POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11-013

ANALYSIS OF THE PROBLEM OF SATURATION OF ICE WITH AIR BUBBLES

Vadim K. Goncharov[1], Natalia Yu. Klementieva[2], Jian-min Qin[3]

[1]Department of Oceantechnics and Marine Technology,
St.-Petersburg State Marine Technical University, Saint-Petersburg, Russia

[2]Ice Laboratory, Krylov Shipbuilding Research Institute, Saint-Petersburg, Russia

[3]Ministry of Education Key Laboratory of Advanced Transducers and Intelligent Control Systems,
Taiyuan University of Technology, Taiyuan, Shanxi, China

ABSTRACT

Results of the analysis of published measurements of the air bubbles content in sea ice are presented. The study of interrelation of porosity (gas content) and salinity of ice was carried out and it was revealed their probably significant correlation. Possible mechanisms of saturation of the lower ice layer with gas bubbles are considered. Simulation of the bubbles containing methane floating up from seabed sediments and natural gas deposits has shown that the increased content of gas bubbles in the lover layer of ice cover can be connected with these sources. Recommendations for development of researches of the given problem are stated.

INTRODUCTION

The ice covering a surface of the seas and fresh-water basins has complicated internal crystal structure. This structure is result of weather and geographical conditions and the interactions of ice floes among themselves under the effects of a wind, waves and currents in turn.

In any conditions, the initial stage of ice freezing is occurrence stable hexagonal crystals of ice from originally astable and close to tetrahedral internal structure of liquid water. The basic law of formation of stable crystals is a minimization of internal energy of a crystal lattice that causes replacement of extraneous substances - impurities from an initial solution, which are salts and gases in the seawater (Maeno, 1988). Air replacement occurs on an interface: water - ice. Partially air diffuses in water space, forming supersaturated solution, therefore some part of gases allocated in the form of bubbles, which are captured – freeze up in ice.

Other mechanisms of saturation of ice with gas bubbles can exist also. Gas bubbles from seawater mass and from bottom sediments, where there is a decomposition of sediment organic remains, can float up on the interface: water - ice. (This variant is most essential one for shallow fresh-water reservoirs (Sea Ice, 1997)). In water areas of the natural gas fields the infiltration of gas in seawater space, formation of the gas bubbles plumes, its rising from the great depths to an ice cover, and saturation of ice by methane is possible.

The probable mechanism of saturation of ice with bubbles is also penetration of atmospheric air into channels that remain in the top ice layer behind the drops of brine, which are flowing down between crystals of ice under the influence of gravity (Tucker at al., 1992).

Gases and salts dissolved before in seawater form the specific clusters: drops of a brine and gas bubbles, in ice floes covering seas. These clusters break the crystalline structure of ice, and strength of sea ice depends on quantity of brine drops and gas bubbles that remain in ice (Andersen, 1958, Sea Ice, 1997). The contents of brine and gas bubbles define as well the properties of an ice cover that appear at microwave sounding (Tucker at al., 1992).

In many publications devoted to research of physicomechanical properties of sea and fresh-water ices, integrated estimations of the air bubbles contents - porosity are stated. On data (Tucker at al., 1992) porosity (here brine drops are included in porosity) lays in a range: 20 - 60‰, also have the greatest sizes near to the lower surface of ice where reaches 200‰. In (Sea Ice, 1997) it is stated that sea ice has porosity 1 - 50‰. Porosity has maximum value: 12 - 18‰ in the top and lower layers of young ice, and it has minimum: 8‰ in the center layer. According to (Andersen, 1958) air bubbles are dispersed on all ice thickness, but the greatest concentration of bubbles was observed near to the top surface of ice.

