Oksala, Sid; Puolakka, Otto; Izadi, Mohammad; Tuhkuri, Jukka

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Salinity-controlled laboratory production of ice

Sid Oksala
Department of Mechanical Engineering
Aalto University, Espoo, Finland
sid.oksala@aalto.fi

Otto Puolakka
Department of Mechanical Engineering
Aalto University, Espoo, Finland
otto.puolakka@aalto.fi

Mohammad Izadi
Department of Mechanical Engineering
Aalto University, Espoo, Finland
mohammad.izadi@aalto.fi

Jukka Tuhkuri
Department of Mechanical Engineering
Aalto University, Espoo, Finland
jukka.tuhkuri@aalto.fi

Abstract: A 2 m by 4 m basin was constructed to grow saline ice. Embedded systems were installed to control both the concentration and temperature of the NaCl solution. The basin along with these control systems is presented. The ice grown in the basin is characterized based on structure and salinity profiles. These parameters are compared against literature values for sea ice with good agreement. The presented method for growing saline is compared to previous methods. The study concludes that using the implemented control systems, up to 300 mm thick columnar saline ice representative of sea ice can be produced in a basin of only 625 mm depth.

Keywords: Ice Mechanics, Laboratory Experiments, Sea Ice

1. Introduction

Typically, experimental ice mechanics research uses a combination of both field and laboratory experiments. Whilst field experiments allow a variety of different scales to be tested, they are physically challenging, expensive, and, crucially, do not allow control over other variables such as temperature or salinity. Laboratory experiments allow good control over experimental parameters, but they have, up until now, been done with relatively small specimens that are typically not in situ (order of centimeters, e.g. Adamson et al. (1996)). Considering that many of the processes occurring in sea ice are scale dependent (Dempsey, 1996), there is a need for large-scale ice mechanics laboratory experiments. To conduct such experiments, large samples are required. These can be either harvested from frozen sea areas or grown in a cold room. To this end, the authors have designed and constructed a basin to grow columnar saline ice in a cold room.

Due to the ice lattice having a low tolerance for impurities, as the solution freezes, most of the dissolved salt is expelled into the solution below. This results in the concentration of the solution increasing. In the ocean this increase is negligible due to the large volumes of water and currents. However, in a relatively shallow basin it becomes significant: it can have effects on the properties of the ice, or given a high enough concentration, completely halt the growth process. There exist three possible solutions to this problem: one can make the basin sufficiently deep that the increase in salinity becomes insignificant, start with a low salinity solution, and allow it to increase with the result hopefully approximating sea water, or control the salinity of the solution during the growth process. The depth required to make this increase in salinity negligible is proportional to the desired thickness of the ice. To the knowledge of the authors, no systematic tests have been conducted to establish what ratio would start to approximate an ocean setting sufficiently well, but ten times the desired thickness of the ice would seem to be a reasonable estimate. Consequently, the required depth of the basin would become impractical if over 100 mm of ice was desired.

Previous attempts for producing saline ice in a laboratory have typically simply allowed the salinity to increase during the growth process. This can be seen for instance from Kuehn et al. (1990) and Dykins (1967). Kuehn et al. (1990) used a freezing plate on top of a cylindrical tank (diameter of 914 mm and depth of 1219 mm) to grow specimens up to 600 mm thick, whilst Dykins (1967) used a rectangular tank (dimensions 1626 mm by 2565 mm and depth of 1016 mm) to grow specimens 560 mm thick. Both these growth basins were so called closed systems, meaning that as the ice grew, salt was expelled, and the salinity of the fluid increased. Kuehn et al. (1990) were able to grow ice with a bulk salinity of 4.3 ppt despite this by reducing the initial salinity of the fluid to 20 ppt, and assuming that the gradual increase in the fluids concentration results in ice with a suitable salinity. However, it is possible that the salinity of the ice was caused in part by other factors, such as increased brine content. Data from tensile tests in which these samples were compared to real sea ice show that while the peak stress values were comparable, the recorded strains differed by a factor of two, therefore indicating that the laboratory grown ice was less stiff. One possible explanation for this could be increased brine at the grain boundaries. Dykins (1967), on the other hand, produced laboratory ice using real sea water with an average salinity of 32.54 ppt. He too had a closed system and simply allowed the salinity to increase throughout the growth process. This resulted in ice with a bulk salinity up to 11 ppt and local salinity values as high as 45.04 ppt. Ice of this high salinity is not typically found in nature and salinity of sea ice has been shown to impact its strength (Weeks, 2010). Therefore, a dilution system was implemented in the tank presented here to control the salinity of the solution during the growth process.

