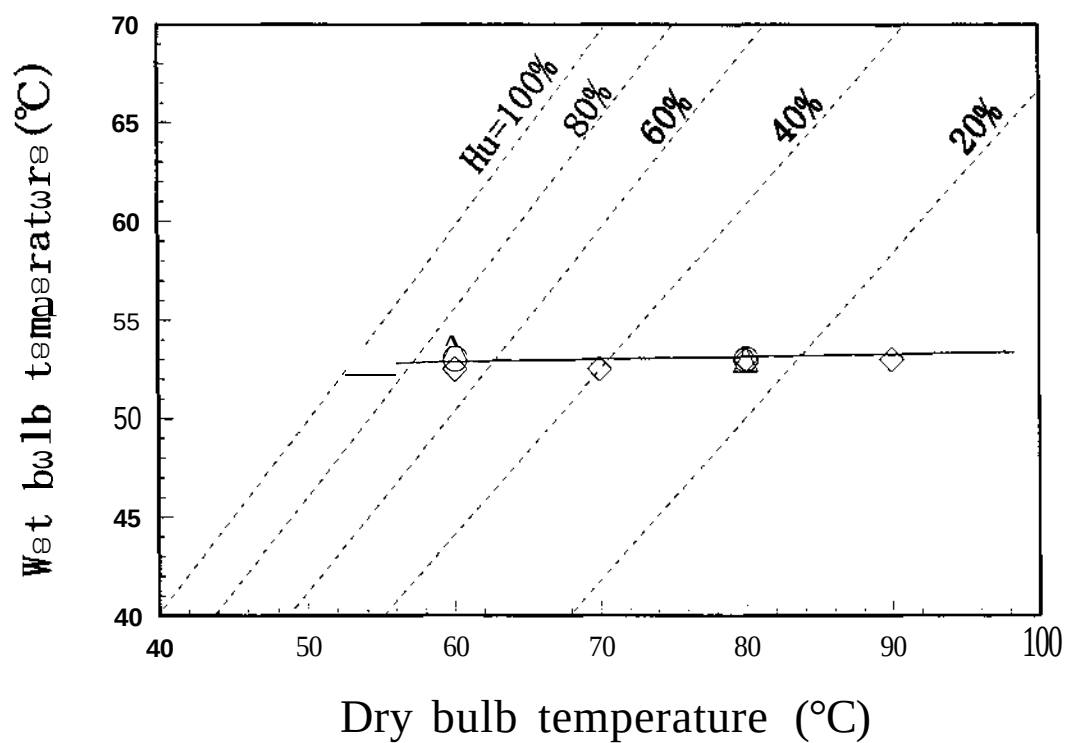


Figure 2. The limitation of breathable temperature. The different symbols identify the results for the different subject.

