Thermal Problems in Hyperbaric Environments

Naoshi KAKITSUBA

Department of Environmental Science and Technology, Meijo University
1-501 Shiogamaguchi, Tenpaku-cho, Nagoya-shi 468-8501, Japan
email: naoshi@ccmfs.meijo-u.ac.jp

Abstract

This paper reviews thermal problems in hyperbaric environments and provides information how to estimate thermal comfort zones in hyperbaric environments.

Divers are exposed to hyperbaric helium-oxygen atmospheres when engaged in saturation diving operations. However, some difficulties to control thermal environments arise from the extremely high thermal conductivity of helium used as a breathing gas and from increased pressure. In order to obtain data available for control of thermal environments, many theoretical and empirical studies have been carried out to estimate heat exchange between man and his environments. For example, male divers wearing different clothing ensembles were exposed to six different pressures for evaluating change in clothing insulation. In addition, a lightly clothed male diver exercised on a bicycle ergometer while exposed to five different pressures to evaluate changes in clothing permeability. The results demonstrated that clothing insulation decreased with change in ambient gases and clothing permeability decreased slightly despite changes in ambient gas and barometric pressure.

As represented by this example, in hyperbaric helium-oxygen atmospheres, the manner of heat exchange between man and his environments becomes apparently different from that in normobaric air. The last part of this paper demonstrates the comfort range of ambient temperatures at increased barometric pressures.

Key words: clothing insulation, clothing permeability, hyperbaric environment, thermal comfort, temperature

1. Introduction

Since a saturation diving system was established in 1970, helium has been used as the major inert breathing gas to prevent decompression sickness because of its low solubility and high diffusivity in the human body tissues. However, a hyperbaric helium-oxygen atmosphere has two unique thermophysical characteristics; high thermal conductivity and low diffusivity of water vapor, relative to normobaric air.

High thermal conductivity of helium increases the amount of convective heat exchange between the human body and its environment for a given temperature difference between the skin and ambient temperature. In addition, convective heat loss or gain by respiration becomes significant. Low diffusivity of water vapor reduces the evaporative capacity of ambient gases. Therefore, an inappropriately controlled exposure causes a diver to undergo serious thermal stresses, *e.g.*, hypothermia, hyperthermia, diuresis and heat stroke.

From the mid-1960s to the end of 1980s, many clinical and scientific studies (for example, Epperson, 1966; Raymond *et al.*, 1968; Timbal *et al.*, 1974; Nakayama, 1979; Kakitsuba *et al.*, 1981) were carried out primarily to evaluate the effects of theromophysical properties on physiological responses that are directly related to the heat exchange between the human body and its environment. At the same time, theoretical studies (for example, Nevins *et al.*, 1965; Nishi & Gagge, 1977) attempted to predict optimal thermal conditions when a man is exposed to hyperbaric helium-oxygen atmospheres.

Although the basic knowledge of controlling thermal environments was provided, more extensive studies have been required for better protection of the divers from heat stress. Regarding thermoregulation, for example, many studies (Cook, 1950; Young & Cook, 1953; Matsuda *et al.*, 1975; Shiraki *et al.*, 1984; Mekjavic *et al.*, 1995) have contributed to understanding of effects of increased pressure or breathing helium-rich gas on thermoregulation when a man is exposed to pressurized atmospheres. This paper reviews these pioneer studies briefly and provides information relevant for controlling thermal environments in hyperbaric helium-oxygen atmospheres.

2. Parameters Relevant for Thermal Control and Comfort in Hyperbaric Conditions

2.1 Convective heat transfer coefficient of the human body in hyperbaric helium-oxygen atmospheres

As indicated in Fig.1, metabolic heat is mainly dispersed from the skin by convection, radiation, evaporation and conduction to maintain body temperature (Hardy & DuBois, 1937). Convective heat transfer coefficient of the human body (h_c) is an essential factor to estimate the amount of convective heat exchange between the human body and its environment. In normobaric air, many prediction equations have been proposed for various activities and postures. For example, the h_c values of 2.0 to 4.0 (W/m^2·°C) are used for the sedentary subjects in still air.

