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EXPERIMENTAL INVESTIGATION OF THE METHOD OF LAYER-BY-LAYER LIFTING BUILDUP OF ICE IN A BATH AND IN CELLULAR CANS

S. O. Filin, B. Zakshevskii, and E. Grushchin'ska

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A new more rapid method of freezing to obtain ice in baths and cans is set forth, and the results of its experimental testing in a bath and in cellular cans of a thermoelectric ice generator are presented. The choice of the type of cooling system is justified, and the experimental rig and the features of the experimental procedure are described. It is shown that dividing the total thickness of the ice block into 3–4 layers allows attaining a maximum effect in increasing the capacity of the ice generator within 15%. The main factors that determine the efficiency of the layer-by-layer lifting buildup of ice were determined and analyzed qualitatively.

Method and Its Theoretical Effectiveness. In [1, 2], a new method of rapid buildup of a block of ice on a flat wall (hereafter, layer-by-layer lifting buildup of ice (LLBI)) was suggested and its efficiency was demonstrated theoretically. The essential idea of the method is that water is poured into cans discretely in doses. After a layer of ice is frozen, it is made to melt down near the walls, the next portion of water is added, the ice floats up, and the water layer under the ice is made to freeze again until it freezes together with the preceding layers. The minicycles are repeated several times until an ice block of needed thickness is formed. The schematic diagram presented in Fig. 1 shows x layers of the same thickness h_i into which the ice block of height H is divided. The basic difference of the present method from the well-known methods of layer-by-layer buildup of ice [3, 4] is that it involves the phase of thawing and floating up, due to which the process of freezing occurs steadily in the immediate vicinity of the cooled surface, namely, in a relatively thin boundary layer. This excludes from the heat-exchange process the thermal resistance of the ice layer, which is the main factor that slows down the process of ice formation at a constant power of the source of cold.

The frequent and rapid changing of the operational regimes of the source of cold according to the cooling–heating–cooling scheme required by the method can be realized in principle in conventional evaporators of compression refrigerating machines with heaters built into the walls of the ice can. However, these regimes can be most simply realized with the highest energy efficiency in thermoelectric coolers based on the Peltier effect. To switch the operational regime of such a cooler, it is sufficient to change the polarity of the power supply of the thermoelectric battery.

The algorithm of the LLBI process in the bath of a thermoelectric ice generator [5] is presented in Fig. 2. Here, the total time $\tau_{(n)}$ of the ice-production cycle by the LLBI method includes the times of three minicycles τ^{I}, τ^{II}, and τ^{III} and the time of the pause $\tau_{(ps)}$ needed to remove an ice block from the can. In each of these minicycles, the switching-on of the cooling regime (line 3) is accompanied by pouring of the next portion of water (position 5). Initially, the temperatures of the ice can (dashed line 2) and of the poured water (dashed line 1) decrease sharply, but then, when the temperature in the bulk of the water reaches 0^{o}C, the

Szczecin Technical University (Politechika Szczecinska) Szczecin, Poland; email: filin@ship-tech.tuniv.szczecin.pl. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 2, pp. 109–114, March–April, 2001. Original article submitted March 27, 2000; revision submitted July 5, 2000.

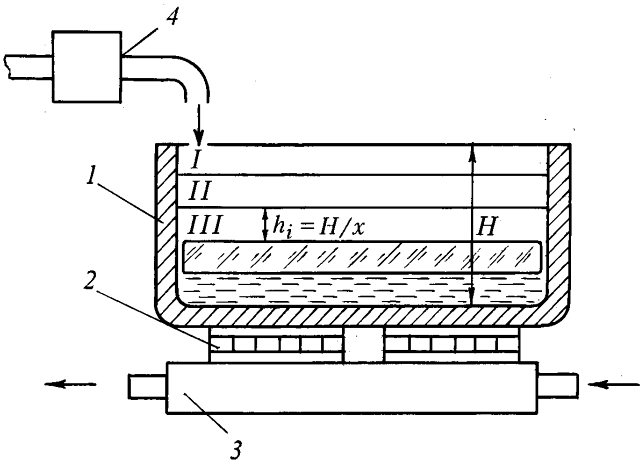

Fig. 1. Schematic diagram of the layer-by-layer lifting build-up of ice: 1) bath; 2) source of cold (thermoelectric battery); 3) continuous water flow heat exchanger; 4) water batcher; I–III) numbers of layers.