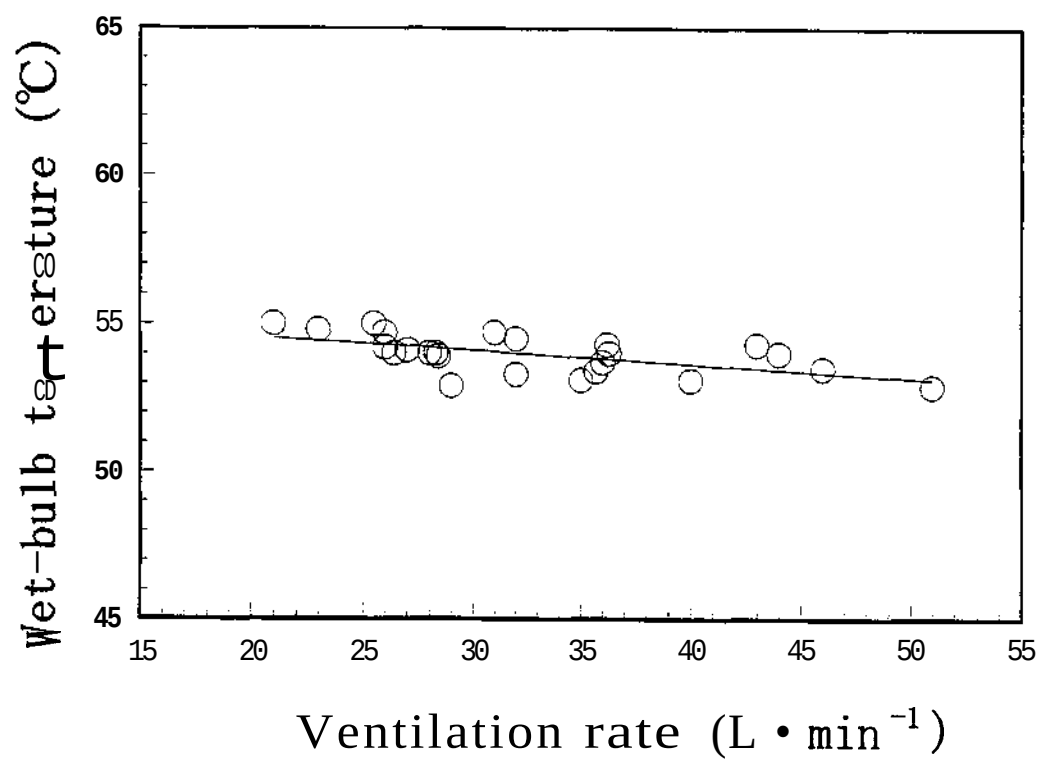


Figure 3. The relationship between ventilation rate and breathable maximum temperature.

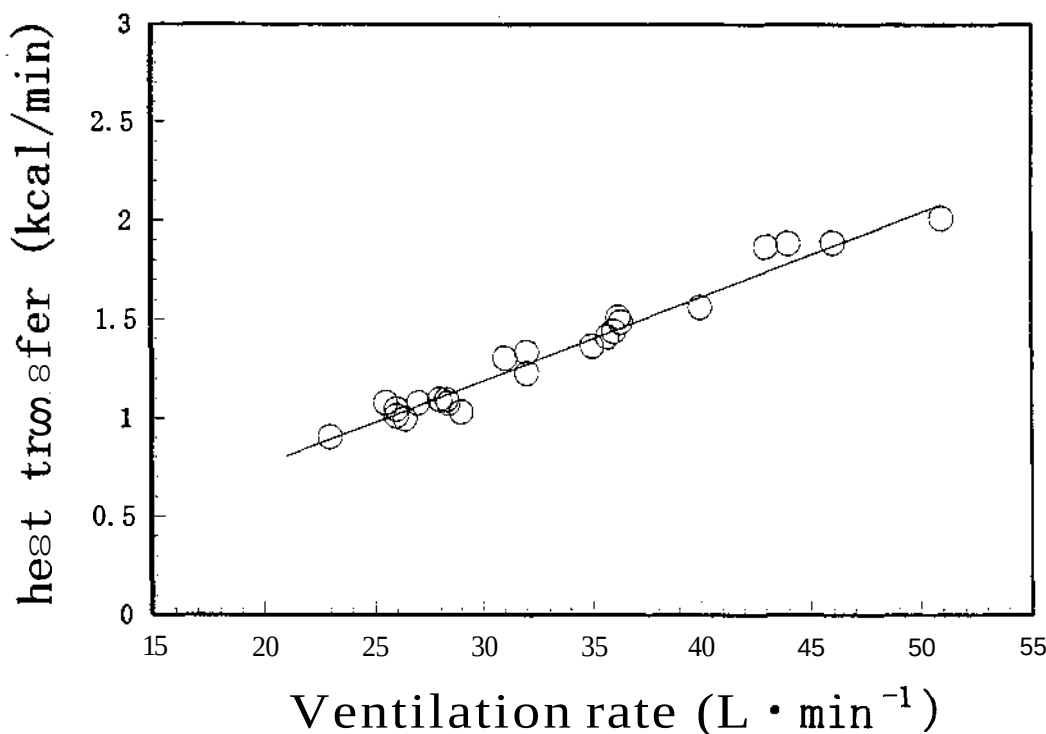


Figure 4. Change in the heat transfer with ventilation rate.

