Research of process of absorption of carbon dioxide with water in capillary-porous elements

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Introduction. The use of capillary-porous elements for absorption of carbon dioxide fluid can intensify the process and ensure the stability of the finished product.

Materials and methods. Investigated the process of saturation of water carbon dioxide. Mass concentration of carbon dioxide in water was determined by the pressure and temperature of the mixture and comparison of tabular data. Pressure water supply to the input capillary-porous device 0.4 - 0.6 MPa; supply pressure of carbon dioxide in the space between the shell capillary-porous element and membrane 0,45-0,65 MPa; water temperature at the site saturation $t = 4 \div 12^0$C.

Results and discussion. Mass concentration of carbon dioxide has a linear dependence on the pressure and nonlinear from temperature changes and diameter of capillary. With increasing pressure from 0.4 MPa to 0.6 mass concentration of carbon dioxide in the liquid increases: at the temperature 4^0C - from 0.59 to 0.73 % mass, at 8^0C - from 0.56 to 0.63 % mass, and at 12^0C - from 0.39 to 49 % mass. Mass concentration of the mixture decreases with increasing temperature: at a pressure of 0.6 MPa - from 0.73 to 0.49 % mass, at 0.5 MPa - from 0.64 to 0.46 % mass, at 0.4 MPa - from 0.59 to 0.41 % mass. With the growth of capillary diameter 10 to 20 mm mass concentration of carbon dioxide in the liquid is reduced: at the temperature 4^0C - from 0.73 to 0.67 % mass, at 8^0C - from 0.62 to 0.57 % mass, and at 12^0C - from 0.49 to 40 % mass.

It is connected with the structural formations of water molecules and their oscillating motion. At low temperatures the oscillating motion of the molecular structures of water are not significant and carbon dioxide molecules easily penetrate into these structures without destroying them. And at high temperatures ($8 \div 12^0$C) oscillatory motion of molecular structures of water becomes higher and not all CO^2 molecules have the ability to penetrate into the data structure.

The mathematical dependence of the concentration of carbon dioxide in water from pressure, temperature and capillary diameter allows you to adjust the process and determine its rational parameters. Rational parameters of saturation: pressure supply water to the absorption P = 0,5 MPa, water temperature 8^0C and diameter capillary-porous channel d_k = 10 mm.

Conclusions. Application results in the production of carbonated beverages to increase productivity, reduce the loss of carbon dioxide and increase for foam stability.

Keywords: absorption,
carbon dioxide,
capillary.

Дослідження процесу абсорбції діоксиду вуглецю водою в капілярно-пористих елементах

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Вступ. Використання капілярно-пористих елементів для абсорбції діоксиду вуглецю рідиною дозволяє інтенсифікувати процес та забезпечити стабільність готового продукту.

Матеріали та методи. Досліджувався процес насичення води діоксидом вуглецю. Масову концентрацію діоксиду вуглецю у воді визначали за тиском та температурою суміші та порівнянням з табличними даними. Тиск подачі води на вхід капілярно-пористого пристрою 0.4 – 0.6 МПа; тиск подачі діоксиду вуглецю в простір між корпусом капілярно-пористого елемента та мембраною 0,45-0,65 МПа; температури води на ділянці насичення $t=4\div12^0$C

Результати та обговорення. Масова концентрація діоксиду вуглецю має лінійну залежність від тиску і нелінійну від зміни температури та діаметру капіляра. При збільшенні тиску від 0,4 до 0,6 МПа масова концентрація діоксиду вуглецю в рідині зростає: при температурі 4^0C – від 0,59 до 0,73 %мас, при 8^0C – від 0,56 до 0,63 %мас, а при 12^0C – від 0,39 до 49 %мас. Масова концентрація суміші при зростанні температури знижується: при тиску 0,6 МПа – від 0,73 до 0,49 %мас, при 0,5 МПа – від 0,64 до 0,46 %мас, при 0,4 МПа – від 0,59 до 0,41 %мас. При зростанні діаметру капіляру від 10 до 20 мм масова концентрація діоксиду вуглецю в рідині знижується: при температурі 4^0C – від 0,73 до 0,67 %мас, при 8^0C – від 0,62 до 0,57 %мас, а при 12^0C – від 0,49 до 40 %мас.

Це пов'язане із структурними утвореннями молекул води та їх коливальним рухом. При низьких температурах коливальний рух молекулярних утворень води не значний і молекули діоксиду вуглецю легше проникають в дані структури не руйнуючи їх. А при підвищених температурах ($8\div12^0$C) коливальний рух молекулярних утворень води стає вищим і не всі молекули CO_2 мають можливість проникати в дані структури.

