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The influence of oxygen-helium mixture properties on the human heat loss in the hyperbaric environment

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Abstract

The properties of gas mixture exert a large effect on thermal exchange from the human body and finally on the comfort temperature in the hyperbaric environment. Equations describing density, viscosity, specific heat capacity, thermal conductivity of real gas mixture as the function of helium contents, temperature and the total gas pressure were derived. It makes possible to improve the comfort equation and finally to determine the comfort temperature and heat losses from the human body more precisely.

1 Introduction

The saturation diving theoretically enables the divers to stay on the bottom for a long time but requires the hyperbaric complexes where the divers live at the pressure equal to the ambient pressure existing at their work site. The divers are prepared for diving in the hyperbaric chambers and transported in saturation to/from the work site in a diving bell or personnel transfer capsule. The major function of the hyperbaric chambers is to simulate pressure environment for experimental diving, to serve as the transportation vessels and as pressurised vessels for the decompression process and recompression for medical treatment. Most of the deep diving operations is based on the breathing gas containing helium as the inert gas. The physical properties of gas mixture exert a large effect on thermal exchange from the human body and the breathing resistance [2,3,5,6,9]. Physical properties of helium-oxygen mixtures: thermal conductivity, specific heat capacity, mass density, viscosity and diffusion coefficient depend upon the total pressure, temperature and gas composition. Thermal conductivity of inert gases is one of the most important thermal properties that causes certain problems related to dangerous cooling of the divers, therefore creating thermal

comfort for the divers in the hyperbaric environment is of the utmost importance. The comfort temperature in the hyperbaric environment increases with the total pressure of gas and should be maintained at a level higher than that in normobaric air environment. The comfort temperature in the hyperbaric environment is the function of environmental variables: relative humidity of gas, mean radiant temperature, activity level of the diver, insulation value of the clothing, relative gas velocity, composition and the total pressure of the breathing gas. One of the major tasks for the life support is to create the comfortable environment inside the hyperbaric facilities. Not many earlier comfort studies [2, 5, 6, 9] for the hyperbaric environment have taken all the above mentioned variables into account. However, few studies have been carried on in man to ascertain the comfort conditions experimentally [5,6,9].
In order to determine the comfort temperature inside the hyperbaric chamber, the comfort equation was derived [4]. It also makes possible to determine all terms of the heat dissipated from the human body exposed to the hyperbaric environment. To perform the accurate calculations, the physical properties of helium-oxygen mixture treated as the real gas should be determined in function of the pressure, temperature and composition of the gas.

2 Thermal comfort in the hyperbaric environment

2.1 Thermal balance

The termoregulatory system of the body is to maintain the constant body core temperature. Metabolic heat is being produced in metabolic processes of food oxygenation etc. and dissipated to environment through four modes: convection, radiation, conduction, respiration, evaporation of moisture by respiration and perspiration and evaporation of sweat from the skin. According to the First Law of thermodynamic energy produced as heat within the body minus heat loss equals stored heat. The overall thermal balance of the man can be expressed with the following eqn :

$$\dot{Q}_m - \dot{W} - (\dot{Q}_d + \dot{Q}_e + \dot{Q}_u + \dot{Q}_j + \dot{Q}_p + \dot{Q}_k + \dot{Q}_r) = \pm \dot{S} \qquad (1)$$

To avoid thermal stresses thermal equilibrium should be maintained. At thermal steady state, there is no heat storage within the body because the body losses heat at the same rate as it is produced metabolically and $\dot{S} = 0$. When there is no steady state heat storage rate may be $\dot{S} < 0$ (therefore hypothermia occurs and fall in core temperature) or $\dot{S} > 0$ (therefore hypethermia occurs and rise in core temperature). According to [1], there are three necessary conditions for thermal comfort for a person under long exposures to a given environment. Satisfaction of the heat balance $\dot{S} = 0$, eqn (1) is the first sufficient condition for a diver's thermal comfort under long exposure to hyperbaric environment. The second and third necessary condition for thermal comfort deal with the skin temperature and the heat loss by evaporation. The overall thermal balance and the comfort equation for the hyperbaric environment have been derived and presented in [4].

