On the curious properties of ice

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Abstract

As the water temperature is lowered to zero Celsius it changes from liquid to solid, becoming ice. But, as water is one of the strangest materials in the universe, it may be expected that ice should have unusual properties too. This work aims to describe experimentally simple ways of observing such behavior in a university teaching laboratory. These activities are realizable by undergraduate science or engineering students with simple equipment and may be also regarded as ideas for starting science projects. The recent discovery of an amorphous type of ice with features different from the two previously known ones is mentioned. The motivation for this paper is the need for easily realizable but nontrivial experimental activities allowing beginning science or engineering students to work at home. This does not mean that they could not be performed while attending a university laboratory where, under the guidance of an instructor, the students may go beyond the activities described. We should emphasize that the ideas for the activities we present are not too elaborated because we never want to interfere with the ones that the students attending a beginning University laboratory are capable of producing on their own.

Keywords: Properties of ice, Thermodynamics, Teaching Physics.

Resumen

A medida que la temperatura del agua desciende a cero grados Celsius, cambia de líquido a sólido y se convierte en hielo. Pero como el agua es uno de los materiales más extraños del universo, se puede esperar que el hielo también tenga propiedades inusuales. Este trabajo tiene como objetivo describir formas experimentalmente sencillas de observar dicho comportamiento en un laboratorio de enseñanza universitaria. Estas actividades pueden ser realizadas por estudiantes universitarios de ciencias o ingeniería con equipos simples y también pueden considerarse ideas para iniciar proyectos científicos. Se menciona el reciente descubrimiento de un tipo de hielo amorfo con características diferentes a los dos conocidos anteriormente. La motivación de este artículo es la necesidad de actividades experimentales fácilmente realizables pero no triviales que permitan a los estudiantes principiantes de ciencias o ingeniería trabajar en casa. Esto no significa que no puedan realizarse mientras asisten a un laboratorio universitario donde, bajo la guía de un instructor, los estudiantes podrán ir más allá de las actividades descritas. Debemos enfatizar que las ideas de las actividades que presentamos no están demasiado elaboradas porque nunca queremos interferir con las que los estudiantes que asisten a un laboratorio universitario principiante son capaces de realizar por sí solos.

Palabras clave: Propiedades del hielo, Termodinámica, Enseñanza de la Física.

I. INTRODUCTION

People usually regard water ($\boldsymbol{H_2O}$) as a rather uninteresting substance because it is an odorless, tasteless, transparent liquid found in many places, even in deep space. Water is a compound of two of the most common reactive elements in the Universe, i.e. two hydrogen atoms bonded to a single oxygen atom, see Figure 1. Few molecules are smaller or lighter than water. It is also a material apparently contradicting its simple molecular structure. It has remarkable properties that differ from those of the majority of substances we may encounter, for further details see [1] or for a much more elementary and briefer account see [2]. We may assert confidently that $\boldsymbol{H_2O}$ is one of the most fascinating materials in the universe in its liquid, gaseous, and solid phases. It is so commonplace that it is often regarded as a typical substance, but it has anomalous behavior which manifests itself immediately and is markedly different from those of comparable substances. For example, it has a high melting point in comparison with similar materials, a high boiling point, a high surface tension, and also a high viscosity which decreases when augmenting the pressure. It is probably the only substance whose chemical formula has entered the vernacular almost anyone with secondary education is able to remember its chemical formula, H_2 O. But if it seems a simple substance the reality is different, H_2 O baffles anyone who peers at it for long enough.

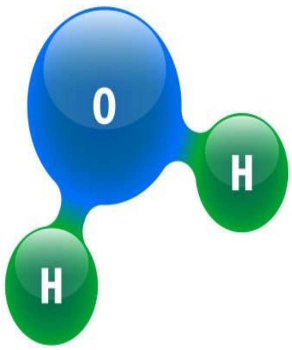

FIGURE 1. Graphical representation of a water molecule. The H-O-H angle is approximately 104.5°. The center of each hydrogen atom is approximately 9.6 × 10−11 m from the center of the oxygen atom [1, 3].