Отримана математична залежність концентрації діоксиду вуглецю в воді від тиску, температури та діаметру капіляру дозволяє регулювати процес та визначити його раціональні параметри. Раціональні параметри процесу насичення: тиск подачі води на абсорбцію P=0,5 МПа, температура води 8^0C та діаметр капілярно-пористого каналу $d_к$=10мм.

Висновки. Застосування результатів у виробництві газованих напоїв дозволить підвищити продуктивність, зменшити втрати діоксиду вуглецю і підвищити піностійкість.

Ключові слова: *абсорбція, діоксид вуглецю, капіляр.*

Исследование процесса абсорбции диоксида углерода водой в капиллярно-пористых элементах

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Введение. Использование капиллярно-пористых элементов для абсорбции диоксида углерода жидкостью позволяет интенсифицировать процесс и обеспечить стабильность готового продукта.

Материалы и методы. Исследовался процесс насыщения воды углекислым газом. Массовую концентрацию диоксида углерода в воде определяли по давлению и температурой смеси и сравнением с табличными данными. Давление подачи воды на вход капиллярно-пористого устройства 0.4 - 0.6 МПа; давление подачи диоксида углерода в пространство между корпусом капиллярно-пористого элемента и мембраной 0,45-0,65 МПа; температуры воды на участке насыщения $t = 4 \div 12^0$C.

Результаты и обсуждение. Массовая концентрация диоксида углерода имеет линейную зависимость от давления и нелинейную от изменения температуры и диаметра капилляра. При увеличении давления от 0,4 до 0,6 МПа массовая концентрация диоксида углерода в жидкости возрастает: при температуре 4^0С - от 0,59 до 0,73% масс, при 8^0С - от 0,56 до 0,63% масс, а при 12^0С - от 0,39 до 49% масс. Массовая концентрация смеси при росте температуры снижается: при давлении 0,6 МПа - от 0,73 до 0,49% масс, при 0,5 МПа - от 0,64 до 0,46% масс, при 0,4 МПа - от 0,59 до 0,41% масс. При росте диаметра капилляра от 10 до 20 мм массовая концентрация диоксида углерода в жидкости снижается: при температуре 4^0С - от 0,73 до 0,67% масс, при 8^0С - от 0,62 до 0,57% масс, а при 12^0С - от 0,49 до 40% масс.

Это связано со структурными образованиями молекул воды и их колебательным движением. При низких температурах колебательное движение молекулярных образований воды не значительное и молекулы диоксида углерода легче проникают в данные структуры не разрушая их. А при повышенных температурах ($8 \div 12^0$С) колебательное движение молекулярных образований воды становится выше и не все молекулы CO_2 имеют возможность проникать в данные структуры.

Полученная математическая зависимость концентрации диоксида углерода в воде от давления, температуры и диаметра капилляра позволяет регулировать процесс и определить его рациональные параметры. Рациональные параметры процесса насыщения: давление подачи воды на абсорбцию P=0,5 МПа, температура воды 8^0С и диаметр капиллярно-пористого канала $d_к$=10 мм.

Выводы. Применение результатов в производстве газированных напитков позволит повысить производительность, уменьшить потери диоксида углерода и повысить стойкость пены.

Ключевые слова: *абсорбция, диоксид углерода, капилляр.*

Introduction

Currently, the increasing interest in capillary hydrodynamics, heat and mass transfer in microsystems that dictated by the rapid development of electronics and medicine, and miniaturization of devices in various fields of technology. Intensified research on the introduction of mini and microsystems in the fields of chemical and food technology.

Capillary effects intensification of processes found application in the following areas: mixing mikrofiltration, heat exchange, during catalytic reactions, synthesis karbon of compounds and vitamins in the production of biodiesel and others.

Actuality of theme confirmed interest in her well-known scientists in the field of absorption. In particular, the process of absorption in exploring: R. S. Abiyev, Kalinichenko VA, Karič SG, Meshenhisser M., Nakoryakov VE, Rebrov EV, Semenov IA, Trushin AM, rank E. A.

However, the process of absorption of carbon dioxide in the capillaries, its features and patterns in the literature are not represented.

Therefore, studies were conducted to justify the use of capillary channels flow for absorption of carbon dioxide with water.

Experimental studies involves determining the effects of key factors on the absorption and intensification of the process.

The object of research - the process of saturation of water with carbon dioxide.

The purpose of research - to examine the process of saturation of water with carbon dioxide in capillary-porous elements and set the parameters of the rational.

Materials and methods

Materials Research - water and carbon dioxide.

Water. We used the water from the water supply system of the city Fastiv, Kiev region, Ukraine. Water was further purified on material filters and cooled to a predetermined temperature.

