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Turbulent Dissolution of a Vertical Ice Wall Into Homogeneous and Stratified Salty Water

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Abstract

We present experimental results of the dissolution of a vertical ice wall in contact with homogeneous salty water. Dissolving velocities and interface conditions are measured over a range of ambient temperatures. The results are consistent with the experiments of Josberger and Martin [5] and are accurately predicted by the scaling model of Kerr and McConnochie [6]. When the salty water is stratified we find that both the dissolving velocity and interface temperature are significantly reduced.

Introduction

Over the past decade, an important component of global climate change has been the increasingly rapid dissolution of the Antarctic and Greenland Ice Sheets in the warming polar oceans [8]. This dissolution is occurring on the underside and fronts of ice shelves formed where glaciers reach the ocean [3] and from the icebergs that calve from them [7].

In this paper we examine the turbulent dissolution of a vertical ice wall, initially in the case of a homogeneous ambient and then in the case of a stratified ambient. First we present our experimental results and those of Josberger and Martin [5]. We then compare the experiments with the dissolving model of Kerr and McConnochie [6]. Finally we present additional experiments that were conducted with an ambient salinity gradient.

Homogeneous Ambient Experiments

The Experiments of Josberger and Martin

Josberger and Martin [5] conducted a careful series of experiments in which a vertical ice wall ablated in contact with homogeneous aqueous solutions of sodium chloride. The ice was bubble-free, up to 1.2 m high, and had an initial temperature T_s of -1 °C. The ambient solutions had compositions C_f from 3 to 3.5 wt % NaCl, and temperatures T_f that ranged from 0 to 27 °C.

Above a turbulent transition height of 10 to 30 cm from the base of the wall they observed an upflow that grew in thickness and velocity with time and had an outer edge that fluctuated with the passage of turbulent eddies.

The turbulent flow data from 7 of the experiments of Josberger and Martin [5] are summarized in table 1. Experiments performed in warmer far field conditions are not included as beyond around 6 °C the ice will melt as opposed to dissolve. In a melting regime the ablation rate is controlled by heat transfer to the wall while in a dissolving regime, both mass and heat transfer are important.

The table lists the ambient temperature T_f and composition C_f of the sodium chloride solutions, the measured interface temperature T_i, and the dissolving velocities V measured at various vertical distances z above the height on the ice wall at which the upward flow became turbulent. The wall temperatures were found to be constant to within 0.02 °C along the ice in each experiment. The dissolving velocities are also reasonably constant, to within about 5–10%.

Experiment number	T_f (°C)	C_f (wt %)	T_i (°C)	z (mm)	V (μm/s)
1	-0.10	2.99	-1.47	360	0.58
2	1.55	2.90	-0.92	70	1.22
				200	1.02
3	2.00	3.00	-0.76	510	1.57
				610	1.56
				940	1.40
4	2.20	3.00	-0.76	115	1.87
				250	1.89
5	2.66	3.44	-0.74	180	2.15
				330	2.33
6	3.42	3.00	-0.59	470	2.47
				520	2.23
7	6.85	3.395	-0.20	220	6.29
				360	5.99

Table 1: The turbulent dissolution results of Josberger and Martin [5] and Josberger [4]. We note that T_i for experiment 7 is taken from Josberger [4], as it is incorrectly given in Josberger and Martin [5].

Our Homogeneous Ambient Experiments

Our experiments were conducted in a rectangular acrylic tank that was 1.2 m high, 0.2 m wide and 1.5 m long. The tank was kept in a temperature controlled room which was maintained at 4 $\pm$ 1 °C for most of the experiments. For the coldest experiments the room temperature was reduced below this point. To further limit heat transfer the walls of the tank were insulated with an 18 mm thick cavity filled with argon gas. One end wall of the tank consisted of an aluminium heat exchanger, through which ethanol was circulated from a Julabo FP50 Refrigerated-Heating Circulator.

The tank was initially filled with fresh water from which ice was grown against the aluminium heat exchanger. To form bubble free ice a constant supply of bubbles was provided by an aquarium air pump. Once approximately 5 - 10 cm of ice had been grown against the end wall the circulator was reset to approximately -2 °C and the ice was allowed to equilibrate.

Following an equilibration period of approximately 1 hour the fresh water was drained from the tank and replaced with salty water. While refilling a barrier was placed against the ice to avoid salty water contacting the ice. Some water did seep past the barrier and contacted the ice but the fluid between the ice and the barrier quickly tended towards the interface conditions and the dissolving was very limited. An example of our experiments is shown in figure 1 where the rising boundary plume can be clearly seen next to the ice. Experiments were conducted with ambient solutions of composition 3.5 $\pm$ 0.1 wt % NaCl and temperatures that ranged from 0.3 to 5.4 °C as shown in table 2.

