Development of a compact, onboard slurry icemaker to rapidly produce optimal ice for maintaining freshness of marine products

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Marine products require optimal cold storage transport to maintain freshness and minimize damage. Slurry ice is suitable for this purpose due to its softness and immediate cooling capability. This paper describes the process from design to commercialization of a compact icemaker that continuously, stably, and rapidly produces slurry ice and can be placed on fishing vessels. This icemaker is expected to increase the competitiveness of both domestic and international cold chains by advancing both food safety and security.

Keywords **:** icemaker, slurry ice, freshness, marine products, cold chain

1 Introduction

In 1965, the Resources Council of the Science and Technology Agency in Japan announced the need for modernization of the transport and distribution system of food (aka cold chain recommendations) to systematically improve the eating habits of Japanese people by ensuring healthy and desirable dietary modification. Thereafter, quality control of food in the distribution system was enforced. In this quality control, broad distribution and long-term preservation have been achieved by minimizing the deterioration of perishables via temperature control during refrigeration or freezing. The consumer's need for food safety and security in the cold chain system has been attained by technological advances as a result of having improved infrastructure for sufficient traceability of transportation routes and their environmental conditions, and also by implementation of severe quality control procedures such as HACCP[Term 1] and the food safety management system of ISO22000. Furthermore, fresh fish will surely have a higher market value. Suitable processing from the time that fish are caught until consumption is critical for maintaining such freshness. To prevent degradation and to maintain quality of the fish, crushed ice and/or the plate ice made from fresh water is generally loaded onto fishing vessels upon their departure from port, and then the caught fish are placed in a tank (on the vessel) cooled with the ice and kept cold until the ship returns to port. An alternative handling procedure called "ike-jime (spiking)" effectively maintains a higher freshness of raw fish by preventing violent motions by the fish itself. This procedure (1) delays the decrease in ATP,[Term 2] which is an energy source for a living body, (2) delays the increase in lactic acid in the fish body, and (3) delays the time until rigor mortis. An additional process called "bleeding" of spiked fish would delay the breeding of microbes that cause deterioration, and would thus yield a higher level of freshness in the fish for a longer time compared with when a fish dies naturally. Although spiking is generally recognized as effective, it is time-consuming and thus expensive because it must be done fish by fish, and consequently is generally not carried out on fish other than expensive and/or relatively large-scale fish. To maintain freshness as high as that achieved using the spiking procedure, the time in which a fish moves violently until it dies must be as short as possible. Slurry ice with small particle diameter and high fluidity (i.e., sherbet-like ice) is suitable for this purpose due to its high contact frequency and high rate of heat exchange with the fish for rapid chilling. If such slurry ice is used in the marine product industry, the freshness of fish can be kept high by preventing deterioration of the fish. Utilization of slurry ice for freshness produces a competitive advantage in this industry domestically as well as internationally.

In this paper, the development of a compact icemaker that produces slurry ice from seawater stably and continuously and that can be easily installed on a fishing vessel is described along with its design policy and the effects of such ice in maintaining freshness of marine products.

2 Development background

Development of an icemaker that produces ice to maintain the freshness of fish is expected to yield higher fish prices, specifically the development of a compact icemaker made in Japan to rapidly produce optimal ice onboard a fishing vessel. As early as the 1980s, the effectiveness of slurry

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ice was already known[1][2] and had attracted attention in Japan. However, most icemakers at that time were located at facilities at ports and required 20–24 hours to produce the required amount of ice for a fishing vessel. As a result, a large-scale tank was necessary to store the ice, thus increasing the cost on the facility-side (Table 1). An icemaker that could supply suitable ice at low cost was not yet available at the commercial level. Even now, a large amount of ice is still used in the marine product industry. Such systems degrade the efficiency of workers by wasting time having to wait for ice to be produced and to load ice onto a fishing vessel. Furthermore, knowing the amount of ice required by a vessel is difficult because prediction of the amount of caught fish is not always accurate. Excess loading of ice increases the cost of both the ice and fuel, whereas insufficient loading decreases the commercial value of the caught fish because their quality cannot be guaranteed. In contrast, if an onboard icemaker is installed in a fishing vessel to provide ice produced from seawater during the fishing voyage, the following time and cost advantages can be realized: (1) short ice-loading time, (2) reduction in fuel consumption, and (3) onboard adjustment in the amount of ice based on the actual fish catch.

