ULTRASONIC SENSOR FOR HELIUM CONTENT IN A GAS MIXTURE

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ABSTRACT

The thermodynamic state of a three component mixture is given by four values: two thermodynamic quantities and concentration of two components. When two independent thermodynamic quantities and one concentration are measured, then it is possible to evaluate the concentration of the two remaining components. This is an idea to measure the helium content in the mixture of oxygen, nitrogen and helium. This attitude was verified on the mixture of helium and air. The sound speed and temperature were measured in a gas sample at the ambient pressure. The relation of helium content, which depends on sound speed and temperature, was developed. A simple laboratory stand was built in order to check the accuracy of the method. The measurement of oxygen concentration was used as a parallel way to determine helium concentration. The obtained measurement error was lower than 2%.

KEYWORDS

Gas content, Gas mixture, Helium, Ultrasonic sensor

1. INTRODUCTION

There is a need to measure the content of a gas mix called trimix, which is composed of three components: helium, oxygen and nitrogen. Trimix is used for breathing in hyperbaric exposures. The main difficulty in measuring this gas is that there are no simple devices available on market, which allow measuring concentration of helium or nitrogen.
The thermodynamic state of a three component mixture is given by four values: e.g. two thermodynamic quantities and concentration of two components. This state might be also given as three independent thermodynamic quantities and one concentration. Moreover there exists a relation between quantities in both descriptions. It means, if it is possible to measure these three quantities and one concentration then it would be possible to evaluate the content fraction of remaining components.
This is the idea to build the device evaluating helium content. It occurs that three independent thermodynamic quantities (temperature T, pressure p and sound speed a_d) and oxygen concentration are easily measured. Simple sensors, which measure these quantities, are available on the market.
This paper is devoted to verification of this idea. In order to know precisely the helium concentration before the measurement the method was verified on the mixture of air and helium (helair). The constant ratio of nitrogen and oxygen allows assessing the precision of the method.
The relation of helium concentration on sound speed and temperature for helair was approximated by polynomials. The true values for this approximation were taken from electronic thermodynamic tables, which are available in a Promix software [1]. The actual helium concentration is evaluated based on oxygen sensor. The measurement is made at the ambient pressure and this variable is not taken into account in evaluations.
A small laboratory stand was made in order to conduct the measurements.

2. APPROXIMATION OF THERMODYNAMIC RELATION

The thermodynamic state of helium-air mixture is defined by three quantities: absolute pressure p, temperature T and one component concentration.
The available tables of mixtures thermodynamic properties [1] allow deriving the value of sound speed a_d as a function of pressure, temperature and component concentration (1).

$$a_d = a_d(p, T, pHe) \tag{1}$$

The relation (1) is monotonic and therefore the inverse relation for helium content can be derived [2]. In this paper the helium content is to be measured under the ambient pressure. The relation (2) is to be approximated.

$$pHe = pHe(a_d, T) \tag{2}$$

This relation was approximated at a constant pressure $p = 0.1$ MPa for temperature range of $278\ K \leq T \leq 306\ K$ with interval 2K and helium content range
$1\% \leq pHe \leq 50\ \%$ with interval 5% (pHe=1% was also included) .
The range of sound speeds comes from these ranges and in this case is given below.

$$338\,\tfrac{m}{s} \leq a_d \leq 620\,\tfrac{m}{s}$$

An introductory analysis of relation (2) shows that the helium content depends mainly on sound speed as shown on Fig.1.
Eventually the relation (2) was approximated in 315 points as a second order polynomial of two variables (T, a_d) :

$$pHe(a_d, T) = w_1 T^2 a_d^2 + w_2 T^2 a_d + w_3 T a_d^2 + w_4 T a_d + w_5 T + w_6 a_d + w_7 \qquad (3)$$

The coefficients $w_1,...,w_7$ in (3) were derived by the least square method (regression). The standard MATLAB package was used for these computations. The data for computations were taken from electronic thermodynamic tables in Promix software [1]. The Fig.2 shows the approximated surface.
Within the considered ranges of temperature and sound speed the maximum errors of helium content was computed.

$$\Delta H_e = 0{,}08\ \%$$

for T = 278 K, *pHe* 50.00 %, $a_d = 590.73$ *m/s*

$$\delta H_e = 0{,}006\ [-]$$

for T = 306 K, *pHe* 4.76 %, $a_d = 374.06$ *m/s*

3. MEASUREMENTS

There are sensors, which measure oxygen content, available on the market. But there are no simple sensors, which measure content of helium or nitrogen. The aim of this paper is to find out, whether it is possible to build a simple device for helium content evaluation based on sound speed measurement. The laboratory stand was build and appropriate measurements were taken out.