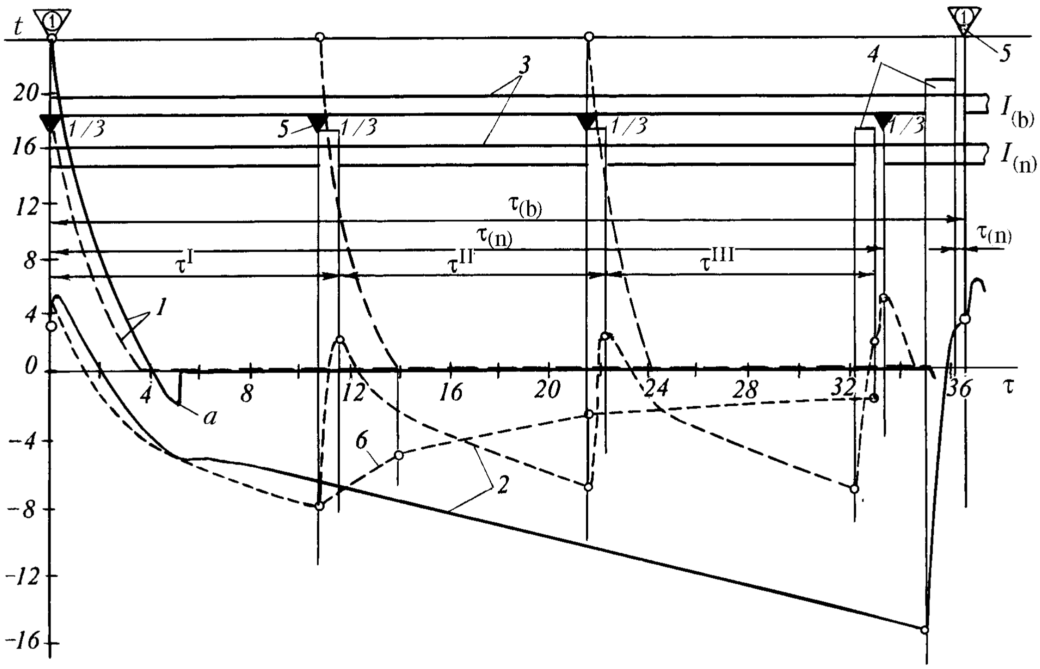

Fig. 2. Algorithm of conducting LLBI in a bath for the case of three layers and qualitative (simplified) dynamics of the temperatures (solid lines) of the elements of the system in comparison with the conventional base method (dashed lines) of build-up of ice (pouring of a subsequent portion of water is performed simultaneously with switching to the heating regime; I = 3.5 A, $T_w = T_{env} = T_p = 20^oC$): 1) mean temperature of a water layer; 2) mean temperature of the ice can; 3) feed current of the thermopile in the cooling regime; 4) feed current in the heating regime (thawing); 5) pouring; 6) change in the temperature at the coldest point of the ice (geometrical center of the lower surface of the first layer); a) effect of water overcooling observed in the case of the base method at relatively small rates of cooling in the absence of water agitation. t, ^oC; τ, min