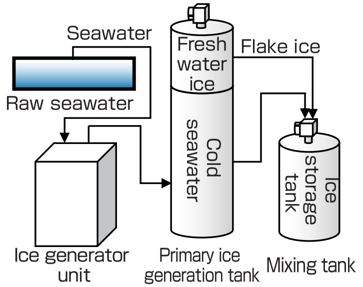
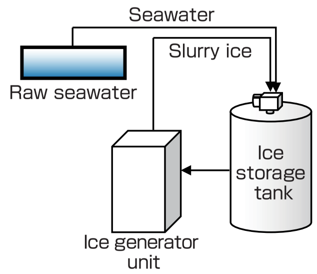
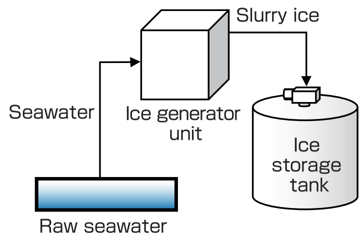
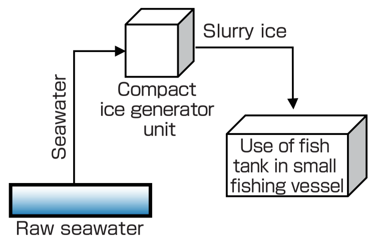
Nikko Co., Ltd. developed technology for fish processing to increase the commercial value of marine products and for the food industry. The company focused on technology to maintain freshness of fish because freshness is considered top priority in terms of commercial value of marine products. The company already had a commercial system for maintaining freshness of vegetables, in which the vegetables were enveloped by pulverized fresh-water ice to maintain an optimum temperature and humidity environment. To apply this technique to maintain freshness of marine products, Nikko surveyed existing icemakers. At that time, several icemakers that could produce slurry ice were developed by other international companies and were commercially available both domestically and internationally. As shown in Table 1, these icemakers produced at that time were all similar in that they used fundamental technologies of ice generation used in Canada, Germany and Iceland, with only a slight difference in the constituting unit and structure of the icemaker. Some patents from these countries were protected, but others were not due to their expiration. The technique to control the actual ice generation mechanism apparently depended on know-how, and thus numerous sections of the mechanism remained unclear, especially details of the ice nucleation process. To determine how to improve these icemakers, starting in 2008, Nikko investigated the ice-making capacity of the icemakers by collecting technical data such as operating temperature, flow rate of feeding sea-water, concentration of sodium chloride and other operating conditions. In addition, interviews were conducted with a person involved in fishery who had used a similar icemaker and ice. Based on the collected data and information, basic specifications of an icemaker and its generated ice were stated, thus defining the (1) performance parameters of the icemaker, such as ice generation rate and capacity per unit time, (2) characteristics of the generated ice, such as ice particle size, ice fraction and temperature, and (3) procedures for using such ice, such as the ice-to-fish ratio and environmental temperature. However, because the internal workings of the generator of the icemaker during ice production could not be observed directly, the ice-generation mechanism and how to improve the ice generation method based on this mechanism remained unclear. Additional unknowns include the technique used to evaluate freshness of the fish, knowledge about the usage of the ice, and knowledge about the effect of the ice in maintaining the freshness of fish and/or marine products. Therefore, Nikko could not completely design the target icemaker alone based on familiar mechatronics techniques.[3][4]

In contrast, the National Institute of Advanced Industrial Science and Technology (AIST) had performed fundamental research on ice nucleation and crystal growth phenomenon, and had gained significant knowledge, such as generation of slurry ice using ultrasonic vibration,[5]–[7] control of generation and growth of ice using antifreeze proteins and a synthetic polymer,[8]–[10] and generation of functional ice that contains bubbles.[11][12] Based on these research activities, in-depth knowledge was obtained on ice-making control technology, especially control of nucleation and crystal growth of ice in the early stages that influences the ice properties, such as cooling capability, that depend on the particle diameter of ice. Such knowledge and technology determined the direction of research of ice used to maintain the freshness of fish. AIST determined the design policy and stated the basic specifications in the development of a prototype icemaker.

The Hokkaido Industrial Technology Center in the Hakodate Regional Industry Promotion Organization (HITEC) has been working on quality preservation technology for fresh fish and shellfish for many years. For example, they quantified freshness and its decline mechanism for squid, and consequently used the resulting data to develop a system to maintain the freshness of squid.[13] Data on maintaining the freshness of fish in general could not be obtained at that time because there was no domestically developed system that could produce enough slurry ice for such a purpose at a reasonable cost. Furthermore, properties of the most suitable ice as well as ice-generation conditions were not yet known.

The above three institutions thus had their respective specialized technical fields, and exchanged information to collaborate in the development of an icemaker as shown in Fig. 1. Such collaboration enabled investigating standards of the ice used for temperature control and freshness management for various species of fish having different body size to plan utilization in the cold chain.

Table 1. Comparison of overseas major slurry icemakers (as of 2008)

Manufacturer	Company A in Canada	Company B in Germany	Company C in Iceland	Developed icemaker (target)
Ice-generation method	Raw seawater is sent to the ice generator unit, and generated slurry ice is sent to an ice generation tank. Ice with no salinity in the separated upper part is scraped off by a scraper, and mixed with cold seawater and flake ice in a mixing tank, resulting in slurry ice. 	Raw seawater is stored in an ice storage tank. Circulation is repeated between this tank and the ice generator unit. About 20–24 hours are needed to generate slurry ice. 	Slurry ice is produced continuously several minutes after startup by direct supply of seawater to the ice generation unit. 	Slurry ice is produced continuously several minutes after startup by direct supply of seawater to the compact ice generation unit. 
Features	· Slurry ice fraction can be adjusted (0–100 %). · Slurry ice tends to melt easily. · Large equipment with complex features make inspection & maintenance difficult. · Slurry ice can be generated continuously. If the generation tank is halted even when ice generation is not needed, the scraper must continue to function because it will freeze otherwise. · Salinity adjustment of cold seawater of the ice generation tank is necessary.	· Slurry ice generation takes a long time (20–24 hours) due to the circulation system. Adjustment in production schedule is therefore difficult. · Generation temperature of the sherbet ice can be adjusted.	· Compact facilities can produce slurry ice instantly by connecting seawater to ice generation unit. · Concentration of slurry ice can be quickly adjusted as requested.	· Compact with high ice-generation rate. · Compact unit installable on small fishing vessels less than 20 tons. · Dense sherbet ice generated faster than conventional equipment. · Refrigeration and ice generation units are separate, resulting in space-saving installation.
Icy property, performance	ca. 50 μm, -1.5 ℃ 10 kw (7.5 t/d ice-generation standard power)	ca. 1 mm, -3.2 ℃ 18 kw (7.5 t/d ice-generation standard power)	ca. 10 μm, -3.2 ℃ 8 kw (7.5 t/d ice-generation standard power)	ca. 10 μm, -3.2 ℃ 8 kw (7.5 t/d ice-generation standard power)
Installation on a fishing vessel	Impractical	Impractical	Practical (100-ton class)	Practical (20-ton class)
Remarks	Large primary ice generation tank needed. Mixing tank for slurry ice generation is required.	Ice storage tank and ice generation tank (combined use) are required.	In land-installation use, ice storage tank is required due to low ice-generation rate.	By using a fish tank as ice storage tank, even a small fishing vessel can utilize this compact icemaker.

