Berlioz and the freezing of boiling water

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Abstract

This article tries to link art and science in proposing the analysis of a text written by Berlioz in his memoirs. His text deals with the cooling of water under vacuum and its spectacular transformation into ice. We provide information allowing this experiment to be reproduced with students. We also focus on the way Berlioz, who is not a scientist, describes the experiment in terms of relationships between facts and models. To situate Berlioz's knowledge in the context of the 19th century, notion from history of science are also provided.

Key words

History/philosophy, physical chemistry, High School, water, thermodynamics, vacuum.

I. Introduction

Most chemists probably do not see literature or art as having a role in chemical education, although a few attempts have been described. Nevertheless, significant contributions have been proposed and tried out with students. For example, chemistry teachers have proposed the activity of writing poems about chemistry to their students with a pedagogical objective [1]. This is a long process as students are not accustomed to this idea. However, providing already-written poems to work on allows it to become a profitable activity. Bridging the gap between science and art has also been done by writing theatre plays in a collaboration between a writer (Carl Djerassi) and a chemist (Roald Hoffmann) [2]. Professional actors performed *Oxygen* in a world premiere in San Diego in 2001. This play deals with the discovery of the eponymous gas and the ever-present question of who deserves to be honored after an important discovery. The argument of the play opposes Scheele who made oxygen for the first time without publishing his discovery; Priestly who published it, but within the unproductive framework of the phlogiston theory; and Lavoisier who interpreted the production of oxygen in his revolutionary theory. Other connections are possible, for example by recalling the work of a famous Russian composer such as Borodine (1833 – 1887) [3, 4] the more contemporary American musician Lejaren A. Miller, Jr. (1924-1994) [5] or the Czech Chemist-Composer-Lexicographer Emil Votoček (1872–1950) [6].

As a chemistry teacher, one of us suffered from a lack of pertinent literary texts to work on with students. This article provides us with a possible text, its analysis, its relation to a laboratory experiment and suggestions to use it with a class. Although this text was written by a 19^{th} century non-scientist, Hector Berlioz, the experiment described is worth being reproduced. We will analyze it with scientific, historical and literary viewpoints. We will also compare Berlioz's description of the experiment with the way students are expected to report their data.

II. Science in Berlioz's Memoirs

Hector Berlioz's reputation is certainly established as a musician, although he was an outstanding writer, mainly known as a chronicler. His memoirs [7, 8], from which the present article shows a piece dealing with science, is certainly his major production as a writer, and several comprehensive English translations are available [9, 10]. In this article, we present quotations from either one or the other translators, preferring the one that is as close as possible to Berlioz's words. Berlioz's French text and both original translations are provided online(W). Several thousands of letters written by Berlioz in his lifetime have also been compiled [11].

The relationship between literature and science appears in Berlioz's *Memoirs*. In fact, in the 40^{th} chapter, entitled "Varieties of spleen – isolation", the writer describes a physical chemistry experiment. This happens as he mentions his stay at the Villa Medicis, after winning the « Prix de Rome » in 1830. This period in his life was painful, for Berlioz felt far away from Paris (the most important place in Europe for composers at the time) and suffered from his rupture with Camille Moke. So in this chapter, Berlioz describes what he calls a "miserable disease (mental, nervous, imaginary)". In reality, he depicts some forms of what French Romantics called "spleen" in the late eighteenth and nineteenth centuries. This word refers to a state of pensive sadness or melancholy, but it seems as if Berlioz found this term too vague, and wanted us to understand the specific expressions of *his* "spleen": *a mix of boredom, despair, unsatisfied desire, isolation and some kind of rapture which overwhelms him*. All these elements appear during fits of melancholy, which are accurately described (note 1):

"*And the paroxysm possessed me in full force. I suffered agonies, and, casting myself down on the ground, groaned and clutched the earth wildly, tore up the grass and the innocent daisies, with their upturned wondering eyes, in my passionate struggles against the horrible feeling of the loneliness and sense of absence.*

I do not know how to convey any adequate expression of this unutterable anguish. A physical experiment alone can give any idea of it. If you put a cup of water and a cup of sulfuric acid side by side under the bell jar of an air-pump, and withdraw the air, you will see the water becoming troubled, coming to a boil, and evaporating. The sulfuric acid absorbs this water vapor as it is given off, and, owing to the capacity of steam molecules to carry off large quantities of caloric, the water which is left at the bottom of the cup soon freezes into a little lump of ice." [10]

III.Science knowledge in Berlioz's time

Understanding Berlioz's words requires situating the knowledge of this time period. This section deals with what was known in the 19^{th} century as concerns the concepts of vacuum, molecule and heat [caloric].