2. Experimental Setup

Ice was grown in an insulated tank equipped with a dilution system and a temperature control system. The dilution system keeps the salinity constant by periodically replacing some of the enriched brine with fresh water (see **Figure 1**).

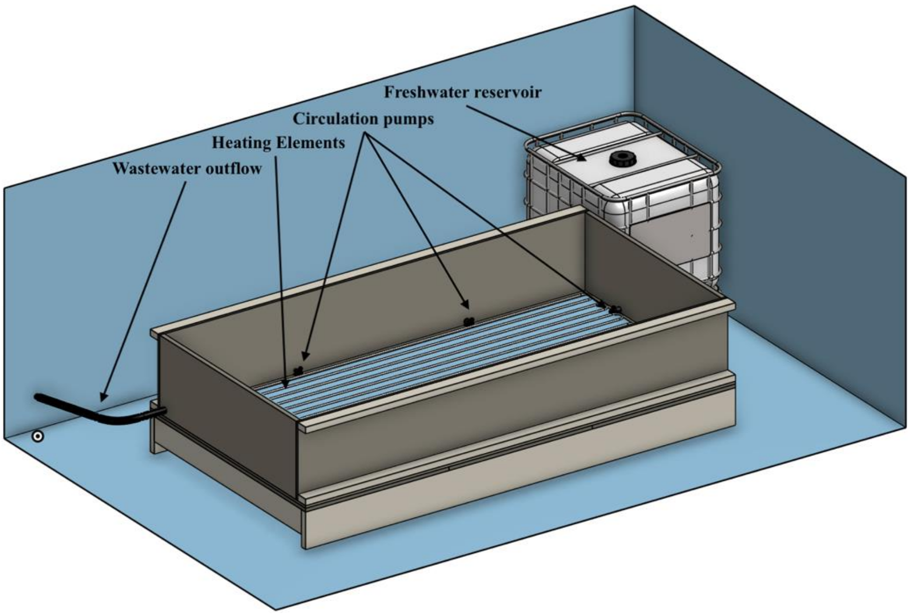

Figure 1. The cold room with the ice growth basin and associated hardware.

The basin is constructed from laminated plywood (21 mm & 40 mm thick for the long and short sides respectively) and reinforced with laminated veneer lumber (LVL) beams. It is insulated on the outside with extruded polystyrene sheets. It has internal dimensions of 1760 m by 3670 mm, and a depth of 625 mm. Circulation pumps (8 in total with rated power of 100 W each) are installed in the bottom to ensure that the solution is as homogeneous as possible. The bottom of the basin has heating elements (total rated power of 950 W) installed to control the temperature of the water. The heating elements are thermostat controlled using two negative temperature coefficient (NTC) thermistor sensors installed 5 cm from the bottom of the basin. The installed systems are controlled using a microcontroller.

The dilution system consists of a 1000 l freshwater reservoir located adjacent to the tank in the cold room. The tank is insulated and has a NTC sensor, a circulation pump, and a heating element to maintain its temperature at 0.2 °C. The dilution is controlled by two positive displacement pumps (rated power of 150 W each) and a Cond 3310 salinity sensor produced by WTW. The system is fully automated and logs both temperature and salinity data throughout the growth process.

In the present study, the basin contains a solution of water and NaCl with a concentration of 32 g/l. Ice is grown in the basin by first cooling the water to 0 °C. This temperature is used rather than the freezing point of the solution to prevent the fluid from super cooling. Once this temperature is reached, the ambient air temperature is reduced to -30 °C to seed the ice. The ice is seeded by spraying a fine mist of fresh water close to 0 °C in the air using an electric spray paint gun. As the water droplets freeze and land on the surface of the basin, they provide nucleation sites for the ice crystals and thus ensure a columnar structure. Once the ice has been seeded, the ambient air temperature is set to -10 °C and the dilution system is engaged. The ice growth rate starts at approximately 1.5 mm per hour and gradually decreases as the ice grows.

A maximum thickness of approximately 300 mm of ice can be grown in the basin. Due to material choices, the ice sheet grows at a uniform rate throughout the entire area of the tank and very little boundary effect is observed at the edges and corners.

