Thermodynamic basis for calculation of quarters in complexes for underwater investigations

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Abstract

The paper presents a short characteristics of hyperbaric environment in which saturated divers are present with particular attention to the influence of thermal-physical properties. The above properties play the important part in the body's functions. They support the divers with comfort and security as well. On the example of a decompression chamber, chosen problems concerning thermal phenomena connected with plotting the energy balance are presented.

1 Introduction

Contemporary modern technology of sea research, specially of sea bottom research, is inseparably connected with saturated diving which enables man to spend a longer time under water. During saturated diving, the diver breathes with correspond with the depth of diving. Besides the physiologically indispensable quantities of oxygen, the main components of the above mixtures are light gases which are indifferent for human body, ex: helium, hydrogen, neon, argon. All the rooms in which divers are present are filled in with such non-typical hyperbaric atmosphere where exchange of heat and mass occurs, as well as flow of the gas in various elements of the installation responsible for the proper microclimate and security of the crew. Studies on literature available for the authors showed that, in most cases, the choice of thermal parameters of gas mixtures as well as technical solutions in saturated diving systems are based on simplified thermodynamic calculations, and particularly on results of long-term experiments in natural and simulated hyperbaric environments. There is a lack of general, analytic description of thermal phenomena present in the above mentioned installations, the knowledge of which would allow to anticipate some of situations with no need of long-term and expensive experiments.
Investigations carried out by the staff of our institute have shown that it is possible to create an analytic description on the basis of current thermodynamic knowledge [1,2,3,4,5,6].

The paper presents only some of the chosen problems, those which, as we think, should be taken into account while plotting balance calculations that allow to define the comfort temperature of a decompression chamber for the steady state.

2 Properties of hyperbaric environment

Compressed mixtures of real gases behave differently from their pure components, especially in case of breathing mixtures containing helium or hydrogen.

Distinct and most often non-linear relation between some thermal-physical properties characteristic for breathing mixtures and their composition and thermal parameters is not always known to designers dealing with installations for underwater research, which in turn, leads to many unpleasant surprises and unforeseen troubles. To give the example, the influence of pressure and helium contents on viscosity (\( \eta \)), thermal conductance (\( \lambda \)), Prandtl number (\( Pr \)), specific heat at constant pressure (\( c_p \)) and specific enthalpy (\( h \)) of helium-oxygen mixture at temperature 0°C is presented graphically on Fig. 1.

![Figure 1: The influence of composition and pressure on physical properties of helium-air mixture at temperature 0°C.](image)

As it can be concluded on the basis of the above figure for some cases, only minimal change of gas composition has a serious influence on a given property of the gas mixture.
The influence of pressure, especially with a high content of helium, is, in general, minimal and when the pressure is low (ex: $P<2$ MPa) it can be omitted in the balance calculations.

The carried out experimental research confirm the influence of pressure on convective heat transfer. To give example, Fig. 2 shows the influence of pressure ($0,1-10$ MPa) on Nusselt number in the range of forced laminar flow. It is worth mentioning that the influence of pressure on free convection is particularly high in the vicinity of the critical point.

Figure 2: The influence of pressure on Nusselt number in the range of forced laminar flow.

Gases indispensable for the breathing installations are kept in pressure containers and then they are throttled to the required final pressure. During a throttling process, there appears the effect of Joule-Thomson which causes the change of final temperature of the gas. In the case of breathing mixtures, temperature of the throttled gas can rise or drop, depending on the composition of the gas in question. Neutralisation heat of Joule-Thomson effect should also be regarded in the heat balance of installations.

District heat effects can also be observed when the compressed real gases are being mixed. For example, mixing helium with oxygen causes the temperature drop, which in turn, causes heat absorption from the environment. In the above case, Dalton and Amagat principles do not apply, they are valid for ideal and real gases at low pressure. Fig. 3 shows the results of calculations for
temperature changes during adiabatic mixing of helium and oxygen, the pressure being constant. The results were achieved by application of the Beattie-Bridgeman equation state which allows to calculate many thermodynamic properties for breathing mixtures \( (P, c_p, h, \delta) \) with precision sufficient for engineering. The obtained result have not been so far verified experimentally. They are, however, in qualitative agreement with the published results of experimental investigations for similar mixtures \( (\text{He} - \text{CO}_2, \text{CO}_2 - \text{N}_2 - \text{H}_2) \) and approximate quantitatively.

In the case when a mixture is prepared inside, for example, a decompression chamber, the mixing heat can be distinct for the heat balance of the whole system. When \( P = 20 \text{ MPa} \) and \( T = 273 \text{ K} \) for equimolar helium-oxygen mixture, the mixing heat amounts circa 600 [kJ/kmol].

If the atmosphere contains helium or hydrogen, diminish heat resistance of porous bodies.

The above fact concerns also the clothes and in consequence there occurs the heat loss from the diver's body in to the environment and thus his thermal well-being is getting worse. The knowledge of heat conductivity of diver's clothes is indispensable to make adequate improvements in the equation of comfort for hyperbaric conditions. Fig. 4 shows the dependency of relative heat resistance of clothes \( \Lambda_{\text{clm}} = \Lambda_{\text{clm}} / \Lambda_{\text{clo}} \) on porosity \( \varepsilon \) and on the ratio of heat conductivity of the mixture \( \lambda_m \) to heat conductivity of the air \( \lambda_p \) \( (\lambda^* = \lambda_m / \lambda_p) \). \( \Lambda_{\text{clm}} \) stands for heat resistance of clothes in the breathing atmosphere in units [clo], whereas \( \Lambda_{\text{clo}} \) stands for heat resistance of the same clothes in the air.