Definition of convective heat transfer coefficient is depended on physical properties of ambient gases. For comparison, theromophysical properties of air and helium are listed in Table 1. Helium (He) is characterized by high thermal conductivity. Figure 2 illustrates change in partial pressure of breathing gas components as a function of depth. According to breathing gas components at depths, Nishi and Gagge (1977) attempted to estimate the convective heat transfer coefficient of the human body from the following equation;

$$h_c \propto \kappa \times \left(\frac{\rho}{\mu}\right) \times \left(\mu \times \frac{C_p}{\kappa}\right) \quad (\mathrm{W/m^2 \cdot °C}) \qquad \text{(eq.1)}$$

where κ = thermal conductivity (W/m·°C); ρ = density (kg/m^3); μ = viscosity (kg/m·h); Cp = specific heat (J/kg·°C).

Equation 1 defines the ratio of h_c in normobaric air to that in hyperbaric helium-oxygen atmospheres in the range of the forced convection, *i.e.*, the range where wind velocity is greater than 0.5 m/s. The results demonstrated that the h_c value at 3,000 kPa was twelve times higher than in normobaric air. Therefore, the human body will lose so much more heat from the skin, even if ambient temperature is controlled within the comfortable range in normobaric air.

Raymond *et al*. (1968) first measured heat exchange between the divers' body and its environments when the divers were exposed to six different pressures up to 1,460 kPa. The amounts of sensible and insensible heat loss from the skin and metabolic heat production were measured while the unclad divers were seated quietly.

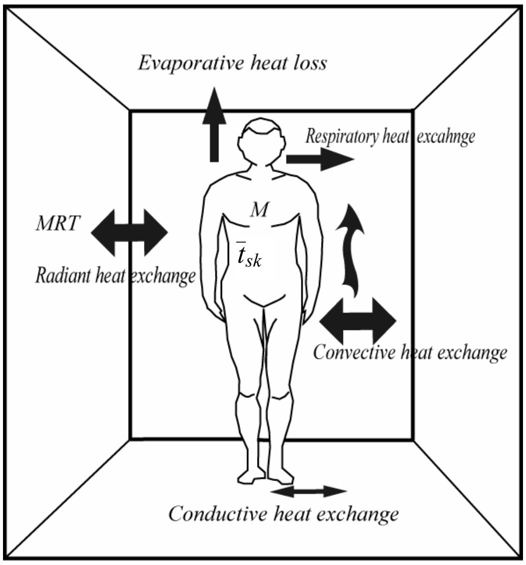

Fig. 1 Heat exchange between the human body and its environments.
Legends in the figure stand for
M: Metabolic heat production (W/m^2)
C: Convective heat exchange (W/m^2)
R: radiative heat exchange (W/m^2)
E_{sk}: Evaporative heat loss (W/m^2)
R_{res}: Respiratory heat exchange (W/m^2)
C_d: Conductive heat exchange (W/m^2).
C, R and E_{sk} can be defined as follows;
$C = h_c \times (\bar{t}_{sk} - t_a)$
$R = h_r \times (\bar{t}_{sk} - MRT)$
$E_{sk} = h_e \times w \times (P_{sk}^* - P_a)$
where h_c, h_r, h_e=convective, radiative and evaporative heat transfer coefficients (W/m^2·°C) in order; $\bar{t}_{sk}$, t_a, MRT=mean skin temperature, ambient temperature and mean radiant temperature (°C) in order; w=skin wettedness; P_{sk}^*=saturated vapor pressure at the skin; P_a=vapor pressure of ambient gas.
The rate of body heat storage can then be defined as follows;
$S = (C_p \times m/A_s) \times d\bar{T}_b/d\,t = M - (\pm R \pm C + E_{sk} \pm C_d)$
where Cp=specific body heat (J/kg·°C), A_s=body surface area (m^2), $\bar{T}_b$=mean body temperature (°C) derived from weighed average of body temperature and $\bar{t}_{sk}$.

