THERMAL TRANSFERS IN WET HYPERBARIC ENVIRONMENT

Tamara STANCIU[1], Anca CONSTANTIN [2], Cecilia ADUMITRESI[3]

Rezumat. *Pierderile de căldură ale organismului uman sunt mai mari în mediul subacvatic decât în atmosferă datorită coeficientului de transfer termic al apei mai ridicat. Temperatura corpului la scafandrii aflaţi în imersiune a fost studiată ţinându-se cont şi de presiunea la care sunt expuşi subiecţii. A fost stabilită ecuaţia teoretică a transferului total de căldură, la amândouă nivelele, cutanat şi respirator, ţinând cont de conducţie, convecţie, şi de încălzirea şi umidificarea gazului respirator. Temperatura corpului scafandrilor a fost măsurată într-o serie de scufundări, la diferite adâncimi, realizate în simulatorul umed al Centrului de Scafandri Constanţa. Rezultatele experimentale au fost în concordanţă cu temperatura calculată după modelul matematic stabilit.*

Abstract. *The heat losses of human body are greater in underwater environment than in dry, normal atmosphere, due to the great heat capacity of water. Body temperature of divers in immersion was studied taking into account the pressure the divers are subjected to. The theoretic equation that describes the total heat transfer- at both levels: skin and respiratory system- was established, considering conduction, convection and respiratory gas heating and humidification. The body temperature of the divers was measured in a series of dives at different depths of immersion, conducted in the wet simulator of the Diving Center, in Constanta. The experimental results were in good accordance with the temperature predicted by the mathematical model.*

Keywords: conduction, convection, thermal balance.

1. Introduction

The diverse actual underwater activity requires man to spend more time in wet hyperbaric environment. Hostile factors like high pressure, low temperature, and weak visibility require appropriate protection equipment for the diver. Thermal comfort is one of the most important requirements for a diver to accomplish his underwater task and return safely to the surface. The comfort is maintained temperature margin 35–37 °C. Under 32 °C for signs of hypothermia, vasoconstriction, tachycardia and tremor [3].

[1]Senior Researcher Eng., "Research Laboratory", "Diving Center ", Constanta, Romania (tamara.stanciu@navy.ro).
[2]Assoc. Prof., PhD Eng., "Faculty of Civil Engineering", University "Ovidius", Constanta, Romania, (aconstantina@univ-ovidius.ro).
[3]Lecturer Doctor, "Faculty of Medicine", University "Ovidius", Constanta, Romania, (cadumitresi@yahoo.com).

Thermal balance of the human body has been studied and depicted by rigorous teams of physiologists and engineers, but the published theoretical and experimental data refer mainly to normal pressure condition or to experiments developed in dry hyperbaric environment. The first form of the biothermal equilibrium equation was developed by Pennes who investigated heat transfer between tissue and blood, and measured temperatures distribution in human body.

His model describes the effects of metabolism and blood perfusion on the energy balance within tissue [4].

$$\rho c \frac{\partial T}{\partial t} = \nabla k \nabla T + q_p + q_m \quad (1)$$

where ρ-tissue density; c –tissue specific heat; T-tissue temperature; k-thermal conductivity; q_p –perfusion heat flux; q_m –metabolic production rate [W/m^3] – metabolic heat flux. Equation (1) reflects the thermal balance of the body in normobaric atmosphere.

Scientists like Klingel , Cheng and Holmes, Nakayama and Kuwahara [5], mainly on the theory of porous media. A simple model for bioheat transfer was proposed by Tarlochan and Ramesh [7].

Divers operating in pressurized dry and wet rooms, as the hyperbaric diving depth ensemble of Diving Center from Constanta, see Figure 1.

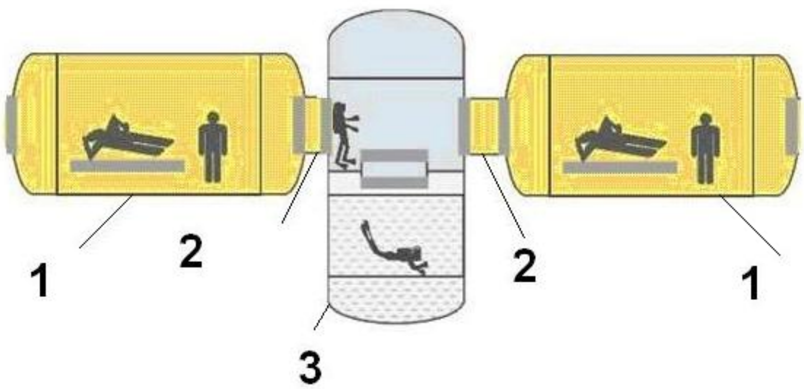

Fig. 1. Hyperbaric Complex: 1) dry hyperbaric chamber, 2) sas, 3) wet hyperbaric chamber.

