Physics Education

The physics of ice cream

To cite this article: Chris Clarke 2003 *Phys. Educ.* **38** 248 www.iop.org/journals/physed

The physics of ice cream

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Abstract

Almost everybody likes ice cream, so it can provide an excellent vehicle for discussing and demonstrating a variety of physical phenomena, such as Newton's law of cooling, Boyle's law and the relationship between microstructure and macroscopic properties (e.g. Young's modulus). Furthermore, a demonstration of freezing point depression can be used to make ice cream in the classroom!

(Some figures in this article are in colour only in the electronic version)

The main ingredients of ice cream are water, milk protein, fat, sugar, flavour (e.g. strawberries, vanilla or chocolate) and a substantial amount of air. But simply mixing these and placing them in your freezer does not produce good ice cream. *How* the ingredients are put together is crucial. We can see why this is so by looking at ice cream at a microscopic level, i.e. on length scales of 1 μm to 1 mm. Figure 1 is a scanning electron micrograph of ice cream, which reveals a complex microstructure of ice crystals (about 30% by volume) and air bubbles (50%) held together by a viscous sugar solution (15%). Close inspection of the air bubbles shows some tiny features on their surface—these are fat droplets (5%). The texture that you experience when you eat ice cream depends on the size of the ice crystals and air bubbles; for example, large ice crystals make the ice cream icy and gritty. To make good quality ice cream, it is necessary to create a fine microstructure. And to do this, you need to know about lots of different aspects of physics.

So how do you form the microstructure? In an ice cream factory, the ingredients are first blended in the correct quantities and this mix is pasteurized to kill any harmful micro-organisms. Next, the mix is homogenized, which breaks the fat globules down into an emulsion of small droplets ($< 1\ \mu$m). To keep the fat droplets small it is necessary to stabilize the emulsion with a surfactant. There are two types of surfactant in ice cream: milk proteins (e.g. casein) and emulsifiers (e.g. mono-diglycerides or lecithin from egg yolks or soy beans). Next, the mix is cooled down to about 5 °C, below the melting point of the fat, which begins to crystallize. This is known as ageing. So now we have created one component of the microstructure—the fat droplets. The reason why we need small, partly crystalline fat droplets will become apparent in the next stage of manufacture, when the mix is converted into ice cream by aerating and freezing it.

It is reputed that Mongolian horsemen on journeys across the Gobi desert in winter were the first to make ice cream by simultaneous aeration and freezing. Their provisions of cream stored in animal intestines were vigorously shaken as they galloped, and frozen at the same time by the sub-zero temperatures. Ice cream is no longer made by this method, but is based on the same principle of simultaneous aeration and freezing.

The first ice cream-making machines appeared in the 19th century. They consisted of a barrel in which the ingredients were placed. A mixture of ice and salt was packed around the outside or bottom of the barrel, and the mix was churned by turning a handle. The freezers you find in an ice cream factory today are remarkably similar in

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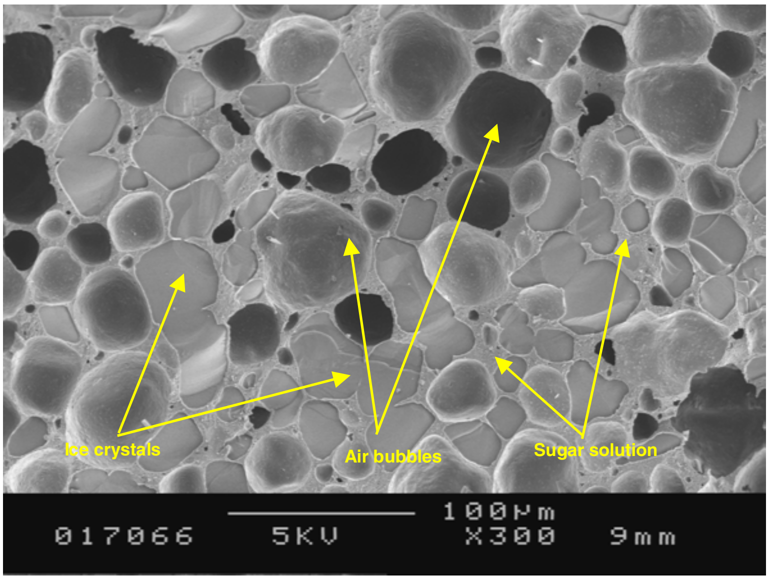


Figure 1. A scanning electron micrograph of ice cream (courtesy of M Kirkland, Unilever R & D Colworth). The scale bar is 100 μm. Ice crystals, air bubbles and sugar solution are marked. The fat droplets are too small to be seen at this magnification.