The mineral composition of water research

№	Name of indicators	Tools	Recommended values
1.	Mineralization total	mg / dm3	250
2.	stiffness total	mgekv / dm3	4
3.	total alkalinity	mgekv / dm3	3,5
4.	magnesium	mg / dm3	10
5.	fluorine	mg / dm3	0,7

Carbon dioxide. For research used carbon dioxide in cylinders under pressure.

The actual composition of gas research

Name of indicators	Extra
1. The smell and taste	Slightly sour taste with no foreign odors
2. Volume fraction (CO_2) carbon dioxide,% not less than	99,99
3. The mass concentration sulfurous anhydride (SO_2), g / m^3,	0,000
4. The mass concentration of water vapor at a temperature of 20^{0}C and a pressure of 101.3 kPa (760 mm Hg), g / m	0,011
5. Saturation temperature of carbon dioxide vapor, which corresponds to the pressure of 101.3 kPa (760 mm Hg) and temperature 20^{0}C	minus 58
6. The mass concentration of vanadium oxide (calculated naV_5O_5), liquefied carbon dioxide mg / kg	0,000

Absent in the gas: mineral oils and mechanical impurities, carbon monoxide (CO), nitrogen oxides (NO, NO_2), hydrogen sulfide (H_2S), hydrochloric acid, ammonia, ethanolamine, and aromatic hydrocarbons.

Experimental studies on the solubility of carbon dioxide in water was carried out on an experimental setup circuit is shown in Figure 1.