3 Development of an icemaker

To determine the optimal shape and size of ice particles in slurry ice produced from seawater, fundamental knowledge of ice formation in seawater must be known. Such knowledge is required to determine the cooling conditions necessary for producing such ice particles, and in developing a built-in control system in the icemaker in which the cooling conditions, which depend on the salt concentration and seawater temperature, can be determined in real time.

Ice formation proceeds via ice nucleation followed by ice growth. For water at subzero temperatures, the solid phase (ice) is more thermodynamically stable than the liquid phase, because the free energy of the solid phase per molecule is lower than that of the liquid phase. However, when a small ice embryo forms and grows in the liquid phase, the total free energy of the system increases as the size of the ice embryo increases, due to the increase in interfacial free energy. Therefore, water is often supercooled without ice nucleation even at subzero temperatures. On the contrary, if the ice embryo size exceeds a critical value, which depends on the degree of supercooling, the total free energy decreases as the ice embryo size increases, and thus ice nucleation proceeds.[14] It is extremely rare that ice nucleation occurs inside homogeneous liquid water. In most cases, ice nucleation occurs on insoluble solid surfaces as heterogeneous nucleation, because the increase in interfacial free energy is mitigated to some extent due to the existence of solid surfaces. After nucleation, ice grows in water accompanied by the diffusion of the latent heat, and also by the diffusion of salt molecules in the case of seawater.

Ice formation from seawater on a cooling solid surface is illustrated in Fig. 2. First, heterogeneous ice nucleation is initiated on the solid surface (Fig. 2a). The ice nucleation temperature is determined by the properties of the solid surfaces, and by the salt concentration of seawater. The subsequent ice growth pattern is influenced by the local growth rate, which is determined by the surface integration of water molecules into ice, the diffusion of latent heat, and the diffusion of solute molecules. When considering ice growth from seawater, the growth rate is dominated by the latter two factors, which are influenced by numerous factors, such as the ice nucleation temperature, salt concentration, flow rate of seawater, and cooling conditions. Therefore, if these factors are adequately controlled, the shape and size of ice particles produced in an icemaker could be optimized. In addition, the force required to peel off the ice from the solid surfaces can be reduced by controlling the ice growth pattern. Based on the above discussion, a built-in control system for an icemaker was developed here to control the cooling conditions in real time.

In the design of a prototype icemaker, the focus was on compact size and on ice generation rate, which are in a