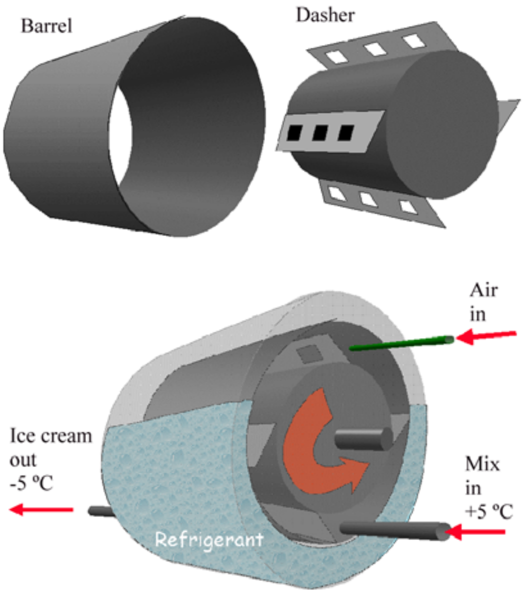


Figure 2. The modern ice cream freezer.

principle. They consist of a refrigerated barrel, with a rotating dasher inside, which is equipped with scraper blades (figure 2). Ice cream mix (at approximately 5 °C) is pumped into the barrel. The barrel wall is cooled, so that when the mix touches it, ice forms instantly, and is rapidly scraped off by the rotating scraper blades. The small ice crystals are dispersed into the mix, and its temperature drops.

The main difference between the Victorian and modern ice cream freezer is the refrigerant. Before the invention of mechanical refrigeration, the best refrigerant available was a mixture of ice and salt (sodium chloride). To understand what happens when crushed ice (at 0 °C) and salt are mixed, we use the freezing point curve (figure 3). Adding a solute to water lowers its freezing point (this is known as freezing point depression). So when the ice and salt are mixed, the mixture is above its equilibrium freezing point, and some of the ice melts. This is the reason why salt is put on icy roads in winter. However, in order to change from a solid to a liquid, the ice must take in its latent heat of fusion. If the ice and salt are insulated from the surroundings, this heat can only come from the ice and salt itself, which causes a drop in the temperature. The latent heat of fusion of ice (3.3×10^5 J kg^{-1}) is much larger than the specific heat capacity (4.2×10^3 J kg^{-1} K^{-1}), so melting a small amount of ice can cause a significant drop in the temperature. If you mix the correct proportions of salt and ice, you can reach temperatures as low as −21.1 °C at a salt concentration of 23.3% (this is the eutectic point). At this point, the salt solution

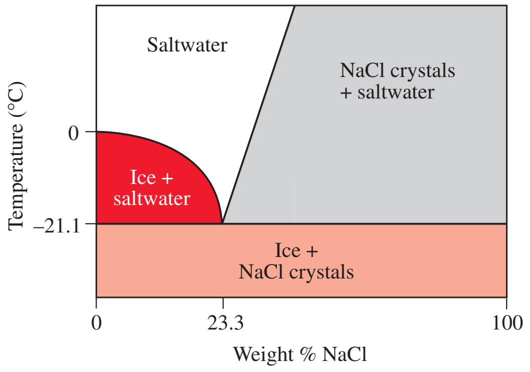


Figure 3. The phase diagram for salt–water mixtures.

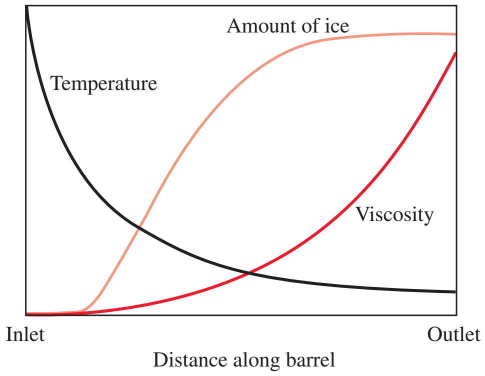


Figure 4. The temperature, ice content and viscosity of ice cream as it passes through the freezer.

becomes saturated (i.e. no more can be dissolved) so that the freezing point cannot be depressed any further.