Throughout the experiments photographs were taken at regular intervals with the shadowgraph method used to visualise the flow. In addition to this thermistors were frozen into the ice at

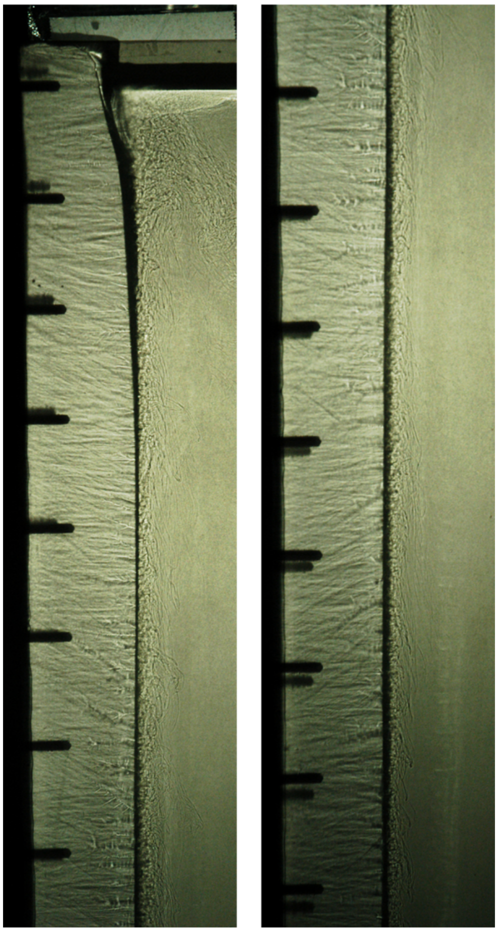

Figure 1: Shadowgraph of a boundary plume flowing up an ice wall. This experiment was conducted at $T_f = 3.9°C$ and $C_f = 3.31$ wt % NaCl. The vertical spacing of black screws in the photo is 60 mm. The left photo shows the ice from a height of 72 cm up to the free surface at 114 cm while the photo on the right shows the ice at heights of 32 cm to 76 cm.

several heights. As the ice melted the thermistors gave a temperature record within the ice, at the interface and finally through the boundary layer. Several extra thermistors were left in the ambient far field to monitor the progress of the first front of meltwater that propagated down the tank throughout an experiment.

The photographs were used to calculate a dissolving rate throughout the experiment. By calculating the difference in ice position between two photographs we could observe how much

Experiment number	T_f (°C)	C_f (wt %)	T_i (°C)	V (μm/s)
A	0.3	3.44	−1.31	0.76
B	1.3	3.49	−1.01	1.27
C	2.3	3.50	−0.76	1.87
D	3.1	3.47	−0.62	2.40
E	3.8	3.46	−0.53	2.70
F	4.2	3.60	−0.55	3.18
G	4.7	3.60	−0.43	3.20
H	5.4	3.49	−0.35	3.69

Table 2: Experimental parameters and results from our experiments

the ice had retreated in a given period of time and hence calculate a dissolving rate. Position measurements were typically done every 30 minutes but this time period was increased for some of the colder experiments where the dissolving rate was reduced. The dissolving rate was ignored above the first front. At this point the far field conditions were neither constant nor known so the measured dissolving rate could not be used. Similarly to the experiments of Josberger and Martin [5] we found that the dissolving rate was constant with height and increased as the far field temperature increased.

The thermistors that were frozen into the ice gave us a clear measurement of the interface temperature. Within the ice the temperature was observed to increase gradually before rising much more rapidly as the thermistor moved beyond the interface into the rising plume. The interface temperature was taken to be at the discontinuity in gradient between these two regimes. Similarly to the dissolving measurements and the interface temperature measurements of Josberger and Martin [5] we observed no dependence on height.

Comparison with the Model of Kerr and McConnochie

In Kerr and McConnochie [6] we presented a simple scaling model of turbulent dissolution of a vertical wall. The model is based on the empirical observation that turbulent heat transfer on a vertical wall is independent of height at very high Rayleigh numbers. Our model predicts the dissolving velocity, V, given by

$$V = \gamma \left(\frac{g(\rho_f - \rho_i) D^2}{\mu} \right)^{1/3} \left(\frac{C_f - C_i}{C_f - C_s} \right) = \gamma \mathcal{V} \qquad (1)$$

and the interface temperature and concentration, T_i and C_i, are given by the liquidus relation

$$T_i = T_L(C_i) \qquad (2)$$

and

$$T_f - T_i = \frac{\rho_s L_s + \rho_s c_s (T_i - T_s)}{\rho_f c_f} \left(\frac{D}{\kappa_f} \right)^{1/2} \left(\frac{C_f - C_i}{C_f - C_s} \right) \qquad (3)$$