ANALYSIS OF EXPERIMENTAL DATA

Detailed investigations of the air content in the sea ice was executed in (Nakawo, 1983), where in two cores of first-year ice in diameter of 75 mm that were sampled in the Baffin Bay (Eclipse Sound, Baffin Island, Canada) the vertical distribution of density, salinity and porosity (air content only) was measured. First core had length of 0.740 m and had been investigated in situ. It was cut on pieces with thickness of 50 mm and each sample was controlled apart. The second core in length of 0.795 mm had been frozen to - 40°C, delivered in laboratory and investigated with discreteness of 25 mm. Arrays of ice characteristics were as a result obtained: core № 1 - 15 values and a core № 2 - 32 values, which allow to get more detailed conception about the considered phenomenon and to draw statistically significant conclusions.

Table 1 contains averages (average-out on length of cores) and dispersions of density, salinity and porosity of ice for each core and for its unified array.

Table 1. Statistical characteristics of the sea ice properties.

Sea ice property		Core No 1	Core No 2	Unified array
Density, g/cm^3	average	0.911	0.913	0.912
	dispersion	$7.533\cdot10^{-5}$	$8.097\cdot10^{-5}$	$7.981\cdot10^{-5}$
Salinity, ‰	average	3.458	3.633	3.577
	dispersion	1.682	2.395	2.133
Porosity, %	average	1.246	1.090	1.140
	dispersion	1.193	1.336	1.269

Comparison of values of the measured properties of ice: density, salinity and porosity (average on height of each of cores) using “Student criterion” has revealed that difference between cores statistically is not significant. That is essential change of characteristics of a core No 2 during transportation and storage has not occurred. (The probability to observe similar or smaller difference between these characteristics of sea ice for two any other cores from same ice field equals from 50 to 70 %). It allows analyzing data on both cores in common, as unified array in volume of 47 values for each characteristic.

Figure 1 presents the porosity change (at the left) and salinity (on the right) along cores (on a thickness of ice). The analysis of these data shows the following: there is a similarity of change of porosity and salinity on length of each core. In turn, change of porosity and salinity on length similarly at comparison of both cores. In both cases substantial increase of value of porosity and salinity on the upper and lower borders of cores and rather small variation of these parameters in middle part of cores is observed. Higher salinity in upper and in lower layers of first-year ice was marked in many researches (Sea Ice, 1997, Backstrom, 2006). Porosity increase in these border layers demands special research.

