Available online at www.sciencedirect.com

ScienceDirect

Procedia IUTAM 15 (2015) 95 – 100

Procedia IUTAM

www.elsevier.com/locate/procedia

IUTAM Symposium on Multiphase flows with phase change: challenges and opportunities, Hyderabad, India (December 08 – December 11, 2014)

Imaging the evolution of brine transport in experimentally grown quasi-two-dimensional sea ice

C. A. Middleton[a,b]*, C. Thomas[a], D. M. Escala[c], J.-L. Tison[b] and A. De Wit[a]

[a]*Non Linear Physical Chemistry Unit, Université libre de Bruxelles (ULB), CP 231, Boulevard du Triomphe, Brussels, B-1050, Belgium*
[b]*Laboratoire de Glaciologie, Université libre de Bruxelles (ULB), CP 160/03, 50 Avenue F.D. Roosevelt B-1050, Brussels, Belgium*
[c]*Nonlinear Physics Group, University of Santiago de Compostela, Rúa Xosé María Suárez Núñez, Santiago de Compostela, Spain*

Abstract

Anthropogenic climate change is affecting the extent and composition of sea ice, modifying the movement of salt, gases and nutrients in the ocean-ice-atmosphere system. In order to understand how these changes will feedback into the climate system, it is necessary to understand how brine and fresher water are transported during the phase changes as sea ice grows and melts. We present here the methodology and preliminary results of an experimental approach visualizing the convective movements of brine and fresher water as sea ice grows in a quasi-two-dimensional set-up, using Schlieren imaging techniques.

Peer-review under responsibility of Indian Institute of Technology, Hyderabad.

Keywords: sea ice; brine transport; convection; Hele-Shaw cell; Schlieren imaging; synthetic Schlieren

1. Introduction

The global climate is in a state of change. As global warming occurs, the presence and composition of sea ice is changing. In particular the areal extent of the Arctic sea ice cover is diminishing, and the amount and distribution of multi-year ice is decreasing compared with first-year ice. These changes will have effects on the physical processes occurring in sea ice, and hence their contribution to feedback mechanisms in the climate system. The transport of brine through sea ice is one of these processes which changes due to the age of the ice, and has important effects on

* Corresponding author. Tel.: +32-2-650-5787
E-mail address: ceri.middleton@ulb.ac.be

Peer-review under responsibility of Indian Institute of Technology, Hyderabad.
doi:10.1016/j.piutam.2015.04.014

the global climate and nutrient cycle. The movement of brine through sea ice exerts a control on the distribution of salt in the ocean and therefore on thermohaline circulation within the oceans. Nutrients and dissolved gases are also entrained in the brines, so understanding brine transport will allow better understanding of the nutrient cycle and of the evolving sources and sinks of climatically important gases such as carbon dioxide [1–3].

The mechanisms of sea ice formation have been well described previously: as ice freezes from sea water, it behaves as a mushy layer in which the salts present are expelled into pockets of increasingly saline brine. These pockets link together at certain critical values of brine volume fraction, temperature, and salinity to form channels by which the dense brine can sink into the underlying sea water, so driving buoyancy-driven convective transport from the ice layer into the sea [1–5]. However, the complex mechanisms of transport of dense brine and less dense fresher sea water through the ice as it freezes are not yet completely understood.

In order to characterize these mechanisms and understand how they will be affected as the sea ice changes, both in thickness and areal cover, we must first understand how these mechanisms occur under controlled conditions in the laboratory. One way of achieving this is to conduct quasi-two-dimensional experiments where single brine channels can be imaged, and convective processes can be observed without the extra complication of a third dimension [4,6–8]. These previous studies have shown that after a certain critical depth of the mushy layer is reached, downward flow is concentrated within the brine channels, and there are two possible methods of replacement by the less dense fresher water; within the channels, and through the ice between channels [4,6,7]. Observations have also been made that show that the position of the brine channels is not constant throughout the experiment, but that the channel position evolves, coupled with ice recrystallization [4].

Previous experiments on two-dimensional freezing fronts in sea ice systems have introduced dye to the system to better highlight the downward motion of denser brine, and the upward entrainment of less dense sea water [4,6]. However, some studies have shown that the introduction of a color indicator can affect the dynamics observed, for example by changing the density of liquids present [9], so should be used with caution, if at all. We present here the first results of an experimental study of these convective processes in a two layer ice/salt water system which does not require the introduction of a dye, so avoiding any potential effect on the dynamics that this species may have.