The strangeness of $\mathbf{H_2O}$ shows itself every time you drop an ice cube into a glass of water: in front of you is a solid floating on its own liquid and you may recall that this fact does not occur for most substances. See Figure 2. For example, solid wax does not float on melted wax, solid butter does not float on melted butter, and rocks also don't float on lava—as can be witnessed in the videos of the 2022 eruption of the Mauna Loa that can be found on the Internet.

Ice floats because water expands when it freezes contrary to what most substances do. If you forget a glass bottle filled with water in the freezer the expansion as it gets congealed would be enough to shatter the bottle. This seems like an inconsequential fact but this anomalous behavior allows for the existence of life on Earth [1]. The described phenomena happen for crystalline ice —the dominant form of ice on Earth— and you should know that there are three varieties of amorphous ice —-the last one named medium-density amorphous (MDA) ice whose discovery was announced on February 2023 [6]. Water still keeps surprises for us!

FIGURE 2. An iceberg is a big chunk of ice floating freely on the sea. The mere fact that an iceberg floats on water is a reminder of H2O surprising properties.

This paper suggests experiments that may be performed in not very advanced labs and by beginning students of engineering or science to exhibit some of the curious properties of ice and describe some of its light polarizing properties. We should also note that, except for mercury (chemical symbol Hg), water has the highest surface tension for all common liquids. Water surface tension is about 72 mN/m at room temperature which is one of the highest surface tensions known for a liquid. Another liquid having higher surface tension is mercury, a liquid metal with a surface tension of almost 500 mN/m. Water's high surface tension is due to the strong hydrogen bonding between water molecules [1, 7] whereas mercury's is due to the metallic bonding. The activities discussed in this work may be done as at-home experiments as could be still needed in these pandemic times [12].

II. CURIOUS FEATURES OF ICE

A. The volume of water increases as it becomes ice

In this section we discuss an anomalous property occurring during H_2O congelation: when the temperature of a water sample is reduced below its freezing point its volume grows, as some of us have witnessed if we had forgotten a glass bottle containing water in the freezer. The bottle explodes as water becomes ice because, in the ice crystals, the hydrogen bonds that link oxygen and hydrogen together are stacked one on top of the other with their arms and legs outstretched. This provides more space between the molecules in the crystal structure of ice than between the molecules in liquid water. As a result, ice is less dense than water. If we want to experimentally prove this —but avoiding the dangerous mess with the glass shards— is better to use a PET bottle with a plastic screw top instead of a glass one. Upon congealing, the frozen water will cause a strong deformation of the plastic bottle but will not break it. Note that to achieve deformations similar to those displayed by the PET bottle the air pressure inside it should be raised above 300 kPa or roughly three times the standard atmospheric pressure.

To measure the volume expansion during solidification you may use a plastic 20 ml syringe (without the needle) where you may put a small quantity of water, let us say 10 ml, and then left the syringe overnight in the freezer. As syringes are made of strong plastic there is little chance of breaking it, the expansion would instead push the piston. Noting the piston change in position is all that is needed to determine an approximate value of the coefficient of thermal expansion, β_V, that may be calculated as:

$$\beta_V = \frac{1}{V_i}\left(\frac{V_f - V_i}{T_f - T_i}\right), \quad (1)$$

where V_i is the volume at the beginning of the process while V_f is the corresponding volume at the end [8]. The process investigated is a contraction, not a dilatation thus the coefficient of thermal expansion β_V obtained is a negative number. Liquid water both expands and becomes more compressible when its temperature diminishes and it gets less viscous when compressed. We pinpoint that expression above is just an approximation since it assumes that β_V is a constant independent of T and that $\Delta V = V_f - V_i$ is small compared with V_i. The value (at one significant figure) obtained by our students for this coefficient was roughly -0.9×10^{-5} K^{-1} with great dispersion, whereas the value reported in The Engineering Toolbox (www.engineeringtoolbox.com) is -0.7×10^{-4} K^{-1}. This gives an error of about 30 % in the student's determination of β_V which is reasonable given the roughness of the method used for evaluating it

FIGURE 3. Michael Faraday (22 September 1791 — 25 August 1867), one of the greatest scientists that ever lived. Besides studying regelation he invented the field concept as an insightful alternative to forces acting at a distance in electromagnetic theory.

