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A method to increase the Arctic sea ice cover

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Proposed in this paper is a new method for preserving the ice in the Arctic regions under the conditions of global warming. The main technique involves artificial polymer films, which are used as an additional cover for the overcooled northern regions. The polymer films are constructed in such a way that they cannot only reflect the incoming solar radiation but also provide additional sites for the nucleation of ice crystals. This feature of polymer films to produce ice crystal aggregation in the larger ice structures in the adjoining area can be achieved by decreasing sea wave amplitudes in the vicinity of the considered area. © *2008 American Institute of Physics*.
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I. INTRODUCTION

In the past few years, the intensive melting of Arctic ice has caused a number of negative consequences. It is known that the ice reflects about 70%–90% of the incoming solar radiation in comparison with the water reflection that is only 7%–10%. This phenomenon creates an energy feedback, which can increase the effects of global warming. It is obvious that when ice melts, the overall water level does not change. However, the sea level could rise, if the snow or ice on the ground melted. If the Arctic ice melted, it would affect the direction of the gulf stream because a huge amount of fresh water would be produced from the melted ice as a result. The recent observation states that the sea level increases by 3 mm per year, which adds 10^{12} tons of water into the world ocean annually. Due to the rotation of the earth, this additional amount of water in the equator region may not only cause storms but can also make them more powerful, frequent, and destructive.

Large areas of the Arctic seas are unstable.[1,2] In these areas supercooled water is mixed with small pieces of solid ice ranging from several millimeters to several meters in size. Even when the air temperatures are between −30 and −10 °C, the ice pieces cannot consolidate into larger ice platforms because of the chaotic movement and the friction of moving water masses. In other words, the sea waves and currents prevent this process. In this study, we focus on developing a method, algorithm, and optimal tools to stabilize the ice cover of the Arctic. Large regions of supercooled water could be covered with a special polymer film containing holes. The practical realization of the method is based on the distribution of such films or separate rafts of this film, by airplane over supercooled water when the weather is not windy. In order to exceed the typical wavelength of the sea, the width of each individual raft should be equal to several meters. The optimal material is a porous polymer whose density should be less than that of the water. A broad class of porous polymers and composites is suitable for this application. The main purpose of small cavities in such porous polymer is to provide additional pores that will ensure very quick crystallization. This leads to high water stability because of the capillary effect and the significant surface forces.

The main physical processes affecting the ice formation are (1) fading of motion for the local water area and decreasing of such motions by feedback mechanisms, (2) increasing of reflectivity of the cover materials in comparison with open water, (3) nucleation of ice crystals by porous polymers, and (4) osmosis of fresh water through the polymer membrane.

II. ANALYSIS

The main idea of the proposed method is to achieve the local surface stability by constructing the additional cover.[3–5] The dissipative energy connected to the set of vibrated particles is increased by enlarging the amplitude of ice particle oscillation. Therefore, energy losses ΔQ_d should be decreased in accordance with the vibration amplitude W. These losses could be simply estimated[6,7] as $\Delta Q_d \sim \mu W^2$; here, μ is the loss coefficient. Dissipation losses depend on the viscosity of the surrounding liquid and are responsible for friction, heating, and melting in the border area. Also, melting of ice can be increased due to the higher viscosity of water at low temperature. It can also be estimated according to the empirical formula[7] $\mu = 0.017\,79(1 + 0.035\,68T + 0.000\,22T^2)^{-1}$; here, μ is the viscosity coefficient in CGS and T is the temperature in °C. As a result, the fading amplitude stimulates the ice formation.

The joint solution for plate vibrations taking into account the surrounding liquid was developed earlier,[8,9] etc. We applied this analytical method to our considered system. The

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initial system of equations for the joint vibrations of the infinite plate on a water and wave equation in the liquid under has the form[9]

$$D\frac{\partial^4 W}{\partial x^4} + 2h\rho\frac{\partial^2 W}{\partial t^2} + P(0,x,t) = 0,$$