Otto von Guericke's 1650 success in producing a vacuum (improved by Boyle and Papin in 1660) paved the way to the discovery of the relationship between pressure and the boiling temperature of water. The behavior of different types of matter under partial vacuum was first described by Boyle (12) and can also be found in the Diderot and D'Alembert *Encyclopedia* (1750 – 1780) [13, 14].

Demonstrations of vacuum experiments were common in the 18th century as Joseph Wright of Derby testifies with his 1768 painting: *Experiment on a Bird in the Air Pump* (Figure 1). In this painting, one can see a "natural philosopher" reproducing several of the experiments published by Boyle the previous century [12]). These forerunners of modern scientists used to spend their time traveling and entertaining people with their vacuum pumps. On the table, the painter has depicted a handle operated double barrel pump. Vacuum can be built up in the glass globe linked to the pump by metallic tubing.

Figure 1 – Joseph Wright of Derby's painting: *Experiment on a Bird in the Air Pump*

Above the globe, an inlet valve held by the demonstrator's left hand can be turned on to let air into the globe. Several other accessories are visible on the table: the famous Magdeburg hemispheres to demonstrate the power of atmospheric pressure, a candle to show the effect of vacuum on combustion, and a water jar, probably to be frozen under vacuum as in Berlioz's experiment. Unfortunately for modern sensibilities, those natural philosophers also found it interesting to demonstrate that birds cannot fly in vacuum. The cruelty of these experiments has been depicted with genius by Wright

Berlioz's father was a physician, and Berlioz himself started to study medicine under duress in 1822. Before he rejected those studies to become a composer, he enjoyed Thénard's and Gay Lussac's lectures (note 2): *"Other powerful compensations were soon added. The lectures given by Thénard and Gay-Lussac at the Jardin des Plantes, the one in chemistry and the other in Physics, and the literature course in which Andrieux's sly humor could hold a class enthralled, all delighted me; I followed them with growing interest"* [1].[9]

Gay-Lussac's biography offers details that allow us to entertain the idea that he might have used such an experiment in his teaching. As a case in point, Gay-Lussac had previously proposed a volume-temperature relationship for real gas at constant pressure. He may also have used a double barrel vacuum pump such as the one in the diagram (figure 2). This diagram was drawn in 1832, a few years after Berlioz was at the university. In addition, Gay-Lussac also improved the industrial production of sulfuric acid. He therefore knew its properties and had an easy access to this substance. Gay-Lussac might also demonstrate the bird in vacuum experiment to Berlioz as the latter mention it in one of these letters to the French writer Victor Hugo.

The concept of caloric used by Berlioz to interpret the boiling water experiment was introduced by Lavoisier in 1783 [17, 18] to interpret the heat exchanged during chemical reactions, after he had proved the incoherence of the phlogiston theory. Within the latter theory, the phlogiston is a fluid (with a mass) that is exchanged as heat between chemical reagents. However, Lavoisier proved conclusively that oxygen (with a mass) was exchanged together with the caloric (heat), the latter having no mass.

I am in Rome, exiled from the musical world for two years […]. I am dying of suffocation, like a bird in a pneumatic jar. I am dying from the lack of music, poetry, theatres, effervescence, and all … [16].

Berlioz also used the concept of "molecule," with a meaning different from its modern acceptation. Long before Dalton proposed the modern notion of the atom (1803) and long before the Karlsruhe meeting where the modern notion of molecule was discussed (1860), the French philosopher René Descartes (1620) coined the notion of *molecule* to name an "extremely minute particle." Lavoiser used the same word when he (19, 20) wrote: *"[...] a small molecule of phosphorous weighing less than a tenth of a grain (1 grain ≈ 50 mg)"*. Therefore, what Berlioz named "molecules of steam", were probably small quantities of water, tiny droplets, possibly invisible, but not the water molecules we know.