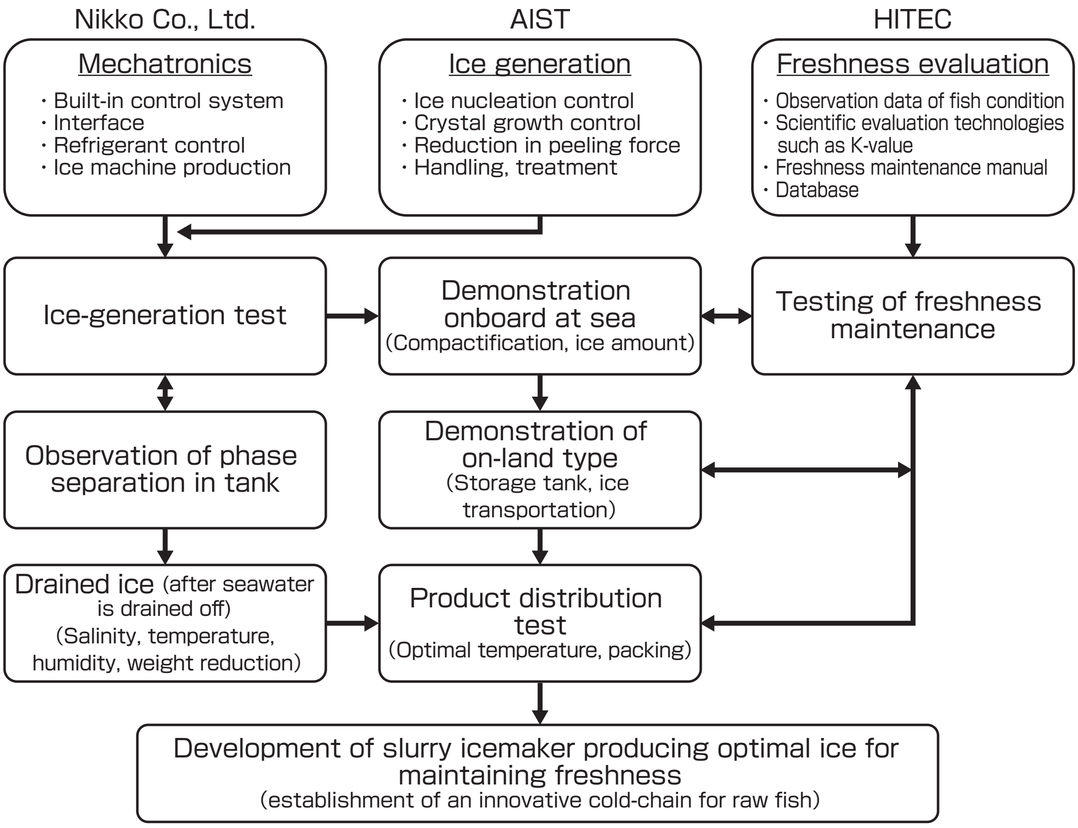


Fig. 1 Scenario of development and introduction of a compact slurry icemaker

trade-off relationship. The icemaker should fit in a narrow empty space of a fishing vessel, taking into consideration the configuration and installation direction of the icemaker to avoid waste of space, without adversely affecting the ice generation rate. Three specifications for the icemaker in this project were set: (1) produce slurry ice appropriate for maintaining freshness of raw fish, (2) have a simple configuration that reduces structural materials and reduces manufacturing costs, and (3) have a high ice generation rate. As for specification (1), the properties of slurry ice can be characterized by several parameters, such as the ice particle size, ice fraction, and temperature. The smaller the ice particle size, the higher the cooling rate of fish. In practice, the ice particle size should range between 10 and 100 μm, but must be at least smaller than 1 mm. The temperature of slurry ice should be lower than the lethal temperature of fish, although both the lethal temperature and time depend on the species of fish. Because slurry ice produced from seawater is actually a suspension in which ice particles are dispersed in seawater that mainly includes sodium chloride (NaCl) as solute, the ice temperature is below 0 °C. The temperature of slurry ice produced from seawater can be calculated based on the initial concentration of NaCl and the ice fraction. For example, when the initial NaCl concentration is 3.5 wt%, the freezing point becomes −2.2 °C, assuming $\Delta T = Km$,[Footnote)] where ΔT is the depression of the freezing point, m is the molality of the solute [mol/kg], and K is the molal freezing point depression constant (K=1.85 K·kg/mol when the solvent is water). By controlling the ice fraction, the concentration of NaCl in the unfrozen part of seawater can be adjusted, and thus the temperature of slurry ice can be controlled in accordance with the above relationship between ΔT and m.

To satisfy specification (2), it is necessary to consider the following three points so as to effectively cool the source seawater even in a simple icemaker configuration:
(a) Increase the effective surface area of the heat exchanger in the generator of slurry ice.
(b) Use materials with high thermal conductivity for the components of the heat exchanger.
(c) Increase the temperature gradient between the source seawater and the refrigerant, by decreasing the evaporation temperature of the refrigerant.
Generally, scaling up of a heat exchanger or adoption of a multi-tube type is effective in increasing the surface area of the heat exchanger. However, we adopted a double-tube heat exchanger using direct expansion of a refrigerant[Term 3] (Fig. 3), so as to simultaneously satisfy the compactness and high ice-generation rate and to produce optimized slurry ice continuously and stably. Stainless steel 316, to which existing manufacturing technologies can be applied, was selected as the heat exchanger material, considering not only its thermal conductivity but also its strength, corrosion resistance, machinability, and cost. In the double-tube heat exchanger, which satisfies specification (2), ice formation likely proceeds via ice nucleation on the inner wall surface of the inner tube, followed by ice growth. If the generator is equipped with a scraper, which rotates in the inner pipe and thus scrapes the ice from the wall surface before it grows and strongly adheres to the surface, slurry ice including fine ice particles that satisfy specification (1) can be produced. The shape of the scraper was designed so that the force required to scrape the ice would be minimized. The scraper also has a function to thin the thermal boundary layer inside the inner tube, so that the temperature gradient in the radial direction would decrease. This change in temperature distribution would help reduce the force required to scrape the ice by changing the ice growth pattern. In addition, if the ice layer on the wall is always kept thin by the scraper, the thermal resistance due to the ice layer could be reduced, and thus help satisfy specification (3).

The separation of ice from the solid wall is classified into two patterns (Fig. 4): (1) peeling off ice completely from the wall surface (perfect separation), and (2) breaking portions of ice off while leaving part of the ice on the wall surface (partial separation). The force required to scrape ice from the wall surface is determined by the lower force of the two patterns, either that for the perfect or partial separation. Which force

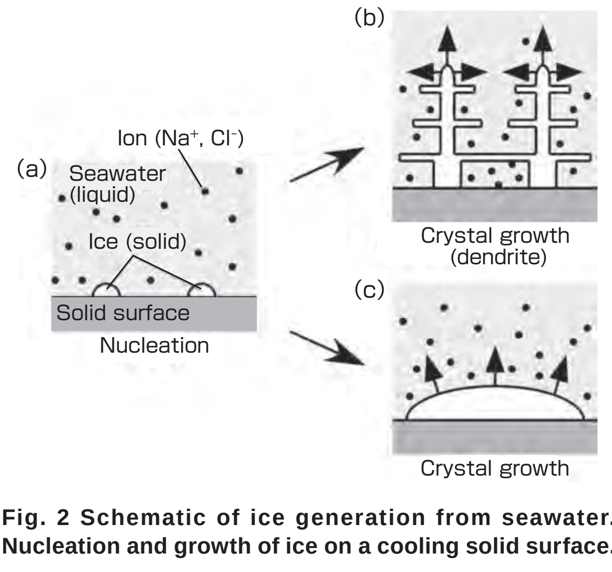


Fig. 2 Schematic of ice generation from seawater. Nucleation and growth of ice on a cooling solid surface.