the inhaled and exhaled gases. The calculations are as follows:

$$P_W = P_S - 0.5 \times (T_D - T_W) \times P / 100.6$$

$$x = 0.622 \times P_W / (P - P_W)$$

$$V_E(\text{STPD}) = V_E(\text{BTPS}) \times ((P - 6.3) \times 273) / (101.3 \times (273 + 37))$$

$$W = V_E(\text{STPD}) / 22.4 \times 29$$

$$H = C_{PA} \times T_D + (r + C_{PW} \times T_D) \times x$$

$$Q = (H_{In} - H_{Ex}) \times W$$

where P_W (kPa) is the vapor pressure of the gas, T_D (°C) is the dry-bulb temperature, T_W (°C) is the wet-bulb temperature, P_S (kPa) is the saturated vapor pressure at temperature T_W , P (kPa) is the ambient

pressure, x (kg/kg) is the absolute humidity, $V_E(\text{STPD})$ is the ventilation rate(L/min) at standard temperature and pressure, dry, $V_E(\text{BTPS})$ is the value at body temperature and pressure, saturated with water vapor, W (kg/min) is weight of inhaled gas as dry air, H (kJ/kg) is enthalpy of hot and humid air, C_{PA} and C_{PW} (kJ/(kg · K)) are specific heat at constant pressure of air and water vapor, r (kJ/kg) is latent heat of water, H_{In} and H_{Ex} (kJ/kg) are enthalpy of inhaled and exhaled gas, and Q (kJ/min) is acquired heat. The inclination of the line in the figure shows that subjects got more heat from the gases at the higher ventilation rate.

Figure 5 shows the temperature of the hard palate at the breathable limit. Open circles indicate the peak values during inhalation, and closed circles indicate the peak during exhalation. All of the values lay between the inhalation wet-bulb temperatures and body temperature which was assumed to be 37°C. The inhalation temperature data was scattered in a wide range, while the exhalation temperature data was more consistent throughout the range of ventilation rates at approximately 42°C.

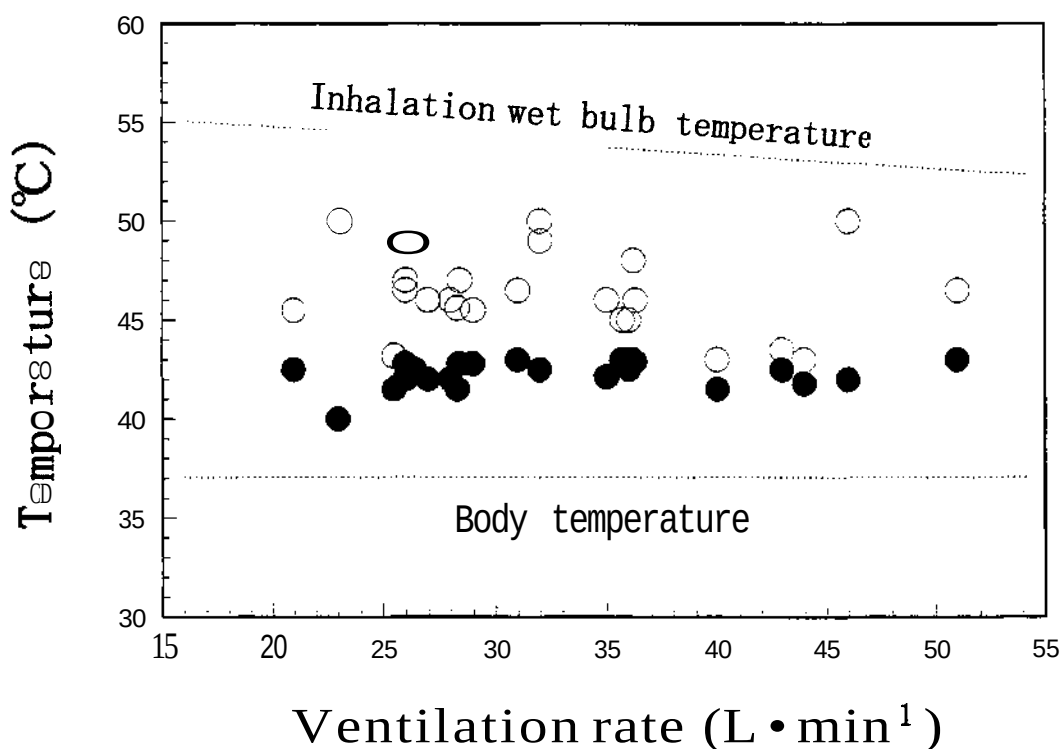


Figure 5. Change in hard palate temperature with ventilation rate: Open circles—at inhalation, Closed circles—at exhalation.