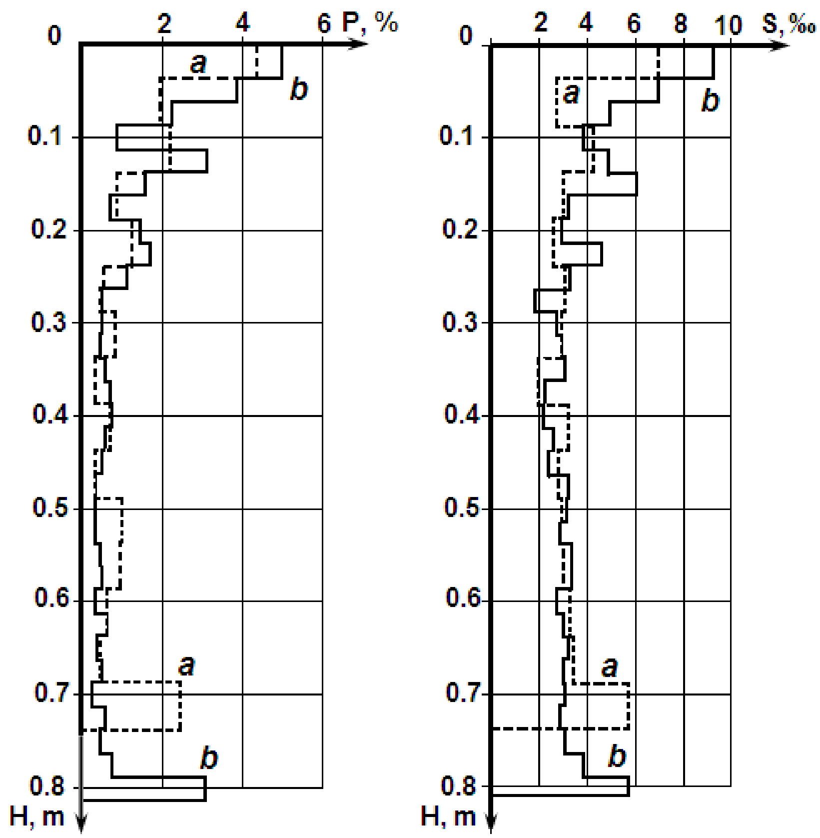

Figure 1. Variation of porosity (on the left) and salinity (on the right) along ice core No 1 (*a*) and core No 2 (*b*), reproduced from Nakawo (1983).

Figure 2 presents the histogram of values of the porosity, constructed on the unified array on both cores. On the histogram average value of porosity P_{av} = 1.140% and a curve of Weibull probability density function, which is in agreement with the histogram form, are presented also.

The correlation analysis between measured characteristics of sea ice: density, salinity and porosity, on base of unified array of their values has been carried out. Table 2 presents results of estimations of coefficients of correlation.

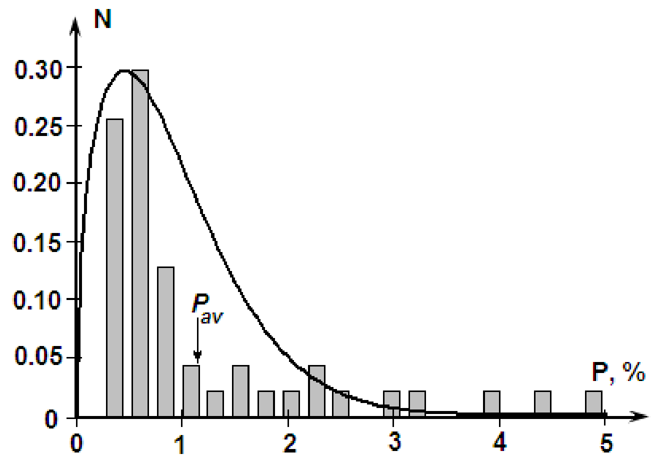

Figure 2. Histogram of porosity for unified sample and Weibull probability density function.

Table 2. Correlation between characteristics of sea ice.

Characteristic	Density	Salinity	Porosity
Density	X	- 0.834	- 0.965
Salinity	- 0.834	X	0.892
Porosity	- 0.965	0.892	X

All values of coefficients of correlation are great enough and it is possible to consider their as statistically significant ones. The analysis of materials of Table 2 allows following conclusions:

1. High correlation between density and porosity is natural and does not demand additional comments.
2. High, but negative correlation between salinity and density seems strange. However, average size of salinity S_{av} = 3.577‰ essentially less than average porosity P_{av} = 1.140%. Therefore, the contribution of porosity into density of ice is more then one of salinity. The negative sign of correlation: salinity - the density, in this case is connected with porosity.
3. High and positive correlation between porosity and salinity demands special research.

Figure 3 presents linear regression of porosity on salinity. These materials show, that high correlation between porosity and salinity is connected with largest values of these parameters, which amount, approximately, 1/5 part of an array. The main bulk of data is grouped in minor area: $S < 4$‰ and $P < 1$%, where any statistically significant interdependence between porosity and salinity is difficultly to establish.

Main mechanism of saturation of the sea ice with air is replacement before dissolved in seawater air into bubbles during the course of formation and growth of ice crystals. According to (Popov et al., 1979) in waters of Northern Atlantic the content of the basic components of air is following: nitrogen 9.2 - 14.4 ml/l and oxygen of 6.99 ml/l. Therefore, the average content of air dissolved in sea water makes: 16.2 - 21.4 ml/l. Take into account the increase in volume of ice in comparison with volume of the frozen water, it is possible to accept, that relative volume of air an origin under review in the ice can make 1.485 - 1.962%. These values exceed porosity in the central part of cores that confirms effect of replacement of gases at ice crystallization. At the same time, porosity on the lower layers of cores turned to water space considerably exceeds the specified values.