Retrospective recent studies of the heat losses at the hyperbaric respiration, provides a physiological database for raising the minimum physiological inspired gas temperature. The curve proposed to maintain the temperature of the inspired gas, is a maximum loss of 20 W/m^2, into a hot water warmed suit. This level of thermal loss by respiratory system, is destinated to fall the rectal temperature with 0.25 °C/h.

Thermal comfort of the diver, a free contaminants respiratory level and maintaining the level of partial oxygen pressure in the normal range, is one of the most important requirements for a diver to accomplish his underwater task and return safely to the surface. For the natural ventilation, at norm baric pressure, the thermal comfort for the body is defined by ASHRAE Standard 55.

$$T_{conf} = 0.31T_{aerext} + 17.8[K] \quad (2)$$

A more elaborated model was conceived by Majchrzycka. Her theoretical researches on bioheat transfer in hyperbaric, but dry environment were sustained by rigorous experimental recordings of human body temperature. She took into account the metabolic heat production, and losses by evaporation from skin, by respiration, by convection and even radiation from the outer surface of the clothing. [2]

The studies effectued in wet hyperbaric environment of the Hyperbaric Complex from Diving Center Constanţa, come to add new data regarding the evolution of human body temperature in the diving, depending on the pressure as the main parameter. We focused on human thermal sub sea comfort, therefore the water temperature was of 20 °C and the duration of a dive was of 30 min.

2. Heat transfer mathematical model

The differential equation that governs the transient heat transfer was derived taking into account both groups of heat losses: through skin (by conduction and convection) and through the breathing system (by convection and humidification of the respiratory gas mixture). [1]

We were interested only in the human body temperature variation in time, related to the sea water temperature and pressure. So we considered the mathematical model offered by the following heat balance equation:

$$mc_b \frac{dT}{dt} = Q_m - Q_c - Q_r \quad (3)$$

m - body mass [kg], c_b - body core specific heat, $\dot{Q}_m$ - metabolic heat flux, T [K] – body temperature (core), $\dot{Q}_c$ - skin level heat flux lost, $\dot{Q}_r$ - respiratory system level heat flux lost.

2.1. Metabolic thermal flux

To keep a better control on the heat production, the divers stood still during the dives. Thus, they produced only the basal metabolic heat. The basal metabolic flux was determined knowing that the heat produced by a healthy man in 24 hours is given by the Harris-Benedict relationship:

$$Q_m = 66.473 + 13.7516\,L - 6.755\,a \text{ [kcal]} \tag{4}$$

were Q_m - basal metabolic heat [kcal]; L- height [cm]; a-age [years].

2.2. Conduction and convection thermal flux at skin level

The heat balance equation (3) was established assuming the human body consists of a core, acting like a homogenous source of metabolic heat, covered by thin insulation layers: subcutaneous fat, dermis and epidermis. Part of the metabolic heat rate is transferred by conduction and convection to the environmental sea water; we drafted in Figure 2 the ensemble human body-skin-water film-suit-water. It may be written:

$$Q_c = \frac{\dot{T} - T_W}{R_{(p)}} A \tag{5}$$

T_W [K] – water temperature, $R_{(p)}$ [$K \cdot m^2/W$] - thermal resistance of the outer layers of human body, t - time [s].

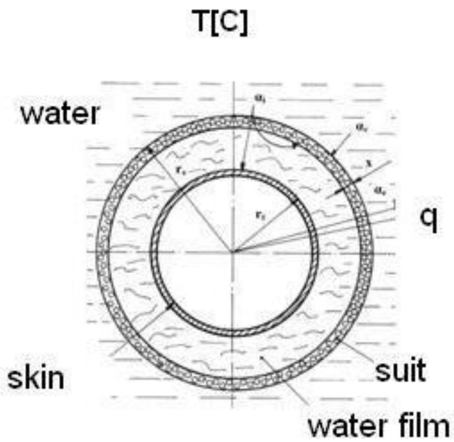

Fig. 2. Heat transfer by ensemble human body-skin-water film-suit-water.