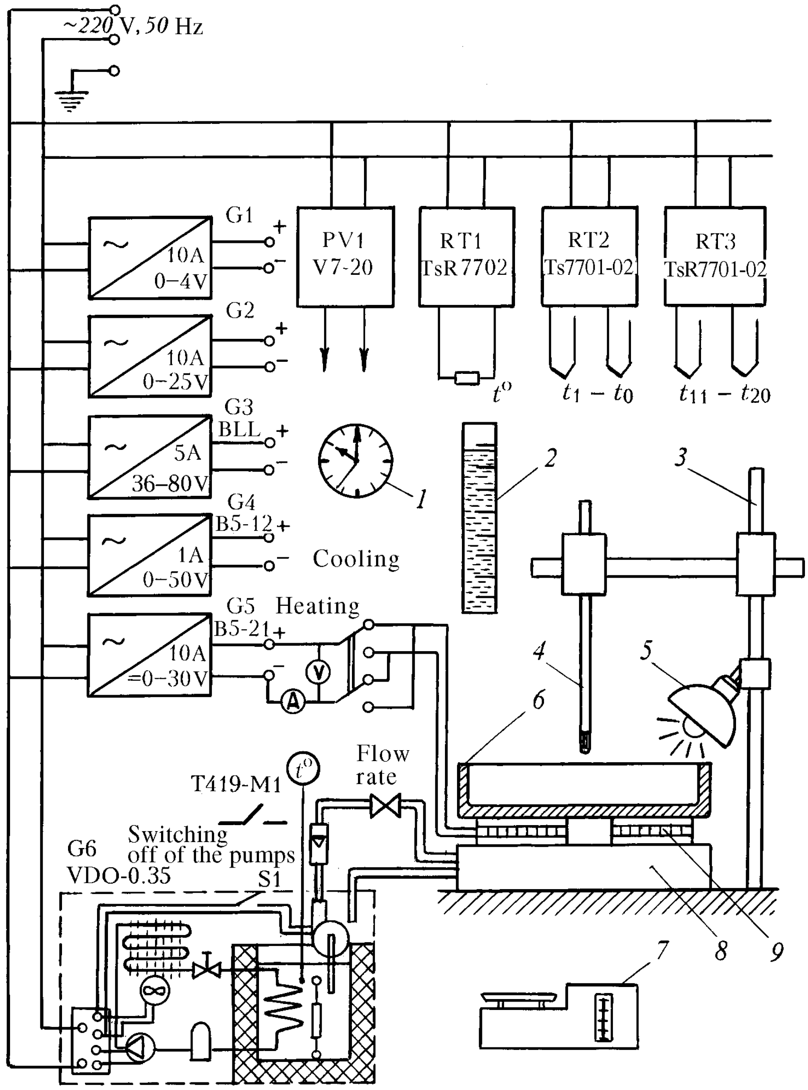

Fig. 3. Schematic diagram of the test rig for investigating LLBI: 1) stopwatch; 2) laboratory measuring glass; 3) stand; 4) device for removing ice from the can; 5) lamp; 6) ice can; 7) balance; 8) continuous water flow heat exchanger; 9) thermoelectric battery; G1–G5) power-supply sources; G6) water thermostat; PV1) millivoltmeter; RT1–RT3) digital thermometers.

temperature is stabilized at this level until the completion of the crystallization process. Then the source of cold is switched to the heating regime (line 4) and, simultaneously, the next portion of water is poured (position 5). The ice can heats up and thus provides thawing of the ice block from the walls. The reverse switching to the cooling regime is performed immediately after the floating-up of the ice block produced. At this moment, the temperature of the ice can is usually 2–4^{o}C.

Experimental Rig. The schematic diagram of the universal test rig designed for investigating the processes of the buildup of ice and testing ice generators is shown in Fig. 3. Below we give a detailed description of the units of this rig that are used in our investigations.

The water-thermostat unit comprising a VDO-0.35 water-cooled assembly with a thermostat of capacity 5 liters and an automatic system allows one to maintain the water temperature at a level of 0–50^{o}C with a regulation differential ±1°C. The hydraulic circuit for coolant circulation includes a rotameter, a valve for regulating the water flow rate, and two (one or three, if necessary) series-connected heat exchangers, on which thermoelectric coolers and the ice cans investigated are installed. To eliminate the influence of the vibration caused by the VDO compressor operation, the water cooler is installed on a damping platform positioned beyond the rig table and connected with the heat exchangers on the table by thermally insulated flexible hoses of length 4 m.