3. Grain structure of produced ice

The grain structure of the ice has been studied through thin section analysis in crossed-polarized light. **Figure 2** presents a horizontal section from a typical ice sheet approximately 20 mm below the top. **Figure 3** presents a vertical thin section of the same ice sheet.

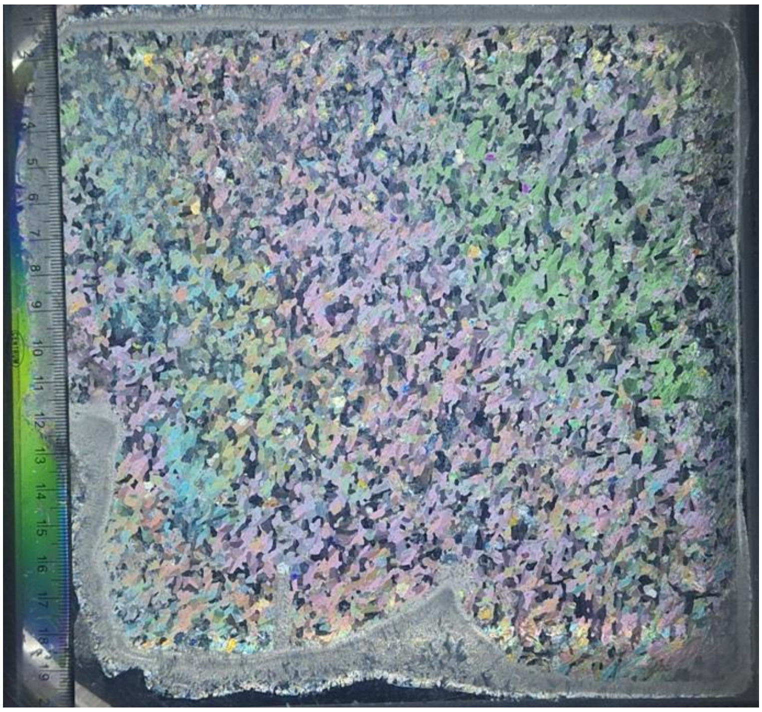

Figure 2. Horizontal 1 mm thin section of the grown ice. Sample is 20 mm from the top.

Figure 3. Vertical 1 mm thin section of the grown ice showing the top 200 mm of the ice.

As a result of the seeding, the ice sheet starts to grow from several nucleation sites, which leads to the fine-grained ice near the top. Due to a larger availability of bonding sites for molecules, grains grow faster perpendicular to their *c*-axis. Consequently, the grains with a horizontal *c*-axis have more space to grow and eventually dominate. This leads to the columnar structure and a gradual increase in grain size that can be clearly seen in **Figure 3**. These processes are typical for sea ice (Weeks, 2010) further demonstrating the suitability of this laboratory grown ice as a substitute for sea ice.

4. Salinity Control

The dilution system works by periodically switching on two sets of pumps. These pumps simultaneously pump freshwater from a temperature-controlled reservoir into the basin and wastewater out of the basin into a drain. The water being pumped out of the tank flows through a salinity sensor which measures the current salinity of the water. This measured salinity is then compared to a target salinity which is set at the beginning of the growth process. If the measured value deviates from the target value by more than 1%, then the duty cycle of the pumps, i.e. the period that the pumps are on expressed as a percentage, is adjusted accordingly. During the beginning of the ice growth, when the growth rate is at its fastest, the system dilutes the basin by approximately 5 l/h. The dilution rate decreases as the growth slows down to approximately half this value.

The salinity of ice can be discussed either as a through thickness profile or as bulk salinity. The salinity profile of the grown ice was measured by taking full-thickness samples which were divided horizontally into sections of 50 mm thickness each, placed into sealed containers and melted. The salinity of the meltwater was then measured using a temperature compensated conductivity meter of model Cond 3110 by WTW. The bulk salinity of the ice was measured by taking a full-thickness sample of the ice, placing it directly into a sealed container and melting it. Once again, the salinity of the meltwater is then measured using the same meter as before. The salinity profiles of three different ice sheets, along with the bulk salinity from the same ice sheets can be seen in **Figure 4**.