The thermal resistance was theoretically determined for each diver, according to his specific physiologic features, at normal pressure. For each depth value, the resistance was corrected considering an isothermal compression for the air in the neoprene cells. It was taken into account only free convection at the neoprene suit-sea water surface, as the divers stood still during the dives.

2.3. Thermal flux at respiratory system level

$$\dot{Q}_r = \dot{Q}_X + \dot{Q}_S \tag{6}$$

$\dot{Q}_x$ latent heat flux that brings the inhaled dry air to 100% humidity exhaled air.

$\dot{Q}_S$ sensible heat flux that increases the inhaled air temperature from $T_W = 20\,°C$ to the body temperature, T.
Both components depend on pressure (depth of immersion), as it may be noticed from their formulas given below:

$$\dot{Q}_X = l_{(p)}\rho_{(p)}x_{(p)}\dot{V}(p) \tag{7}$$

Were $l_{(p)}$ – specific vaporization latent heat [J/kg], $\rho_{(p)}$- air density [kg/m^2]; $x_{(p)}$- absolute humidity of respiratory air [kg/kg]; $\dot{V}_{(p)}$ - respiratory volume flow rate [m^2/s].

$$\dot{Q}_S = \rho_{(p)}c_{(p)}\dot{V}(p)\,(T - T_W) \tag{8}$$

c – air specific heat at constant pressure, [J/(kg·K)]

2.4. Thermal balance equation

The equation (3) becomes:

$$mc_b\frac{dT}{dt} = \dot{Q}_m - \frac{T - T_W}{R_{(p)}}A - l_{(p)}\rho_{(p)}x_{(p)}\dot{V}(p) - \rho_{(p)}c\dot{V}(p)\,(T - T_W) \tag{9}$$

and the solution is:

$$T = \left(T_0 - T_W - \frac{\dot{Q}_m - l_{(p)}\rho_{(p)}x_{(p)}\dot{V}_{(p)}}{\frac{1}{R_{(p)}} + \rho_{(p)}c\dot{V}_{(p)}}\right)e^{-\frac{\frac{1}{R_{(p)}}+\rho_{(p)}c\dot{V}_{(p)}}{mc_b}} + \frac{\dot{Q}_m - l_{(p)}\rho_{(p)}x_{(p)}\dot{V}_{(p)}}{\frac{1}{R_{(p)}} + \rho_{(p)}c\dot{V}_{(p)}} + T_W \tag{10}$$

Were,
$c_b = 3470[J/kgK]$, – the specific heat of the human body (core), $T_0[K]$- the initial body temperature

3. Experimental procedures

The experimental study of human body temperature variation in hyperbaric conditions was developed in two stages: the first focused on the heat lost through the respiratory system and the second on the total heat loss, during immersion.

The theoretic values of thermal resistance, for each diver, were experimentally validated in a first dive down to 15 m. Resistance $R_{(p)}$ has the most important variation on this range of immersion depth, as the hydrostatic pressure increases significantly.

All the dives were conducted in the simulator of the Diving Center from Constanta. They used air as respiratory mixture.

In the first stage were conducted a series of SCUBA diving, with breathing air, in the wet simulator. The breathing air was dry and at the same temperature as water. Each one of the three divers wore, by turn, a wet neoprene suit of 5mm and respectively 7 mm thickness. Body temperature was measured by a thermometer placed inside the ear and skin temperature by a thermometer placed on the arm. Water temperature was kept at 20 °C. The duration of each dive was of 30min and temperatures were measured at every 2 min. The first set of measurements was carried out at normal pressure, 0 m depth. The second set of measurements was carried out at 15 m depth. These data were used to correct the theoretically determined thermal resistance $R_{(p)}$. The third set of measurements was developed at 30 m depth of immersion.

Attended by two groups of three divers to testing. We exemplified the divers group 1, 2 and 3. Thermal comfort is differently perceived by individuals. It depends on their own physiological features and own thermoregulatory system. Their physiologic features are given in Table 1.

Table 1. Divers physiologic features

Diver	*Ages [year]*	*Mass [kg]*	*Height [m]*	*Body area [m^2]*	*A/m ratio [m^2/kg]*	*Metabolic heat flux [W]*
1.	31	78	1.78	2	0.02564	88
2.	27	100	1.74	2.15	0.0215	103
3.	29	80	1.8	2.05	0.02563	93

It may be noticed that the divers 1 and 3 slender, having very similar characteristics, while diver 2 is more corpulent. It is known that individuals with more fat content can survive longer in cold water as the fat is a natural insulator to the body .[6]

Resistance $R_{(p)}$ has the most important variation on this range of immersion depth, as the hydrostatic pressure increases significantly.