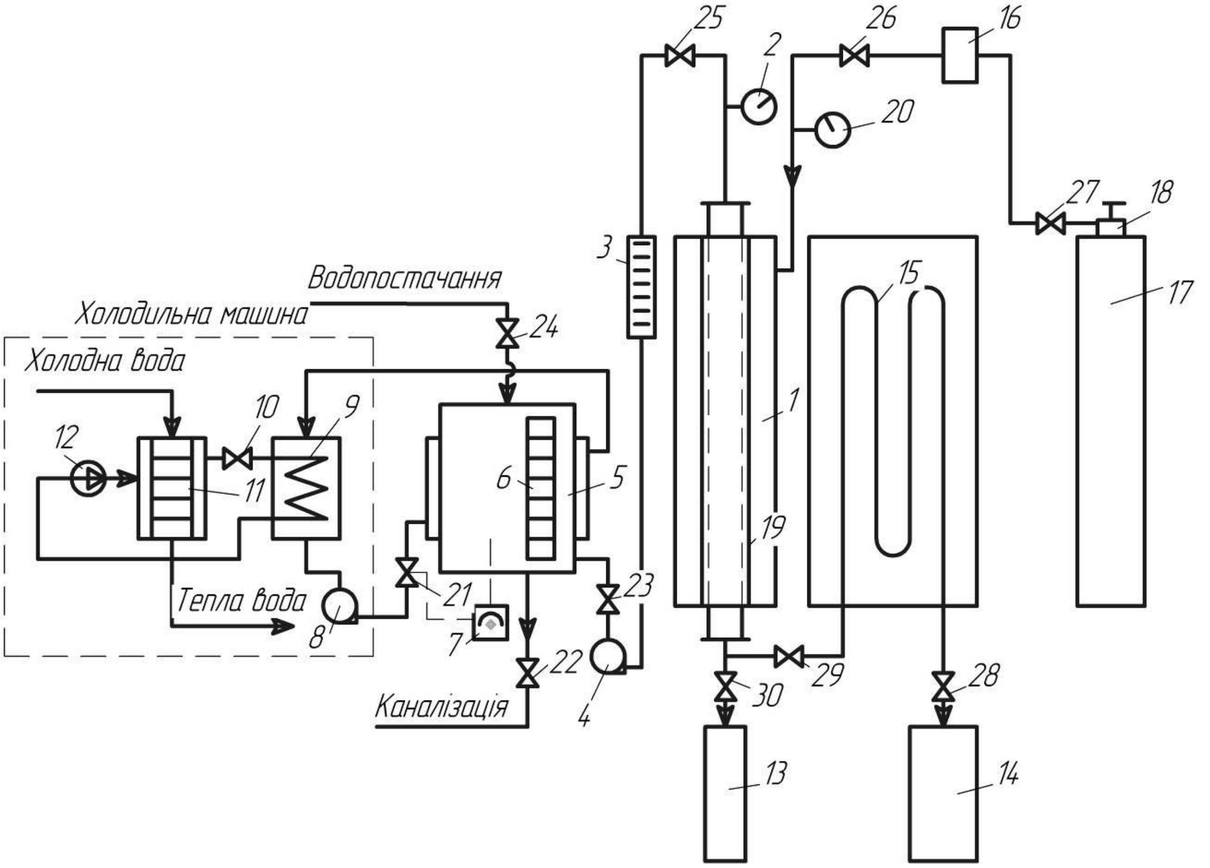

Fig. 1. Scheme of the experimental setup

Installation consists of a capillary-porous device 1, into inside of which served water at a certain temperature and pressure. Preparation of water conducted in tanks 5, which is equipped with water gauge glass 6 and cooling jacket. Filling capacitance 5 with water and release of water from the reservoirs is due to opening and closing the valve 22, 24. In jacket capacitance, 5 served chilled souse from the refrigeration unit. Of souse capacitance, where an installed evaporator 9, the souse pump 8, through the automatic valve 21 is supplied in the jacket 5 capacitance. Souse removes the heat from the water and returns to the souse capacitance. For obtaining water certain temperature serves as temperature dial 7, which automatically operates the valve 21 and controlled by feed coolant in jacket capacitance 5. Refrigeration machine consists of a compressor 12 of the refrigerator 11 and the throttle 10. To maintain a certain water pressure in the cavity of capillary-porous device serves as a valve 25, 29 and 30, and the meaning of the water pressure manometer indicates 2.

Capillary-porous device consists of a thin perforated metal tube (capillary) of a certain diameter, the outer perimeter of which is attached gas membrane 19. In the space between the membrane and corps of the device is supplied carbon dioxide. Gas pressure that moves in this space, is regulated by the valve 26 i 27, and value of gas pressure indicate manometer 20. The costs of gas carbon dioxide monitors the counter 16. Since the gas cylinder 17 via the reducing valve 18, carbon dioxide gas is fed into the gas line. Water moves through the inner cavity of the capillary gas bubbled through the membrane, and interact with the process of water absorption of carbon dioxide. Carbonated water through the valve 30 is sent to the volumetric plastic bottle 13. Filling bottles with carbonated water is fixed automatic stopwatch.

To increase the interaction between the gas and liquid phases are provided bypass capillary tubes 15. To maintain a predetermined pressure in the capillary tubes 15 are provided valves 28 and 29. Carbonated water, after passing through the bypass capillary tubes is directed to a volumetric plastic bottle 14.

Sampling of sparkling water was carried out according to the standard which extends on production of the nonalcoholic industry (liquid soft drinks, concentrates of drinks in a retail container, syrups, concentrates of a kvass mash, concentrates and extracts of kvass, a color, etc.) and establishes acceptance procedures and methods of sampling.

The temperature of the gas in the bottle of water was measured with a thermometer TL-4 in accordance with a measuring range from 0 to 50^0C and a scale division $0,1^0$C.

The mass concentration of carbon dioxide content in water (% by weight) was determined according to method for the determination of carbon dioxide in beer, soft drinks and mineral waters bottled in PET plastic bottles brand. The method involves determining the CO_2 in the water after filling the plastic bottle in a capacitance of 2 дм^{3}and its special closing cap. This method is based on measuring the pressure of carbon dioxide in the gas space of the bottle for the water temperature to 25^0C.

Device for determining the pressure in the bottle consists of a manometer with a measuring range 0-0,1MPa, a hollow needle which is connected to a manometer and the cap. The cap is screwed on to the neck of the bottle, the needle device is in a gas bottle.

A bottle filled with carbonated water, stoppered special cap and shaken by rotating it around a horizontal axis within 1-2 min. At the end of shaking the bottle is transferred to the vertical condition and removed indicators manometer. Unscrew the cap and with a thermometer measuring the temperature of water. The mass concentration of carbon dioxide in the water are on the table, depending on the values of the measured pressure and temperature.

The result should be the arithmetic mean of the results of three parallel determinations. The calculations are carried out with an accuracy of 0.001% by weight, followed by rounding the result up to 0.01 mass %.

In studies used the channel diameter of 10mm, 12mm, 15mm and 20mm.

Channels Ø10 and 12mm are makrochannels and channels Ø15 and 20mm are convective channels.

Mode of the movement of two-phase gas-liquid system is a projectile.

At research the solubility of carbon dioxide in water of different factors: the water supply pressure at the entrance of the capillary-porous devices $P_L = 0{,}4 - 0{,}6 МПа$; carbon dioxide supply pressure in the space between corps the capillary-porous element and the membrane P_G=0,45-0,65 МПа; the water temperature at the saturation t=4÷12^{0}C. Change only the value of the test factor in the selected range, and the rest of the factor values were maintained at a constant level for their least influence on the process of dissolution and to prevent significant errors of research results.

Results and discussion.

The dependence of the mass concentration of carbon dioxide in the water from the pressure change in capillary- porous device the diameter 10mm presented in Figure 2.