2. Methods

2.1. Hele-Shaw cell

To visualize the density driven convective flow of liquids caused by temperature and salinity changes, and the evolution of brine channel structures within a growing sea ice layer, we use a Hele-Shaw cell [4]. This cell is a quasi-two-dimensional experimental set-up, where two clear Plexiglas plates are oriented vertically, separated by a small gap (3mm) filled with pure water or an aqueous NaCl solution of controlled concentration. This apparatus is mounted within a temperature controlled environment. A temperature gradient is applied to the cell, cooling from the upper boundary, so forming a two-dimensional model of the freezing front which develops in natural sea ice.

2.2. Schlieren imaging

In order to image the movement of brines both within sea ice, and under the ice-water interface in the Hele-Shaw cell, we use Schlieren visualization methods. These methods exploit the fact that the physical properties of a liquid change its index of refraction. Parallel light which passes through two liquids of different density, and therefore different refractive index (e.g. sea water and brine), will be refracted differently, as in the diagrams in Figures 1 and 2. By observing these refractive changes, we can visualize the areas of different density. We therefore observe the downward flow of denser brine through fresher water as the freezing front progresses. These methods have previously been used for a wide range of applications, including heat flow and fluid dynamics [10].

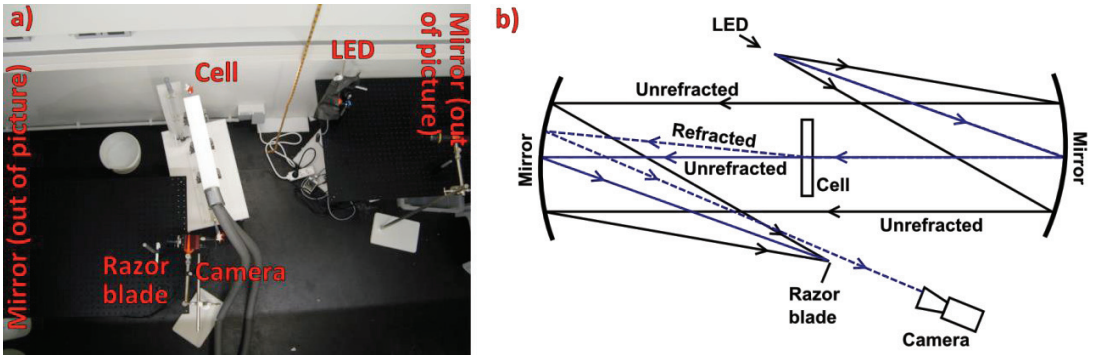

Fig 1. a) Traditional Schlieren assembly seen from above in an environmental chamber. Visible are the Hele-Shaw cell, LED light and razor blade (obstacle) and camera positions, mirrors are out of shot. b) Schematic showing the Z-type Schlieren assembly and the refracted (dashed line) and unrefracted (solid lines) light paths.

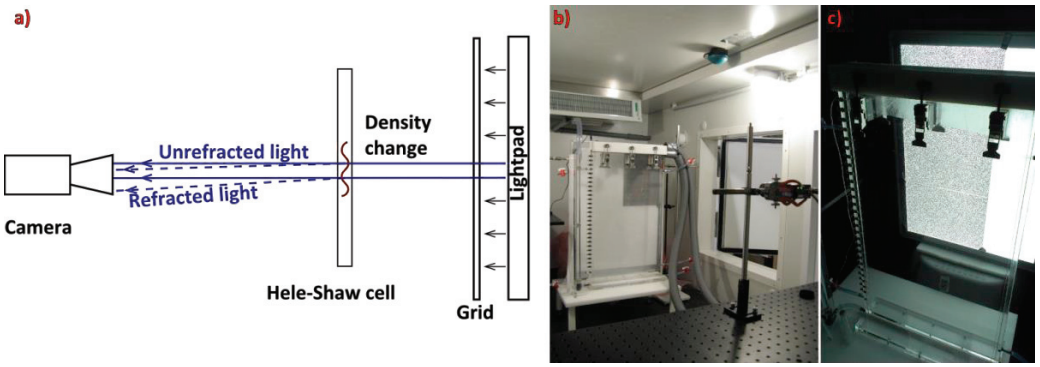

Fig 2. a) Synthetic Schlieren assembly a) s schematic showing the refracted (dashed lines) and unrefracted (solid lines) light paths. b) System in the environmental chamber. c) Close up view with ice growing.

Two distinct Schlieren techniques are used in this study: traditional Schlieren and synthetic Schlieren (also known as background oriented Schlieren) [10,11]. With a Z-type mirror traditional Schlieren system, direct imaging of the density differences is possible through observations of the refracted light. In the simplest version of this system, as shown in Figure 1b, unperturbed light rays which remain parallel are refocused to a point and blocked by an obstacle – here we use a razor blade - resulting in a dark image; only light which has been refracted due to an interaction with a disturbance in the cell will pass the blade and interact with the camera sensor positioned behind the razor. In reality, this razor blade is positioned so that it does not block all of the refocused light, resulting in a gray background, on which darker and lighter areas will appear due to refraction onto or away from the razor respectively.