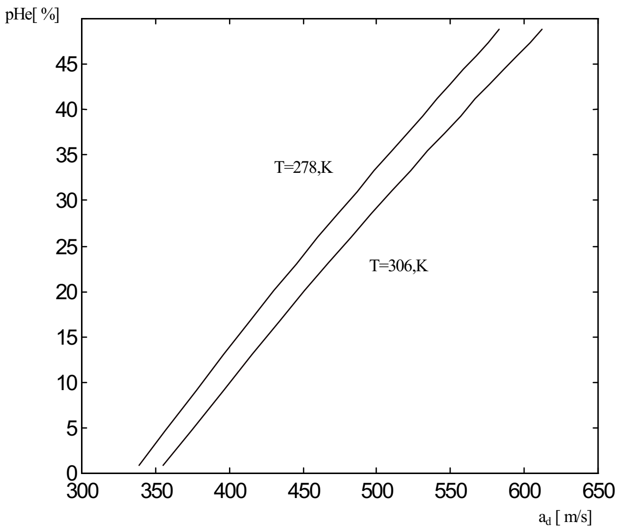

Figure 1.The relation pHe=pHe(a_d) for T=278K and T=306K, p=0.1 MPa

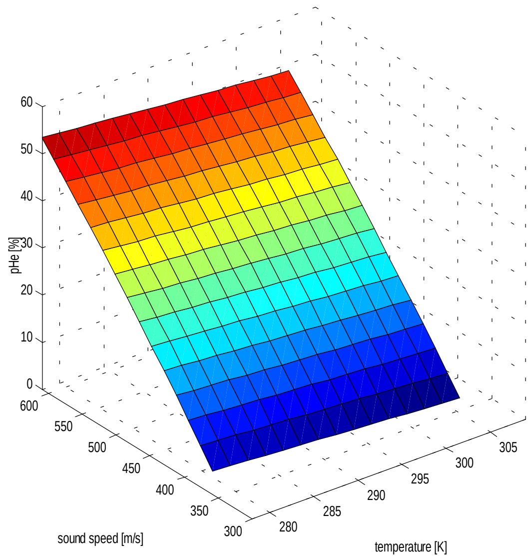

Figure 2.The surface of the relation pHe=pHe(a_d,T), p=0.1 MPa

The laboratory stand (Fig.3) consists of a vertical cylinder with a gas inlet and outlet. A measured gas mixture is delivered to the inlet from a high-pressure tank (used in hyperbaric exposures, e.g. in diving). The gas from the cylinder flows out to the atmosphere. The upper part of the cylinder is movable. If the pressure in the cylinder were higher than the ambient, then it would open. It assures that all measurements were taken at the ambient pressure. The sound speed is measured along vertical axis of the cylinder by an ultrasonic distance sensor [3], which is placed on the upper side of the cylinder. On the side of the cylinder a temperature sensor (Pt100) is placed. Both measured quantities are converted to standard current signal 4-20mA and delivered to the PC by Analogue/Digital Converter (ADC board).

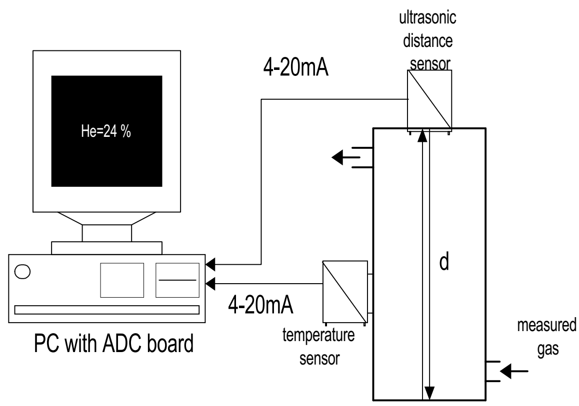

Figure 3.The helium content measurement system

The distance to the bottom of the cylinder is constant and equal to $d = 0.24$ [m]. Therefore the ultrasonic sensor measures the sound speed. When the gas containing helium is delivered to the cylinder, then the ultrasonic sensor output is falling down until it reaches the constant value. The measured value represents a time τ, which lasts when the sound wave goes from the transmitter (source) to the bottom of the cylinder and then back to the receiver. The distance made by the sound wave is equal to $2d = 0.48$ [m]. The sound speed in the examined mixture is given by

$$a_d = \frac{0.48}{\tau}\left[\frac{m}{s}\right].$$

The measuring system does not evaluate time τ in an explicit form. Therefore a calibration of the relation sound speed – measured current was required. It was done using two gas mixtures, in which helium content and sound speed were precisely known.
The PC computer evaluates on-line the helium content (in helium-air mixture) based on measured sound speed, temperature and polynomial approximate relation developed in Section 2.
The results were compared with helium content estimation based on oxygen content measurement – as sea divers usually do it. The MiniOX® oxygen sensor with transducer VN202 (VANDAGRAPH Ltd) was used. The accuracy of the oxygen content measurement was 1% - which means that the helium content in He-Air mixture is estimated with 5% error.
The He-Air mixtures with 7% - 40% helium contents were examined. The measurement of the mixtures containing more that 40% of helium were impossible, because of too low frequency used in the ultrasonic sensor. For these helium contents the sound speed was over 550 [m/s] and the sound wave was not recognised by the receiver.
All measurements were conducted at room temperature 275 [K] (22°C). The results are gathered in Table 1.
The measurements made with ultrasonic sensor were highly repeatable. This can not be said about the measurements made by the oxygen sensor, which required multiple calibration in air.
The highest absolute error of the helium measurement was equal to 2% in measure no 5. If this case is neglected, then the error is lower than 1.5%.
The highest absolute error approximate relation (3) and variance of the measurements of helium content are lower than the error made in measurements by oxygen sensor.

