WAVE-ICE INTERACTION DURING ICE GROWTH: THE FORMATION OF PANCAKE ICE

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ABSTRACT
The Antarctic sea ice consists largely of granular crystals derived initially from frazil ice. Observations made on research cruises in and out of the pack ice zones suggest that the ice covers were products of the frazil-pancake ice cycle (Lange et al., 1989). The formation of pancake ice has been associated with the ubiquitous waves in the Southern Ocean. However, due to its rapid formation process, pancake ice is difficult to study from field experiments. This paper describes two sets of laboratory experiments conducted at the USA Cold Regions Research and Engineering Laboratory (USA CRREL), one set in a large outdoor test pond and the other in a cold room flume. We previously hypothesized that either bending or tension failure could control the floe diameter of pancake ice. The experimental data provide a good fit to a prediction of floe diameter based on the tension failure model.

INTRODUCTION
Field investigations of Antarctic sea ice have shown, by its fine grained frazil ice structure and surface topography features, that ice growth in the presence of waves accounts for a major fraction of the initial ice cover in the Antarctic regions (Lange et al., 1989, Wadhams, 1991). Pancake ice has been observed to grow in the presence of waves, on the few cruises that have been in the vicinity of the ice edge when the ice growth is occurring. Better modeling of ice cover growth and correct parameterization of ice cover thickness, therefore mandates better understanding and quantification of the wave and ice interaction during ice growth in the presence of waves. Two laboratory campaigns were conducted, both at the US Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH, USA. The first experiments were in an outdoor basin approximately 20 m long, 8 m wide, and 2 m deep, using salt water in ambient winter conditions. The second experiments were conducted in a 35 m long, 1.3 m wide, and 0.6 m deep hydraulic flume in a cold room at the same facility. The flume used urea doped water which, when frozen gives a sea ice simulant of slightly different mechanical properties. In this paper we describe these experiments and data collected on parameters relating the growth of the pancake ice and its evolution. Similar experiments at a smaller scale focused on the effect of grease ice on wave attenuation and dispersion relations have been conducted by Newyear and Martin (1997,

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THE POND EXPERIMENT

The first experiment was conducted in an outdoor pond on Feb. 3 and Feb. 11. Clear and cold nights were chosen for these experiments. Each test started after dark and lasted until sunrise. The air temperature and the long wave radiation dominated the heat loss process. The layout of the instrumentation is shown in Fig. 1.

Fig. 2 shows the ambient temperature. Left side is the air temperature obtained from the thermometer hanging next to the wave pond at about 2 m above the water surface. Right side is the water temperature from the thermometer measured near the bottom of the pond. A thermister string monitored the temperatures near the surface of water/ice.

The ice surface temperature was recorded with an infrared camera. Fig. 3 is the index page of IR images from 3–6:15 am. The order of images in the index page goes from top left to bottom right. The change of brightness in the last two images is due to the change of center temperature setting. The final ice cover and surface temperature evolution are also shown in Fig. 3. Water sample was taken every hour at two locations, one near the paddle and the other near the beach. The salinity evolution was obtained with these samples. An upward trend throughout the test was found consistent with the ice growth.

Ice cover thickness was measured every hour and the thickness profile was obtained at the end of the test. The floe diameter was also measured. Fig. 4 shows the ice thickness and the floe size evolution, the final ice thickness profile, and the wire scoop used for thickness measurements.
Wave amplitude is calculated every 15 minutes. Because the wave paddle was small compared with the channel width, the wave in the pond had complicated reflection patterns. The amplitude of the wave was different at different locations. The test done on Feb. 11–12 was similar.
THE FLUME EXPERIMENT
The second experiment was conducted in an indoor flume on May 10–17. The flume was filled with urea-doped water at 1% concentration. All tests started with the open water condition. Both the air and the water temperatures dictated the ice growth. The experimental setup is shown in Fig. 5. Eight pressure transducers formed two separate groups. Transducers 1–4 were fixed throughout the test. Transducers 5, 6, 7, and 10 were moved between two position 1 and 2 to take two consecutive readings each time data were taken. In the following we will present the data on May 15 as an example.

Figure 5: Locations of the pressure transducers.

The ambient air and water temperatures from the thermometers are given in Fig. 6 and the surface temperature of the water or ice cover from the IR camera is given in Fig. 7. Water samples were collected and analyzed using a spectrophotometer for the urea concentration. The values show slight trend of increase in concentration.

Figure 6: Ambient temperature evolution. Time started at 8:45am.

Figure 7: Water or ice surface temperature evolution. Time started at 8:45am.
Because of the planar nature of the waves in the flume, the pancakes were not as circular as in the pond test. We defined the dimension along the wave propagation as the floe size. The *in situ* ice cover thickness was measured at the glass sidewall of the flume every hour after the ice production became sufficient. The final ice thickness profile and the floe size evolution are presented in Fig. 8.

Due to beach reflection, wave amplitude at different locations varied. We used the redundancy of the pressure transducers 5–8 at positions 1 and 2 to determine the following parameters: incoming wave amplitude, wavelength, reflection coefficient, and the phase lag between the incoming and reflected waves. The change of ice cover appearance during this test is given in Fig. 9. In general, wave amplitude decayed as the ice cover grew. However, the wavelength did not change significantly.

DISCUSSION AND CONCLUSION
In an earlier paper (Shen et al., 2001) we proposed an analysis that determines the ice floe diameter based on either bending failure or tension failure. Bending failure yielded

$$D_{\text{max}} = \frac{C_1 L^2}{2\pi^2 E A},$$

where $C_1$ has the dimension $\frac{F}{L^2}$, $L$ is the wavelength, $A$ is the wave amplitude and $E$ is Young’s modulus of the ice. Tension failure yielded

$$D_{\text{max}} = \left(\frac{2F_f L^2}{\pi^3 A g (\rho_w h + C_d \rho_w A)}\right)^{1/3}$$

where $F_f$ is the force from the freezing bonding, $h$ is the ice floe thickness and $C_d$ is the drag coefficient. To test the theory, we used the flume data only, because the pond data consisted only two tests, insufficient to show
trend. These two tests cannot be plotted together with the flume case, because of the different wave geometry and chemical composition. Fig. 10 is the plot of the final pancake ice size with respect to the final wave condition as well as the final ice thickness. This result suggests that there is roughly a $\frac{1}{3}$-power relationship between the maximum diameter and the parameter $L^2/2\, Ah$. The amount of data is not sufficient to determine if the proposed theory is valid or not. But based on the existing data, it seems that tension failure could be the dominant mode in these tests.

$$\text{y} = 26.157x^{0.3239}$$

![Graph showing the relationship between the final floe size and the wave characteristics.](image)

Figure 10: Relationship between the final floe size and the wave characteristics.

From the two experiments we found similar pancake ice formation. To develop and validate a theory that can accurately predict pancake ice formation in field conditions require more experimental data. Pond conditions more closely resemble the ocean. It is however difficult to have enough suitable weather conditions to conduct these outdoor tests. Cooling of the water before suitable weather condition is also a challenge due to the large thermal mass in the pond. In order to maximize the length of the test with minimum crew hours, indoor flume tests seem to be more advantageous.

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