Newton's law of cooling states that the temperature difference between the refrigerant (T_r) and the mix (T_{ic}) determines the rate at which it cools down:

$$\frac{dT_{ic}}{dt} \propto (T_r - T_{ic}).$$

Thus the colder the refrigerant, the faster the ice cream is cooled down. Whilst the coldest refrigerant available to the Victorians was about −20 °C, today ice cream factories typically use liquid ammonia at −30 °C, and ice cream making is much faster. In fact, Newton's law of cooling explains why the world record for the fastest ice cream ever made used liquid nitrogen at −196 °C [1].

At the same time that the ice cream is frozen, air is injected, forming large bubbles, which are broken down into many smaller ones by the beating of the dasher (figure 2). The fat droplets and milk proteins adsorb to the surface of the air bubbles and help to stabilize them, in the same way that the milk protein and emulsifiers stabilize the fat droplets. Since the fat droplets are partially crystalline, they form a strong, rigid coating, which prevents collapse of the air bubbles.

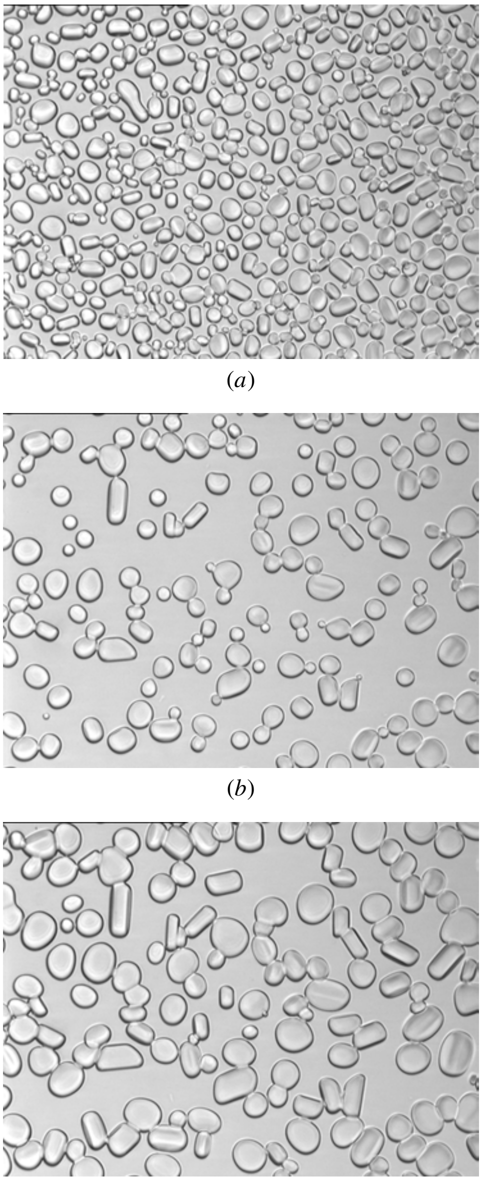
As the ice cream passes through the freezer, its temperature drops, and more ice is formed. This is shown in figure 4.

The viscosity of the ice cream also increases, for two reasons. Firstly, the viscosity of the liquid (η_0) increases as it gets colder. Secondly, the viscosity of a suspension of solid particles (η) increases as the volume fraction (ϕ) of solid (in this case, ice) increases. Einstein proposed the equation that describes this:

$$\eta = \eta_0(1 + 2.5\phi).$$

This approximation works for small solid volume fractions (another term is needed to account correctly for higher volume fractions). The result of the increase of the viscosity means that the mix becomes harder to beat—and the power needed to rotate the dasher is greater. This extra energy is dissipated in the ice cream as heat. Eventually, when the temperature of the ice cream reaches about −5 °C, the energy input through the dasher equals the energy removed as heat by the refrigerant, and it is not possible to cool the ice cream any further: the process becomes self-limiting. At −5 °C, the ice cream is too soft for further processing, such as covering it in chocolate, and the microstructure is unstable. Therefore the ice cream is extruded from the freezer and cooled rapidly ('hardened') by blowing air at about −40 °C over it in an enclosed chamber. After hardening, the ice cream is packaged, and is transported from the factory to the shop. Having successfully created the microstructure of ice crystals, fat droplets and air bubbles in the freezer, the next challenge is to preserve it through the distribution system so that it reaches the consumer in perfect condition.

