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EXPERIMENTAL RESEARCHES OF THERMAL PHENOMENON DURING THE SATURATION DIVING

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Abstract— Saturation diving is based on the principle that the tissues and blood of a diver's body absorb inert gases and reach saturation point where the pressure of the dissolved gas in the blood and tissues is the same as that of the gas in the lungs. Saturation diving allows divers to remain at working depths without concern for decompression and it makes deep diving operations more efficient.
Thermal comfort during the helium –oxygen breathing mixture saturation diving, was verified by experimental determinations and calculation of thermal flux density lost. The results were compared with those obtained from the air unit diving, of the subjects with similar physical, in similar conditions of temperature and deep.

Keywords— experimental researches, saturation diving, thermal comfort.

I. Saturation Diving

SATURATION diving is a difficult operation, which allows the divers to leave and work long time, in a hostile environment. The divers are compressed at the „living depth", were they live for a long period. Hence they descend into the wet hyperbaric chamber, until the „working depth" and they return at the „living depth" day after day, as far as finality of tasks.

Saturation diving is based on the principle that the tissues and blood of a diver's body absorb inert gases and reach saturation point where the pressure of the dissolved gas in the blood and tissues is the same as that of the gas in the lungs. Saturation diving allows the divers to remain at working depths without concern for decompression and make deep diving operations more efficient.

The Deep diving course from Diving Center imposes prosecution of saturation diving with binary gas mixture (helium and oxygen).

II. THEORETICAL CONSIDERATIONS

The definition of half saturation period H is the appropriate time of exposure to achieve a pressure of dissolved gas [1].

p_0 = initial pressure of the disolved gas

p_i = exposure pressure of the disolved gas

H = half saturation period

$$\mathbf{p_0 + (p_i \quad p_0)/2 = (p_i + p_0)/2} \qquad (1)$$

Although shown as hydrogen and other inert gases can be use in breathing mixtures for deep diving, most of the experiments have been done with helium.

Helium causes problems because the thermal conductivity $k = 352(\mu cal / cmsK)$ and specific heat $c_v = 0.745([\text{cal/g K})$ are higher than the coefficients of the nitrogen, $k = 58(\mu cal / cmsK)$ and $c_v = 0.177(\text{cal/g K})$ and they lead to dangerous cooling of the divers.

Therefore, the comfort temperature in the hyperbaric environment increases with the total pressure of the gas and should be maintained at higher level than the level from the atmospheric air.

One of the major tasks of the life support systems of the hyperbaric facilities is to create the environment which maintains the partial pressure's level of oxygen, required level of contaminants and the thermal comfort for the divers.

There are many variables which influence the thermal comfort condition in hyperbaric environment: pressure, composition, temperature, humidity of the breathing mixture, activity level and thermal insulation of the diver's clothing.

It is impossible to consider independently the effect of any of the above mentioned variables. The thermal comfort can be influenced by the human factories (stress, fatigue).

III. THERMAL BALANCE EQUATION

The thermal balance equation for the human body of the diver is [2]:

$$\mathbf{Q_m = \dot{Q}_{resp} + Q_p + Q_r + \dot{Q}_e} \qquad (2)$$

$\dot{Q}_m$ = metabolic thermal flux, positive, calculated by Harris-Benedict relation :

$$\mathbf{Q_m = 66.4730 + 13.7516m + 5.0033h \quad 6.7550a} \qquad (3)$$

m(kg) = diver's body mass
h (cm) = diver's height
a (years) = diver's age

$\dot{Q}_{resp}$ = thermal flux lost by respiration

$\dot{Q}_p$ = thermal flux lost by skin through conduction and convection

$\dot{Q}_r$ = thermal flux lost by radiation

$\dot{Q}_e$ = thermal flux lost by evaporation

Thermal flux lost by skin results by summing the conductive flux and the convective flux [3], [4]:

$$\mathbf{\dot{Q}_p = \dot{Q}_c + Q_{cv}} \qquad (4)$$

$\dot{Q}_c$ = thermal flux lost by conduction

$\dot{Q}_{cv}$ = thermal flux lost by convection

The thermal flux lost by respiration is [5]:

$$\mathbf{Q_{resp} = \dot{Q}_v + \dot{Q}_i} \qquad (5)$$

Q_v = thermal flux lost by vaporization from breathing gas

Q_i = thermal flux lost by heating of the breathing gas

We assume thermal flux lost by radiation and evaporation failure, because the hyperbaric environment. The thermal balance equation becomes:

$$\mathbf{Q_m = Q_v + \dot{Q}_i + Q_c + \dot{Q}_{cv}} \qquad (6)$$

If the metabolic flux doesn't cover this thermal consumption, imbalance occurs which leads to the heat loss for the human body. The thermal balance equation becomes [6]

$$\mathbf{Q_m + \dot{Q}_l = Q_v + \dot{Q}_i + Q_c + \dot{Q}_{cv} \Rightarrow \dot{Q}_l =}$$

$$\mathbf{Q_v + \dot{Q}_i + Q_c + \dot{Q}_{cv} \quad Q_m} \qquad (7)$$

$\dot{Q}_l$ = total thermal flux lost by the human body

The calculation of total thermal flux lost has been fixed in a precedent scientific project [7]:

$$\mathbf{\dot{Q}_l = \Delta t_m \frac{m \times C}{\tau}} \qquad (8)$$

$$\mathbf{\dot{q} = \dot{Q} / S} \qquad (9)$$

$\dot{q}$ = thermal flux density, S = surface of human body (Dunn diagram)

$$\mathbf{\Delta t_m = t_1 \quad t_2} \qquad (10)$$

Δt_m = variation of body temperatures, before diving (t_1) and after diving (t_2)
τ = immersion time