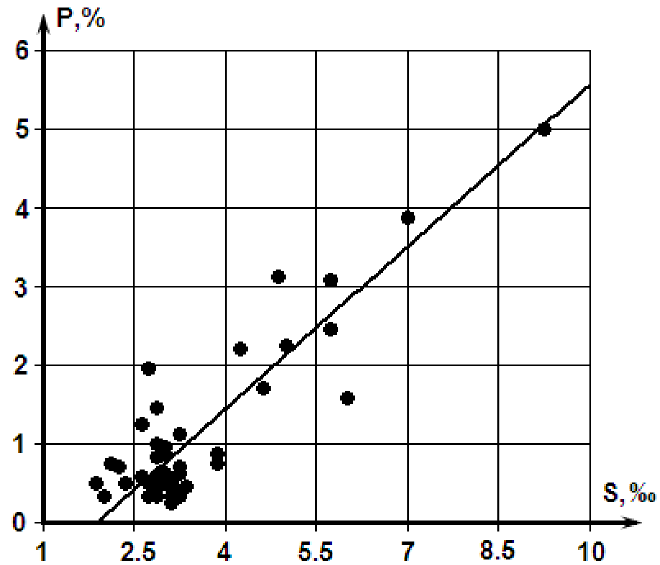

Figure 3. Linear regression porosity on salinity for integrated samples.

The zone of contact: ice - water space, is area of continuous interaction of these environments. Therefore, characteristics of ice and water in this zone considerably differ from other volume of ice and water (Qin et al., 2008). It is possible to expect, that the crystal structure of ice in the bottom layer is less compact, than in overlying layers. Hence, this layer is capable to contain larger quantity of gas bubbles in case of its inflow from water column. Drops of "brain" gradually flow down in the same layer from overlying ice layers, and these can explain correlation of porosity and salinity in bottom layers of both cores.

ANALYZE OF MECHANISMS OF SATURATION OF ICE WITH AIR BUBBLES

To evaluate a reality of pointed mechanism, it is necessary to examine following sources of bubbles. Air bubbles appear in near-surface layers of sea owing to breaking down of wind waves and as a result others, including biological, processes. Wind heaving is absent in the presence of an ice cover of sea surface. Therefore it is necessary to pay attention to the bubbles of a various origin exist long time in water space owing to an organic film of surfactants preventing their dissolution.

Results of researches by various methods of the content of air bubbles in near-surface layer of sea (Akulichev et al., 1986, Goncharov, 1997) had shown that bubbles in radius from 2.5 microns up to 20 microns were registered on depths greater 5 m using various methods. Their volume concentration, accordingly, is in a range from 1300 to 25 1/m^3. Based on these data, it is possible to estimate a flux of air from water column on the lower surface of an ice cover.

As stated by Nakawo (1983) the average rate of ice growth was about ≈ 0.05 micron/s. It is possible to assume that the bottom layer of cores by thickness 50 mm freeze up on an extent about 278 hours. Velocity of air bubbles floating up (if representing them in the form of sphere and applying Stokes decision) can be estimated using the following formula

$$w = \frac{2 g R^2}{9 \nu} \qquad (1)$$

where g - acceleration of gravity (9.81 m/s^2), ν - kinematic viscosity of sea water ($1.826 \cdot 10^{-6}$ m^2/s for 0°C and 34.3 ‰), R - radius of bubble. For bubble in radius R_1 = 2.5 microns speed of emersion is equal $w = 7.46 \cdot 10^{-6}$ m/s, and for bubble R_2 = 20 microns - $w = 4.68 \cdot 10^{-4}$ m/s. The flux of air from a water column through area unit (1/m^2·s) can be estimated using the following formula