The instrumentation of the rig includes a B5-21 d.c. source with regulated output voltage and current, which in addition is fitted with a switch of the power-supply polarity for switching the operational regimes in the process of work of the thermoelectric cooler. In the course of the experiments, the temperature was controlled by means of two sets of Chromel–Copel thermocouples connected to digital devices of the type Ts7701 and a resistance thermometer (50 Ω) complete with a recording and controlling Ts7702 digital device. The multiplying digital scale factor of the above-mentioned devices was 0.1°C. The current control of the indications of the digital thermometers and the calibration of the thermocouples were performed using standard mercury and alcohol thermometers with a scale multiplier of 0.1°C. The electric parameters were controlled by Ts4301, Ts20, and V7-20 devices. The heaters (not shown in the figure) blown on by air were positioned in the testing room; they provided the conditions of a climatic chamber with the ambient air temperature maintained at 15–35°C to within ±1°C.

The ice-can unit includes a cooler that contains five batch thermoelectric modules of type MT-3-1.8-39A. The ice can 6 was fixed by KPT-8 paste to modules 9. The latter are drawn tight into the flanges of the heat exchanger 8 by screws through a special strap (not shown in the figure) thermally insulated from the ice can by bushes. Stand 3 positioned on the table of the rig provided vertical movement of rod 4 on the face of which the thermocouples or devices for removing a ready block from the can were mounted. The visual control was provided by light from lamp 5 and also by polarized light from an additional source with a set of removable light filters.

The poured water doses (layers) were metered by a volumetric method by means of a laboratory measuring glass 2 with a scale factor 1 ml. The mass of the ice produced was controlled on a balance of WS-21 type with a scale factor of 1 g and then, after melting of the ice block, it was verified by the volumetric method using the same measuring glass. The time was controlled by a stopwatch.

Experimental Procedure. The actual thermal and hydraulic processes occurring in the course of LLBI are much more complex than the processes described by the simplified theoretical model proposed earlier in [2]. Therefore, optimization of the algorithm of the implementation of LLBI and the correctness of the experimental procedure are of great importance. Along with the verification of the efficiency of LLBI as regards the increase of its rapidity, we aimed at finding the optimum regimes of the processes of thawing and pouring of a subsequent layer, namely, to determine as exactly as possible the start of pouring, reverse switching to the cooling regime, the rate of pouring, and the place or places where the water is to be poured. Moreover, the main concern of the experiment, among others, was to determine the optimum (from the viewpoint of the rapidity of LLBI) number of layers into which the ice block is to be divided.

The thermocouples and inserts needed for removing ice from the can must not hinder free floating-up of ice when just another layer of water is poured in the process of thawing. This made it necessary to exclude freezing-in of the thermocouples into the ice layers that float up in the process of LLBI and restrict ourselves to measurements of temperature in the bulk of water, at different points in the ice can, and also in the ice itself (but only in the last cycle of freezing before the forced lifting of the completely built-up ice block), and also to visual control of the freezing together of ice layers, for which purpose the bath, along the height of one wall, is provided with a narrow window of a transparent material (acrylic plastic) which only very slightly distorts, near itself, the temperature field within the ice can.

The LLBI theory implies that the floating-up of ice is the closing stage of the *i*th cycle of the buildup of the ice layer and is simultaneously a signal to switch the operational regime of the cooler. But the pouring of warm water into the ice can is, in essence, a discrete-pulsed introduction of a large amount of heat into the system. This heat is transferred to the near-wall layer not immediately, but in a finite interval of time of about 5–15 sec. If the amount of heat Q_i introduced by the new water exceeds the amount of heat Q_h liberated by the thermopile for this time interval, this means that the thermopile can simply be switched off, and if $Q_i < Q_h + Q_0$, it can even be switched to the cooling regime simultaneously with the pouring. This is a direct way of decreasing the energy consumption and the time for the production of ice.