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} = 0|x| \leqslant \infty, \quad z \geqslant 0, \tag{1}$$

where x is the direction of the interface of the plate/water, z is the perpendicular direction from the water surface to its depth, $W(x,t)=W(x)\exp(-i\omega t)$ is the sagging amplitude for the plate, $P(z,x,t)=P(z,x)\exp(-i\omega t)$ is the additional periodical pressure in the adjoined liquid, $2h$ is the plate thickness, ρ is the plate density, c is the sound velocity, $D=2Eh^3/[3(1-\nu^2)]$ is the plate rigidity, ν is the Poisson coefficient, and t is time. The boundary equation at the plate/water interface is

$$\left.\frac{\partial P}{\partial z}\right|_{z=0} = -\rho\frac{\partial^2 W}{\partial t^2}. \tag{2}$$

The joined mass of surrounding water concentrates near the vibrated cantilever and deprives the energy from the excitation source. The joint solution was substituted into initial equations. After the separation of the time multiplicands, the following system was produced to find plate amplitude and water pressure:

$$\left[D\left(\frac{\pi}{L}\right)^4 - \Omega^4\right]W + P_0 = 0,$$

$$\left.\frac{dP_0}{dz}\right|_{z=0} = \omega^2\rho W, \quad \Omega^4 = 2\omega^2\rho h,$$

$$\frac{d^2P_0}{dz^2} - \left[\left(\frac{\pi}{L}\right)^2 - k^2\right]P_0 = 0, \quad k = \frac{\omega}{c}, \tag{3}$$

where α is a parameter, the real part is $\alpha=(\pi/L)^2-k^2>0$, L is the half of the length of the hydroelastic wave in the plate, and P_0 is the interface pressure. The fading pressure allows the following assumption far from the plate:

$$P_0(z) = P_0\exp(-\alpha z). \tag{4}$$

Taking into account low pressure in the boundary equation at $z=0$, the following general equation was produced for the key parameter α for the pressure fading:

$$\alpha^5 + 2k^2\alpha^3 - \left(\frac{\Omega^4}{D} - k^4\right)\alpha - \frac{\Omega}{D}\frac{\rho_w}{2h\rho} = 0. \tag{5}$$

This method gives the approximate formulas for the amplitude and pressure fading for the first oscillation mode due to the action of the point force Q in the middle of the plate:

$$W_1(0) \approx \frac{Q}{\alpha_1^2 D}(0.0325 + 0.1i), \tag{6}$$

$$\alpha_1 \approx \left(\frac{\omega^2\rho_w}{D}\right)^{1/5}. \tag{7}$$

Approximate numerical values are[10] $E=0.7\times10^9$ Pa, $\nu=0.48$, $\rho=950$ kg/m^3, and $h=0.2$ m. The resulting calculations of the first mode amplitude $W_1(0)$ in the center of the plate according to Eq. (6) were performed by using force dependence from the sea wave according to approximate formula $Q_w\approx\rho_w H_w{}^3 g$; it was the plate amplitude $W_1(0)\approx1.6\times10^{-6}$ m that caused the water wave with the height of about $H_w=1$ m. Similar calculations were done for the finite plate with a size of $10\times20\times0.2$ m^3; they gave[5] $W_1(0,0)\approx1.8$ mm. The rigidity ribs in the composite construction decrease the oscillations more significantly.[6]

The role of pores is important because of the absorption and ability to preserve the water by means of capillary forces. They provide high stability for the supercooled water to form the initial clusters for ice formation. Simple numerical estimation gave the optimal capillary diameter. It is approximately 150 μm for capillary diameter with height $h=0.2$ m in the porous-polymer raft sample with similar height. This porous-polymer raft may be compared to a big floating refrigerator as it preserves the capillary power. Due to destructive forces of storms and pushes by the wave affecting the raft, it is necessary to compensate the saved energy in all pores. High conductivity of the heat could be achieved in the process of heat transfer from freezing air to the surface water by ice bits with high conduction coefficient $\lambda_{ice}=2.2$ W/m K. The perspective porous rubbers[10] have a high coefficient of thermal conductivity $\lambda_{rub}=0.120-0.17$ W/m K. It is an interesting fact that natural snow has approximately the same coefficient of thermal conductivity $\lambda_{snow}=0.160$ W/m K as novel rubbers.[10] Another possibility to activate the surface processes of ice formation is based on the fractal aggregates in polymer equal to the natural ice crystallization. The fractal aggregates from the porous polymer provoke a fast increasing of the natural ice in the surrounding region. The modern technology[10] with a set of different polymer fractal aggregates can change the fractal dimension in a wide diapason, so this approach involving fractal mechanisms provides a possibility to perform fast ice formation in wide regions near the samples.