$$q = \frac{4 \pi R^3 w}{3}. \qquad (2)$$

Calculation shows that inflow of gases on the bottom surface of ice cover for the period freeze up of ice layer in thickness 50 mm can have following values: for bubbles R_1 = 2.5 microns inflow $Q_1 = 6.40 \cdot 10^{-7}$ ml/m^2·s, and for R_2 = 20 microns inflow $Q_2 = 4.00 \cdot 10^{-4}$ ml/m^2·s. These quantities are negligible small in comparison with porosity of the ice cores in lower layer. Therefore, the examined source of saturation of ice with air does not play an essential role.

Other sources of gas bubbles in seawater space are seabed natural gas fields where plumes of bubbles containing gas methane are observed, and organic bottom sediments that in the course of decomposition release methane in form of the bubbles emerging to the sea surface. In the course of floating bubbles are dissolved, and as a result waters of oceans contain the dissolved methane in concentration of 10^{-3} ml/l in a near bottom layer and to 10^{-4} ml/l in overlying water space (Popov et al., 1979). The researches executed, for example, in Black and Okhotsk seas (Goncharov and Klementieva, 1996, Sovga et al., 2008) confirm the reality of these sources.

Methane can play an essential role in increase of the sea ice porosity in the case that bubbles containing methane have possibility to emerge from the seabed (that is they will not be dissolved) to the lower border of an ice cover. Possibility of dissolution of bubbles in turn depends on their original sizes and from depth, from which they begin floating (Goncharov and Klementieva, 1996).

Water area the Eclipse Sound is concerning deep-water one (717 m) with sharp increase in depth at removal from the coasts. Occurrence of bubbles containing methane from bottom sediments is the most probable on depths less than 250 m as on the greater depths methane can exist only in the form of crystalline hydrate of methane. It can be assumeв that the ice cores studied in Nakawo (1983) were taken off in an inshore part of water area most likely.

For an estimation of possibility of emersion of bubbles containing methane on the lower surface of ice cover the mathematical model of floating and dissolution of single gas bubble in sea environment has been applied (Goncharov and Klementieva, 1996). This model includes:

1. The equations of movement of the gas bubble that takes into account the variation of resistance of bubble movement at change of its volume and the form, caused by dissolution or decrease of external hydrostatical pressure in process of floating

$$\frac{dz}{dt} = w, \quad \frac{dw}{dt} = 2 g - \frac{3}{4} \zeta \frac{w^2}{r}, \qquad (3)$$

2. The equation of variation of radius of a bubble owing to diffusion of gases containing in a bubble through its surface and owing to change of external pressure,

$$\frac{dr}{dt}=\left\{\frac{\rho_w g\, r\, w}{3}-\frac{r\, w}{3}\left[p_a+\rho_w g\left(H-z\right)+\frac{2\sigma_w}{r}\right]\times\right.$$
$$\times\frac{\sum_{j=1}^{3}\rho_{a\,j}\frac{d\kappa_j}{dt}}{\sum_{j=1}^{3}\rho_{a\,j}\kappa_j}+\frac{1.45}{\pi}\sqrt{\frac{w}{r}}\sum_{j=1}^{3}\rho_{a\,j}\varepsilon_j\sqrt{k\,D_j}\times \tag{4}$$
$$\times\left[\alpha_{w\,j}\,p_a-\left(p_a+\rho_w g\left(H-z\right)+\frac{2\sigma_w}{r}\right)\kappa_j\alpha_{s\,j}\right]\times$$
$$\left.\left[\sum_{j=1}^{3}\rho_{a\,j}\kappa_j\right]^{-1}\right\}\left[p_a+\rho_w g\left(H-z\right)+\frac{4\sigma_w}{3r}\right],$$