The global coefficient of thermal transfer for diver's body was experimental calculated and we obtained in hyperbaric condition: C=0.5 $(kcal / kg\,^0C) = 2.1(kj / kg\,^0C)$ [7]. We propose to verify the thermal losses during helium - oxygen saturation diving by using C, the global coefficient of thermal transfer for diver's body. C formulas was determined at air unit diving, but the respiratory thermal loss was considered 25% Q_{total} and the breathing gas's parameters not have any influence, then it can be used for helium - oxygen too.

IV. EXPERIMENTAL DETERMINATIONS

The tests were done at Hyperbaric Complex of Diving Center, by divers from Deep diving course, during the saturation diving on 61 m and 31 m. To determinate the temperatures, we used two thermometers:

a) Temperature controller from analyse panel with two probes into the pressure chambers RTD air probe and RTD immersion probe industrial Cole – Parmer. Features: temperatures -50– 200 ^{0}C; response time 1 second; connector ANSI; material stainless steel.

b) Digital thermometer – hygrometer, mobile, with an external probe. Features: temperatures -40– 150 ^{0}C;

TABLE I
FEATURES OF DIVING AND BREATHING GAS

Parameter	Saturation 61 m	Saturation 31 m
maximal depth	71 m	38 m
compression time	61 minutes	31 minutes
velocity of compression	1 m/min	1 m/min
living depth	61 m	31 m
working depth	71 m	38 m
stationary time on living depth	46 hours	46 hours
stationary time on working depth	minimal 3 hours	minimal 3 hours
total diving time	5 days	4 days
diving table used	COMEX	COMEX
compression mixture	HeOx 5,5% until 30 m and 0,9% between 40 – 60 m	HeOx 5,5%
breathing mixture on living depth	HeOx 5,5 – 9,2% la 71 m	HeOx 5,5%
breathing mixture on working depth	HeOx 5,5 – 5,9 at 61 m	HeOx 5,5%

response time 4 seconds; link cable of temperature transducer is limited on 3 meters longer; non industrial temperature transducer. The test was recorded into the dry chamber and the wet chamber too.

Every diving 4 divers participated on tests; they alternatively were subjects and tender divers.

The measurements for thermal losses were made at working depth 71 m and respectively 38 m, into the wet pressure chamber. It was recorded water temperature.

A full equipped diver and a tender diver went into the wet pressure chamber, from dry pressure chamber, in saturation on 61 m, into the wet pressure chamber, but on surface, was a security diver.

TABLE II
FEATURES OF SUBJECTS ON SATURATION 61 M

Subject	Body mass (kg)	Height (m)	Body surface (m^2)	Age (year)	Surface temperature		
					t_i (^{0}C)	t_e (^{0}C]	t_c (^{0}C)
1	128	1.94	2.6	40	25.6	33.5	36.3
2	84	1.78	2.05	42	25.6	32.8	36.5
3	94	1.80	2.15	45	25.6	30	37
4	96	1.80	2.2	47	25.6	30.2	36.4

TABLE III
FEATURES OF SUBJECTS ON SATURATION 31 M

Subject	Body mass (kg)	Height (m)	Body surface (m^2)	Age (years)	Surface temperature		
					t_i (^{0}C)	t_e (^{0}C)	t_c (^{0}C)
5	93	1.73	1.21	2.1	30	17.8	32
6	84	1.81	0.96	2.05	43	17.8	32
7	68	1.68	0.92	1.85	39	17.8	33
8	94	1.91	1.15	2.3	39	17.8	30

Diver and his tender (S1 and S3) descended into the water until working depth. Security diver was on living depth, at surface and he communicated with tender diver, he recorded water and precinct temperature with the RTD probes. Before the start of the diving, he measured the temperatures t_1 of the two divers, on their arms, with the temperature transducer of the digital thermometer.

The two subjects have executed a few workout exercises and after getting out of the water, the security diver measured their temperatures t_2 with the digital thermometer. The security diver timed dive time τ, on working depth. The values were recorded into the table 4 (S= subject).