where $\gamma = 0.097 \pm 0.010$, g is the acceleration due to gravity, ρ_f is the far field density, ρ_i is the density of the fluid at the interface, ρ_s is the density of the solid, D is the compositional diffusivity, μ is the fluid viscosity, C_f is the far field composition, C_i is the composition of the fluid at the interface, C_s is the composition in the solid, T_f is the far field temperature, T_s is the temperature of the solid, L_s is the latent heat of the solid, c_s is the specific heat of the solid, c_f is the specific heat of the far field water and κ_f is the thermal conductivity of the fluid.

Figure 2 shows the measured interface temperatures of the experiments of Josberger and Martin [5] compared with those predicted by equation (3) while figure 3 shows the same comparison using our experimental data. It can be seen that there is very good agreement when the far field temperature is less than about 4°C. Above this point the observed interface temperature becomes increasingly lower than that predicted by equation (3). This reflects the transition from turbulent dissolution to turbulent melting.

Figure 4 shows the experimental dissolving velocities from both our experiments and those of Josberger and Martin [5] compared with the predicted dissolving scale from equation (1). The

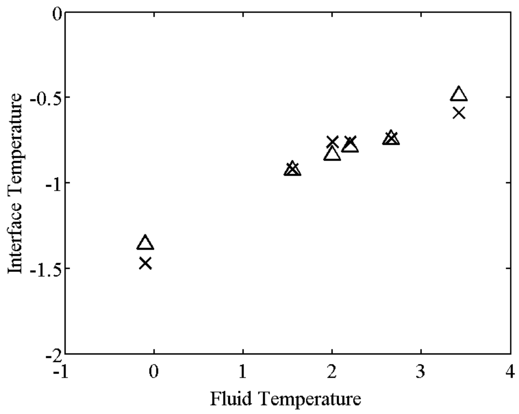

Figure 2: A comparison of the predicted (△) and measured (×) interface temperature T_i from the experiments of Josberger and Martin [5], plotted as a function of the temperature T_f of the NaCl solution. All temperatures are in °C.

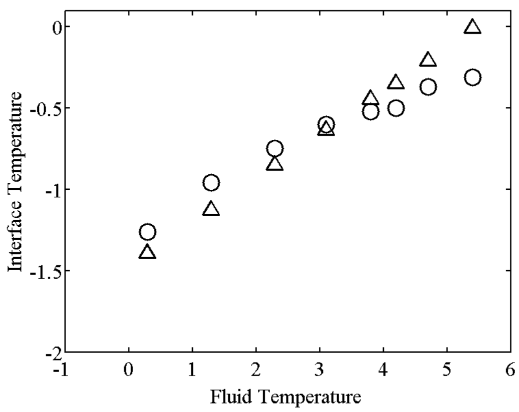

Figure 3: A comparison of the predicted (△) and measured (◯) interface temperature T_i from our experiments, plotted as a function of the temperature T_f of the NaCl solution. All temperatures are in °C.

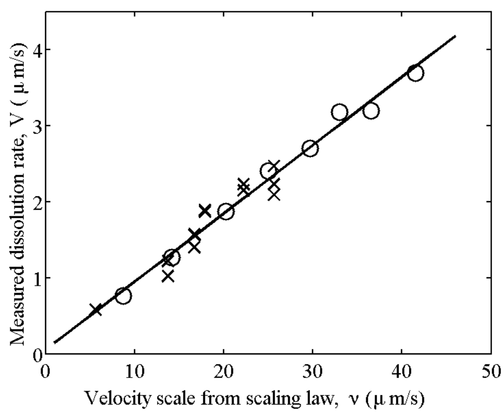

Figure 4: The dissolving velocities V (in μm s^{-1}) of our ice dissolution experiments (◯) and the experiments of Josberger and Martin [5] (×) compared to the velocity scale $\mathcal{V}$ defined by equation (1).

dissolving velocities are seen to lie on a straight line whose slope, $\gamma = 0.090$, is consistent with the predicted value of 0.097 ± 0.010.

Figures 2, 3 and 4 show that the model is able to predict both the interface conditions and the dissolving velocity with excellent accuracy. Knowledge of the dissolving rate is crucial to understanding the future development of Antarctic ice shelves and it is very promising that both sets of experimental data agree with the model predictions. Since we observe no height dependence on either the dissolving rate or interface conditions we expect the results to hold for the full height of ice shelves or icebergs.