A high reflectivity could be achieved by an additional covering. The advantage of the polymer materials is their higher reflectivity and lower absorption compared to ocean water. The refractive index of most polymer materials ($n\approx1.65-1.48$) is higher than the similar water index ($n\approx1.37-1.32$), and the resulting reflectivity coefficient R could be easily estimated as $R=[(n-1)/(n+1)]^2$. Furthermore, pure dielectric materials, such as Teflon, etc., are not heated by visible radiation. By contrast, typical absorption coefficient for sea water is as high as 0.52–0.62 m^{-1} for visible light diapason and is higher in the infrared spectrum. The thin-film mechanism[11] provides high reflectivity due to the presence in both film sizes of a phase. Additional thin film could be placed on top of the polymer raft to increase the light reflection. A series of calculations was performed to improve light reflection and the results are presented in Fig. 1. These calculations in Fig. 1 were done for the 30° angle

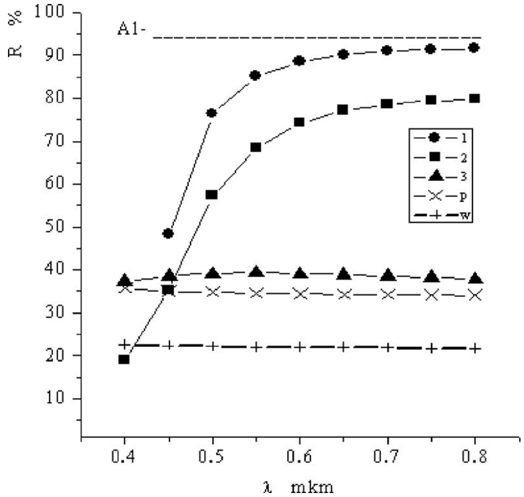

FIG. 1. Calculation of the film's reflectivity. These graphs are as follows: (W) water reflectivity, (P) polymer reflectivity, (1) reflectivity of TiO_2 film on a water (n_3=1.33), (2) reflectivity of TiO_2 thin film on a polymer (n_3 =1.65), (3) reflectivity of thin-film polymer's composition (n_{tf}=1.65, n_3 =1.58, h_{th}=0.101 μm).

from the horizon for the real situation in the north seas. The calculations were done for light incidence from the air (n_1 =1) with different refractive indices of background (n_3) and samples of thin films (n_{th}), the film thickness being about $h \approx 0.1$ μm. The layer of TiO_2 (n_{tf}=2.45) was modeled as the material for this dielectric thin film because it is commonly used for surface cover. The increase in the reflectivity was achieved due to the special structure of the air/TiO_2/water model with the results shown in curve 1 of Fig. 1. The case of application of TiO_2 films as a cover of a polymer surface is presented in curve 2. Curve 3 in the middle demonstrates the possibility of improvement of the reflectivity up to 5% by combining different polymer layers with refractive indices of n_3=1.65 and n_{th}=1,58: Al cover for the polymer surface is an alternative variant. The following reflection for the aluminum film was estimated according to the appropriate approach[11] $R \approx 1-2\sqrt{\nu/\sigma_{\mathrm{cond}}}$. The resulting reflectivity is R =94%, and it depends on the average metal conductivity $\sigma_{\mathrm{cond}} \sim 5\times10^{17}$ s^{-1} and the blue light frequency $\upsilon \sim 5 \times 10^{14}$ s^{-1}. Finally, we note that the perspective covering material such as aluminum and corrosion-resistive dielectric substances used as thin surface films could also provide high reflectivity to the polymer raft.

III. EXPERIMENTS

The series of simple experiments demonstrated the effective wave fading in the vicinity of artificial polymer rafts. The aim of these model experiments was to show the influence of the artificial rafts and also their specific shape to the dynamics of ice formation in the vicinity of these samples. These experiments were performed in two stages. The first stage was conducted at the end of autumn on the natural river at the period of ice formation. This river was located in the Moscow region and has a speed of water flow equal to 0.5 m/min on a windy day; the measured water wavelength was approximately 10 cm and the wave height was up to 2 cm. The raft of size $30\times20\times1.2$ cm^2 was made from a