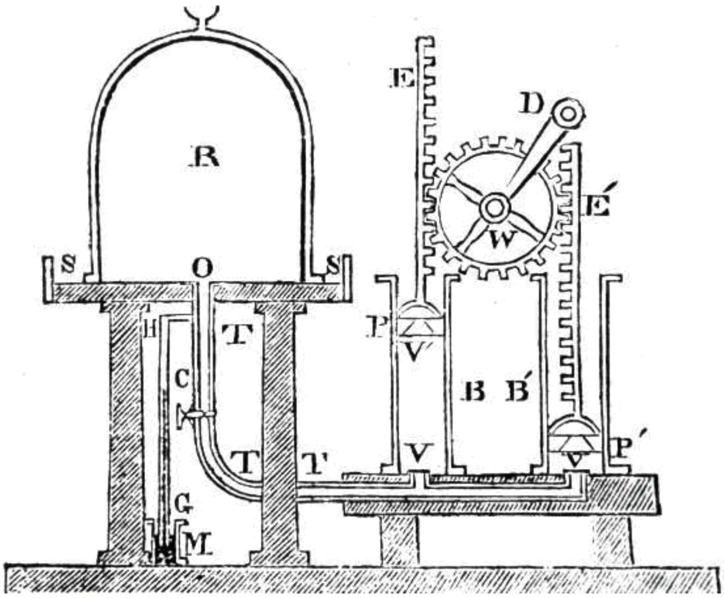

Figure 2 – Diagram of a vacuum pump in 1832

IV. Analysis of Berlioz's words

The words students use to describe experiments and interpret them are often inappropriate. However, Berlioz's words are surprisingly correct, as long as they are considered in the 19th century context. Our analysis of Berlioz's words can thus help students to understand how the report of data can be used to defend an idea.

In his chapter on *spleen*, Berlioz uses his scientific knowledge to make his state of mind more concrete for the reader. He creates an analogy between his emotional state and a physical chemistry experiment, to better describe the unutterable anguish he felt. It is worth noting that in teaching, analogy is frequently used to make science understandable, whereas what Berlioz did is exactly the opposite. We have found interesting to compare the way this musician describes and interprets the experiment to what is required from students who are reporting an experiment.

The composer starts by describing a personal experience. He tells of his suffering. He recounts how he cast himself to the ground and recalls seemingly inconsequential details such as tearing up grass and daisies. But this literary description is not satisfying enough for Berlioz: language fails to depict his state of mind accurately. In fact, the writer wants us not only to know about the psychological aspects of his condition, but also about the physical aspects of it. He wants the reader to understand him from the inside. That is why Berlioz chooses to use a scientific analogy. Berlioz proceeds methodically; first, he precisely lists the objects involved in the experiment (a cup of water, a cup of sulfuric acid, etc.) and the events he observes (set up of the cups, exhaust of the air, water becoming trouble, boiling, and finally evaporating). Then, he suggests an interpretation of the phenomenon he observed (absorption of the vapor by sulfuric acid, the property possessed by the steam of carrying off the caloric). Debating this highly scientific method (first: observation of the objects and events, then: interpretation) with students is a possible way to have them using it in their own reports.

After this detour, the writer is able to interpret what happens during his fits of melancholy (note

3): “*The same sort of thing happens when I become possessed by this feeling of loneliness and absence. There is a vacuum all round my throbbing breast, and I feel as if under the influence of some irresistible power my heart were evaporating and tending towards dissolution. My skin begins to pain and burn; I get hot all over; I feel an irresistible desire to call my friends and even strangers to help me, to protect me, to console me and preserve me from destruction, and to restrain the life which is being drawn out of me and scattered to the four corners of the globe. […] This state is not yet spleen but leads it. It is the boiling, the evaporation of the heart, the senses, the brain and the nervous fluid. Spleen is the freezing of all that, it is the lump of ice.*” [10, p. 163-164]

When he concludes this reflection about his “spleen”, Berlioz uses vocabulary derived from the vacuum experiment. For example, the expansion of his heart under a suction force corresponds to the liquid water becoming molecules of steam under the effect of the pump. Berlioz maintains the metaphor with the evaporation / dissolution of his heart which refers to the boiling of water and its absorption by the sulfuric acid. Finally, the notion of Berlioz’s overheating can be linked with the large quantities of caloric that are carried off by the molecules of steam.

The analysis of Berlioz’s description of “spleen” should be given as a model to students who confuse observation and inference, or who believe that using a metaphor is an explanation in itself. Berlioz not only clearly gives the facts, but also interprets them, and finally links both the source and the target of the metaphor in order to provide a comprehensive explanation of his “spleen”.

V. The experiment

Reading Berlioz’s words can motivate students to want to see a reenaction of the low pressure experiment. The experiment can be performed either under a vacuum bell as in the *Memoirs*, or under the simplified conditions described below. It is essential to use a vacuum pump, as neither a water aspirator nor a solvent evaporator pump can freeze water, even though both can create enough vacuum to boil and cool water. However, obtaining ice does add a spectacular effect that should not be missed!