Theoretically, we can switch the thermopile to the cooling regime even before the pouring, keeping in mind that the amount of heat in the portion of water is so large that a momentary advanced switching of the cooler to the heating regime only aids in heating the ice can to the temperature needed for the floating-up of ice. It is rather difficult to determine this time of advance theoretically (without preliminary experiment) and, moreover, it has a very unreliable result. First, because the ratios between the total mass heat capacities of the system units change from cycle to cycle, and also the final temperatures of the ice can change from cycle to cycle. Second, the ratio between the start of pouring and the onset of heating of the ice can is not yet established. Analysis of the situation of the simultaneous start of pouring and heating shows that a premature contact of a warm water with the ice surface causes its intense melting from above, especially in the central region where the temperature is highest and, naturally, leads to direct losses of the builtup ice layer. If we want to minimize losses in the upper layer of ice, we must pour water closer to the ice can walls and, moreover, uniformly over the perimeter, excluding the spreading of water to the central zone of the cell and at the time when the ice can has been already heated to a temperature above $0^{o}C$ and there is already at least a minimum water layer between the wall and the ice surface that allows the water to propagate relatively rapidly down under the ice through the gradually expanding gap and the ice to float up. But this brings us back to the initial variant of the obvious overexpenditure of heat in the cooler.

Ultimately we adopted the following algorithm of conducting the LLBI stages as the best approximating the calculated scheme and best corresponding to the assumptions made:

1) the termination of the buildup of the first ice layer and switching to thawing is determined visually by the fact that the process of crystallization at the geometrical center of the free water surface is completed;

2) since thereafter the point mentioned under item 1) can no longer be observed, the time of completion of the buildup of the second and subsequent layers is determined in two ways: visually, by observing through the window the merging of the crystallization front of the lower freezing layer with the floating ice block or by a fixed time determined as the time of production of the first layer minus the time of its preliminary cooling to $0^{o}C$, with subsequent control of the freezing together of the layers after the ice is removed from the can;

3) the moment of reverse switching of the thermopile to the cooling regime is determined by the fact of the ice can attaining a temperature of $0^{o}C$ at the controlled point;

4) a subsequent dose is poured simultaneously with the switching of the thermopile to the cooling regime at one point positioned in one of the four corners of the ice can (bath) with a mean rate of 10–15 mliter/sec.

Analysis of Experimental Data. The experimental investigation of LLBI was carried out using a bath-like ice can of size $92 \times 92 \times 15$ mm and also cylindrical and conic cells. For convenience in evaluating the deviation of the actual conditions of heat exchange within a bulk of water from the classical (linear) problem of the buildup of ice on a flat wall, we considered the geometrical parameter of the ice can H/d that determines the ratio of the height of the cell to its equivalent diameter. The maximum value of the parameter H/d (when the water is poured to the fullest) was 0.163 for the bath and 1.0 for the cells, respectively.

First, we consider the results obtained for the bath. The total fixed volume of the water poured 100 g (H = 12 mm, H/d = 0.13) was divided into equal parts. Generally it should be noted that under these conditions the maximum number of layers x into which we managed to divide the total thickness H was four.