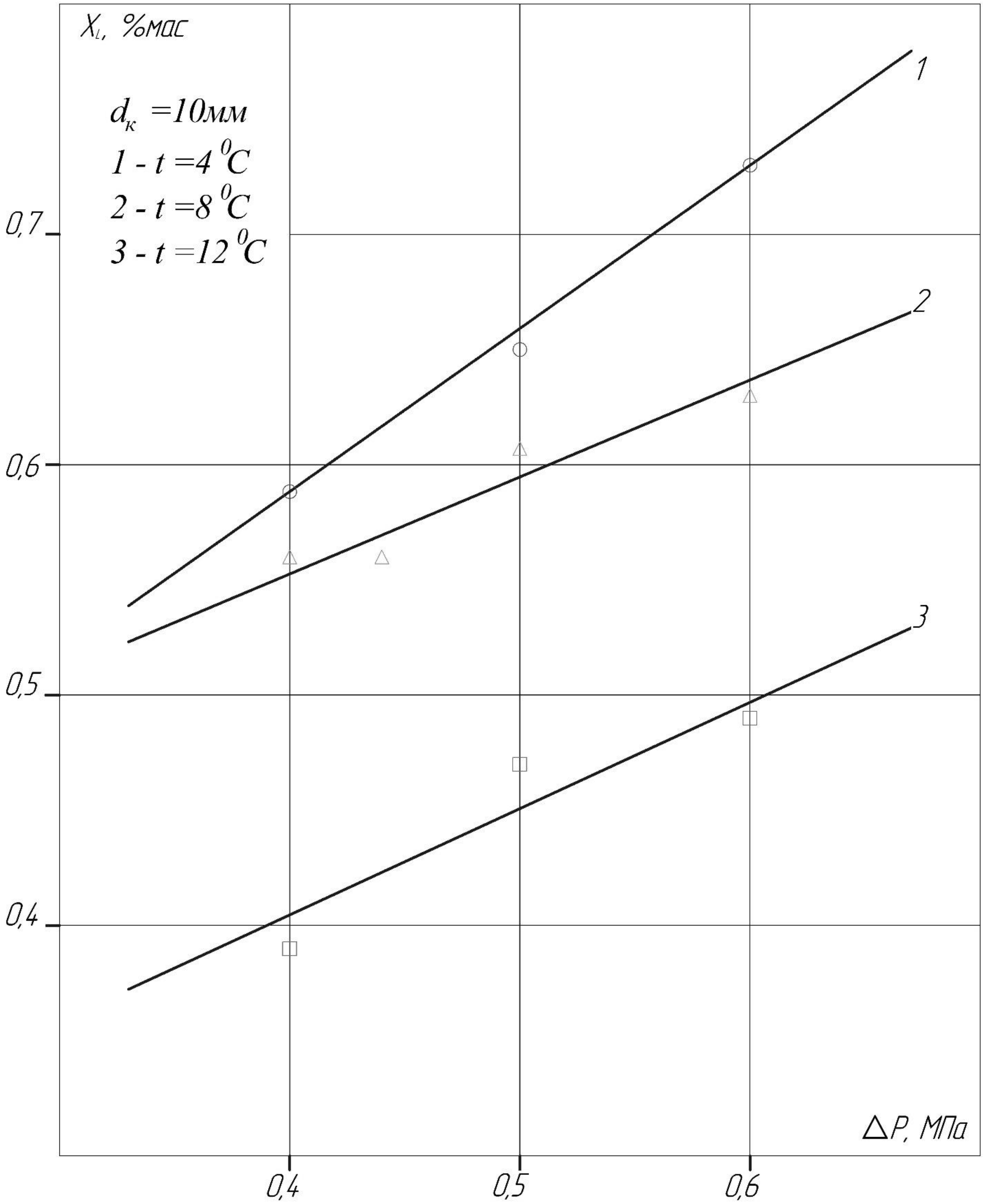

Fig. 2. The dependence of the mass concentration of CO_2 in the water with changing pressure in the absorber

Water supply pressure changed in the range from 0.4 to 0.6 MPa at an interval of 0.1 MPa. The water temperature was maintained at a level of 4, 8, and 12^0C.

With increasing water pressure in the device increases the solubility of carbon dioxide. Solubility with an increase in gas pressure increases according to the equation Henry. For the water temperature 4^0C - solubility of CO_2 in water with an increase in pressure in the system more rapidly than water temperatures 8 and 12^0C.

The growth rate of carbon dioxide solubility in water at temperatures 8 and 12^0C, at high pressure feed water from 0.4 to 0,6MPa is 16,5 ÷ 18% and for water at a temperature of 4^0C and pressure change of water in the same range is 23.7%.