TABLE IV
HEAT LOST BY DIVERS SATURATION 61M

S	Living depth (m)	Working depth (m)	Water temp. (^{0}C)	Precinct temp. (^{0}C)	t_1 (^{0}C)	t_2 (^{0}C)	Time τ (s)	Flux density $q_l [W/m^2]$
1	61	71	20	26.4	35.1	28.6	900	433
2	61	71	20	24	32.4	27.3	900	488
3	61	71	20	26.4	34.2	26.9	900	419
4	61	71	20	24	34.7	25.6	900	811

The exercises were resumed on second day for the other two divers (S2 and S4) from the first team, participated on saturation 61 m. The operations described above, were executed on the saturation 31 m too, as the divers have been pressured from the living depth 31 m to the working depth 38 m.

Using the calculation relations (8) and (9) we determined the heat lost by divers after the saturation diving, with immersion activities on working depth. The measurements and the results are recorded into the tables IV and V.

TABLE V
HEAT LOST BY DIVERS SATURATION 31M

S	Living depth (m)	Working depth (m)	Water temp. (^{0}C)	Precinct temp. (^{0}C)	t_1 (^{0}C)	t_2 (^{0}C)	Time τ [s]	Flux density $q_l [W/m^2]$
5	31	38	17	22.8	33	27.9	900	1186
6	31	38	17	22.8	33,2	2.	900	1098
7	31	38	17	22.8	33,7	28.2	900	1062
8	31	38	17	22.8	32,3	25.1	900	687

V. THE INTERPRETATION OF THE RESULTS OBTAINED

For the interpretation of the results, we used to be compared, the tests effectuated on three subjects, participants on unit air diving 30 m, in similar conditions, from the period September – October 2011: S1a, S2a and S3a.

The subjects have similar physical with that of the divers from saturation. The dates are recorded into the following table:

TABLE VI
HEAT LOST BY DIVERS ON STUDY 2009 AIR DIVING

Subject	Body mass (kg)	Body surface (m^2)	Depth (m)	Water temp. (^{0}C)	t_1 (^{0}C)	t_2 (^{0}C)	Time τ [s]	Flux density $q_l (W/m^2$
S1a	80	2.05	31	21.5	34.5	29.8	900	150
S2a	100	2.15	31	21.6	34.8	32.1	900	200
S3a	78	2	31	22	35.2	31.9	900	180

We compared subjects with similar physical and immediate body surface.

For subjects S3, S5 and S2a we obtained the following results:

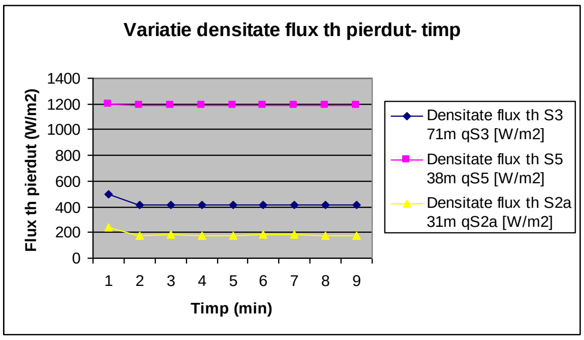

Fig. 1. Thermal flux density lost by divers with S=2.15 from air simulated diving at 31 m and on helium-oxygen at 38 m and 71 m

For subjects S2, S6 and S1a we obtained the following results:

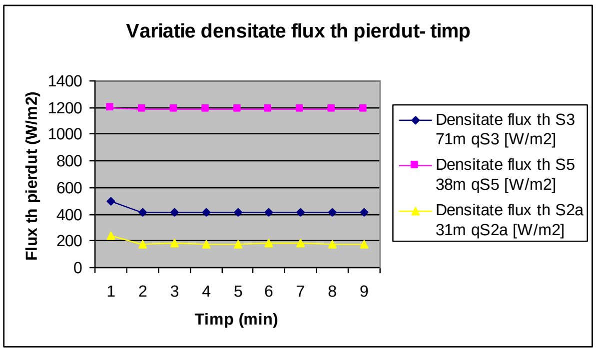

Fig. 2. Thermal flux density lost by divers with S=2.05 from air simulated diving at 31 m and on helium-oxygen at 38 m and 71 m

V. CONCLUSION

For immediate depth (31 and 38 m), in both cases, the thermal flux density lost is evident smaller for the air (yellow line – 200 W/m^2), than for the helium - oxygen (pink line – 1100-1200 W/m^2).

Due to the water temperature, the helium - oxygen saturation diving, in water temperature of 20^{0}C, the heat lost by subjects on 71 m, (blue line – 400-500 W/m^2), is less than the heat lost on 38 m, in water temperature of 17^{0}C, (pink line – 1100-1200 W/m^2).

Comparing the three series from the diagrams, can be seen as the water temperature has the greatest influence on the increase of thermal flux density by a diver.

The composition of the breathing gas can't be neglected because in case of helium - oxygen, the heat lost by subjects with similar physical, is two to three times higher than that suffered similar water's temperatures (20-22^{0}C), but with atmospheric air.

The problems generated by the cold water and by the composition of the breathing gas during the diving, are in attention of the entire professional world. [8], [9].

Fig. 3. Registrations of the temperatures, under pressure, into the dry hyperbaric chamber

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