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Presented paper is aimed at improvement of the comfort equation by introducing physical properties of gas mixtures considered as the real gas mixtures. The paper discusses some heat loss terms dependent upon the pressure. Detailed discussion of the results obtained will be presented at the Conference.

2.2. Heat loss by evaporation of moisture

Heat loss by evaporation of moisture consists of three parts: heat loss by perspiration (by skin diffusion) $\dot{Q}_d$, heat loss by evaporation of sweat secretion $\dot{Q}_e$ and latent respiratory heat loss $\dot{Q}_u$.

2.2.1 Heat loss by perspiration (by skin diffusion)

Water vapour diffusion through the skin covered with clothing is proportional to the difference between the saturated vapour pressure at the skin and partial pressure of water vapour in the breathing gas. As there are no any data concerning the water vapour transport coefficient in the hyperbaric environment, except [4], it was assumed that water vapour diffusion in the hyperbaric environment changes proportionally to diffusion of water from free surface [4]. The water vapour transport coefficient for the hyperbaric environment was determined from an experimental investigations [4]:

$$\beta = (3{,}51 + 4{,}8x_{He}) \times 10^{-6} p^{-0{,}4544} \tag{2}$$

Based on experimental results eqn (2) and the water vapour transport coefficient determined in air [3], the equation describing heat loss by perspiration by the clothed skin can be written as follows:

$$\dot{Q}_d = \dot{q}_d A_{Du} = 1.27 \times 10^{-9} \beta \beta_a^{-1} r F_{pcl} A_{Du} (p_s - \varphi p_{sw}) \tag{3}$$

Moisture permeation factor F_{pcl} for natural mass convection is defined [4] as :

$$F_{pcl} = \frac{I_{dm}}{I_{dm} + I_{dcl}} = [1 + (574{,}13 - 0{,}048\dot{q}_m) \frac{\beta \times I_{cl}}{D_{w-m}}]^{-1} \tag{4}$$

2.2.2 Heat loss by evaporation of sweat secretion

The second basic comfort condition enables to determine heat loss by evaporation of sweat secretion. It can be expressed [1,4]for the hyperbaric environment with the following equation:

$$\dot{Q}_e = \dot{q}_e A_{Du} = w \beta r F_{pcl} A_{Du} (p_s - \varphi p_{sw}) \tag{5}$$

Poor evaporative rate may induce in a diver a feeling of high humidity (discomfort) and will prevent evaporative cooling of the skin. The diver is in thermal comfort when his sweat secretion is maintained within narrow limits [1].

2.2.3 Latent respiratory heat loss.

Latent respiratory heat loss is concerned with humidification of the breathing gas. During inspiration the respiratory gas is heated up and humidified between the nasal passages and alveoli. Because the expired gas contains more moisture than that inspired, the latent respiratory heat loss from the body occurs. Latent respiratory heat loss is a function of the pulmonary ventilation and the difference between humidity ratio of the expired and the inspired gases[1, 4].

$$\dot{Q}_u = \dot{q}_u A_{Du} = \dot{m}r(X_{ex} - X_{in}) = \dot{V}pr(X_{ex} - X_{in}) \tag{6}$$

2.3 Dry respiratory heat loss

Dry respiratory heat loss results from the difference between the expired and inspired gas temperatures:

$$\dot{Q}_j = \dot{q}_j A_{Du} = \dot{m}c_p A_{Du}(t_{ex} - t_i) \tag{7}$$

According to [3] the expired gas temperature can be expressed as the function of the inspired gas temperature :

$$t_{ex} = 29.3 + 0.09t_i + 0.004t_i^2 \tag{8}$$

In most cases the inspired gas temperature is the same as the comfort temperature, therefore the eqn (7) can be written as follows:

$$\dot{Q}_j = 4{,}1 \times \dot{q}_m c_p pR^{-1} A_{Du}(29.3 - 0.91 \times t + 0.004 \times t^2) \tag{9}$$