Ice cream is very sensitive to temperature: if it warms up too much, it will melt. However, even at temperatures below the melting point, its quality can deteriorate due to changes in the microstructure. The microstructure



(*a*)

(*b*)

(*c*)

Figure 5. Ice crystals recrystallizing (courtesy of M Izzard, Unilever R & D Colworth). (*a*) Ice crystals at −10 °C. (*b*) Warmed up to −7 °C: the smallest crystals melt. (*c*) Then cooled back down to −10 °C: the ice reforms on the surviving crystals, which become larger.

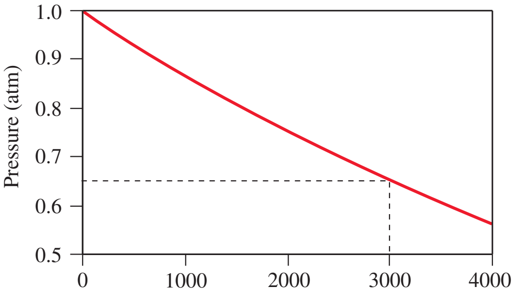


Figure 6. The variation of pressure with altitude.

was *kinetically* stabilized at the end of the manufacturing by storing it at a low temperature. However, it is *thermodynamically* unstable: the dispersed ice crystals and air bubbles can lower their energy by forming fewer, larger particles. This might be familiar if you have ever kept a large tub of ice cream in your freezer for a long time. Every time you take it out to eat some, it warms up so that some of the ice melts. Large ice crystals become smaller, and small ones may disappear completely. When you put the ice cream back in your freezer, it cools down again, and the ice that had melted refreezes. However, it can only freeze on the crystals that have survived. The effect is that the total number of crystals is reduced, and their mean size increases, while the volume fraction of the ice is unchanged (see figure 5). If this happens a number of times, the ice crystals become very large ($\gtrsim 100\ \mu$m) and are detectable in the mouth, producing an icy, gritty texture. This process is known as Ostwald ripening.

But ice cream is not only sensitive to temperature—because it is a foam, it is sensitive to pressure too. For most of us, the variations in atmospheric pressure that the ice cream experiences between being made in the ice cream factory and being consumed are small. But what would happen if you wanted to eat ice cream on top of a very high mountain? Figure 6 shows how atmospheric pressure changes with altitude.

Typically, about half of the volume of ice cream is made of air (if there were no air, the ice cream would be far too hard to get a spoon into), so a 1 litre tub of ice cream contains about 0.5 litres of air. Imagine what would happen if we took a tub of ice cream up to the top of a mountain 3000 m high. Figure 6 shows that the pressure at 3000 m above sea level is about 0.65 atmospheres. Boyle's law tells us how the pressure and volume are related (assuming that the temperature is constant):

$$P_1 V_1 = P_2 V_2.$$

Here P_1 is 1.0 atmosphere, V_1 is 0.50 litres and P_2 is 0.65 atmospheres. Therefore, Boyle's law

Making ice cream at home or in the classroom.

You can easily make some ice cream at home or in the classroom, using ice and salt as the refrigerant. You will need:

Ingredients (This recipe makes a good portion for one person.)

- 1/2 cup (125 ml) milk
- 1/2 cup (125 ml) whipping cream
- 1 tablespoon (15 ml) sugar
- 1/2 teaspoon (2 ml) vanilla (or other flavouring, e.g. crushed fruit. You can also use chocolate/strawberry flavoured milk instead of normal milk for flavour).

Equipment

- 8 cups (2 l) crushed ice
- 8 tablespoons (120 ml) salt
- 1 large Zip lock bag (large enough to contain all the ice comfortably)
- 1 small Zip lock bag (to contain the mix)
- a hand towel or gloves to keep fingers from freezing.

Method

Mix the ingredients together in the small Zip lock bag and seal tightly (very important!), only allowing a small amount of air to remain in the bag—too much can force the bag open during shaking. Put half of the ice in the large bag and sprinkle half of the salt on it. Then put the bag containing the mix on top of the ice. Finally, add the rest of the ice, sprinkle salt on top and seal the bag, making sure to remove all the air. The ice and salt should get very cold (if you have a suitable thermometer you can follow the temperature), so wrap the bag in a towel (or use gloves) and shake vigorously for several minutes. A more exciting, but riskier, alternative is to wrap the bags up in newspaper; tape well with parcel tape to form a ball. You then throw this around for several minutes—preferably outside. You can minimize the risk of salt and ice leaking into the ice cream by double-bagging the mix.

How does it work?