Our efforts never led to freezing water under static vacuum. The evaporation process is far too slow. Even with appropriate insulation, a natural tendency toward warming overcomes the cooling produce by the vacuum. In addition, insulating the experiment makes it impossible to observe the boiling and the freezing of the water. On the other hand, dynamic vacuum does not require sulfuric acid. Having a cup of acid corresponds to the Berlioz description, but increases the risk and the waste of such a demonstration. Therefore, a conflict exists between reproducing the historical experiment and proposing an acceptable modern experimental setup. We describe below an experiment that combines a spectacular demonstration with a fruitful data collection procedure.

Experimental – 50 mL of distilled water and a magnetic stir bar are introduced in a 100 mL round-bottom flask with a ground glass joint neck. An adaptor with a valve is connected to a pump via a cold trap. The trap protects the pump but does not intervene in the water cooling process. The ground glass joint is greased.

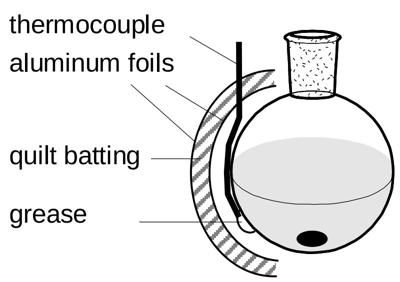

Figure 3 – Set up for temperature measurement

A thermocouple T_1 is taped outside the flask, below the water level. The best thermal contact between the tip of the thermocouple and the glass is obtained with a drop of grease. Aluminum foil is wrapped around half of the flask. Hence, observation of the water is still possible. Then a piece of quilt batting is taped above the aluminum, and another piece of aluminum foil is taped above the batting (figure 3).

A second identical flask full of ice and water is equipped with an identical thermocouple T_2 and similarly insulated. The difference Δ_t between the temperature θ_1 and θ_2 of thermocouples T_1 and T_2 is recorded every 15 s to a precision of 0.1°C.

Results – As soon as vacuum is applied, water starts boiling as in Berlioz's experiment. The difference Δ_t decreases as in figure 4. Negative temperatures are observed for water after 8 minutes and become as low as –3°C. All of a sudden at 11 min., a lot of ice forms and the temperature climbs up to –0.3°C and remains stable. During the decrease of temperature, bubbles are still visible but become progressively smaller and less frequent. Once Δ_t has reached –0.3°C, mercury thermometers plunged into both flasks do indicate 0°C, which allows the precision of the measures to be evaluated. About 3 g of water have evaporated.

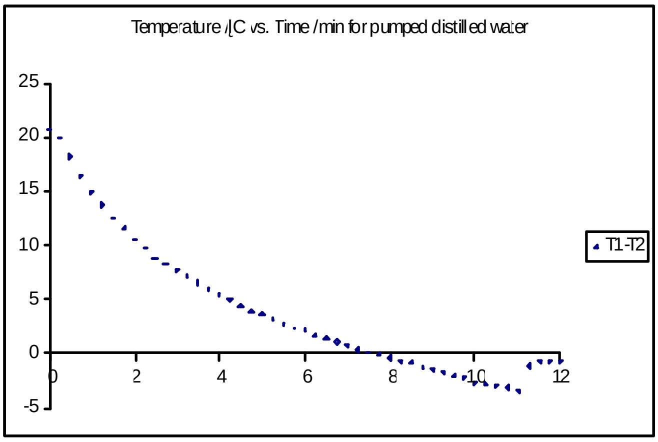

Figure 4 – Evolution of the temperature of the pumped water ($\Delta_t = f(t)$)

Merits and limits of the setup – The measurement of the relative temperature θ_1–θ_2 was found to be the most precise and reproducible set up, as long as the insulation was the same for the air pumped and the reference flasks. For example, based on the type of insulation used, θ_1 and θ_2 is as much as 1 to 2.5°C above its real value for both temperature gauges. The experiment therefore demonstrates a more spectacular supercooling. In addition to this, the final temperature of the ice is close to 0°C which is more credible for students.

The temperature gauge was found to be "late" by 15 to 30 s, for it takes time to transfer heat through the glass of the flask. This effect is visible on the curve (figure 2), at the beginning of experiment and directly after freezing.

Discussion

Two points can be useful for teaching the notions related to this experiment, one historical and one pedagogical.