Table 1 Theromophysical properties of various gases. (Nishi, Y., 1981)

Gases	Specific heat (J/kg·°C)	Thermal conductivity (W/m·°C)	Density (kg·m^3)	Diffusivity (m^2/h)
Air	1004	0.023	1.2	0.088
O_2	911	0.026	1.33	0.088
N_2	1027	0.026	1.17	0.088
He	5200	0.148	0.166	0.271

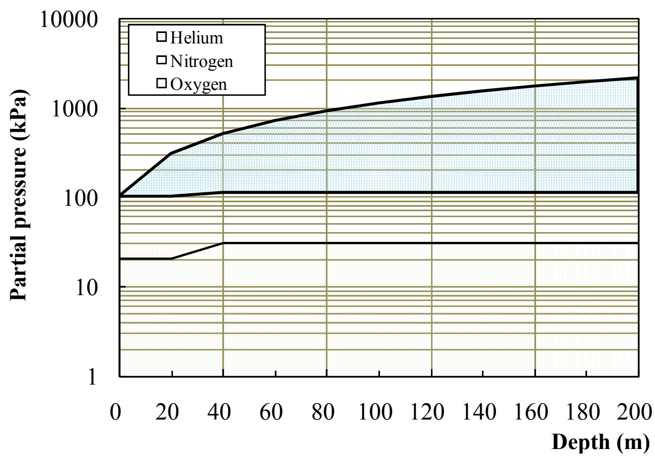

Fig. 2 Change in breathing gas components at depths.
Total pressure is equal to pressure at depths. Oxygen partial pressure is controlled at 30 kPa more than 40 m depths. Nitrogen partial pressure is constantly controlled at 83 kPa.

The h_c value was then defined as a function of barometric pressure. However, since overestimation of the h_c value due to disregard of respiratory heat loss was pointed out, they repeated the human experiment during the simulation diving at the dry chamber in 1974. The divers were exposed to seven different pressures up to 4,950 kPa. The amounts of sensible and insensible respiratory heat losses were measured while the divers were seated quietly. They then proposed another prediction equation (Raymond *et al.*, 1974). In the same year, Timbal *et al.* (1974) also measured heat exchange between the divers' body and its environment with a partitional calorimetry when the divers were exposed to six different pressures up to 3,080 kPa. The partitional calorimetry developed by Burton (1935), Stolwijk and Hardy (1966) and Winslow *et al.* (1936) has been widely used to estimate body heat balance. In their experiments, divers were nude and in a supine position. The h_c value was then defined as a function of pressure and the convective constants, *i.e.*, $\beta \times Cp \times \kappa/\mu$, which was introduced by Webb and Annis (1966). The results demonstrated that the h_c value was correlated more closely with the convective character than with barometric pressure. According to the definition by Webb (1970), the convective character is *"a ratio that normalizes the fluid to air by dividing the convective constants of the fluid by that of normobaric air."*

Kakitsuba *et al.* (1981) measured heat exchange between the divers' body and its environments with the partitional calorimetry when the divers were exposed to nine different pressures up to 3,100 kPa. They were nude and in a sedentary position during experiments. The h_c value was then defined as a function of barometric pressure. Figure 3 relates empirical data and corresponding equations for the convective heat transfer coefficients (h_c) to barometric pressure. Although the h_c values in normobaric air are markedly different due to the difference in posture, all the equations may predict adequate h_c values in hyperbaric helium-oxygen atmospheres. However, those prediction equations are only applicable to sedentary divers in still air. The h_c values become much greater when a diver moves around or is exposed to high wind velocity. For example, the h_c value was estimated to be 23 (W/m^2·°C) when wind velocity increased to 1.0 m/s at 3,100 kPa (Kakitsuba *et al.*, 1980).