3. Equations for mole fraction of methane originally filling a bubble and for mole fractions of nitrogen and oxygen those diffuse in it or from it in the course of floating up

$$\frac{d\kappa_j}{dt}=\frac{4.35}{\pi}\sqrt{\frac{w}{r^3}}\left\{\sum_{i=1}^{3}\frac{\kappa_j}{\kappa_i}\left[\alpha_{s\,j}\sqrt{k\,D_j}-\alpha_{si}\sqrt{k\,D_i}\right]\varepsilon_i-\right.$$
$$-\frac{p_a}{p_a+\rho_w g\left(H-z\right)+\frac{2\sigma_w}{r}}\times \tag{5}$$
$$\left.\times\sum_{i=1}^{3}\frac{\kappa_j}{\kappa_i}\left[\frac{\alpha_{w\,j}}{\kappa_j}\sqrt{k\,D_j}-\frac{\alpha_{wi}}{\kappa_i}\sqrt{k\,D_i}\right]\right\}\left(\sum_{i=1}^{3}\frac{\kappa_j}{\kappa_i}\right)^{-2},$$

Where t and z are time and vertical coordinate with origin on seabed; r and w are radius of bubble and its velocity of floating up; ρ_{aj}, μ_j and κ_j are density j-gas inside bubble under normal atmospheric pressure, its gram-molecular weight and mole fraction; α_{sj} and α_{wj} are saturant and background (in seawater) relative volumetric content of j-gas; D_j is diffusion coefficient j-gas through bubble surface in seawater without surfactants; k is coefficient to account the effect of surfactant film on diffusion, H and p_a are initial depth and atmospheric pressure; ρ_w and σ_w are mass density and capillary constant of seawater; g is gravity acceleration, ζ is coefficient of resistance and ε_j is relative part of bubble surface, through which j-gas diffuse.

Value ε_j depends on fraction of j-gas in total gas flux and following form determines it

$$\varepsilon_j=\frac{\mu_j\sqrt{D_j}\left|\left(\alpha_{w\,j}-\alpha_{s\,j}\right)\right|}{\sum_{i=1}^{3}\mu_i\sqrt{D_i}\left|\left(\alpha_{wi}-\alpha_{si}\right)\right|} \tag{6}$$

Initial data about background concentration and solubility of the gases proper to seawater pointed in (Popov et al., 1979) have been used for simulation. The correction to diffusion coefficient (k = 0.10) considering influence of a surfactant film forming on border of a bubble and inhibiting its dissolution have been made (Goncharov & Klementieva, 1995). In the course of simulation, the initial sizes of bubbles and initial depths were varied. The range of the initial sizes of bubbles (0.5 - 3.0 mm) has been chosen from the results of acoustic sounding pointed in (Sovga et al., 2008). The range of initial depths was restricted to 250 m. Simulation determined depths, from which emersion of bubbles to an ice cover is probable, and amount of methane in relation to initial one that bubbles were capable to carry out from seabed to an ice.

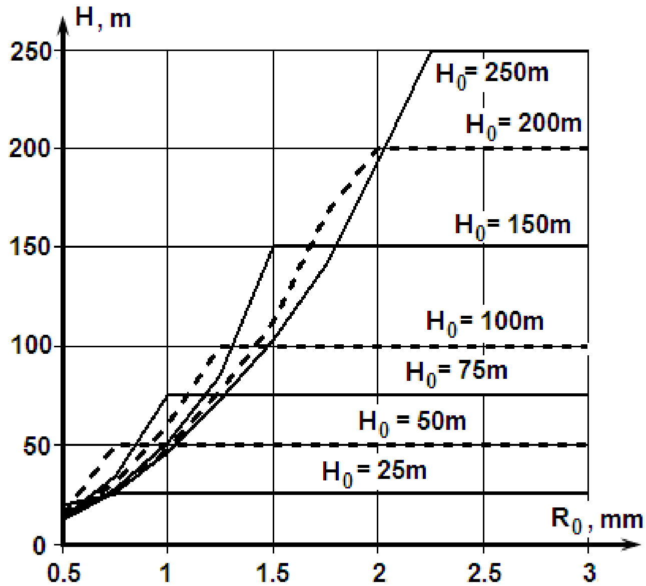

Figure 4. Height above seabed that methane bubbles with various initial dimensions (R_0) are capable to float for various depth of emission (H_0).