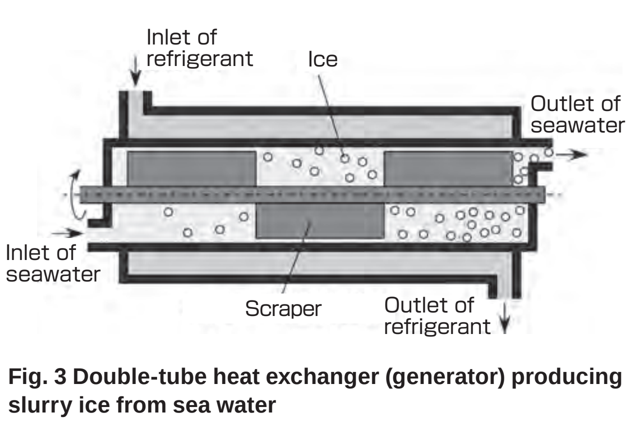


Fig. 3 Double-tube heat exchanger (generator) producing slurry ice from sea water

dominates depends on the operational conditions of the icemaker. The force required for the perfect separation can be effectively decreased by increasing the temperature of the wall surface[15] or by reducing the contact area between the wall and ice. However, increasing the wall surface temperature is undesirable because the higher the temperature of the wall surface, the lower the ice generation rate. Therefore, to decrease the force required for perfect separation, it is preferable to reduce the contact area between the wall and ice. The contact area can be effectively reduced by inhibiting ice growth along the wall surface by reducing the points of ice nucleation on the wall surface.

In contrast, the force required for partial separation can be decreased by making the ice porous, and therefore dendritic growth pattern is desirable, which is often found when the rate-determining process for ice growth is thermal diffusion or mass diffusion. As the ice growth rate is increased by decreasing the evaporation temperature of the refrigerant, the diffusion of NaCl can no longer catch up with the ice growth rate, and finally the porous structure of ice including unfrozen seawater at high NaCl concentration would be formed, which decreases the force required for partial separation.

According to the above discussion, in either perfect or partial separation, the force required to scrape ice from the wall surface can be decreased even when the evaporation temperature of the refrigerant is low, while maintaining a high ice-generation rate. Filtration of seawater to remove small insoluble particles, which induce heterogeneous ice nucleation on their surfaces, is also an efficient technique

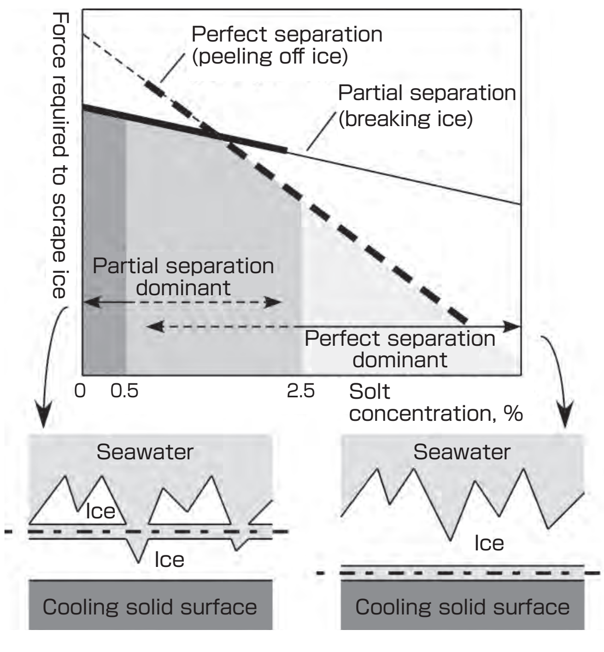


Fig. 4 Schematic of force required to separate ice from a solid surface for perfect separation and partial separation, as a function of salt concentration

to decrease the force required for ice separation. After separation of ice from the wall surface, ice particles gradually increase in size in the generator due to sintering or Ostwald ripening. However, the ice particle size can be kept almost as small as the initial size by controlling the residence time in the generator.

Based on the above design principles, we developed a prototype icemaker. Its operating conditions were then optimized through preliminary tests under various operating conditions. In general, separating ice from solid walls at temperatures below −15 °C is difficult due to the strong adhesion force. However, a generator in which ice can be continuously scraped even at such low temperatures was developed here by optimizing the operating conditions of the prototype. This generator was successfully installed in the prototype icemaker. A testing device simulating large 3-D ship motions such as pitching, rolling and yawing was developed for demonstration of the prototype icemaker. In addition, to address transport of slurry ice between fish holds in a fishing vessel, the technique for stirring slurry ice in a fish hold was optimized to prevent phase separation between the ice dominant phase and seawater phase. This knowledge on stirring was also useful for designing the stirring blades of storage tanks for slurry ice, and such stirring is required for icemakers installed on land. The prototype icemaker also allowed us to easily test oversea transport of raw fish and to examine the freshness of raw fish by scientific analyses. All these tests provided insights into the optimum conditions for maintaining freshness of raw fish and into the optimum shape and size of ice particles, depending on the species of fish. Recently, by making use of these data, we developed an icemaker that produces slurry ice that can efficiently maintain the freshness of raw fish.