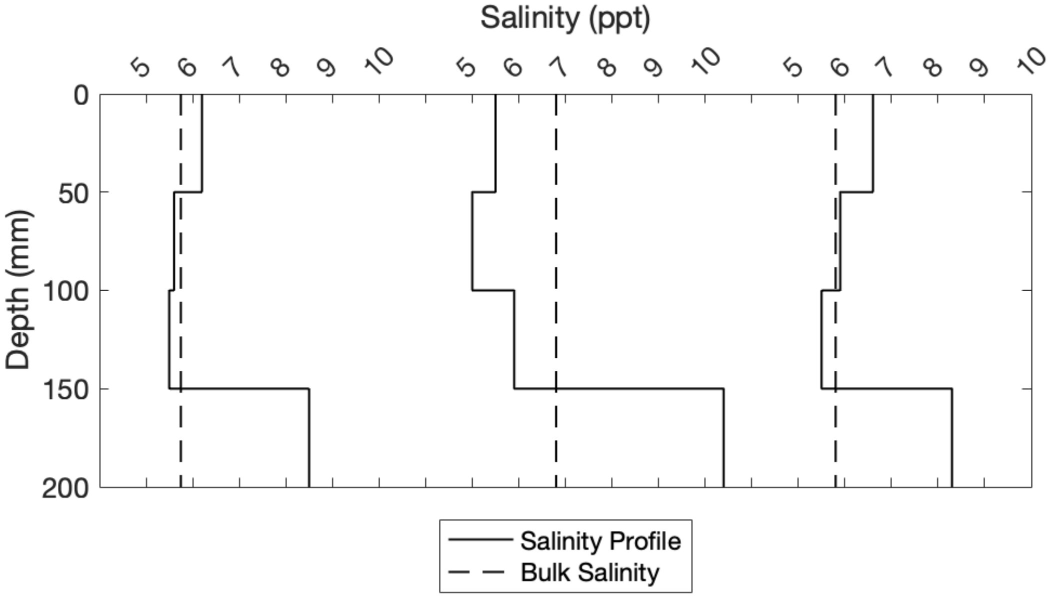

Figure 4. Salinity profile and bulk salinity of three produced ice sheets grown for approximately 300 hours each. Salinity measured from horizontal sections of 50 mm thickness.

The range of possible salinities for first-year sea ice is large and local values between 2 ppt and 15 ppt are all possible depending on temperature, age, and location, among other factors. For young sea ice values between 5 ppt and 7 ppt, with the top and bottom layer being saltier, are often taken to be the norm (e.g., Nakawo and Sinha 1981)). Furthermore, the C-shaped salinity profile that can be seen in **Figure 3** is typical for young sea ice, indicating that the laboratory grown ice is going through similar processes to real sea ice, such as brine drainage (Weeks, 2010). Consequently, the salinity of this laboratory-grown ice can be considered acceptable as a substitute for first-year sea ice.

5. Temperature Control

The rate at which heat energy is lost through the top of the basin is high compared to the amount of heat energy stored by the solution due to its large surface area and shallow depth. Consequently, the entire volume of NaCl solution very quickly reaches its freezing point. Simultaneously, due to the freezing process, the salinity of the solution close to the ice-liquid interface increases, and eventually the temperature of this high salinity layer is lower than the freezing point of the rest of the solution. This, coupled with the entire solution being very close to its freezing point, results in the freezing process becoming unstable. A vertical columnar structure is then no longer the most favorable structure and instead a far more random grain structure dominates. This phenomenon can be seen in the vertical ice thin section presented in **Figure 5**. The thin section was made from ice which was approximately 80 mm thick. At the top, one can see a layer of seeded primary ice followed by the beginning of a columnar structure. As the fluid cools, this columnar structure was eventually interrupted, and a granular grain structure, similar to frazil formation, can be seen. A similar phenomenon has been described by Timco (1984).

Figure 5. Vertical thin section of laboratory-grown saline ice with a thickness of 80 mm. A mixture of different grain structures can be seen.

To prevent this interruption of columnar grain structure, heating was installed at the bottom of the basin. Heating cables run along the entire surface area and are covered with an aluminum sheet 5 mm thick to diffuse the heat. These heating elements are thermostat controlled and maintain the temperature at the bottom of the tank at -1.5 °C. This ensures entirely columnar grain structure in the grown ice.

6. Summary and Conclusions

Saline ice was grown in a shallow basin in a cold room. Both the temperature and salinity of the NaCl solution used to grow the ice were controlled during the process. Using these processes, an ice thickness of approximately 300 mm could be reached in a basin of only 625 mm depth. The grain structure and salinity of the grown saline ice was studied and compared against literature sources for sea ice. A good agreement between the two was found. A shallow basin with salinity control is shown to be a suitable alternative to deeper basins.

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