Synthetic Schlieren, on the other hand, is an indirect imaging method where the density disturbances are not imaged directly with the camera, but become evident only after the results are processed. Images of a pattern, lit from behind by a lightpad, are taken through the cell; firstly a reference image before the experiment begins, and then at regular intervals during an experiment. The reference image of the pattern is then compared to those taken during the experiment using image processing software, and any changes to this pattern caused by the refraction of the light are used to reconstruct the processes within the cell (Figure 2). By adapting these imaging systems we can also visualize the movement and evolution of brine channels within the ice layer as it grows.

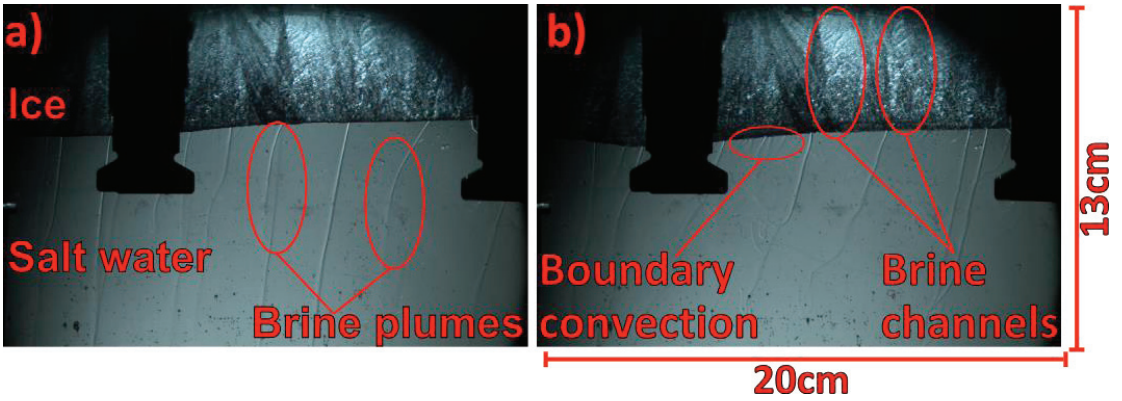

Fig. 3. Traditional Schlieren imaging of brine rejection. a) image taken 4 hours 20 minutes after ice growth began; b) 40 minutes after image a. Clips which attach the cooling lid to the cell are visible as the dark areas which obscure the image in two areas at the top of the images. The circular shape of the mirror can also be seen at the top of the images.

3. Results

3.1. Traditional Schlieren

Figure 3 shows traditional Schlieren images of ice growing from a 35 ppt NaCl salt water solution in the Hele-Shaw cell, the solution is cooled from above, ice propagates downwards. The temperature at the top of the cell was set to -20°C, and the surrounding environmental chamber to -1°C. This method can be used to visualize both within the sea ice, showing brine channels and ice crystal structures, and under the ice-water interface. In the underlying salt water layer, the rejected brine plumes are visible as areas of different luminosity to the surrounding water. In some places the brine channel structures which drain to form these plumes can be seen within the ice layer. Brine plume evolution is observed in the second image, where a new plume has been generated at the right hand side of the image. Boundary layer convection, with smaller plumes developing near the ice-water interface, also appears to be more important in the second image.

3.2. Synthetic Schlieren

We first used the synthetic Schlieren method to visualize the behavior in a system with a temperature gradient, but no phase change; a non-freezing fresh water system. The external temperature was measured at 23°C, and the imposed temperature at the top of the Hele-Shaw cell was set to 5°C, above the freezing point of pure water. The results of this test are shown in Figure 4, where convective plumes can be seen as white on the black background. These differences become more distinct with time, as the plumes evolve and the difference from the original reference image becomes more pronounced. New plumes develop from the top edge of the cell (t = 20; 40 seconds) and internal structure within the plumes can be observed (t = 30 seconds).

Figure 5 shows the results of another synthetic Schlieren experiment, where a 35 ppt NaCl solution was cooled from above to generate a freezing front. Original and processed images are shown for comparison, and to demonstrate that it is possible to acquire complimentary information from the two images. In the original image, structures can be seen within the ice, in the processed image the positions of brine plumes under the ice-water interface become apparent. The position and number of brine plumes can be seen to change between the first images, taken after 1 hour 23 minutes of cooling, and the second set of images taken 1 hour 40 minutes after cooling began. Carrying out an equivalent experiment with pure water rather than salt water results in no convection plumes being observed under the ice-water interface, with neither thermally driven convection, as in Figure 4, nor salinity driven convection, as in Figure 5, present.