4. CONCLUSIONS

The laboratory stand based on ultrasonic sensor, which allows measuring helium concentration in He-Air mixture, was built. The carried out measurements have shown that the error in helium evaluation was lower than 2%. The repeatability of measurements was better than the repeatability obtained by oxygen concentration measurement. The stand built so far allows measuring helium concentration up to 40%. For higher helium concentrations an ultrasonic sensor with a broader frequency band should be used. The measurements are usually taken at the ambient pressure and room temperature. In that case the sound speed in the mixture depends mostly on the helium concentration.
The obtained results have shown that the proposed method of the helium concentration evaluation is prospectively a good way of gas mixture analysis in see-diver's practice.

Table 1. Measurements of the helium content in He-Air mixture at ambient pressure and temperature 275 [K].

nr	I [mA]	a_d [m./s]	pHe [%]	pO_2 [%]	$pHe(O_2)$ [%]	|error (pHe)|
1	7.06	547.54	39.658	12.50	40.48	0.83
2	7.38	487.04	28.566	15.00	28.57	0.04
3	7.55	460.03	23.425	15.90	24.28	0.85
4	7.77	429.23	17.420	17.10	18.57	1.15
5	7.88	415.32	14.659	17.50	16.66	2.00
6	7.93	409.29	13.453	18.30	12.85	0.60
7	8.21	378.03	7.101	19.50	7.14	0.04
8	7.92	410.49	13.550	18.30	12.80	0.75
9	7.97	404.60	12.370	18.30	12.80	0.43
10	7.98	403.44	12.130	18.40	12.38	0.25
11	8.0	401.14	11.670	18.45	12.14	0.47
12	7.11	537.12	37.600	13.40	36.19	1.41
13	7.15	529.06	36.100	13.50	35.71	0.39
14	7.19	521.24	34.700	13.80	34.28	0.42
15	8.10	390.05	9.420	19.00	9.50	0.08

Acknowledgements

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References

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[3] Ebel F., Nestel S., Proximity sensor, textbook-FESTO KG, Esslingen (1992)

Nomenclature

a_d [m/s] - sound speed
p [Pa] - pressure
T [K] - temperature
pHe [%] - helium concentration (volume percentage)
pO_2 [%] - oxygen concentration (volume percentage)
d [m] – distance to the bottom (cylinder height)
I [mA] – sensor output current
τ [s] - time

LE CAPTEUR ULTRASONIQUE POUR LA MESURE DE LA TENEUR DU HELIUM DANS LE MELANGE DES GAZ.

Il est nécessaire de mesurer la teneur des constituant dans le mélange ternaire contenant hélium, azote, oxygène, utilisé par les plongeurs en exposition hyperbarique.
La difficulté principale à mesurer un gaz est une manque d'appareils nécessaires qui permettent de mesurer la concentration d'hélium ou d'azote.
L'état thermodynamique du mélange ternaire est déterminé par quatre grandeurs, par exemple: par deux variables thermodynamiques et par la concentration de deux constituants ou par trois variables indépendantes thermodynamiques et une concentration.
Il existe une relation entre ces deux descriptions. Ainsi, s'il est possible de mesurer la température, la pression, la vitesse sonique et une concentration dans le mélange, il sera possible évaluer la teneurs des autres constituant.
C'est sur ce concept qu'a été réalisé un capteur pour la mesure de la teneur en hélium du mélange. Par suite de cela, on a élaboré une méthode qui permet d'évaluer le pourcentage d'hélium dans le mélange, fondée sur la mesure de la température, de la pression, de la vitesse sonique et de la concentration en oxygène. On peut réaliser facilement ces mesures en utilisant les appareils commerciaux.
Cet article présente la validation expérimentale de ce concept de mesure. La vérification a été menée pour le mélange hélium – air. Le rapport constant de la teneur d'azote et d'oxygène permet d'estimer facilement la précision de la méthode.
Pour conduire les recherches , on a construit un banc d'essais dans laquelle le gaz étudié est introduit dans un cylindre vertical sous la pression atmosphérique. La vitesse sonique est mesurée le long de l'axe vertical du cylindre à l'aide du capteur de distance qui est installé en haut du cylindre. La mesure de la température est réalisée à l'aide du capteur à résistance.
Les résultats des mesures sont transmis dans l'ordinateur par l'intermédiaire de la carte du convertisseur analogique – digital.
L'ordinateur évalue la concentration d'hélium en mélange d'après un polynôme d'interpolation, dont les coefficients ont été identifiés sur les valeurs réelles issues du logiciel Promix.. Ces coefficients sont calculées en fonction de la vitesse sonique et de la température.
La méthode proposée a été vérifiée en tenant compte de la connaissance de la proportion dans le mélange hélium – air. Cette proportion a été obtenue à l'aide du capteur de l'oxygène.
Des mélanges contenant jusqu'à 30% d'hélium ont été testés et l'erreur relative de la mesure est restée inférieure à 2%.