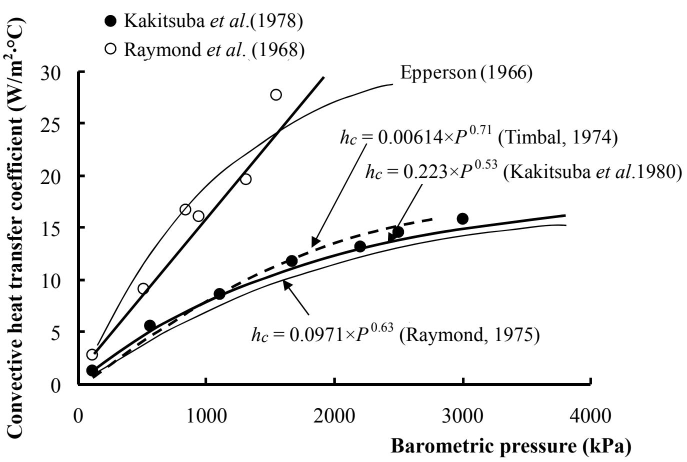

Fig. 3 Change in convective heat transfer coefficients with barometric pressure.

Empirical data was described with corresponding equations for h_c to barometric pressure. Although the h_c values in normobaric air are markedly different due to the difference in posture, all the equations may predict adequate h_c values in hyperbaric helium-oxygen atmospheres.

2.2 Clothing insulation in hyperbaric helium-oxygen atmospheres

The main functions of clothing are its insulation and permeability. In general, clothing insulation is mainly dependent on the insulative value of still air trapped within the clothing fabrics because still air is the most insulative material. Therefore, clothing with high porosity in the range of 70% to 80% is commonplace if high insulation is required in everyday life. However, when the air trapped with fabrics is displaced with a different gas such as helium, clothing insulation is changed by the thermal characteristics of ambient gas.

Kakitsuba *et al.* (1981) took advantage of Mochida's model (1975) and proposed the following prediction equation;

$$I_{cle} = \frac{0.03 \times I_0}{0.75 \times \kappa_{He-O_2} + 0.015} \quad \text{(clo)} \qquad \text{(eq.2)}$$

where $\kappa_{He\text{–}O_2}$ = thermal conductivity (W/m·°C); I_0 = clothing insulation in normobaric air (clo). In addition, $\kappa_{He\text{–}O_2}$ was defined by the following equation;

$$\kappa_{He-O_2} = 0.21 - 0.157 \times \left(\frac{p-1}{101}\right)^{-0.24} \quad \text{(W/m·°C)} \qquad \text{(eq.3)}$$

where p = pressure (kPa).

In order to verify reliability of the equation, three different ensembles of training wears were tested while they were worn by the divers in hyperbaric helium-oxygen atmospheres. Training wears tested were woven by cotton and polyester. As indicated in Fig. 4, clothing insulation decreased significantly in the range of 1,000 kPa to 1,500 kPa where the major displacement from air to helium rich gas took place. Once displacement is completed, however, clothing insulation may not decrease markedly. So, the results demonstrated that there was a good agreement between experimental data and predictions by eq.2 and eq.3.

2.3 Insensible heat loss and sweat evaporation in hyperbaric helium-oxygen atmospheres

Heat loss by sweat evaporation prevails when the human body is exposed to temperature higher than body temperature. Although the entire skin is covered with sweat, evaporation is limited by the maximum evaporation (E_{max}) that is a product of evaporative heat transfer coefficient (h_e; W/m^2·kPa) and vapor pressure difference between the skin and ambient gas. Since vapor pressure is independent from barometric pressure, vapor pressure difference between the skin and ambient gas may be in the same range as compared with that in normobaric air for a given thermal condition. The h_e value is then estimated as $h_c \times LR$. The Lewis relation (LR) can be defined by the following equation;

$$LR = 133 \times \left(\frac{D}{\kappa}\right)^{\frac{2}{3}} \times \left(\beta \times C_p\right)^{-\frac{1}{3}} \quad \text{(°C/Pa)} \quad \text{(eq.4)}$$

where D = diffusivity of water vapor (m^2/h).

