Alexis Thèrése Petit

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Resumen

Petit fue un joven prodigio que hizo muchas contribuciones científicas en su corta vida y alcanzó las más altas posiciones académicas y científicas a una edad más temprana que todos sus colegas franceses. Petit fue un experimentador muy diestro, que con mucha paciencia y habilidad determinó (solo o con Dulong) el calor específico de sólidos, líquidos y gases, así como el poder refractante de una sustancia en sus varios estados de agregación. Sus extraordinarias habilidades matemáticas lo llevaron a desarrollar una ecuación que puede ser considerada como la primera versión de la que describe las pérdidas calóricas por radiación.

Abstract

Petit was a prodigy child that made many important contributions during his short life. He reached the highest academic and scientific standing at a younger age that all of his French colleagues. Petit was a skillful, thorough, and patient experimenter that carefully determined (alone or with Dulong) the specific heat of solids, liquids, and gases, as well as the refractive power of a substance in different stages of aggregation. His mathematical abilities lead him to state what should be considered the first version of the equation describing heat losses by radiation.

Chemists, physicist, and chemical engineers are familiar with Petit through Dulong-Petit's rule, a rule stating that atoms of all simple bodies have exactly the same capacity for heat. They are generally unaware that although he died very young he made substantial contributions in other areas such as determination of heat capacities, the refractive power of simple and composed substances, the conversion of kinetic energy to mechanical power, and many others done in collaboration with Pierre Louis Dulong (1785- 1838).

Here we describe his personal life and career, his scientific achievements and how these have influenced different scientific and engineering ideas and applications.

Life and career [Biot, 1821; Lemay and Oester, 1948; Fox, 1971]

Alexis Thèrése Petit was born at Vesoul, Department of the Haute-Saône, on October 2, 1791. Little is know about his childhood except that he was a very precocious boy [Lemay and Oester, 1948]. He went to school at *École Centrale de Besançon* and by the age of 10½ years he had already completed all the entrance requirements of the École Polytechnique. It was then that he came to the notice of Jean Nicolas Pierre Hachette (1769-1834), who invited him to a private school in Pairs run by teachers from the École and directed by Thurot. Here he received a more intensive training in mathematics and literary subjects while he filled in the time before reaching the statutory age for entry (16). He passed the entrance exam to the École with flying colors, ahead of all other candidates.

In 1809 Petit finished the two-year course at the École Polytechnique with extraordinary distinction, being placed *hors de ligne*, with the next student in the year designated *first.* Petit was probably the most gifted member of the new generation at least as far as traditional academic qualifications were concerned.

Petit received his doctorate in november 1811, his thesis was entitled Théorie *Mathématique de l'Action Capillaire* (Mathematical Theory of Capillary Action), a study of capillary action treated in the Laplacian manner and with full and respectful acknowledgment to Pierre-Simon Laplace (1749-1827) [Biot, 1821; Petit, 1813]. It is said that the examiners were amazed by the lucidity of his defense of the work. His presentation was memorable for its clear, elegant, and logical presentation. These qualities were the result of Petit's constant rehearsing of the factors that make for good lecturing and logical presentation. For him to know was to know how to express his thoughts.

After graduation from the École Polytechnique the École hired him first as *répétiteur de analyse* and then *répétiteur de physique.* At the same time he was also appointed professor of physics at the Lycée Bonaparte (which became Collége de Bourbon after the Restoration). In September 1814, at the age of twenty-three, he became *professeur adjoint* (associate professor), taking over all of Jean-Henri Hassenfratz's (1755-1827) duties in the course of physics. In October 1815 his position was confirmed and he was promoted to the rank of *professeur titulaire* (full professor of physics). In 1818 he was appointed member of the Societé Philomatique, the only academic distinction he would receive in his short life.

A few words about Hassenfratz are in place. In March 1794, after the Revolution, the *Comité d'Instruction Publique* (Committee for Public Education) adopted the idea of creating a school that would give a common formation to all civil and military engineers. The commission named for this

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purpose included famous scientists such as Gaspard Monge (1746-1818), Hassenfratz, Claude-Louis Berthollet (1748-1822), and Louis-Bernard Guyton de Morveau (1737-1816). The resulting school, École Polytechnique, opened its doors on September 29, 1795. Both Monge and Hassenfratz were heavily involved in politics, with the result that after the restoration of the Bourbons both would lose their appointments at the École. Fox [Fox, 1971] indicates that memories of Hassenfratz's earlier Jacobin associations and membership in Pairs Commune, may well have served to hasten his enforced retirement at this time, but it seems clear that in any case his replacement by a younger, more able man (Petit) was already long overdue. Thus the official reason for Hassenfratz's removal from office was given as "health and age" in a report by Étienne Pierre Durivau, the Director of Studies at the École.