Because knowledge on the technologies of control, ice making, and maintaining freshness has been accumulated efficiently by the cooperation of the three collaborating institutions through this research project, it took relatively a short period from the start of the project to the commercialization of the icemaker. After commercialization, cooperation remains among the institutions to promote the distribution of this icemaker by improving the icemaker according to various needs of the users.

4 Effect of slurry ice from seawater

The effect of the slurry ice generated by the developed icemaker is described below for maintaining the freshness of fish. A fish will not be damaged by slurry ice due to its softness. Such slurry ice made from seawater is also effective in maintaining the color and musculature of the fish itself because osmotic pressure surrounding the fish in the melting water after having been cooled is near that of the original seawater (Fig. 5). When a fish dies thus breathing stops, and the supply of oxygen to the necessary part of the cell stops, the reproduction of ATP, which is its energy source, soon stops. While ATP decomposes as follows, the freshness of the fish degrades.

ATP→ADP→AMP→IMP→HxR→Hx[Term 2, 4–8] (1)

When the progression of decomposition of ATP with products derived from ATP is known, the degree of freshness can be determined. Although the rate of this decomposition varies according to environmental conditions and to the species of fish, the decomposition process is approximately the same and is irreversible. Therefore, progression of the decomposition process can be used as an index of the change in freshness. In general, an often used indicator of the freshness of fish is the K-value, which is defined as follows as the percentage of the quantity of (HxR+Hx) with respect to the total of all ingredients in the decomposition product including ATP.

K-value(mol.%)=(HxR+Hx) /
(ATP+ADP+AMP+IMP+HxR+Hx)×100 (2)

Freshness is higher when K is lower. Figure 6 is a representative comparison of the K-value when using slurry ice from seawater with immediate cooling capability and when using ordinary crushed ice (seawater + crushed freshwater ice). The K-value when slurry ice was used was lower, indicating a higher freshness of the fish. But care must be taken to not freeze the fish by "over cooling". Cells of fish bodies are damaged when ice crystals increase by freezing. Crystal growth of ice causes drip (body fluids flow out of the fish body), resulting in degradation of the quality when the fish is defrosted. After a fish dies by rapid cooling, it should be kept at a temperature higher than the freezing point (depending on the species of fish, e.g., dark meat fish:around −1.8 to −1.5 °C, white/light meat fish:around −1.5 to −0.5 °C) to prevent actual freezing of the fish. In practice, this can be done by adjusting the amount of ice for the caught fish or by maintaining a suitable temperature in the tank by heat balance calculation, for example. Moreover, to control the breeding of microbes, the temperature should be about 5 °C or less. To maintain the freshness of the fish after transferring and transporting the fish from the onboard tank into the marketing route on land, the low temperature zone should be the same as described above. A "drained ice" method can be used to realize such an environment. In this method, the seawater is drained from the slurry ice and seawater combination, and the fish is left packed in the resulting lightweight drained ice, and because its salt concentration is low, the ice temperature is higher than the freezing point. Using this method during transfer and transport extends the time of high freshness by maintaining a stable low temperature via latent heat of the ice. The advantage of utilization of the ice produced by the icemaker is its effectiveness in adjusting to onboard conditions and long-distance transport. This new technology will raise the economic value produced in the transport and distribution of marine products, the so called *advanced cold chain system*. However, to optimize this technology, the specific fish species must be taken into account to determine the optimal ice conditions such as desired temperature.

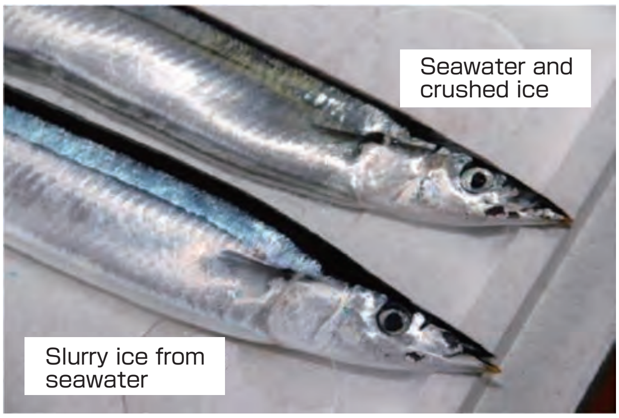


Fig. 5 Comparison of Saury caught during an onboard field test (Blue color on surface indicates high freshness)
Kokonimoatta Sansoken, No.2, p.24–25 (2014)

5 Conclusion

Usage of this compact onboard icemaker and its slurry ice described here is a new freshness management technology and system as well as a health management system. Future study is needed to determine the specifications of the ice to maintain optimum freshness for a specific fish species. "Washoku (traditional Japanese cuisine)" was added to UNESCO's Intangible Cultural Heritage list, in which "sashimi (sliced raw fish)" is part. Freshness management is crucial technology for sashimi. Japan as an advanced country