The result of the experiment agrees with Berlioz's *Memoirs* although he may have had to wait for more than a dozen minutes to observe ice formation, due to the poorer vacuum pumping that he probably encountered. Indeed, as described in the Diderot and d'Alembert *Encyclopedia*, joints for vacuum experiments were made of wet leather. In addition, since pumping resulted from muscular efforts, as turning the handle in figure 2 and 3, it was likely to be less dynamic and regular than modern electric pump.

It can be interesting to discuss boiling under a vacuum either from a macroscopic viewpoint - the entire phase diagram of water - or from a microscopic viewpoint - the explanation of what happens in the gas phase. If the level of students is high enough, they can also calculate how much water must be evaporated in order to freeze. This can be calculated from the enthalpy of boiling water (2.26 kJ.g^{-1}) and its heat capacity (4.185 J.g^{-1}); calc. 2.3 g; obs. 2.9 g.

VI. Conclusion

The connection between literature and science proposed in this article allows many aspects of science to be presented to students. Based on texts written by a famous writer, this article shows how students' curiosity can be awakened. The analysis of the water under vacuum experiment is interesting as it involves basic thermodynamics that is never easy to teach and to learn. Berlioz use of vacuum as a metaphor for 'spleen' is also worth being evoked as an example of data reporting. In addition, using a technical approach within the context of the history of science is fascinating. Working with vacuum is commonplace nowadays, but understanding how it was obtained without electricity and without high quality oil or technology demystifies our current pumping devices. Last but not least, this article recalls many fundamental discoveries such as: what is air and how can it be removed; what is in air and why under partial vacuum do birds not fly but die; or how water can boil without being heated and freeze without being cooled. All these questions were posed and resolved by scientists with almost no theoretical background and fascinated their contemporaries such as the well-known Berlioz or the anonymous characters depicted by Wright. Couldn't these ideas help to fascinate our students?

Acknowledgements

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Notes

1. We have modified Holmes' translation when it was not close enough to the following Berlioz's text: « *Et l'accès se déclara dans toute sa force, et je souffris affreusement, et je me couchai à terre, gémissant, étendant mes bras douloureux, arrachant convulsivement des poignées d'herbe et d'innocentes pâquerettes qui ouvraient en vain leurs grands yeux étonnés, luttant contre l'absence, contre l'horrible isolement.*

Je ne sais comment donner une idée de ce mal inexprimable. Une expérience de physique pourrait seule, je crois, en offrir la ressemblance. C'est celle-ci : quand on place sous une cloche de verre adaptée à une machine pneumatique une coupe remplie d'eau à côté d'une autre coupe contenant de l'acide sulfurique, au moment où la pompe aspirante fait le vide sous la cloche, on voit l'eau s'agiter, entrer en ébullition, s'évaporer. L'acide sulfurique absorbe cette vapeur d'eau au fur et à mesure qu'elle se dégage, et, par suite de la propriété qu'ont les molécules de vapeur d'emporter en s'exhalant une grande quantité de calorique, la portion d'eau qui reste au fond du vase ne tarde pas à se refroidir au point de produire un petit bloc de glace. »

2. Cairns' translation of the following Berlioz's text: « Bientôt les leçons de Thénard et de Gay-Lussac qui professaient, l'un la chimie, l'autre la physique au Jardin des Plantes, le cours de littérature, dans lequel Andrieux savait captiver son auditoire avec tant de malicieuse bonhomie, m'offrirent de puissantes compensations; je trouvai à les suivre un charme très-vif et toujours croissant. » (*Memoirs*, chap. 5).

3. Holmes' translation of the following Berlioz's text : *Eh bien! il en est à peu près ainsi quand cette idée d'isolement et ce sentiment de l'absence viennent me saisir. Le vide se fait autour de ma poitrine palpitante, et il semble alors que mon cœur, sous l'aspiration d'une force irrésistible, s'évapore et tend à se dissoudre par expansion. Puis, la peau de tout mon corps devient douloureuse et brûlante; je rougis de la tête aux pieds. Je suis tenté de crier, d'appeler à mon aide mes amis, les indifférents mêmes, pour me consoler, pour me garder, me défendre, m'empêcher d'être détruit, pour retenir ma*

vie qui s'en va aux quatre points cardinaux. […] Cet état n'est pas le spleen, mais il l'amène plus tard : c'est l'ébullition, l'évaporation du cœur, des sens, du cerveau, du fluide nerveux. Le spleen, c'est la congélation de tout cela, c'est le bloc de glace. »

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