B. Regelation

Regelation is the name given to the fact that ice melts under pressure and refreezes again when the pressure is reduced. This phenomenon was discovered by Michael Faraday in 1842, see Figure (3). It may be easily demonstrated by looping a not-very-thick metallic wire [13] around a block of ice with a weight hanging at each one of its extremes. If you wait a certain time (roughly 30 minutes) you surely observe how the wire travels across the whole thickness of the ice slab—traversing through it in its totality— without splitting it in two. At the end of the process, the wire will be below the ice slab while the slab itself will remain unsplitted. The explanation of the phenomenon is rather direct, the pressure exerted on the slab by the wire lower the temperature of fusion thus ice slowly melts around the point of contact allowing it to go through the ice, while it remains intact even after the wire passes through it completely since the cut made is quickly refilled with water and promptly refreezed [8]. The phenomenon works best with high thermal conductivity copper wires, for example, since the latent heat of fusion needs to be transferred to the lower side supplying the energy needed for the melting [1].

Regelation is what allows ice skaters to glide on an ice surface and also explains why ice skates need a sharp metal blade, which increases the pressure at the line of contact, for proper skating. It is also due to regelation that skiing on snow is possible. Water is formed due to the increase of pressure under the skis and it plays the role of lubricant. It is to be noted that a consequence of these facts is that ice skating is practically impossible at temperatures below −35◦ C [1].

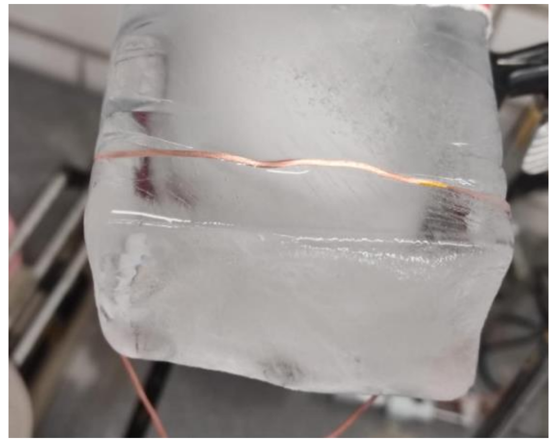

FIGURE 4. Our experimental set-up for observing regelation in a University teaching lab. The wire looping the block of ice is recommended to be made of copper due to its high thermal conductivity.

C. Polarization of light and ice crystals

Putting a not-so-thick slab of ice between crossed linear polarizers and illuminating it with a beam of linearly polarized light we find that the slab is able to rotate the plane of polarization of the incoming light. If the slab has irregularities it may show a nice image of many small ice crystals some of them darker than others. However, a more colorful image may be obtained using a thinner slab. Here, the students may investigate if small quantities of other substances may create crystals with a variety of colors. Another possibility for investigation is if ice produced by supercooled water [2] has different polarization properties than crystalline ice. Ice is birefringent, thus each color's vertical and horizontal components travel through the ice at slightly different speeds, changing their relative phase.

The emerging light signal from a particular region of the ice still has all the colors but each color now has a different phase relationship between its horizontal and vertical components. Thus only one particular color, the one whose components combine so that it can make it through the analyzing filter on the front side of the polarizing filter, is the color that dominates the image at that location. The resulting rainbow hint at the competing stresses as the ice crystals were forming slightly different speeds, changing their relative phase [7, 9, 10].