The second stage aimed to determine the breathing features variation with the depth of immersion. There were measured and recorded: the respiratory volume flow rate, breathing frequency, duration of one breath, and the air temperature before and after exhalation. All these data were collected during a series of simulated dives, in dry environment, at the following depths: 9 m; 21 m; 30 m; 51 m; 60 m. Breathing flow rate $\dot{V}_E$ of each diver was determined by the use of lung function recorder type SP-10, with an accuracy of $\pm 2\,\%$.

The human thermal comfort is maintained as long as the body temperature is between 37 °C and 35 °C. As the temperature decreases down to 32 °C mild signs of hypothermia may occur: hypertension, vasoconstriction, tachycardia, tachypnea, and shivering. [3].

4. Results

The results with respect to body temperature variation during the immersion are graphically presented below, allowing one to compare the theoretical and the experimental data (Figures 3-5). The theoretical curve is the graphical representation of relationship (10). 1 good correlation of the theoretic and experimental data may be observed in graphics, where temperature decrease is presented for the three divers, in immersion at 30 m depth. Therefore we considered that the mathematical model is valid and we used it to estimate the temperature variation for longer duration of the dive.

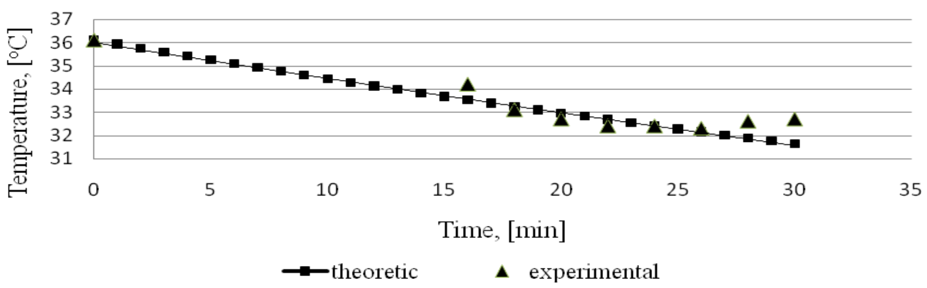

Fig. 3. Body temperature variation for the diver 1, at 30 m depth. Theoretic and experimental curves, $R^2 = 0.84$

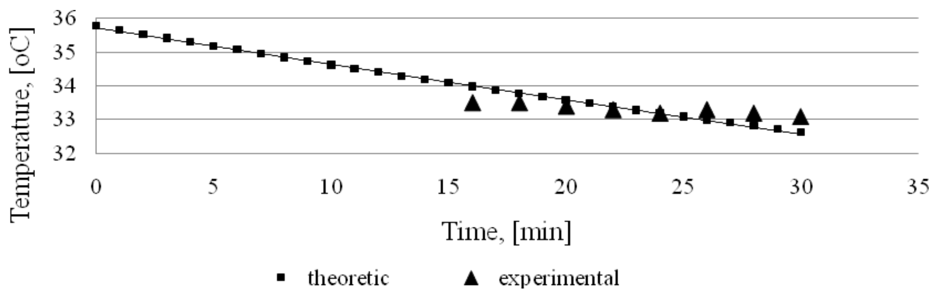

Fig. 4. Body temperature variation for the diver 3, at 30 m depth, wearing a 7 mm neoprene wet suit. Theoretic and experimental curves, $R^2 = 0.78$

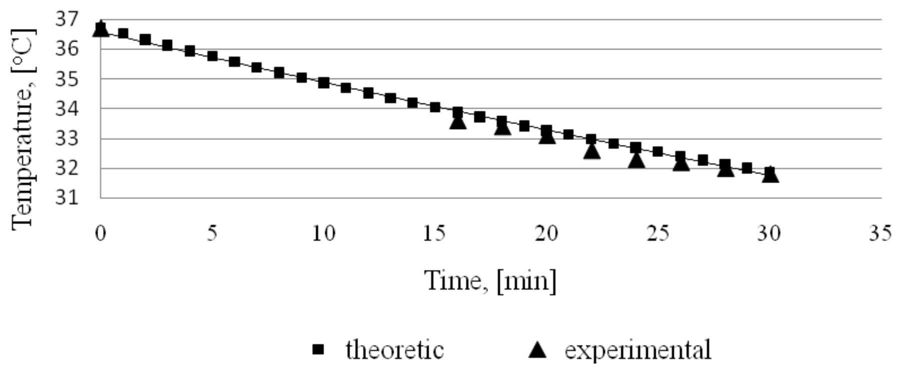

Fig. 5. Body temperature variation for the diver 2, at 30 m depth, wearing a 5 mm neoprene wet suit. Theoretic and experimental curves, $R^2 = 0.8$.