The temperature of the ice/salt mixture can get down to as low as about $-20\,^{\circ}\mathrm{C}$. This freezes the mixture into ice cream, while shaking stops the ice crystals becoming too large and mixes in some air (so that the ice cream is not too hard).

tells us that V_2 is 0.77 litres! This could lead to a number of problems. Obviously 0.5 litres of ice, sugar and fat and 0.77 litres of air cannot fit in a 1 litre tub. Thus the lid of the tub could get blown off. There are also consequences for the structure of the ice cream. The air bubbles will expand as the external pressure decreases. The rest of the ice cream may be able to expand with them to some extent, but there will come a point when the expansion ruptures the air bubbles. As they burst, the air can escape from the ice cream, resulting in collapse of the whole structure, and an unappetizing mess for the consumer! One possible solution is to put in less air, so that the change in volume is smaller. A very neat solution would be to create a microstructure in which the air structure is continuous (like a sponge) rather than in discrete bubbles, so that it could flow in and out as the pressure changes. However, this is technically very challenging!

Having preserved the microstructure through the distribution system, the ice cream finally reaches the consumer in perfect condition. This is not the end of the physics, however. The microstructure of the ice cream determines its texture—for example whether it is hard, soft or chewy when you eat it. Ice cream scientists need to understand the relationship between

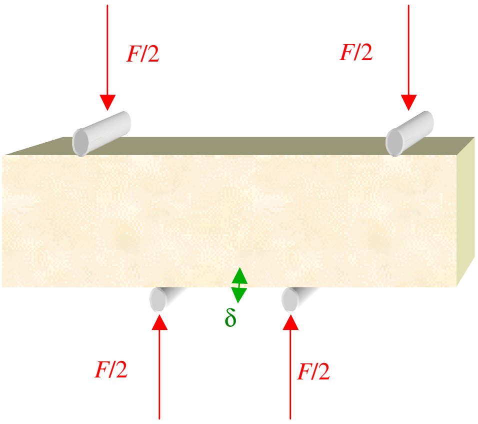


Figure 7. Schematic diagram of the four-point bend test.

microstructure and texture, and the way that we do this is to ask how soft and how chewy it is—i.e. to measure its mechanical properties, such as the Young's modulus. To do this, we often use an experiment called a four-point bend test.

Four bars hold a standard size block of ice cream as shown in figure 7. The top two are fixed, while the bottom two are slowly moved upwards. The force (F) required to move them is measured and plotted against the resulting displacement (δ). Figure 8 shows a series of such curves for four ice cream samples that contain a range of different volume fractions of air from 16.6% to 50.0%.

All the curves have the same shape, but the initial slope, the maximum force and displacement increase as the volume fraction of air is reduced. The initial slope is directly related to the Young's modulus (through the dimensions of the sample). It is clear that reducing the air content makes the ice cream much harder. Other mechanical properties can be related to textures—for example, the work of fracture (i.e. the area under the curve in figure 8) relates to the 'chewiness'. So the next time you eat some ice cream, think of Newton, Einstein, Ostwald, Boyle and Young—and all the physics that has gone into making and eating it!

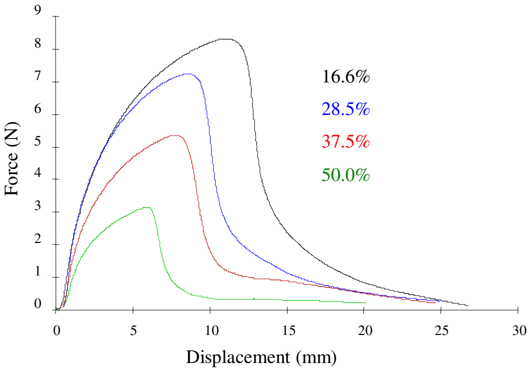


Figure 8. Force–displacement curves from the four-point bend test for ice cream samples with air volume fractions from 16.6% to 50.0%.

Received 14 February 2003
PII: S0031-9120(03)59581-8

Reference

[1] Guinness World Records 2002 *Guinness Book of Records 2002* p 266

Further information

An excellent website on ice cream can be found at: www.foodsci.uoguelph.ca/dairyedu/icecream.html

Chris Clarke is a research scientist who studies colloidal and crystallization phenomena in ice cream at Unilever R & D Colworth. He is currently writing a book entitled *The Science of Ice Cream* which will be published by the Royal Society of Chemistry in 2004 (see www.rsc.org for details).