Nishi (1981) calculated the LR values for hyperbaric helium-oxygen atmospheres from equation 4, and found a dramatic decrease to 6.65 (°C/Pa) at 3,000 kPa as compared with 293 (°C/Pa) in normobaric air. The h_c value, however, increases twelve times more than in normobaric air. Therefore, according to the definition, the h_e value decreases to 0.23 (W/m^2·kPa) at 3,000 kPa that is about one forth of 0.96 (W/m^2·kPa) in normobaric air. Since E_{max} is solely estimated from h_e for a given vapor pressure difference between the skin and ambient gas, a man may not survive for long in the heat when exposed to hyperbaric atmospheres due to limited heat loss by evaporation.

The amount of heat loss by insensible perspiration from the skin (E_{diff}) is about one forth of metabolic heat production when man is exposed to optimal thermal conditions in normobaric air. According to the prediction equation applicable for normobaric air, E_{diff} may change with E_{max}, so that the E_{diff} value in hyperbaric atmospheres decreases to one forth of that in normobaric air. Nevertheless, E_{diff} values of 8 to 20 (w/m^2) at 3,000 kPa were recorded from the human experiments in hyperbaric environments (Raymond *et al.*, 1974; Timbal, 1974; Kakitsuba *et al.*, 1981). They reported no statistical difference as compared with those in normobaric air. Although, as opposed to their results, Carlyle *et al.* (1979) reported significant decrease in E_{diff} in hyperbaric environments, it is plausible that E_{diff} remains unchanged under pressurized atmospheres. If so, a fixed value of 0.06 for skin wettedness in the thermoneutral zones may not be applicable in hyperbaric environments. Instead, skin wettedness may increase with barometric pressure because of unchanged E_{diff}.

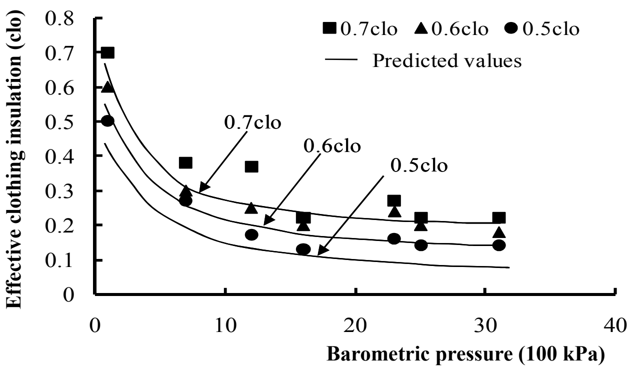

Fig. 4 Change in effective clothing insulation at depths.

Clothing insulation decreased significantly in the range of 1,000 kPa to 1,500 kPa where the major displacement from air to helium rich gas took place. The results demonstrate that there is a good agreement between experimental data and predictions by eq.2 and eq.3.
Clothing ensembles are as follows;
●: Training trousers, half sleeve shirts, socks
▲: Training trousers, half sleeve shirts, long sleeve shirts and socks
■: Training trousers, half sleeve shirts, long sleeve shirts, trainer, and socks

2.4 Clothing permeability in hyperbaric helium-oxygen atmospheres

Kakitsuba *et al.* (1980) proposed the prediction equation for clothing permeability in hyperbaric helium-oxygen atmospheres as follows;

$$\xi = \frac{\mu}{1 + f_{cl} \times \frac{h_{ea}}{h_{ecl}}} \quad \text{(N.D.)} \quad \text{(eq.5)}$$

where μ = porosity (N.D.); h_{ea} = evaporative heat transfer coefficient of ambient gas (= $LR \times h_c$; W/m^2·kPa); h_{ecl} = evaporative heat transfer coefficient of clothing layer (= $k \times$ D; W/m^2·kPa; k is the constant).