TABLE 1. Results of Experimental Investigation of LLBI in a Bath

Water temperature, $T_w = T_{env} = T_p$, °C						
Number of layers	12		20		27	
One layer is controlled, m_w = 100 g, m_{ice} = 92 g	$\tau_f = 32.0$ $G = 0.167$	$\tau_f^* = 31.2$ $\tau_{th}^* = 56$ $G^* = 0.178$	$\tau_f = 43.0$ $G = 0.126$	$\tau_f^* = 42.0$ $\tau_{th}^* = 50$ $G^* = 0.129$	$\tau_f = 62.0$ $G = 0.090$	$\tau_f^* = 60.4$ $\tau_{th}^* = 50$ $G^* = 0.092$
Two layers, m_w^Σ = 100 g (50 + 50)	$\tau_f^I = 13.5$ $\tau_f^{II} = 12.5$	$\tau_{th}^I = 35$ $\tau_{th}^{II} = 40$	$\tau_f^I = 16.0$ $\tau_f^{II} = 15.25$	$\tau_{th}^I = 40$ $\tau_{th}^{II} = 40$	$\tau_f^I = 22.5$ $\tau_f^{II} = 21.5$	$\tau_{th}^I = 35$ $\tau_{th}^{II} = 35$
	Σ 26.0	75	Σ 31.25	80	Σ 44.0	70
Increase in G as compared with the control value ⇒	m_{ice} = 87 g		m_{ice} = 90 g		m_{ice} = 89 g	
	$G = 0.192$	$G^* = 0.199$	$G = 0.164$	$G^* = 0.169$	$G = 0.115$	$G^* = 0.118$
	11.8%		31.0%		28.2%	
Three layers, m_w^2 = 100 g (34 + 33 +33)	$\tau_f^I = 8.66$ $\tau_f^{II} = 8.0$ $\tau_f^{III} = 8.0$	$\tau_{th}^I = 30$ $\tau_{th}^{II} = 40$ $\tau_{th}^{III} = 45$	$\tau_f^I = 13.0$ $\tau_f^{II} = 11.5$ $\tau_f^{III} = 11.5$	$\tau_{th}^I = 35$ $\tau_{th}^{II} = 35$ $\tau_{th}^{III} = 35$	$\tau_f^I = 15.5$ $\tau_f^{II} = 14.5$ $\tau_f^{III} = 14.5$	$\tau_{th}^I = 30$ $\tau_{th}^{II} = 40$ $\tau_{th}^{III} = 35$
	Σ 24.66	115	Σ 6.0	105	Σ 44.5	105
Increase in G as compared with the control value ⇒	m_{ice} = 84 g $G = 0.195$ 0.6%		m_{ice} = 88 g $G^* = 0.139$ 7.8%		m_{ice} = 86 g $G^* = 0.112$ 21.7%	
Four layers, m_w^Σ = 100 g, (25 + 25 + 25 + 50)	$\tau_f^I = 7.0$ $\tau_f^{II} = 6.5$ $\tau_f^{III} = 6.5$ $\tau_f^{IV} = 6.0$	$\tau_{th}^I = 35$ $\tau_{th}^{II} = 30$ $\tau_{th}^{III} = 30$ $\tau_{th}^{IV} = 30$	$\tau_f^I = 9.0$ $\tau_f^{II} = 8.5$ $\tau_f^{III} = 8.5$ $\tau_f^{IV} = 8.5$	$\tau_{th}^I = 35$ $\tau_{th}^{II} = 30$ $\tau_{th}^{III} = 30$ $\tau_{th}^{IV} = 30$	$\tau_f^I = 11.33$ $\tau_f^{II} = 10.5$ $\tau_f^{III} = 11.0$ $\tau_f^{IV} = 11.0$	$\tau_{th}^I = 30$ $\tau_{th}^{II} = 30$ $\tau_{th}^{III} = 30$ $\tau_{th}^{IV} = 30$
	Σ 26.0	125	Σ 34.5	125	Σ 43.83	120
Increase in G as compared with the control value ⇒	m_{ice} = 83 g $G^* = 0.177$ –0.6%		m_{ice} = 84 g $G^* = 0.138$ 7.0%		m_{ice} = 82 g $G^* = 0.107$ 16.3%	

Note: τ_f and τ_f^* are the time of freezing when water is poured into a "warm" ice can (first cycle) and the time of freezing when water is poured into a preliminarily cooled ice can (second cycle), respectively (min); τ_{th} is the time of thawing (sec); G and G^* are the production capacities of ice in the first and second cycles of freezing, respectively (kg/h). In all the experiments, the condition Q_0 = const was fulfilled at a feed current of the thermopile of 3.2 A.

When the number of layers was larger, the upper ice layer lost its shape after many times of being washed out by water.

Analysis of the results presented in Table 1 shows that there is a fairly large spread in the values of the parameters G and τ^Σ, thus hampering the plotting of the dependences $\tau^\Sigma(x)$ or $\tau^\Sigma(T_w)$ even in a narrow range of change of these parameters. This is explained largely by the fact that technically it is very difficult to ensure absolutely identical initial conditions and regimes of freezing of each layer, especially when their number is large. Visual determination of the moment of termination of the freezing of a layer also introduces a certain subjectivity into the evaluation of the results obtained, though the error occurring due to this measurement technique is to be considered as systematic and, consequently, it can, in principle, be taken into ac-