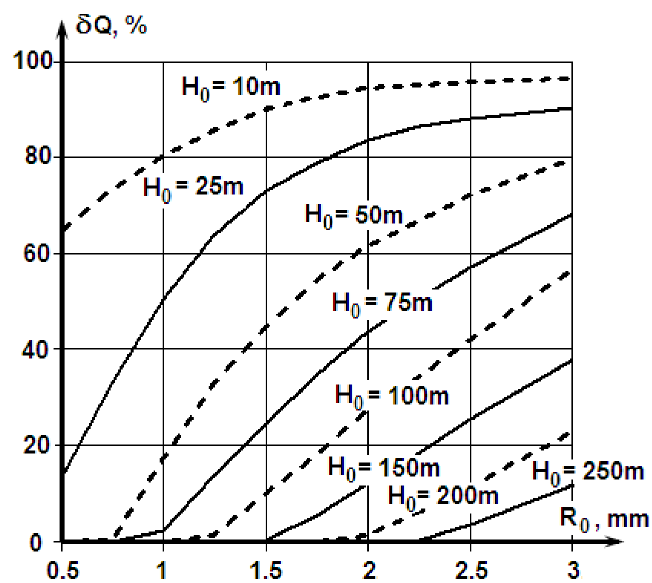

Figure 5. Relative quantity of initial content of methane (δQ) that bubbles with various initial dimensions (R_0) are capable to carry out on the lower surface of ice cover for various depth of emission (H_0).

Figure 4 shows ranges of heights on which bubbles fumed by sediments on various depths are capable to float up and not dissolve completely. Figure 5 illustrates amount of methane that the emerged bubbles are capable to carry out on the lower surface of ice.

These materials show, that fumed by seabed sediments on depths to 100 - 150 m filled with methane bubbles with initial radius more than 1.5 mm are capable to cause real increase of porosity on the lower surface of an ice cover. Thus, it is possible to explain porosity of the lower layer of the ice cover, which exceeds values which it is possible to explain by the replacement of the gases dissolved in seawater at formation of crystals of ice can are .

The considered mechanism can be real also for deep-water sources of the bubbles containing methane, which form plumes on the marine natural gas fields. In this case, there is a consecutive transformation in process of emersion of bubbles: a bubble with methane - globule of crystalline hydrate of methane - a bubble with methane (Goncharov, 2002). Disintegration crystalline hydrate of methane with formation of usual bubbles occurs on depths 200 - 150 m. Therefore, simulation of this process will yield the results similar to those presented in Figures 4 and 5.

The increased porosity in the top layer of ice cover adjoined with a snow cover and atmosphere it is possible to explain by the air replacement of channels, which are formed at running off brine drops in depth of ice (Tucker at al., 1992). At the same time, results of measurements of the salinity in ice cores, presented in Figure 1, do not give the necessary bases for the analysis of this process, for example, by methods of the theory of a filtration as salinity does not increase and even decreases in a direction to the middle parts of both ice cores. It is possible to assume, that process of filtration of a brine occurred at early stages of formation of an ice cover when temperature of air and ice was higher than in time of sampling of cores. Then at fall of temperature of air and ice, this process gradually stopped, and the examined profile of salinity and porosity was generated. This phenomenon requires special researches, for example, by the survey of the cores selected at different stages of ice cover freezing, by a technique used in Nakawo (1983).

CONCLUSION

The problem of saturation of sea ice with gas bubbles is insufficiently investigated at present time and demands the further studying. This problem has practical value as porosity defines strength of ice cover. The studies of laws of considered process will allow predicting the strength characteristics of sea ice based on a place of its formation. It would be very interesting the experiments in laboratory on base special variation of conditions of air access to the ice samples during their freezing.