2.4 Heat conduction through the clothing

Clothing insulation is the result of complex interactions between heat transfer mechanisms (convection and radiation inside the layer of the clothing), the clothing thermal resistance and environment. It seems that hyperbaria changes the heat transfer through the clothing because of the thermal conductivity of the breathing mixtures used. There are no sufficient experimental data in the literature that deal with clothing insulation in a hyperbaric environment, therefore an analytical expression [4] is applied:

$$\dot{Q}_p = \dot{q}_p A_{Du} = \frac{(t_s - t_{cl})A_{Du}}{0{,}155 I_{cl} \dfrac{\lambda_a}{\lambda}} \tag{10}$$

2.5 Heat loss by convection

The rate of convective heat transfer from the outer surface of the clothed body is given as follows:

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$$\dot{Q}_k = \dot{q}_k A_{Du} = \alpha f_{cl} A_{Du}(t_{cl} - t) \tag{11}$$

The ratio of the surface area of the clothed body to the surface of the nude body is given as [1]:

$$f_{cl} = 1 + 0{,}31 \times I_{cl} \tag{12}$$

Thermal properties of the breathing mixture also contribute to a major increase in convective heat transfer coefficient as :

$$\alpha = f(c_p, \lambda, t, x_{He}, v, p) \tag{13}$$

3 The comfort equation

Substituting all the terms of the heat losses derived [4] into the heat balance eqn (1) it can now be written as:

$$\begin{aligned} &C\dot{V}_{O_2} - 1.27 \times 10^{-9} \beta\beta_a^{-1} r F_{pcl} A_{Du}(p_s - \varphi p_{sw}) - w\beta r F_{pcl} A_{Du}(p_s - \varphi p_{sw}) + \\ &- \dot{V}\rho(X_{ex} - X_{in}) - 4{,}1 \times \dot{q}_m c_p p R^{-1} A_{Du}(29.3 - 0.91 \times t + 0.004 \times t^2) = \\ &= \frac{(t_s - t_{cl})A_{Du}}{0{,}155 I_{cl} \frac{\lambda_a}{\lambda}} = \alpha f_{cl} A_{Du}(t_{cl} - t) + 4 \times 10^{-8} f_{cl} A_{Du}[(t_{cl} + 273{,}15)^4 +, \\ &-(t_r + 273{,}15)^4] \end{aligned} \tag{14}$$

Eqn (14) is the comfort equation for the hyperbaric environment [4]. It enables to determine the comfort temperature inside the diving complex. The comfort temperature is the function of the kind of the breathing gas; its composition, the total pressure, humidity and the relative velocity, the diver's activity, thermal resistance of clothing and mean radiant temperature. The comfort equation makes possible to calculate all those combinations of above variables which will create thermal comfort in the hyperbaric chamber. Moreover, it is possible to determine all terms of the heat dissipated from the human body exposed to the hyperbaric environment.

4 Thermal properties of helium-oxygen mixture

It is worth of notice that in many engineering calculations it is necessary to use the physical properties of the breathing gas mixtures treated as the real gas mixture. Determination of gas mixture thermal properties as the function of gas ratio, pressure and the temperature is essential for solving the comfort equation

Transactions on the Built Environment vol 68, © 2003 WIT Press, www.witpress.com, ISSN 1743-3509

and contributions of the heat loss to the overall diver's thermal balance in the hyperbaric environment. Based on experimental data for pure gas components of the mixture[8] and the relationships for real gas mixtures [7], the equations describing: specific heat at the constant pressure, thermal conductivity, mass density, as the functions of gas pressure and temperature and helium percentage were derived. The equations were derived for the temperature range of t=0-80°C, the total pressure range of p=0,1-1,8 MPa, oxygen partial pressure was maintained at the constant level of p_{O2} =35 kPa, helium contents x_{He}=0,8-1. An example equations describing specific thermal conductivity, specific heat at the constant pressure and mass density are given below:

$$\lambda = -0,0429 + 2,1188 \times 10^{-3} p + 3,1898 \times 10^{-4} t + 0,1850 x_{He} \quad (15)$$

$$c_p = 1648,39 + exp(\; 0,0344 + 2,4717 \times 10 \;^{3} p \quad 1,2602 \times 10 \;^{4} t x_{He}) \quad (16)$$

$$\rho = 2974,9520 + 28,1176 p + 1,5787 t - 2878,7407 x_{He} \quad (17)$$

Figure 1 shows the relationship between thermal conductivity of helium-oxygen mixture, temperature and pressure, eqn (15). It is evident from Fig.1 that thermal conductivity of helium-oxygen mixture increases with the total pressure, temperature and helium contents, therefore some heat loss from human body will increase due to the pressure increased.

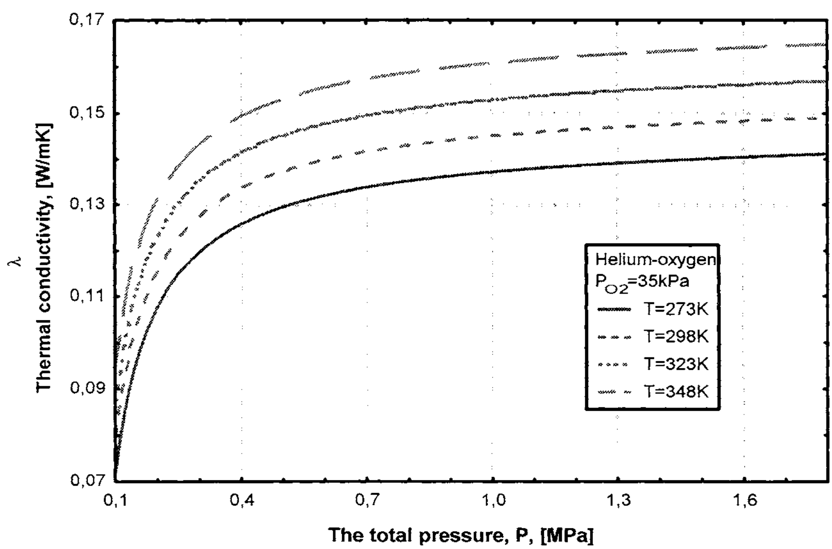

Figure 1:The relationship between thermal conductivity of helium-oxygen mixture and its temperature and pressure.

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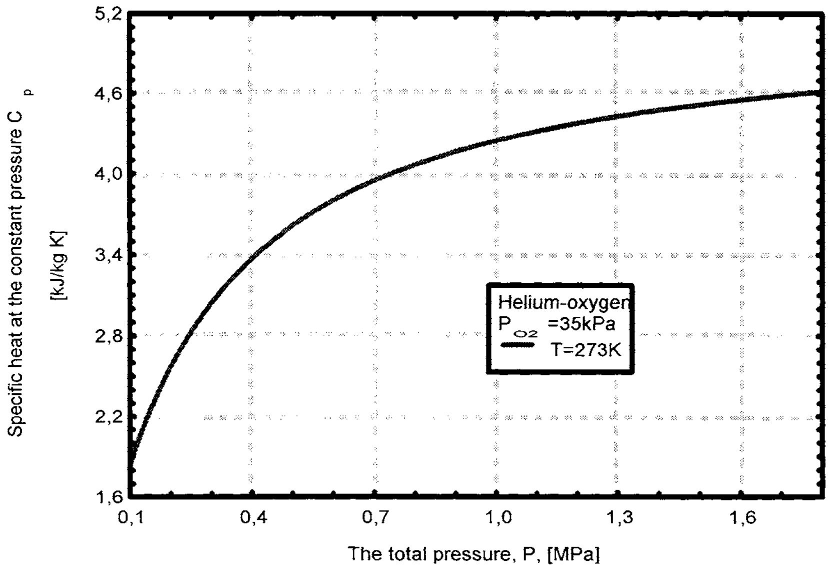

Figure 2: The relationship between specific heat at the constant pressure of helium-oxygen mixture and temperature and pressure.