This phenomenon is due to the structural formation of water molecules and the intensity of oscillatory motion of the dipoles of water. At low temperatures the water dipoles oscillatory motion is not significant and carbon dioxide molecules easily penetrate into the data structure and without damaging them.

When water pressure is increased from 0.4 to 0.6 MPa, for a capillary with a diameter of 10mm and a water temperature of 4, 8, and 12^0C, the solubility of carbon dioxide in water is described by the equation

$$x_L = A \cdot P + B$$

where A, B - coefficients given in Table 1; P - pressure of water supplied to the capillary-porous device.

Table 1

The value of the experimental coefficients

Coefficients	Temperature, ^0C		
	4	8	12
A	0,7	0,4	0,48
B	0,31	0,39	0,21

According to Henry's law [1], the concentration of the soluble gas into the liquid equilibrium with the gas phase, in which the partial pressure of the component is absorbed p_A.

With increase in water temperature, with equal other conditions increases the coefficient Henry and accordingly decreases the solubility of the gas.

Water temperature changed during the experimental studies in a range from 4 to 12^0C at interval 2^0C.

The results of experimental studies on the effect of water temperature on the solubility of CO_2 in water are shown in Figure 3.

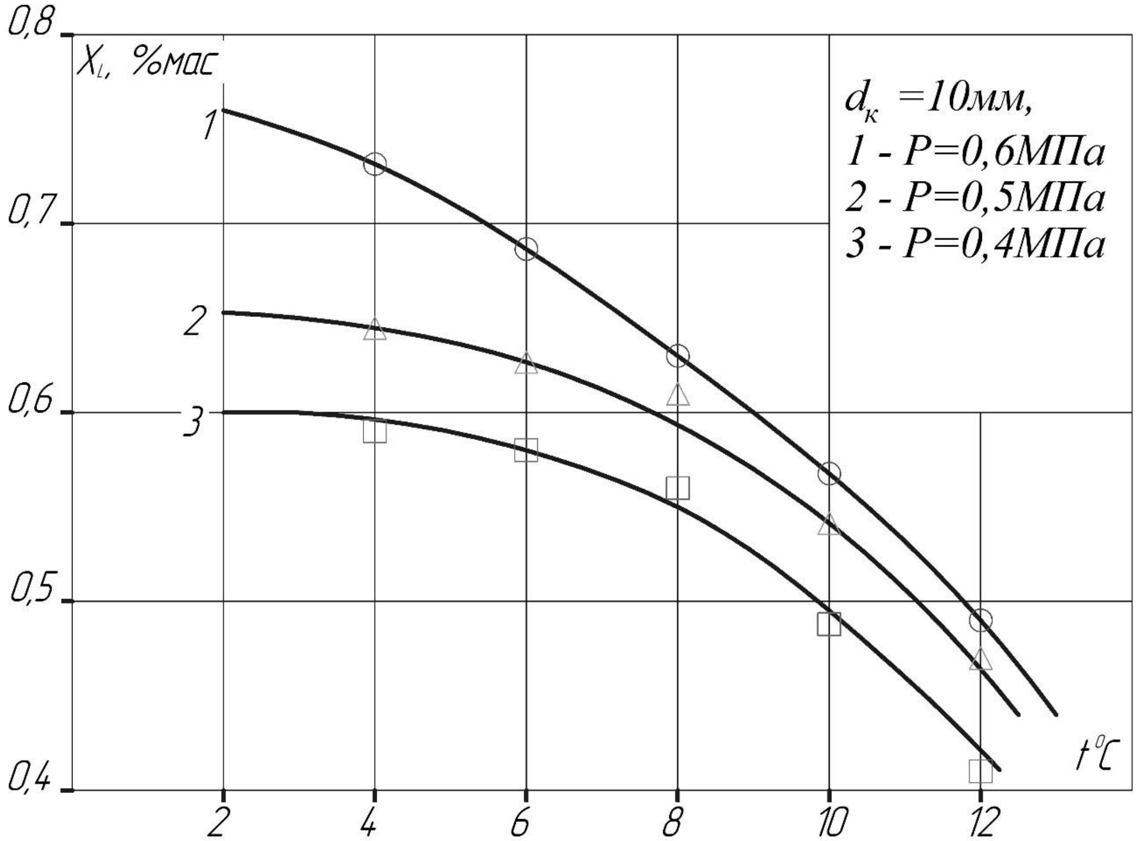

Fig. 3. The dependence of the mass concentration of CO_2 in the water from the water temperature changes

With increasing temperature of the water solubility of CO_2 in water is reduced. Reducing carbon dioxide solubility in water depends on the coefficient Henry, which increases with increasing temperature.