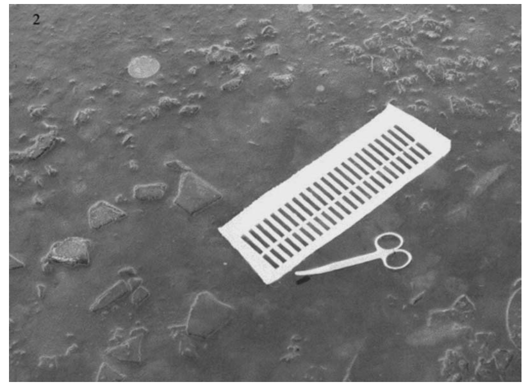

FIG. 2. The plastic raft with a number of ribs provides rapid formation of thick ice with the metal scissors on it.

white plastic material lighter than water with windows of size 4×0.7 cm^2. Our experiments were conducted on sunny and windy days and they were performed in supercooled water at a temperature of T_w=−1 °C with an air temperature of T_a=−3 °C. Two holes were made in the natural ice cover in the vicinity of the riverside and in the area with an ice thickness of 1–2 mm. The diameters of the holes were about 1 m. In one hole, the sample of an artificial raft was put in the water (Fig. 2). The next hole was empty for the purpose of a comparison with the other one (Fig. 3). After 20 min, the experiments showed that the ice in the vicinity of the rafts was so thick that iron scissors of 47 g can be placed on new ice cover (Fig. 2). Figure 3 shows the drowning of the metal scissors in comparison with Fig. 2; the ice formation in the empty hole only occurred in the initial stage, so this ice cannot stand the iron sample. Complete ice formation took here 45 min for the adjacent hole of the same size but without an artificial raft. In real situation in the Arctic, these polymer samples should have the size of approximately 10 m $\approx \lambda_{\mathrm{sea}}$(10 cm/30 cm) because the Arctic seas have a typical wavelength of $\lambda_{\mathrm{sea}} \sim 3$ m.

Various laboratory experiments in salty water were performed outdoors during a frosty winter to measure the ice dynamics in the vicinity of the polymer or plastic materials, which had different forms. The salty water (3% NaCl) prepared was 30 l; the mentioned salt concentration imitates the ocean water. These series of experiments were undertaken on various days with winter frost and an air temperature ranging

FIG. 3. The ice hole was left empty as a control case with the drowned scissors due to the thin ice in it. Both photos at Figs. 2 and 3 were taken at the same time ~20 min from the start of experiment.

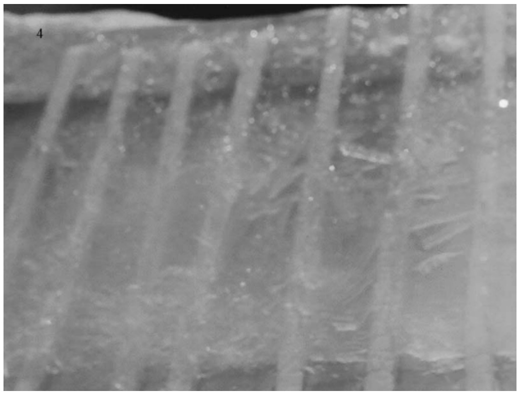

FIG. 4. There were many natural ice crystals after 2.5 h in an upside-down structure; they were located almost perpendicular to the polymer bridges.

from T_a=−2 to −30 °C. The set of measurements of the ice formation and hundreds of photos were taken during the experiment to study the ice dynamics. Also, some other experimental features were analyzed. After the formation of the thick ice, the experimental volume was returned to a warm (200 °C) room and the series of photos was taken again to study the process of the melting of ice near the artificial samples. For example, Fig. 4 shows the sample of 12 bridges fabricated from the porous polymer. This structure was placed in salty water at the temperature of T=−100 °C and the size of each bridge was $30\times2\times1$ cm^3. After 2.5 h, this structure was removed from the salty water; when it was turned upside down, there were many natural ice crystals connecting the porous polymers to each other, as can be seen in Fig. 4.