Using the same clothing ensembles for determination of clothing insulation (= 0.2 clo in normobaric air), a diver underwent exercise on a bicycle ergometer until the whole skin was covered with sweat. Under the condition of fully wetted skin, we could theoretically estimate vapor pressure at the skin. Clothing permeability was then calculated from the partitional calorimetry. The results are indicated in Fig. 5. The important finding is the slight decrease in clothing permeability in hyperbaric helium-oxygen atmospheres as compared with that in normobaric air and a good agreement between experimental data and predictions by eq.5.

2.5 Respiratory heat exchange in hyperbaric helium-oxygen atmospheres

Respiratory heat exchange in hyperbaric helium-oxygen atmospheres becomes a major pathway for heat loss or gain. Particularly, attention must be paid when a diver undergoes exercise or are exposed to low ambient temperatures. In such cases, a significant increase in respiratory heat loss is expected. The amount of dry

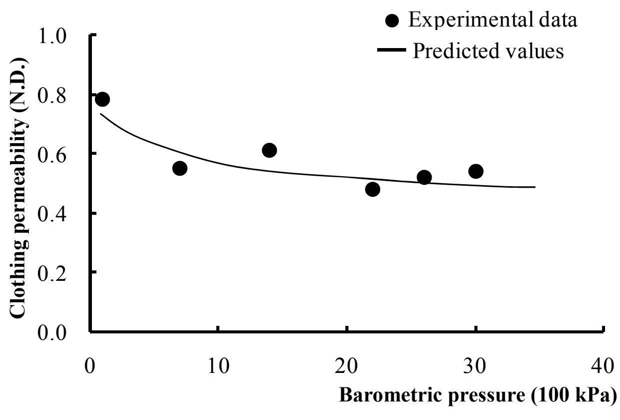

Fig. 5 Change in clothing permeability in hyperbaric atmospheres.

The results indicate a slight decrease in clothing permeability in hyperbaric helium-oxygen atmospheres as compared with that in normobaric air.

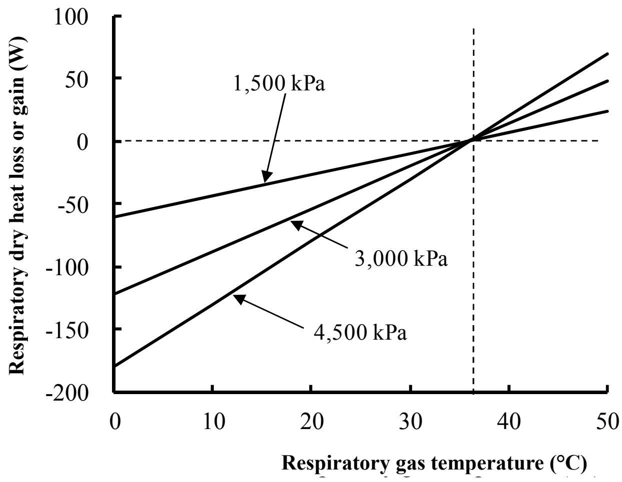

Fig. 6 Change in respiratory dry heat loss in hyperbaric atmospheres (Webb & Annis, 1966).

The amount of respiratory gas was set at 10 liter/min. When respiratory gas temperature is constant, the amount of heat loss increases with barometric pressure.

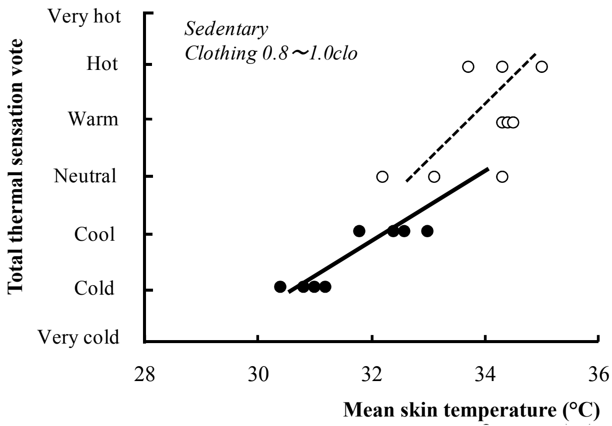

Fig. 7 Relation of mean skin temperature and the relative magnitude of thermal sensation at 1,620 kPa.