5 Results

Heat losses from the human body and the comfort temperature in oxygen-helium atmosphere were determined from the equations presented here and derived in [4] at the following assumptions:

- the diver was assumed as the vertical cylinder of the area $A_{Du}=1,8\ m^2$
- oxygen partial pressure was maintained at the constant level of $p_{O2}=35\ kPa$
- the total pressure within the range of $p=0,1\text{-}1,8\ MPa$, that corresponds to the depth of simulated diving from the surface up to depth of 170 m,
- the clothing thermal resistance $I_{cl}=0,3\ clo$,
- oxygen consumption for a resting diver : $\dot{V}_{O_2}=5cm^3/s$, $C=20,88J/cm^3$,
- humidity of helium –oxygen gas mixture $\varphi=0,4$,
- natural convection inside the hyperbaric chamber, convective heat transfer coefficient was determined from equation given in [5].

The comfort temperature for helium-oxygen mixture was determined from eqn (14). The comfort temperature changes from t=31-33,5 °C within the pressure range of p=0,1-1,8MPa. The comfort temperature increases with the pressure, however, since the pressure reaches p=1,5 MPa the temperature becomes approximately constant as the helium contents is maintained at the nearly constant level of x_{He}=0,977-0,981. Based on experimental investigations of evaporative coefficient eqn (4),[4] evaporative heat loss from the skin was determined. The results are presented in Fig.3.

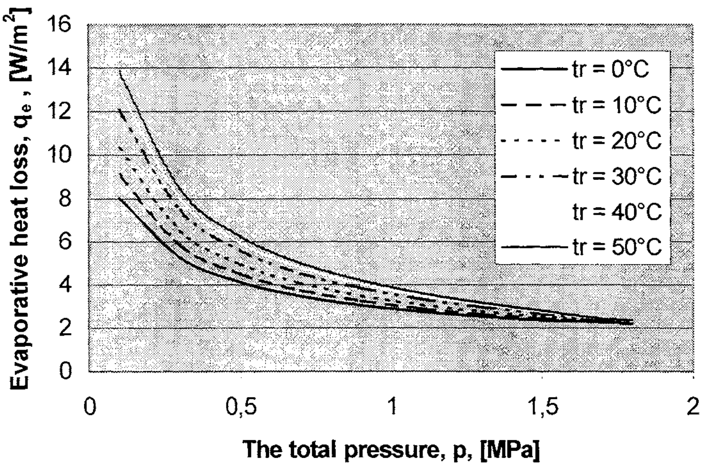

Fig. 3. The relationship between evaporative heat loss from the skin and the pressure of helium–oxygen mixture and mean radiant temperature.

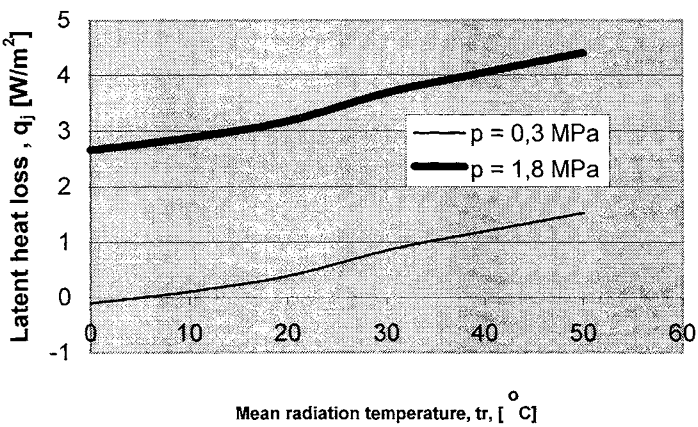

Fig.4. The relationship between latent heat loss and the pressure of helium–oxygen mixture and mean radiant temperature.