Increased temperature of the water of 8 to 12^0C, regardless of the supply pressure to the capillary, resulting a rapid decrease the solubility of CO_2 in water is 19-22%.

For the water supply pressure of 0.4 and 0.5 MPa with an increase in its temperature from 4 to 8^0C solubility of CO_2 in water decreases by 7,7 - 8,3%.

The dependence of the mass concentration of CO_2 in the water changes its temperature is described by the equations which are given in Table 2.

Table 2

Functional dependencies mass concentration of CO_2 in the water changing its temperature.

Changing the levels of the factors research		Functional dependence mass%.
$d_к = 10мм$	P=0,6МПа	$x_L = -0{,}0013t^2 - 0{,}0083t + 0{,}778$
	P=0,5МПа	$x_L = -0{,}0023t^2 + 0{,}0143t + 0{,}635$
	P=0,4МПа	$x_L = -0{,}0024t^2 + 0{,}016t + 0{,}572$

On the principle of creating a thin film of fluid moving through the capillary, which bubbled through the membrane, carbon dioxide, developed capillary-porous elements absorption devices [3, 4].

With the increase in diameter of the perforated capillary thickness increases the liquid phase through which carbon dioxide bubbled.

Increasing the diameter of the porous capillary causes reduced solubility of carbon dioxide with water (Fig.4).

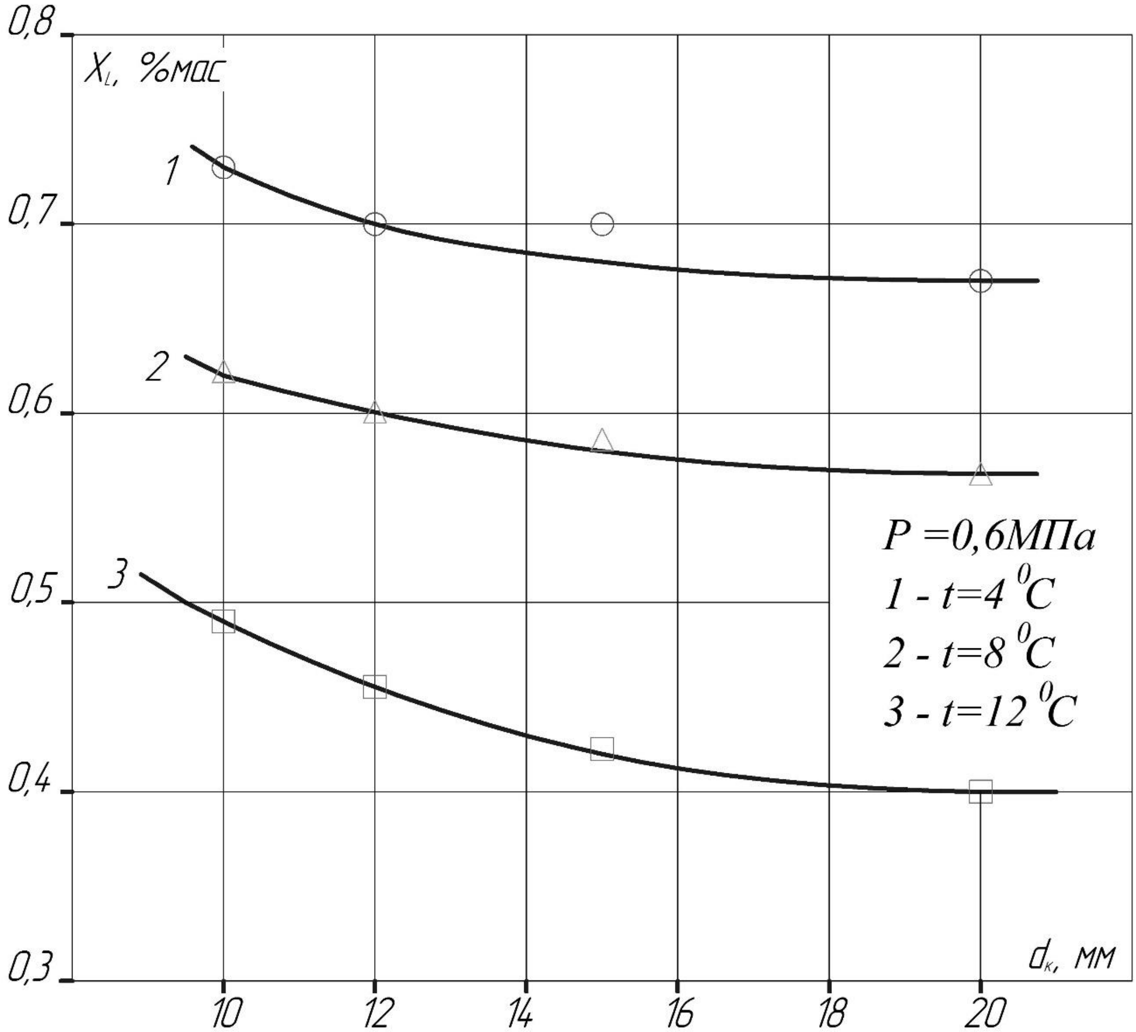

Fig. 4. The dependence of the mass concentration of CO_2 in the water at change diameter of the capillary