Carried out researches have shown that porosity increase on the lower border of an ice cover can be a consequence of capture of bubbles with methane formed at decomposition of seabed sediments or at leaks of methane from marine natural gas fields. It allows expecting that the ice cover formed in shallow water areas would have smaller strength than ice in deep water areas. On the other hand, the increased porosity or concentration of methane in the lower layer of ice cover can specify the probable existence of seabed deposits of natural gas in the given water area.

ACKNOWLEDGEMENT

The Russian Foundation for Basic Research (Grant No 08-08-92205) and the National Natural Science Foundation of China (Grant No 60811120556) supported this work.

REFERENCES

Akulichev V.A., Bulanov V.A., Klenin S.S., 1986. Acoustical probing of the gas bubbles in the sea space. Akusticheskii zhurnal, Vol. 32, No 3, pp. 289 – 295, (in Russian).

Andersen, D.L., 1958. A model for determining sea ice properties.// Arctic Sea Ice. Proceedings of the Conference conducted by the Division of Earth Sciences and supported by the Office of Naval Research. Easton, Maryland. February, 1958. pp 148 – 152.

Backstrom, L.G.E., Eicken, H., 2006. Capacitance probe measurements of brine volume and bulk salinity in first-year sea ice. Cold Regions Science and Technology, No 46, pp 167 -180.

Goncharov, V.K. and Klementieva, N.Yu., 1995. Investigation of surfactant film influence on solution of a moving bubble in sea water. Izvestya Rossiiskoi Akademii Nauk. Physika atmosphery i okeana. Vol. 31. No 5, pp. 705 – 712, (in Russian).

Goncharov V.K. and Klementieva N.Yu., 1996. Modelling the dynamics and conditions of sound scattering by gas bubbles floating up from deep water oil and gas deposits. Acoustical Physics, Vol. 42, No 3, pp. 323 – 328.

Goncharov, V.K., 1997. Investigation into bubble contents in the upper ocean from their cavitation manifestation in water flow: Analytical treatment of results. Oceanology, Vol. 37, No 4. pp. 465 – 471, (in English).

Goncharov, V.K., 2002. Modelling of evolution of the bubble plumes arising under leaks of natural gas from deep-water pipeline. Proceeding of the Twenty-fifth Arctic and Marine Oil Spill Program (AMOP). Technical Seminar. Canada. Vol. I. pp. 45 – 56.

Maeno N., 1988. Science about Ice. Moscow: Mir, 231 pp., (in Russian, translation from Japanese).

Nakawo M., 1983. Measurement on air porosity of sea ice. Annals of Glaciology, No 4, pp. 204 – 208.

Popov N.I., Fedorov K.N., Orlov V.M., 1979. Sea Water. Reference manual. Moscow: Nauka, 328 pp., (in Russian).

Qin J., Cheng P., Zhao B., Du Y., Li X., Zhou J., Li Z., 2008. Research on a new measurement method of ice-thickness. Proceedings of 19^{th} IAHR International Symposium on Ice. Canada. Vol. 1, pp. 409 – 416.

Sea Ice. Reference manual. 1997. Saint-Petersburg: Gidrometeoizdat, 402 pp., (in Russian).

Sovga, E.E., Lyubartseva, S.P., Lyubitsky, A.A., 2008. Investigation of methane biogeochemistry and mechanisms of its transport in the Black Sea. Morskoi gidrophisicheskii zhurnal, Sevastopol, No 5, pp. 40-56, (in Russian).

Tucker, W.B., Perovich, D.K., Gow, A.J., Weeks, W.F., Drinkwater, M.R., 1992. Physical Properties of Sea Ice relevant to Remote Sensing. Chapter 2. Microwave remote Sensing of Sea Ice. Geophysical Monograph 68, American Geophysical Union, pp. 9 – 28.