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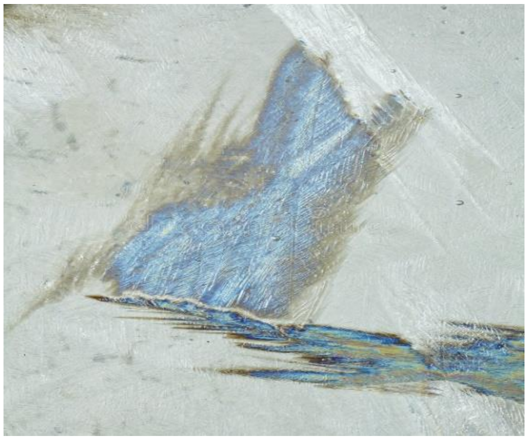

FIGURE 5. Colors in a not-so-thick slab of ice illuminated with linearly polarized light and observed under crossed linear polarizers.

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Crystalline ice is a doubly refracting hexagonal crystal with a long axis and three identical, short ones. Is the existence of this anisotropy in ice that causes its multi-facetious color display under polarized light which, as it must be clear, depends both on its thickness and on its orientation within the sample and concerning the imaging setup? The orientation of the long axis in a crystal of ice concerning the surface depends on its growth conditions. Spontaneous nucleation under very low temperatures yields sheets of large crystals with a vertically oriented long axis, while heterogeneous nucleation involving the seeding of cold water by dust or precipitation yields columns of crystals with a horizontally oriented long axis; ice formed by the accumulation of diminutive ice crystals on ice slabs are distinguished by the apparition of small crystals.

D. A challenge

According to anecdotal reports known to us, you can make what is called an ice shell by putting a balloon filled with water in the freezer for 5 or 6 hours. At the end of this period, you are supposedly not going to find an ice-filled balloon but just a balloon that has only a layer of ice surrounding a liquid water interior—what we may call an ice shell.

The challenge is, first and foremost, to discover if the phenomenon does occur, and, if it does, to explain how can it be possible that the H2O inside the ice shell could remain liquid. For a basic explanation take a look at the following footnote [14].

III. CONCLUSIONS

We have explained how water ice has different properties from the solid phase of the majority of substances. These differences just contribute to our conception of water (H2O) as a unique substance. We may assert that water has surprising properties, making it an extremely valuable material for its use in physics laboratories. We pinpoint again that water is an interesting material both in its solid (ice) as well as in its liquid and gaseous phases. To emphasize its amazing properties, we mention that the type of ice existing on Earth is crystalline, but in extraterrestrial regions there exist two more types of ice both of them amorphous. A third form of amorphous ice, the medium density amorphous ice or MDA, has been recently discovered —almost as an afterthought— with a density nearly equal to water's, as was announced in the February 3, 2023 issue of Science [6]. This new form of amorphous ice has a density very nearly equal to that of pure water. So if you drop a small piece of this amorphous ice in a flask with water it would bob around, floating undisturbed at the deepness of your choice. As to the coefficient of thermal expansion, β_V, the value our students were able to obtain is good (relative error compared to the value given in tables 30 %) given the crudity of the employed method.

The phenomena discussed in this work try to make evident the curious properties ice can manifest. As in a previous paper [2], among the objectives of this work is to show the easiness with which we can perform experimental activities with unexpected results even in undergraduate labs. Such experimental outcomes should help science or engineering students to appreciate the value of the experimental approach to the study of nature.

To finalize, we find it appropriate to repeat Confucius's dictum, wisdom delights in water [11] to which we add even in its solid state and act in consequence.

ACKNOWLEDGEMENTS

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[12] We are referring to the COVID-19 pandemic of the years 2020–2023.
[13] Cooper wire is excellent for this purpose given its high thermal conductivity.
[14] An explanation for the phenomenon with the ice shell is as follows: water should attain a temperature slightly below the melting point to begin freezing. But, when this occurs, it has still to transfer heat to its surroundings quickly cooling in this way to 0° C. A thin layer of ice is therefore formed close to the internal surface of the balloon and ice has lower thermal conductivity than water. Heat can then only be extracted from the water inside through the ice layer, thus the ice shell easily forms. For comparison, we mention that ice thermal conductivity is just 0.56 W m^{-1} K^{-1} whereas water's is 2.2 W $m^{-1}\cdot$ K^{-1} roughly 4 times that of ice.