Open and closed circles indicate warm sensations and cold sensations, respectively. A thermally neutral $\overline{T}_{sk}$ of 33.0°C was predicted from the regression line (dashed line) under warm or hot conditions whereas a thermally neutral $\overline{T}_{sk}$ of 34.0°C was predicted from the regression line (solid line) under cool or cold conditions.

respiratory gas heat exchange can be estimated as follows;

$$C_{res} = V_e \times \rho \times C_p \times (T_{in} - T_{ex}) \times \frac{60}{A_s} \quad (\text{W/m}^2) \quad \text{(eq.6)}$$

where V_e: respiratory gas volume (liter/min. BTPS), A_s: body surface area (m^2), T_{in}, T_{ex}: respiratory and expiratory gas temperature, respectively.

With the exception of extreme conditions such as high ventilation rates due to vigorous exercise and inhalation of cold and dry air, inhaled air is generally heated to body temperature and is saturated with vapor in normobaric air when being expired. Therefore, heat loss or gain by respiration may be negligible. In hyperbaric helium-oxygen atmospheres, the expired gas may not be heated to body temperature due to high conductivity of helium. In order to predict expired gas temperature, the following equation was proposed by Webb and Annis (1966) and Goodman *et al.* (1971);

$$T_{ex} = 24 + 0.32 \times T_{in} \quad (°\text{C}) \quad \text{(eq.7)}$$

Thus, assuming respiratory volume of 10 liter/min for a sedentary subject, the amount of respiratory heat exchange can be estimated from equations 6 and 7. The results are presented in Fig. 6 for the condition of a constant respiratory gas temperature. The amount of respiratory heat exchange increases with barometric pressure.

3. Evaluation on Thermal Comfort in Hyperbaric Helium-oxygen Atmospheres

3.1 Mean skin temperature and thermal sensation

Breathing compressed air at more than 600 kPa may induce nitrogen narcosis and breathing hydrogen or helium with oxygen at more than 3,000 kPa may induce hyperbaric nervous syndrome (HPNS). These symptoms are known to directly affect sympathetic or parasympathetic nervous systems (Bennett, 1982). In order to mitigate these symptoms, tri-mixed breathing gas, *i.e.,* helium, oxygen and nitrogen mixtures, was deployed (Shilling *et al.*, 1976). Since human temperature regulation is controlled by sympathetic or parasympathetic nervous systems, artificial breathing gases may change their functions. Considering this point of view, Mekjavic *et al.* (1995) demonstrated effects of narcosis on temperature regulation.

Under normobaric air, a linear relation of the relative magnitude of thermal sensation (RMTS) to mean skin temperature $(\overline{T}_{sk})$ is confirmed by many scientists (for example, Winslow *et al.*, 1936). Generally, a man will vote *thermal neutral* when $\overline{T}_{sk}$ is about 33.5°C. As shown in Fig. 7, a relation of RMTS to $\overline{T}_{sk}$ when divers were exposed to various temperatures at 1,620 kPa implies that psychological thermal neutrality may correspond with $\overline{T}_{sk}$ in the range of 33.0°C to 34.0°C even in hyperbaric helium-oxygen atmospheres. However, it is interesting to note that a thermally neutral $\overline{T}_{sk}$ of 33.0°C was predicted from the regression line (dashed line) under warm or hot conditions whereas a thermally neutral $\overline{T}_{sk}$ of 34.0°C was predicted from the regression line (solid line) under cool or cold conditions. This discrepancy may be resulted from increased sensibility of temperature sensations in hyperbaric atmospheres demonstrated by Mekjavic *et al.* (2003).