Discussion

The surface temperatures of the tissue in the mouth and respiratory tract are the major determiners of human heat perception. If the surface of a material is wet, the surface temperature will be close to the wet-bulb temperature of the ambient air. The temperature of a dry surface, however, will be the dry-bulb temperature of the ambient air. From a thermodynamic point of view, at a dry surface, the heat transfer will continue between the surface and the environment until the both temperatures are equal. But when the surface is wet, thermal equilibrium will be reached at a lower surface temperature than the value at a dry surface because heat is removed from the surface as the latent heat of water vaporization. The temperature of the wet surface will be coincident with the wet-bulb temperature of the ambient air. So, considering the wet conditions in the mouth and respiratory tract, as Gallagher *et al.* (1985) reported, we can rely on the wet-bulb temperature of the inhaled air to evaluate the thermodynamic impact of CCBAs on humans. If, however, an apparatus produces hot and dry air sufficient to dry

out the normally wet surfaces of the mouth and respiratory tract, the dry-bulb temperature of the inhaled gas will better approximate the temperature of the mouth and respiratory tract. This temperature is higher than the wet-bulb temperature except in the case of completely saturated gas. But Fig. 2 showed that the hottest air that was breathable was not depending upon the dry-bulb temperature, but it was clearly defined by the wet-bulb temperature. The driest air in these tests was at 90 dry-bulb and 53 wet-bulb with a relative humidity of less than 20%. Since this condition was representative of KO2-type CCBAs, and since the supply of saliva in the mouth and respiratory tract was enough to keep the tissues wet, we can be confident in using only wet-bulb temperature to evaluate the thermal impact of CCBAs.

Since higher ventilation rates result in more heat transfer to the body while the subject is breathing a hotter gas than the body temperature, we considered the possibility that the highest tolerable

air temperature would be lower at higher ventilation rates. But, as Fig. 3 shows, we did not find any substantial effect of ventilation rate on heat perception. The increase in heat transfer from elevated ventilation might lead to an expansion in the region of higher temperature in the respiratory tract, but it did not result in an increase in the surface temperature near the outlet of the mouthpiece, as shown in

Fig. 5. It seems, therefore, that ventilation rate need not be considered when setting an upper wet-bulb temperature limit on inhaled air. So it could be said that, for considering the criteria of the thermodynamic property of inhalation gas, the ventilation rate is not very a important factor to decide the permissible wet-bulb temperature.

Conclusions

Acceptability of elevated breathing gas temperature and humidity was studied in 11 male subjects. It has been demonstrated that, at a moderate exercise level, the wet-bulb temperature was the controlling

factor in the user's perception of heat, the dry-bulb temperature had no effect on the heat perception, and the maximum breathable temperature did not practically depend on the ventilation rate.

Acknowledgement

We are very grateful to thank Dr. Nicholas Kyriazi of the U.S. National Institute for Occupa-

tional safety and Health for constructive comments during the preparation of this manuscript.

References

- Babb T., Turner N., Saupe K., Pawelczyk J. Physical performance during combinations of hypercapnic, resistive, and hot air breathing. *Am. Ind. Hyg. Assoc. J.* 50: 105-111, (1989).
- Dahlback G. O., Jorfeldt L. Work performance when using a closed-circuit oxygen breathing apparatus. */ ISRP 4* : 95-123, (1986).
- Gallagher S., Vercruyssen M., Deno N. S. Hot air breathing: Effects of elevated wet bulb temperature on tissue temperature of the mouth. *Am. Ind. Hyg. Assoc. J.* 46 :332-335, (1985).
- Gallagher S., Vercruyssen M. Interaction of temperature and humidity of inspired air on tissue temperature of the tongue and hard palate. */ ISRP 4* : 20-42, (1986).
- Gwosdow A. R., Nielsen R., Berglund L. G., Dubois A. B., Termml P. G. Effect of thermal condition on the acceptability of respiratory protective devices on humans at rest. *Am. Ind. Hyg. Asso. J.* 50: 188-195, (1989).
- Killick E. M. Physiological response to breathing hot air. */ Hyg.* 32 : 332-339, (1932).
- Kyriazi N. Fast-Response, Wet-Bulb Thermocouple. */ ISRP 6*:12-14, (1988).
- Lind A. R. The influence of inspired air temperature on tolerance to work in the heat. *Brit. J. Ind. Med.* 12 : 126-130,(1955).
- McCutchan J. W., Taylor C. L. Respiratory heat exchange with varying temperature and humidity of inspired air. */ Appl. Physiol.* 4 : 121-135, (1951).