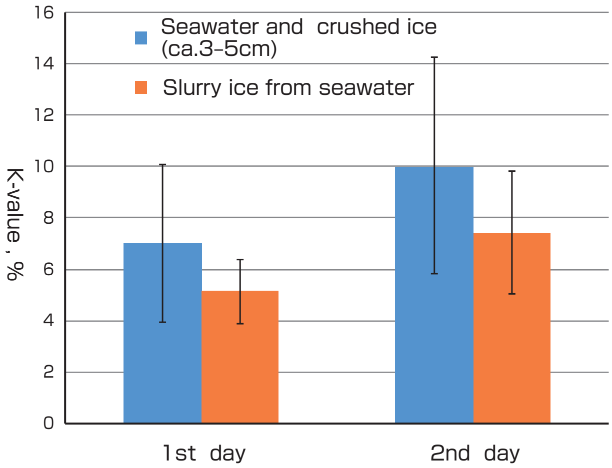


Fig. 6 Comparison of K-values for two different cooling methods
Freshly caught Saury were soaked in seawater with crushed ice (blue shading) or slurry ice from seawater (orange) and kept in a styrene foam container. The quantity of a nucleic acid related ingredient was determined for 6 tail muscles, and then used to calculate the K-value.

familiar with the highest freshness of fish is expected to lead and to globalize such freshness management technology to increase the value of marine products. In this way, utilization of sherbet-like seawater ice as slurry ice would lead to a unique business model that would add value at the highest grade level in the advanced cold chain system.

Acknowledgements

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Footnote) Strictly speaking, the formula used to estimate the freezing-point depression depends on the concentration of sodium chloride. The salinity of the surface layer of seawater ranges between 3.2 and 3.7 wt%, and the surface temperature of seawater is approximately 35 °C near the equator, −2 °C in the Arctic Ocean, and around 15 to 20 °C around Japan.

Terminologies

Term 1. HACCP: Hazard Analysis Critical Control Point. Basics of the hygiene management system recommended internationally, e.g., an inspection system required for import into the European Union and the United States.

Term 2. ATP: Adenosine triphosphate. Comprised of an adenine ring, a ribose sugar, and three phosphate groups, a nucleoside triphosphate, and coenzyme used as an energy carrier in the cells. When ATP breaks into ADP and phosphate, the breakdown of the linkage liberates energy used for functions such as muscular contraction.

Term 3. Direct expansion of refrigerant: Using a refrigerant vapour expansion/compression cycle to directly cool an item. The evaporator is located so that it is in contact with the space to be refrigerated. When the refrigerant inside this space expands (i.e., the double tube as an evaporator), it cools the space by absorbing heat from it.

Term 4. ADP: Adenosine diphosphate. A nucleotide with one less phosphoric acid than ATP.

Term 5. AMP: Adenosine monophosphate. A nucleotide with one phosphoric acid.

Term 6. IMP: Inosine monophosphate. A nucleoside monophosphate deaminated from a base of AMP, and is widely used as a flavor enhancer.

Term 7. HxR: A purine nucleoside that has hypoxanthine linked by the N9 nitrogen to the C1 carbon of ribose.

Term 8. Hx: Hypoxanthine. A purine derivative and deaminated form of adenine. It's a nucleic acid base portion of IMP and HxR, and has a bitter taste.

References

[1] M. Kauffeld, M.J. Wang, V. Goldstein and K.E. Kasza: Ice slurry applications, *Int. J. Refrig.*, 33 (8), 1491–1505 (2010).

[2] M. Kauffeld, M. Kawaji and P.W. Egolf (eds.): *Handbook on Ice Slurries: Fundamentals and Engineering*, International Institute of Refrigeration (IIR), (2005).

[3] The Small and Medium Enterprise Agency, Ministry of Economy, Trade and Industry: *Senryakuteki kibangijutsu kodoka shienjigyo* (Collection of examples of R&D results of the project to support the advancement of strategic core technologies), 6–8 (2011) (in Japanese).

[4] The Small and Medium Enterprise Agency, Ministry of Economy, Trade and Industry: *Chushokigyo Shiensaku o katsuyoshita seikajireishu* (Collection of examples of results that utilized programs to support small and medium enterprises), 4 (2016) (in Japanese).

[5] T. Inada, X. Zhang, A. Yabe and Y. Kozawa: Active control of phase change from supercooled water to ice by ultrasonic vibration 1. Control of freezing temperature, *Int. J. Heat Mass Transfer*, 44 (23), 4523–4531 (2001).

[6] X. Zhang, T. Inada, A. Yabe, SS. Lu and Y. Kozawa: Active control of phase change from supercooled water to ice by ultrasonic vibration 2. Generation of ice slurries and effect of bubble nuclei, *Int. J. Heat Mass Transfer*, 44 (23), 4533–4539 (2001).

[7] X. Zhang, T. Inada and A. Tezuka: Ultrasonic-induced nucleation of ice in water containing air bubbles, *Ultrason. Sonochem.*, 10 (2), 71–76 (2003).

[8] T. Inada and SS. Lu: Thermal hysteresis caused by non-equilibrium antifreeze activity of poly(vinyl alcohol), *Chem. Phys. Lett.*, 394 (4–6), 361–365 (2004).

[9] T. Inada and P.R. Modak: Growth control of ice crystals by poly(vinyl alcohol) and antifreeze protein in ice slurries, *Chem. Eng. Sci.*, 61 (10), 3149–3158 (2006).

[10] T. Inada, T. Koyama, F. Goto and T. Seto: Inactivation of ice nucleating activity of silver iodide by antifreeze proteins and synthetic polymers, *J. Phys. Chem. B*, 116 (18), 5364–5371 (2012).

[11] K. Yoshimura, T. Inada and S. Koyama: Growth of spherical and cylindrical oxygen bubbles at an ice-water interface, *Cryst. Growth Des.*, 8 (7), 2108–2115 (2008).

[12] T. Inada, T. Hatakeyama and F. Takemura: Gas-storage ice grown from water containing microbubbles, *Int. J. Refrig.*, 32 (3), 462–471 (2009).