The next series of experiments was conducted to study the ice destruction in an area near the sample of a porous polymer in warm air surrounding. The photo at Fig. 5 shows the stable ice crystal near the frame of a porous polymer. This structure was exposed for 12 h of frost (T_a=−50 °C) and it was placed for 8 h in a warm room (T_a=+20 °C). The size of the experimental samples made of porous-polymer material was 9×5 cm^2; this frame has a window in the middle with the size of 6×2 cm^2. The model shows that the window in a frame provides good cooling effect from supercold air for a stable water surface in such windows; it could be the reason of deep frost for this frame sample with developing ability to improve further ice keeping. Similar natural materials with a big overall surface, such as spruce or pine needles, are not as effective as synthetic polymers.

FIG. 5. Naturally buoyant analogous materials such as spruce or pine do not stimulate ice formation as effectively as porous polymers.

FIG. 6. Optimal construction keeps more thick ice near itself in warm weather.

The typical situation in the north seas is that the air is colder than the water surface. The special experiments were undertaken to improve the ice formation under the water surface with the help of vertical metal ribs in the raft. The steel elements have a high coefficient of thermal conductivity[12] $\lambda_{st}\sim80$ W/m K and the water has the lower one, λ_w =0.568 W/m K. Combined designs were fabricated for comparative measurements of ice dynamics. The improved sample has the window-type fragments from Fig. 2, the porous-polymer frame from Fig. 5, and also the vertically pleased steel bleed. The test in salty water was carried out at −150 °C after 60 min. Also, the measured ice thicknesses H were H_1=15 mm (±0.5 mm) in the vicinity of the steel elements, H_2=6 mm in the vicinity of the porous polymer outside the frame, H_3=9 mm inside the polymer windows, and H_4=3–4 mm was the common icy depth in a surface of salty water far from both structures.

A last improved sample was constructed based on the previous experiments in the form of a natural snowflake, as shown in Fig. 6. The bottom layer consisted of a sponge type of a polymer put inside water. The middle layer was constructed from a material lighter than water. The upper reflecting layer was a very thin slice of aluminum. Inside the sample, the copper wire was attached. This metal wire was aimed to preserve the shape of construction and also to cool the underwater part of the sponge material. This sample has a form of a six-branch star with a diameter of 120–140 mm. The construction was placed in the salty water at the air temperature of −20 °C. When it was frozen, it could be seen that near this star, the crystallization occurs faster and that the ice is 1.5–2 times thicker than that on a far surface after a long time. After several hours, the air temperature was changed up to +1 °C, but the artificial snowflake kept ice at the area near the raft very well with a similar result after 12 h, which is shown in Fig. 6. The series of experiments showed that an optimal porous-polymer film can keep ice near itself in an area about ten times bigger than its own surface, which one can see from the additional series of photos.[4] The resulting ice was two times thicker under the artificial snowflake (Fig. 7) in comparison with the free water surface according to the measurements carried out after the experiment. The series of experiments shows that the optimal porous-polymer raft can keep ice in a region more

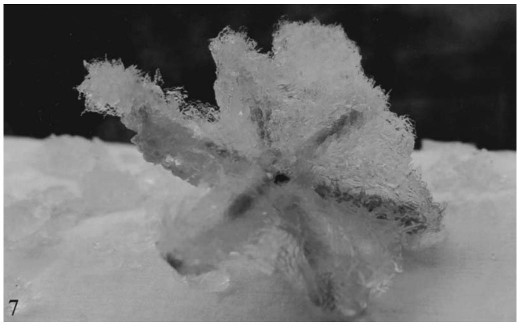

FIG. 7. Ice structure of the crossover of the star cover just when it was taken out of the ice.

than 10S near the raft[4] with own surface S. Further sample optimization could decrease the cost of artificial ice covering with further improvements of the desirable effects.

IV. SUMMARY

The method of additional covering films constructed out of porous polymers that are to be placed into ocean water can provide a simple and effective method for increasing the area of ice in supercooled water. The optimized polymer films produce fast ice formation because of the joint action of local wave fading, the help of the high reflectivity, and the capillary forces in the porous polymer. Prior to the experimental part of this study, theoretical considerations were made for composite polymer rafts and for the upper reflected layer in order to show the main features of the considered system operation and also to estimate the optimal dimensions of the rafts depending on the conditions of the natural surroundings. In addition, it was shown that by using the steel ribs in the construction, it is possible to simplify the ice formation. The initial experiments in accordance with the above theoretical background proved the approach to achieve desirable effects. This means that the proposed approach can be used for reducing the effects of global warming at the present time or possibly in the future.

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