4. Discussion and conclusions

The imaging methods detailed here show great promise for the investigation of the flow of liquids in a temperature gradient and also the flow of brine and fresher water in a freezing or melting sea ice layer, without the addition of a dye. Both of these optical methods have advantages and disadvantages associated with them; notably the limited field of view of the traditional Schlieren, and the need to process images before density contrasts become visible with the synthetic Schlieren system.

From these results we can say that the adapted traditional Schlieren method can be used to visualize the brine channel systems within the ice and the brine plumes below the interface. These images show that the processes of desalination of the sea ice evolve with the growth of the ice; e.g. the plume position and number has changed with time.

Here we have shown that the synthetic Schlieren method can be applied to both a one phase system and a multiphase system. The preliminary images show tantalizing results which must be examined further, such as the internal structure within the temperature driven plumes, and the difference in size of the temperature and salinity driven plumes. Optimization of these Schlieren methods to observe flow in the multiphase system of sea ice growth is continuing. Further experiments will allow quantitative analysis of the relationship between brine plumes and ice layer thickness, and the effect that changing the initial temperature and salinity in the reservoir has on the evolution of the structures formed and brine plume dynamics.

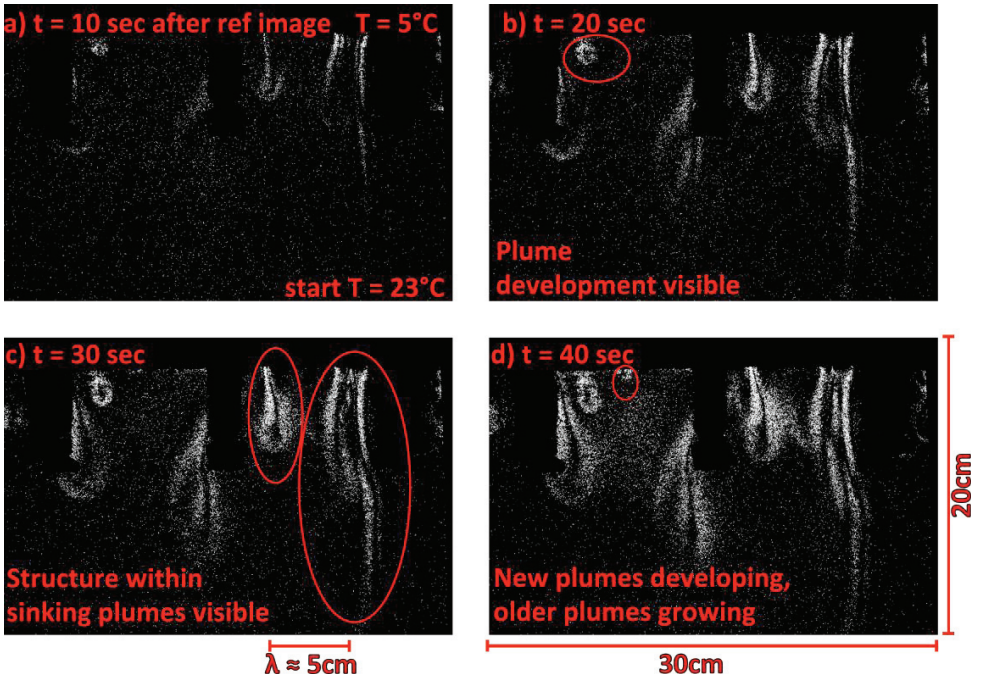

Fig. 4. Cooling of pure water from top of cell in absence of freezing. Temperature (T) at top of cell fixed at 5°C, room temperature 23°C; reference image taken ~24 hours after cooling began. Temperature induced density driven convection can be seen developing and evolving, with structures within the plumes visible, over the short period of time shown. Dark areas at top of image are clips connecting temperature control lid to the H-S cell, blocking imaging of the cell and the pattern behind.