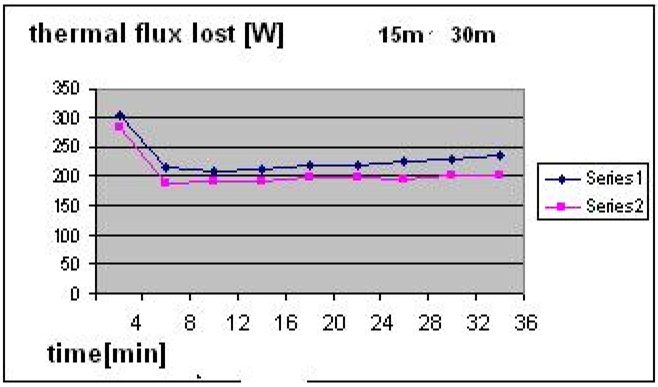

Fig. 6. Lost thermal flux variation [W/m^2] by diver 1, in time, at 15 m and 30 m depth.

Equation (3) was used to determinate the thermal flux lost by a diver, at two levels 15 m and 30 m, Figure 6. Earlier diving body temperature drops quickly, but after about 10 minutes slower heat flow is lost. Heat flux lost to 30 m at the same moment of time, is slightly lower than body temperature is 15 m, therefore the body temperature is higher than 30 m depth, than at 15 m, due to pressurization simulator.

The theoretical study led to the assessment of diver's temperature evolution over diving time and of his lost heat flux. For the same diver, at the same depth of immersion, the increase with 2 mm of the insulation neoprene wet suit resulted in about 50 W/m^2 decrease of the lost heat specific flux. In Fig. 7 there is represented the body temperature of diver 3 for 5 mm and respectively 7 mm thickness of the diving suit.

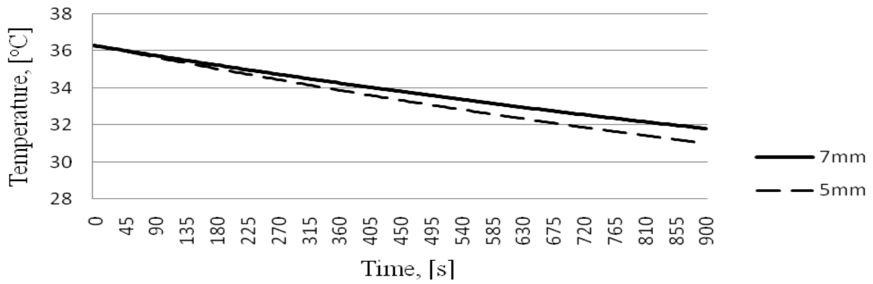

Fig. 7. Body temperature variation for the diver 3, at 30 m depth, for two different thickness of the neoprene wet suit: 5 mm and 7 mm.

Conclusions

(1) The study of thermal transfers in wet hyperbaric environment provided an easy-to-use mathematical model for body temperature decrease, for a diver at rest during immersion. The proposed thermal balance equation is a simplified model of very complex phenomena. It takes into account only part of the involved variables: sea water temperature and hydrostatic pressure corresponding to the depth of immersion, the main physiologic features of healthy individuals, their breathing characteristics, and respiratory air properties.

(2) The proposed mathematical model is valid, as it was proved during a series of wet diving down to 60 m, conducted in a hyperbaric facility. The theoretic and experimental study pointed out a few data useful to choose the most appropriate diving suit, according to the level of effort the diver is going to deliver in the subsea working site. In the first 1.5 hours of immersion, body temperature decreases faster at small depths of immersion. The increase with 2mm of the insulation neoprene wet suit resulted in about 50 W/m^2 less heat loss. Temperature differential across the neoprene suit varies from $1.5^0 C$, at surface, to $0.7^0 C$, at 30 m depth. A difference of $1^0 C$ in body temperature was recorded for the same diver with 2 mm thickness difference of the neoprene suit, after 15 min at 30 m depth.

(3) The diagrams presented above show the most unfavorable situation, the most enhanced temperature decrease, as the study was developed for divers at rest. In practice the metabolic heat production is higher and the thermal comfort lasts longer.

(4) The next step in our study is to validate the model for artificial breathing mixtures.

R E F E R E N C E S

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