3.2 Comfortable and safety thermal conditions in hyperbaric helium-oxygen atmospheres

As mentioned earlier, data necessary to predict the ranges of comfortable and safe thermal conditions in hyperbaric helium-oxygen atmospheres have been acquired. So, we now have a powerful tool to predict the comfortable zone in hyperbaric helium-oxygen atmospheres. For example, by incorporating thermophysical factors for hyperbaric environments into the heat balance equations, a comfortable range was predicted on a

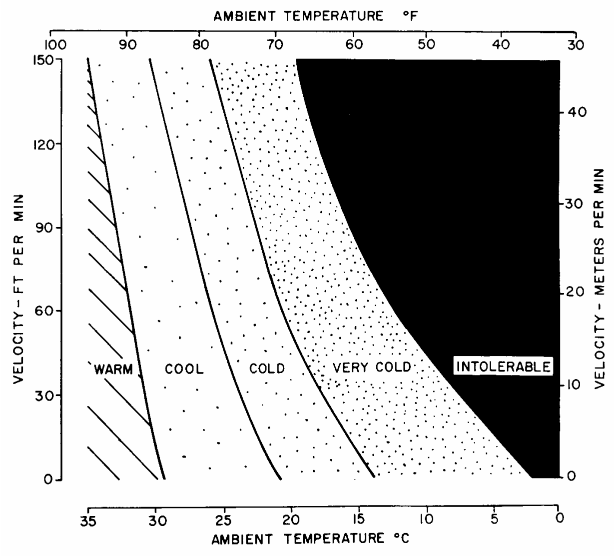

Fig. 8 Change in the thermal comfort zone at 3,140 kPa (Raymond, 1971).

Raymond *et al.* (1971) provided the thermal comfort zone for unprotected subjects at 3,140 kPa, and demonstrated that the comfortable temperature range is narrowed with increasing wind velocity. To ensure thermal comfort in hyperbaric helium, a careful control over the target temperature is requisite. In this chart, the target temperatures may be identified with the line between warm and cool zones. Therefore, the thermal comfort zone at 3,140 kPa can be specified with the range of 29°C in still air to 34°C at 0.6 m/s.

psychometric chart for various barometric pressures (Kakitsuba, 1988). More specifically, as shown in Fig. 8, Raymond (1971) provided comfortable temperature ranges for unprotected subjects at 3,140 kPa, and demonstrated that the comfortable temperature range is narrowed with increasing wind velocity.

The chart shows that a wide range of ambient temperature is thermally acceptable same as normobaric air if warm and cool zones are included into the comfortable zone. For example, ambient temperatures of 22°C to 35°C may be thermally accepted in still air. However, the reality is different. To ensure thermal comfort in hyperbaric helium, a careful control over the target temperature is requisite. In this chart, the target temperatures may be specified with the line between warm and cool zones. Therefore, the thermal comfort zone at 3,140 kPa can be identified with the range of 29°C in still air to 34°C at 0.6 m/s.

4. Conclusions

This paper reviewed thermal problems in hyperbaric environments and provided information available for controlling thermal environments within comfortable ranges in hyperbaric helium-oxygen atmospheres.

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Naoshi KAKITSUBA

In 1979, Naoshi Kakitsuba was granted Ph.D in Eng. from Graduate School of Engineering, Nihon University. After granted Ph.D, he was a research fellow in the research center, Nihon University for one year. From 1981 to 1983, he was a postdoctoral fellow of School of Medicine, Hawaii University. From 1983 to 1984, he was a postdoctoral fellow of U.S. National Research Council to work at the Submarine Base at Groton, Connecticut. From 1984 to 1986, he was a research fellow of School of Kinesiology, Simon Fraser University. After back to Japan in 1986, he run the consultancy company from 1986 to 1993. He was an associate professor of Department of Architecture, Toyota National College of Technology in 1993, and then promoted to be a professor in 1996. From 1999 to 2004, he was a professor of Department of Architecture Ashikaga Institute of Technology. From 2004, he is currently a professor of Department of Environmental Science and Technology, School of Eng., Meijo University. Although his basic training was Architecture, his doctor thesis is entitled "A study of evaluation on thermal environments in hyperbaric helium atmosphere" because he was involved in a series of Diving Simulation Projects in 1976-1979. Since then, his major interest has been evaluation on indoor and outdoor thermal environments.

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