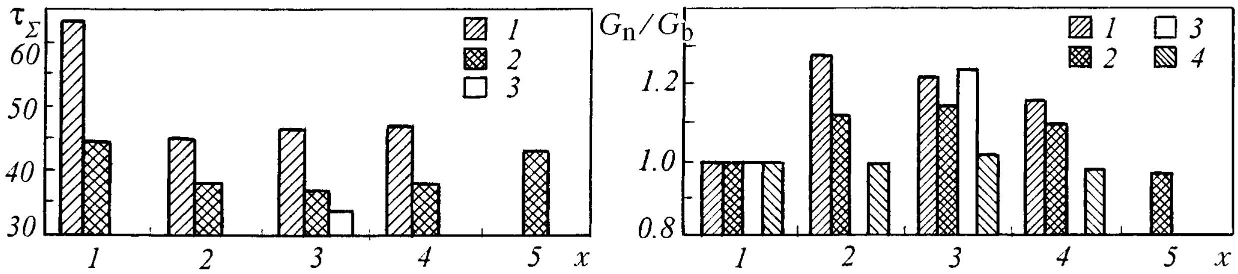

Fig. 4. LLBI efficiency in the form of the experimental dependences $\tau_\Sigma(x)$ and $G_n/G_b(x)$ for an initial temperature of the media of 27°C: 1) bath; 2–4) conic cell [2) with centering of the ice block; 3) with division into layers 25%–25%–50%; 4) without centering].

count. The data presented in each box of the table on LLBI with the number of layers 3–4 are not the results of averaging over all the experiments with the above-mentioned initial and external conditions but over a number of experiments in which the regime of conducting the LLBI was closest to the optimum regime, starting from the following considerations. We illustrate this with the example of the box selected from the table. The time of freezing of the first and second layers was varied in actual conditions from 9 to 7.5 min with an interval of 20–30 sec. With decrease in the time, the losses of ice increase and, consequently, the production of ice decreases. At certain values of τ_f^{I} and τ_f^{II} (these values are given in the table) the conflicting factors come into equilibrium when, because of the decrease in the production of ice, a further decrease in the time of freezing of the first layers does not already give an increase in the production G^*. And if a block of ice was produced without the destruction of its integrity*), this regime was taken as the optimum one, and further experiments were carried out at these empirically determined values of τ_f^{I} and τ_f^{II}. If the integrity condition was not fulfilled, as the optimum regime we took the regime with higher values of τ_f^{I} and τ_f^{II}, at which the integrity was ensured.

Figure 4 presents the averaged experimental data in the form of the dependences $\tau_\Sigma(x)$ and $G_n/G_b(x)$ for a bath and a conic cell. Experiments with other shapes of cells were fragmentary in character, and we do not analyze their results in the article. In both cases, the maximum output of the ice generator was obtained for $x = 3$. As was predicted by the theory, the efficiency of LLBI in the bath is 2–2.5 times higher than in the cell. At the same time, while, according to calculations, at T_{env} = 27°C the LLBI gives a positive effect in a cellular can on condition that $h/d_{eq} < 0.42$, experiments with a conic cell broaden this range toward much larger values of h/d_{eq} (1–1.2 in reality). Apparently, this can be explained by the more favorable conditions for the floating-up of ice in a conic cell in comparison with the calculated variant of the cells having vertical walls. We managed to reveal a strong effect of the shape of the can on the efficiency of LLBI in conic, pyramidal, and spherical cells which is given in terms of the condition of centering of the ice block about the cell axis. In the absence of forced centering, the smallest deviation of the cell from the horizontal position sends the floated-up block to the wall. As a result, the LLBI efficiency is practically

*) Footnote: By the integrity of the block of ice built-up by the LLBI method is meant its state when it is not decomposed into individual layers when being removed from the ice can and being left to fall to the bottom plate from a height of 15−20 cm and also such a structure and a density (porosity) of the upper ice layer when it is not washed out immediately after contact with a stream of water. When these conditions are fulfilled at the moment of removal of the ice block from the can, the layers can be frozen together not at all the points of the plane of their mutual contact. Actually, we frequently in the experiment observed closed slot cavities ("water tables or lenses") between the upper and the second (from above) layers, which accounted for as much as 20−30% of the contact surface between the layers. Because of the effects of the equalization of temperature over the volume of the block and ice recovery [6], the water stables were converted into ice in 45−80 sec after the removal of the ice block.

reduced to zero, which is well seen from Fig. 4. The influence of centering is most appreciable for a small number of layers.