It is evident from Fig.3 that as the depth increases (helium contents in helium-oxygen mixture increases due to the depth increase) skin evaporative heat loss decreases. Evaporation heat loss from the skin is strongly effected by pressure and mean radiant temperature. Experiment carried out in helium-oxygen atmosphere have shown[4] that evaporation coefficient from the free surface of the water decreases as the pressure increases, eqn (4). The effect of the total

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pressure on evaporative heat loss is large, particularly within the total pressure 0,1-1,5 MPa. Latent heat loss was determined from eqn (6). The results are shown in Fig.4. It is evident from Fig.4 that the pressure of helium rich atmosphere and high radiation temperature exert a large effect on latent heat loss.

6 Conclusions

- Determination of gas mixture thermal properties as the function of gas ratio, pressure and the temperature is essential for solving the comfort equation and determination of the heat loss in the hyperbaric environment.
- The equations describing physical properties of oxygen-helium mixture treated as the real gas were derived. It makes possible to improve calculation of heat losses and the comfort temperature in the hyperbaric environment.
- The required comfort temperature increases progressively with increasing the total pressure of the He-O_2 mixture and contents of helium.
- Evaporation heat loss is strongly effected by pressure and mean radiant temperature. Poor evaporative rate may induce in a man a feeling of high humidity (discomfort) and will prevent evaporative cooling of the skin. In helium rich atmospheres it may lead to changes in mean body temperature.
- Respiratory and convective heat loss increase with the increase of the total pressure and helium contents.

Nomenclature

c_p -	specific heat at the constant pressure , J/kg K,
D_{w-m} -	diffusion coefficient of water vapour into gas mixture, m^2/s,
f_{cl} -	ratio of the surface area of the clothed body to the surface area of the nude body,
I_{cl} -	thermal resistance from skin to surface of the clothed body, clo,
I_{dcl} , I_{dm} -	diffusive resistance for vapour through the clothing, through gas mixture , m^2sPa/kg,
$\dot{m}$ -	the mass rate of the inspired gas, kg/s
p -	total pressure of the breathing mixture, Pa,
p_i -	partial pressure of the gas component, Pa,
p_s , p_{sw} -	saturated water vapour at skin temperature, at gas mixture, Pa,
$\dot{Q}_d$, $\dot{q}_d$ -	heat loss by water vapour diffusion through the skin, W, W/m^2
$\dot{Q}_e$, $\dot{q}_e$ -	evaporative heat loss, W, W/m^2
$\dot{Q}_j$, $\dot{q}_j$ -	latent respiration heat loss, W, W/m^2
$\dot{Q}_k$, $\dot{q}_k$ -	convective heat loss, W, W/m^2
$\dot{Q}_m$, $\dot{q}_m$ -	metabolic heat, W,W/m^2
$\dot{Q}_p$, $\dot{q}_p$ -	heat loss from the skin to the surface of the clothing, W, W/m^2

$\dot{Q}_r, \dot{q}_r$ - heat loss by radiation, W, W/m^2

$\dot{Q}_u, \dot{q}_u$ - latent respiratory heat loss, W, W/m^2

r - specific latent heat of vaporisation, J/kg,

R - gas constant of the breathing mixture, J/kg K,

t - the comfort temperature, $^\circ$C,

t_{cl}, T_{cl} the temperature of the outer surface of the clothing, $^\circ$C, K,

t_{in}, t_{exp} the temperature of the inspired and expired gas, $^\circ$C,

t_r, T_r - mean radiant temperature, $^\circ$C, K,

t_s - temperature of the skin surface, $^\circ$C,

$\dot{W}$ - work rate, W

$\dot{V}$ - the volume rate of the inspired gas, m^3/s

x_{He} - molar helium contents

X_{in}, X_{exp} - humidity ratio of the expired and the inspired gas, kg/kg

α - the convective heat transfer coefficient, W/m^{2}K,

β, β_a - water vapour transport coefficient in the hyperbaric environment, in normobaric air, kg/m^{2}sPa,

φ - relative humidity of the breathing mixture,

λ, λ_a - thermal conductivity of the breathing mixture, air W/m K,

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