Change the solubility of CO_2 in water is not linear growth of the diameter of the porous capillary. The solubility of carbon dioxide decreases on the diameter of the capillary, as the increased thickness of the fluid through which bubbbled dissolved gas.

Intensive decrease the solubility of carbon dioxide in water occurs during the diameter growth of the capillary of 10 to 15mm. Increasing capillary diameter of 15 to 20mm hardly changes the solubility of CO_2 in water.

Functional dependences on influence of diameter of a porous capillary on degree of solubility of CO_2 in water are given in table 3.

Table 3

Functional dependences of solubility of CO_2 in water from change of diameter of a porous capillary

Value of the studied factors		Functional dependence mass%.
P=0,6МПа	t=4⁰C	$x_L = 0{,}0011d_к^2 - 0{,}0408d_к + 0{,}789$
	t=8⁰C	$x_L = 0{,}0006d_к^2 - 0{,}0231d_к + 0{,}791$
	t=12⁰C	$x_L = 0{,}0009d_к^2 - 0{,}0315d_к + 0{,}958$

In studies of changing factors at two levels: upper and lower. In dimensionless terms will be denoted by the upper level (1) and nether (-1).

Determine the number of experiments

$$N = 2^3 = 8 \quad (2)$$

Number of parallel set of experiments m=3, corresponding to P(t)=0,95 trusting probability experiments and standard deviation of parallel experiments σ=0,1.

To convert natural factors in dimensionless quantity using the formula

$$x_i = \frac{z_i - z_{i_0}}{\Delta z_i} \quad (3)$$

where z_i - a natural value factor; z_{i0} - the value i factor to zero; Δz_i - interval variation i factor.

To convert natural variables in coded x_i fill in the table coded variables at two levels (Table. 4)

Table 4

Encoding factors

Interval variation and level of factors	The pressure in the system, P, MPa	Water temperature, ^{0}C	diameter of the capillary, $d_к$,mm
Zero level x_i =0	0,5	8,0	15
The interval of variation, Δz_i	0,1	4,0	5
Lower level x_i =-1	0,4	4,0	10
Upper level x_i=+1	0,6	12	20
Coded designation	x_1	x_2	x_3

After normalization, we have a regression equation

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3 \quad (4)$$

We form full factorial of experiment matrix composed as follows: x_1 for alternate levels in each experiment, x_2 - across two experiment, x_3 - across four.

Table 5

Extended planning matrix full factorial experiment

№ досліду	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	y_1	y_2	y_3	$\overline{y_i}$
1	+	+	+	+	+	+	+	0,4	0,42	0,41	0,41
2	-	+	+	-	-	+	-	0,41	0,4	0,39	0,4
3	+	-	+	-	+	-	-	0,65	0,68	0,68	0,67
4	-	-	+	+	-	-	+	0,58	0,53	0,54	0,55
5	+	+	-	+	-	-	-	0,48	0,47	0,49	0,48
6	-	+	-	-	+	-	+	0,45	0,44	0,40	0,43
7	+	-	-	-	-	+	+	0,72	0,73	0,74	0,73
8	-	-	-	+	+	+	-	0,60	0,58	0,59	0,59
9	0	0	0	0	0	0	0	0,53	0,55	0,54	0,55

As a result of calculations received regression process of absorption of CO_2 in water for capillary-porous modules

$$x_L = 0{,}533 + 0{,}04x_1 - 0{,}103x_2 - 0{,}025x_3, \quad (5)$$

The regression equation of the process of absorption of carbon dioxide in water for capillary-porous modules for natural factors takes the following form

$$X_L = 0{,}45 + 0{,}4P - 0{,}0052t - 0{,}005d \quad (6)$$

Conclusions

- Degree of solubility of carbon dioxide in water is influenced by factors in the following order: pressure in the course of absorption, water temperature, diameter of a porous capillary.
- Increasing pressure causes an increase in the absorption process CO_2 solubility in water;
- Growth of water temperature and diameter of a porous capillary reduces solubility of carbon dioxide water;
- Rational parameters of saturation: pressure supply water to the absorption P=0,5 MPa, water temperature 8^0C and diameter capillary-porous channel d_k = 10 mm.

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