Our Stratified Ambient Experiments

Since the polar oceans are weakly stratified in both temperature and salinity we have commenced a series of experiments examining the effect of stratification on dissolution. A double bucket system was used to create a linear salinity gradient. The experiments had far field temperatures, T_f, of 3.5 $\pm$ 0.2 °C, a mean salinity, C_f, of 3.5 $\pm$ 0.1 wt % NaCl and a Brunt–Väisälä frequency, N, that ranged from 0.02 to 0.24 s^{-1}. The parameters and results for the stratified experiments are shown in table 3 along with one homogeneous experiment for comparison.

Huppert and Josberger [1] and Huppert and Turner [2] conducted a series of experiments with ice melting into a strong salinity gradient. They described the formation of double diffusive layers where the fluid inside a layer became well mixed with sharp temperature and salinity gradients across layers. The circulation was caused by the diffusion of heat forcing a sinking flow near the rising boundary plume. Our dissolving experiments with weak gradients observe the same flow structure as those of Huppert and Turner with a layer scale that is consistent within error with their scaling.

As shown in table 3 the presence of stratification reduces both the dissolving velocity and the interface temperature with stronger stratifications having greater effects. Experiment *a* shows that for an ambient stratification of $N = 0.02$ s^{-1} the dissolution becomes indistinguishable from the homogeneous case despite double diffusive layers forming. This suggests that it is not the formation of double diffusive layers that causes a reduction in the ablation rate.

Unlike the homogeneous experiments there was a height dependence on dissolving velocity and interface temperature with both the ablation rate and interface temperature decreasing with height. This reduction is far greater than what would be expected from the changing far field properties.

The values presented in table 3 are taken at roughly half the height and are representative values only. Figure 5 shows the dissolving velocities as a function of height for experiments E,

Experiment number	T_f (°C)	C_f (wt %)	N s^{-1}	$\overline{T_i}$ (°C)	$\overline{V}$ (μm/s)
E	3.8	3.5	0	−0.53	2.7
a	3.7	3.5	0.02	−0.53	2.6
b	3.3	3.5	0.07	−0.62	1.9
c	3.7	3.6	0.08	−0.76	2.1
d	3.7	3.6	0.17	−1.30	0.8
e	3.7	3.5	0.24		0.7

Table 3: Experimental parameters and results from our stratified experiments (*a* to *e*) with homogeneous experiment E included for comparison. The interface temperature was not measured for experiment *e*. Note that $\overline{T_i}$ and $\overline{V}$ are mean quantities as there is a height dependence in the stratified case.

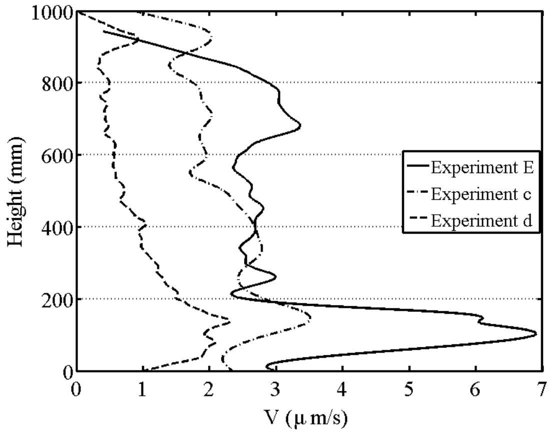

Figure 5: The dissolving velocity, V, from experiments E, *c* and *d* The transition to turbulence occurs at approximately 160 - 180 mm where the dissolving velocity is at a maximum.

c and *d*. The region of maximum dissolution is at the turbulent transition where there is a flow perpendicular to the ice as observed by Josberger and Martin [5].

Near the top of the ice the first front would have reduced the far field temperature and salinity and caused a decrease in the dissolving velocity. This is particularly apparent in experiment E above 800 mm where the dissolution is significantly reduced.

Experiments *c* and *d* both exhibit a height dependence on the dissolving velocity that is not present in the homogeneous experiments. This dependence appears to be increased in more strongly stratified ambients. We plan to conduct further experiments to fully investigate the stratified case and provide explanations for the reduced dissolving velocity and height dependence.

Conclusions

We have presented experimental results showing the turbulent dissolution of a vertical ice wall and compared these with model predictions. It is seen that both the dissolving velocity and interface temperature increase with far field temperature over the experimental temperature range and have no dependence on height. Past this point the ice starts to melt as opposed to dissolve and the relationship begins to break down.

It is shown that the model predictions do not agree with the experimental data when ambient stratification is included. This is an important limitation as the oceans are generally stratified, often in both salinity and temperature. A height dependence in the dissolving velocity and the interface temperature is also observed in the stratified experiments. It is unclear how this height dependence will scale to the heights of Antarctic ice shelves and icebergs but future work will hopefully clarify this.

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