We point out some of the tendencies and qualitative interdependences of the parameters, which follow from the data presented in this article.

1. The reduction of the time of freezing by the LLBI method in comparison with the control tests of single-layer freezing coincides more or less satisfactorily with the calculated data presented in [2] and accounts for 72% at maximum of the base time for a bath and 84% for a conic cell.

2. There is a clearly defined dependence of the time of freezing on the initial temperature of the media. The effect of the use of LLBI increases with increase in these temperatures.

3. The production of ice decreases with increase in the number of layers.

4. Because of the above-mentioned dependence $m_{ice}(x)$, the optima of the functions $\tau_n/\tau_b(x)$ and $G^*(x)$ do not coincide in the number of layers. Thus, of $[G^*(x)]_{max}$ is observed already for two layers, then $[\tau_n/\tau_b(x)]_{max}$ is for x = 3–5 or more. As a whole, the optimum of the function $\tau_n/\tau_b(x)$ is shifted to the side of significantly smaller values of x as compared with the calculated dependences. From the viewpoint of practical implementation of LLBI, this fact favors the attainment of the maximum possible effect of rapidity and indicates that the calculation method should be corrected.

5. The influence of the initial temperature of the ice can, which is associated with the difference between the first and the next cycles of freezing, on the LLBI efficiency is observed only in the case of two-layer freezing. As the number of layers increases, it levels off and can be ignored in the calculations. As for the case $x = 2$, it was found that on the average the LLBI efficiency in the first cycle of freezing is 15% higher than in the second cycle.

6. Comparison of the results of the LLBI in the bath with x = 2, 3, and 4 shows that the variant of LLBI with nonuniform division of the ice block into layers, for example, according to the law $h_i = H/2^{(i+1)}$ presented in [2], can have a very limited application, since it does not give a considerable gain as compared with LLBI with uniform division, but is even more difficult for practical implementation. As an exception, we can recommend using the following scheme of nonuniform division: the first layer is to account for 25%, the second layer for 25%, and the third layer for 50% of the total thickness of the ice block. With this division, the value of G^* obtained experimentally (for $T_w = 27^oC$) was 0.12 kg/h, which is somewhat better than for $x = 2$. This conclusion is supported by the results obtained in similar experiments by the LLBI method in a conic cell (Fig. 4). For $x = 3$, such a division gives a result which is 3–4% better than the result obtained with uniform division.

7. Qualitatively the results obtained confirmed the efficiency of LLBI and the advisability of its use to produce block ice; simultaneously, they can be used as a basis for further investigations aimed at refining a variety of quantitative dependences and the algorithm of conducting LLBI.

NOTATION

T, temperature, K; Q, quantity of heat, W; Q_0, refrigerating capacity, W; I, strength of current, A; m, mass, kg; G, production capacity, kg of ice/h; H, height of a cell (bath) and the total height of an ice block, mm; h_i, height (width) of the ith layer of ice, mm; d, diameter of a cell; d_{eq}, equivalent diameter of a cell of arbitrary shape, mm; $d_{eq} = 4S/P$; P, perimeter of a cell, mm; S, area of the bottom (cross section) of a cell, mm^2; x, number of layers; i, layer number; τ, time, sec; τ_n and τ_b, total time of ice production by the new and conventional (base) method, sec; τ_{th} and τ_p, time of thawing and pouring, sec. Subscripts: n and b, new and base variants, respectively; f, freezing; p, pouring; th, thawing; env, environment; h, hot side of the thermopile; ps, pause; w, water; ice, ice; Σ, total, I, II, and III, numbers of layers. The other subscripts are explained in the text.

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