[13] T. Yoshioka: Development of technologies for quality preservation and transportation of fresh squid, *Bulletin of the Japanese Society of Scientific Fisheries*, 77 (5), 787–790 (2011) (in Japanese).

[14] N.H. Fletcher: *The Chemical Physics of Ice*, Cambridge Univ. Press, (1970).

[15] H.H.G. Jellinek: Adhesive properties of ice, *J. Colloid Sci.*, 14 (3), 268–280 (1959).

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Atsushi SATO

President of Nikko Co., Ltd. Graduated from Hokkaido Asahikawa Technical high school. Joined the company in Tokyo for food packaging manufacturing, and after leaving, established Nikko Co., Ltd. in 1977. After establishing the company, continued in development and production of processing machinery for food industry. Received the Monodzukuri Nippon Grand Award in 2005. Selected by The Ministry of Economy, Trade and Industry (METI) as one of the "Active Small and Medium Enterprises Selection 300" in 2007 and as one of the "Next GNT, Global Niche Top Companies Selection 100" in 2014. Received the Hokkaido Innovative Technology and Product Award for a 3D measurement system in 2011, and for a continuous silk ice system (Kaihyo) in 2013, and received the 14th Minister of Economy, Trade and Industry Award for industry, academia and government collaboration in 2016.

Discussions with Reviewers

1 Overall

Comment (Hiroo Matsuda, AIST, Tohoku)

This article describes the development process of a new icemaker and the freshness maintenance of marine products using the seawater ice produced by this icemaker. I acknowledge that this paper is reasonably significant as a *Synthesiology* article as it seeks quality improvement of marine products by integrating several elemental technologies.

Comment (Noboru Yumoto, National Cerebral and Cardiovascular Center)

In this article, the development process of an icemaker that can supply ice stably at low cost and can be installed on a fishing boat is described with attention to the freshness maintenance of the fish using slurry ice. I judge that this paper is suitable as a *Synthesiology* article because it describes cooperative work based on a clear scenario in the industry-academia-government collaboration with each institution having their respective specialty field of mechatronics technology, ice-making technology and freshness evaluation technology to solve difficult problems in past technology development.

2 On the logic constitution and its refinement

Comment (Hiroo Matsuda)

How was the study on each elemental technology conducted? The description of the process is insufficient. There is either simply expressions quoted or just data given from previous studies. Expressions are also insufficient. To clearly describe the development process, I think that you should show the points of improvement (using figures) in the newly developed icemaker compared with the icemakers of previous technology.

Comment (Noboru Yumoto)

In the *Synthesiology* journal, the originality of the author about a scenario and the element constitution (selection and integration) are requirements of an article. Please clarify how you composed elements based on the scenario in Fig. 1 to develop a desired icemaker capable of producing slurry ice.

Answer (Hiroshi Nagaishi)

I reviewed the overall composition again and added a description of the problem and its solution. The description is now divided into background development and development underway of both the embedded software and prototype icemaker up to the point of commercialization.

The manuscript now includes description of the steps of the development process in the following order: (1) development of the control system, such as integration software, (2) design of a prototype icemaker, and (3) demonstration tests of the icemaker. In addition, information about current icemakers has been added to Table 1. Note, however, details and know-how are not disclosed because of a request from the company that carried out the collaboration work.

3 About a new freshness index

Comment (Hiroo Matsuda)

A new freshness index is suggested in this first article, but there seems to be no attempt at standardization. The K-value is utilized in the manual of maintenance freshness issued by many local governments to obtain consensus of those involved. For this proposed new index to obtain consensus, it is necessary to open the index to the public and thus enable those involved to compare its practicality.

Comment (Noboru Yumoto)

A new freshness index is suggested in the first article. I think that the validity of this index should be evaluated in a specialized journal. The *Synthesiology* journal is intended to indicate what to do to utilize an outcome of research and development in society. The validity of this new suggested index cannot be evaluated in this journal. But if standardization of the freshness management technique is achieved, the process can become a subject of this journal.

Answer (Hiroshi Nagaishi)

The freshness index described in the first manuscript is a new suggestion. In this revised manuscript, reference to this freshness index has been significantly reduced. I think that this freshness index itself cannot be patented. With the cooperation of the Intellectual Property and Standardization Promotion Division in AIST, however, I am examining a technique in the cold chain using this index.

4 Improvement of previous technology

Comment (Hiroo Matsuda)

I can understand the need to conceal the know-how. But what points were improved based on a machine of a leading company?

Answer (Hiroshi Nagaishi)

The machine developed here is based on a machine developed in advance. Although the ice-making method and the constitution of the machine are similar for both machines, the machine developed here is compactly made to fit a typical small Japanese vessel. The four main improvements are the (1) cooling surface (inner wall) of the generator, (2) number of fins of the scraper, (3) position and flexibility of the scraper, and (4) control of the ice generation conditions in the generator. As noted in the previous answer to comment (2) above, details of these improvements are not disclosed because of a request from the company. In the revised manuscript, description of the design policy has been added.

5 On freshness of fish

Comment (Hiroo Matsuda)

Are there no experimental results on freshness that the authors performed other than the K-value comparison for Pacific saury?

Answer (Hiroshi Nagaishi)

Numerous experiments and results for evaluation of freshness of fish were obtained by HITEC (by T. Yoshioka).

Here, because the effect of ice generated by the developed icemaker is considered, I believe that the K-value comparison is sufficient as an example.