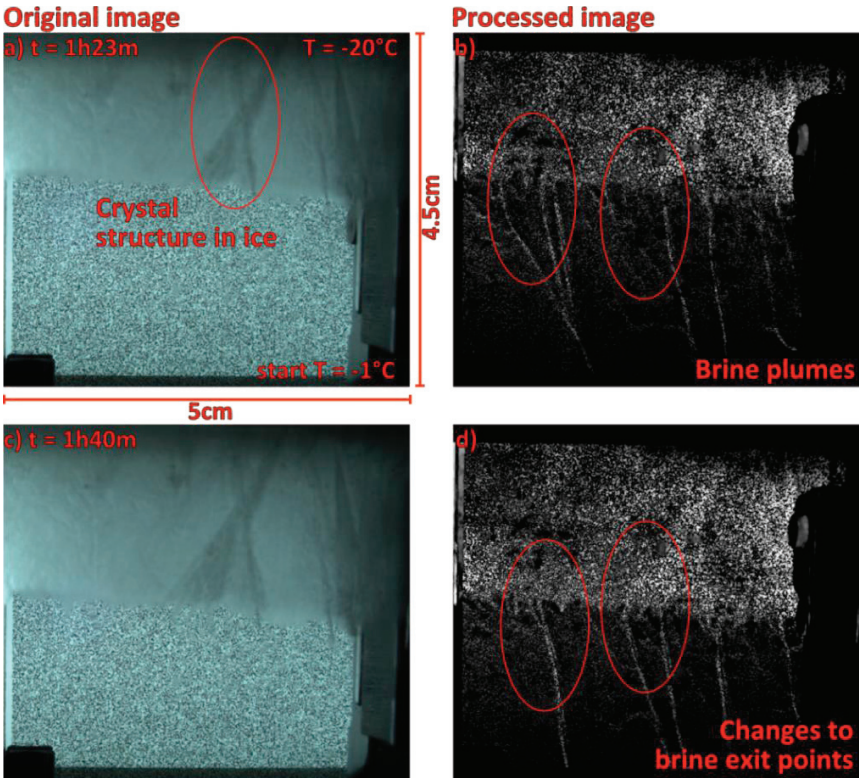

Fig. 5. Original (a,c) and processed (b,d) images of synthetic Schlieren imaging of ice forming from an aqueous 35 ppt NaCl solution. The temperature (T) at top of the cell was fixed at -20°C, room temperature -1°C. The upper set of images was taken 1 hour and 23 minutes after ice began to grow, the lower set 1 hour and 40 minutes. The ice layer has grown in thickness, and the crystal structure can be seen to have continued to grow (original images), and the position and number of brine plumes has changed. Structures in ice appear slightly out of focus due to focal point of camera being in the plane of the pattern.

Acknowledgements

We thank B. Knaepen, and P. Bunton for fruitful discussions. We acknowledge financial support by the ARC CONVINCE research programme.

References

1. Notz, D. & Worster, M. G. Desalination processes of sea ice revisited. *J. Geophys. Res.* **114,** C05006 (2009).
2. Wells, A. J., Wettlaufer, J. S. & Orszag, S. A. Brine fluxes from growing sea ice. *Geophys. Res. Lett.* **38,** L04501 (2011).
3. Jardon, F. P., Vivier, F., Vancoppenolle, M., Lourenço, A., Bouruet-Aubertot, P. & Cuypers, Y. Full-depth desalination of warm sea ice. *J. Geophys. Res. Ocean.* **118,** 435–447 (2013).
4. Eide, L. I. & Martin, S. The formation of brine drainage features in young sea ice. *J. Glaciol.* **14,** 137–154 (1975).
5. Feltham, D. L., Untersteiner, N., Wettlaufer, J. S. & Worster, M. G. Sea ice is a mushy layer. *Geophys. Res. Lett.* **33,** L14501 (2006).
6. Niedrauer, T. M. & Martin, S. An experimental study of brine drainage and convection in Young Sea ice. *J. Geophys. Res.* **84,** 1176 (1979).
7. Wettlaufer, J. S., Worster, M. G. & Huppert, H. E. Natural convection during solidification of an alloy from above with application to the evolution of sea ice. *J. Fluid Mech.* **344,** 291–316 (1997).
8. Peppin, S. S. L., Aussillous, P., Huppert, H. E. & Worster, M. G. Steady-state mushy layers: experiments and theory. *J. Fluid Mech.* **570,** 69–77 (2007).
9. Almarcha, C., Trevelyan, P. M. J., Riolfo, L. A., Zalts, A., El Hasi, C., D'Onofrio, A. & De Wit, A. Active Role of a Color Indicator in Buoyancy-Driven Instabilities of Chemical Fronts. *J. Phys. Chem. Lett.* **1,** 752–757 (2010).
10. Settles, G. S. *Schlieren and Shadowgraph Techniques: visualizing Phenomena in Transparent Media*. (Springer Verlag, 2001).
11. Dalziel, S. B., Hughes, G. O. & Sutherland, B. R. Whole-field density measurements by "synthetic schlieren."*Exp. Fluids* **28,** 322–335 (2000).