![Figure 3: Temperature change during adiabatic mixing of helium and oxygen at constant pressure.](image)

![Figure 4: Influence of porosity and relative heat conductivity on relative heat resistance of clothes.](image)

The cellular model of a porous body was assumed to obtain the results. Internal radiation within the fabric, gas movement in the clothes and water vapour diffusion were neglected in the calculations. The above factors diminish...
the total heat resistance of the garments. With regard to the introduced simplifications and high porosity of the clothes, the extreme case of $\varepsilon = 1$ was used for balance equations, and then:

$$\Lambda_{clm} \equiv \Lambda_{clo} \frac{\lambda_p}{\lambda_m}$$

(1)

It is easy to estimate the heat resistance of given clothes in the breathing atmosphere of any composition, as heat resistance of clothes in the air is available in popular tables and heat conductivity of applied breathing mixture can easily be determined. Resistance of water vapour diffusion through a usual garment set is relatively low and all the sweat given off by man in the conditions of heat comfort in the air can evaporate. In hyperbaric conditions the sweat evaporation velocity drops with the pressure rise, with simultaneous rise of diffusion resistance of clothes. It results from the research carried out by Webb that, in the environment of breathing mixtures, water evaporation intensity is $5 \div 10$ times lower than in the air. The above fact is confirmed by calculations and experiments carried out in the Institute of Heat Engineering of Technical University of Szczecin (Fig. 5).

![Figure 5: Influence of pressure on the water evaporation factor.](image)

Just general presentation of properties of the hyperbaric environment in which divers remain show its definite dissimilarity from the natural environment. Independently from physiological influence of breathing mixtures on the human body, thermal-physical properties of breathing mixtures can disturb the normal functioning of a body as well as the functioning of installations and systems ensuring the comfort and security for divers.
3 Equation of comfort for hyperbaric interiors

With regard to properties of breathing mixtures dealt with in heat balance for steady-state conditions, the equation of heat comfort was written as well as the equation of heat balance for any hyperbaric interior for divers (underwater habitat, decompression chamber, diving bell). Equation of comfort in the form proposed by Fanger was used in the calculations:

\[ \dot{Q} - (\dot{Q}_o + \dot{Q}_w) = \dot{Q}_p + \dot{Q}_r \quad [W] \]  

(2)

where:

- \( \dot{Q} \) [W] - heat stream given off to the environment by the diver’s body,
- \( \dot{Q}_o \) [W] - heat stream given off to the environment during breathing,
- \( \dot{Q}_w \) [W] - heat stream given off to the environment during sweating off the body surface,
- \( \dot{Q}_p \) [W] - heat stream conducted by the clothes,
- \( \dot{Q}_r \) [W] - heat stream received from the body surface and from the cloth through convection,
- \( \dot{Q}_k \) [W] - heat stream radiated into the environment.

Equation of comfort with most important physical parameters of the environment \((P_m, \varphi, t_m, w, X_j)\) and the kind of clothes as well as movement activity of the diver \((A_{cl}q_m)\), with regard to the changeability of physical properties with the change of pressure and breathing mixture composition allow to calculate the comfort temperature of gas atmosphere while deep diving.

Comparison of calculations results with comfort temperature determined experimentally for the equal environment shows good agreement of both values \((t_{exp} = 30.8^\circ C, t_{cal} = 31.2^\circ C)\), though the state of comfort is perceived differently by various people.

The above results confirm directly the correctness of assumptions made for the equation of comfort.

Physiologists may be interested in the data concerning the quantities and changeabilities of particular heat streams given off to the environment.

It is necessary to know the comfort temperature by making the heat balance of a hyperbaric habitat.

Analysis of particular streams of energy supplied from the system allows to write the equation of thermal balance for a sample decompression chamber (Fig. 6). The equation can be presented as follows:

\[ \sum_{i=1}^{n} H_i + \dot{Q}_p + N \dot{Q} + \sum_{r=1}^{R} \dot{Q}_{lr} + H_{m1} = H_{m2} + \sum_{k=1}^{K} \dot{Q}_{kk} \]  

(3)
Figure 6: Scheme of a decompression chamber.

where:

\[ \dot{Q}_p \] - heat stream indispensable to keep the comfort temperature [W].

The heat of mixing and the heat of neutralisation of Joule-Thomson effect are being taken into regard,

\[ N\dot{Q} \] - heat stream given off to the environment by bodies N of divers present in the chamber,

\[ \sum_{r=1}^{R} \dot{Q}_{jr} \] - heat stream given off by installations of the chamber (lamps, cookers, etc.),

\[ \sum_{r=1}^{n} \dot{H}_i \] - the stream of enthalpy of fresh gas mixture supplied in the chamber,

\[ \dot{H}_{ml}, \dot{H}_{m2} \] - the stream of enthalpy of mixture that is supplied and taken out of the regeneration system,

\[ \sum_{k=1}^{k} \dot{Q}_{kk} \] - the heat stream penetrating through the wall, access doors and illuminators of the chamber.

In order to quickly solve the complicated balance equations, a set of computer programs was written to make calculations by use of EMC. These programs are a distinct help when installation for saturated diving are designed and exploited.
4 Conclusions

The short characteristics of hyperbaric environment properties in which saturated divers are present and the description of heat flow that are present in this environment presented in the paper show visibly that hyperbaric environment differs distinctly from the natural environment.

Even if physiological influence of compressed gases on human body is neglected, their thermal-physical properties can disturb the normal functioning of the body as well as of various installations and systems ensuring divers comfort and security.

Theoretical investigations and experiments carried out in the Department of Heat Engineering of Technical University of Szczecin let: on one hand explain some little known thermodynamic processes present in compressed breathing atmospheres and on the other hand they contain clues how to design the new systems for saturated diving.

Literature

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