During his studies at the École Petit took several of the courses dictated by Hachette and Monge, in particular those on physics and machines. Fox [Fox, 1971], who had the opportunity to read the notes of the course *Programmes d'un cours de physique*, dictated by Hachette[1], comments that the course was firmly based on Laplacian principles and this justifies Petit's Laplacian approach to the interpretation of the physical phenomena he investigated. Petit seems to have been particularly attached to Hachette and the course the latter taught on machines originated Petit's interest in this subject in later years.

The notes that Auguste Comte (1798-1857) took of the course of physics dictated by Petit show that Petit, the same as Hachette, was a fervent follower of Laplace's ideas. The notes show Petit to be a believer in the caloric theory, without any reference to the vibrational theory. Accounts of other physical phenomena, including both electricity and magnetism, were also given without question in terms of imponderable, elastic fluids and, although Petit did not cover light in these lectures, there seems no reason to doubt that here too he would have supported the material theory [Fox, 1971].

Petit's first important paper was a joint publication with his brother-in-law François Arago (1786-1853), where they reported their results about the variation of the refractive power of a substance in different states of aggregation [Arago and Petit, 1816]. Arago was also an alumnus of the École Polytechnique, where he was professor of analytical geometry.

Petit was particularly interested in the theory of machines, a course he was teaching at the École. He published his first results on the subject in 1818 "*D'Emploi du Principe des Forces Vives dans le Calcul des Machines*" [Petit, 1818].

Petit collaborated actively with Pierre Louis Dulong (1785-1838) in several research projects related to the theory of heat. Petit and Dulong compared the heat capacity of solids for caloric at different temperatures and found that it increased with an increase in temperature. They also studied the physical laws that govern the cooling of bodies in vacuum, air, or in another gas. Their first joint paper was related to the laws of expansion of solid, liquids, and elastic fluids and the measurement of temperature. Another paper, published in three parts [Dulong and Petit, 1818a,b,c] under the general title *Recherches Sur la Mesure des Temperatures et sur les Lois de la Communication de la Chaleur* (Studies on the Measurement of Temperatures and the Laws of the Communication of Heat) was acclaimed as a model of experimental method by such authorities as August Comte (1798-1857), Poisson, Gabriel Lamé (1795-1870), and William Whewell (1794-1866). In 1818, as a result of this work, Dulong and Petit were awarded the annual prize in physics, consisting of a gold medal valued at 3 000 francs.

Petit's rapid academic progress and his notable scientific achievements took their toll from his none too vigorous physique. In November 1814 he married the daughter of Carrier, a graduate of the *École des Ponts et des Chausses*; by this marriage he became Arago's brother in law. Six months after their marriage his wife became ill and died on April 5, 1817. This was too much for him. He suffered spells of physical and mental lassitude and exhibited the symptoms of premature senescence [Biot, 1821]. When Petit was no longer able to speak in public, Dulong and Arago took over his lectures so that he might continue to draw his salary.

Petit's tragic early death from tuberculosis on June 21, 1820, at the age of 29, was a serious blow to French science in general and to Dulong in particular. His grave in the Cimetière de l'Est (now Père Lachaise) is marked by a small monument inscribed

A Petit, Les élèves de l'École Polytechnique

It is of interest to mention that Dulong is also buried in the same cemetery,

There is a crater in the moon named in 1976 after Petit, it is five km in diameter and its coordinates are 2.3 N, 63.5 E.

Let us discuss in some details Petit's most important contributions.

Scientific Achievements

Here we will discuss some the researches done by Petit alone or with others. The ones done with Dulong have been described in a previous publication [Wisniak, 2001].

Capillary phenomena

The first research project of Petit was his doctorate thesis on the subject of capillarity, which he presented in 1811 [Petit, 1813]. In the opening statement Petit wrote that the different states of aggregation of a substance were the result of the forces of attraction among molecules and the expansive force of caloric. Refractive power and the elevation or descent of a liquid column in a capillary was one of the most striking manifestations of these forces. While the refractive power was the result of the attractive power of all the molecules of the substance, capillary phenomena was the result of the same forces, modified by the curvature of the free surface. Petit indicated that the purpose of his memoir was to determine the laws that described the elevation or descent of liquids in capillary spaces, using Laplace's theory [Laplace, 1806].

The fundamentals observations of Laplace on the subject of capillarity did not arise in connection with any abstract study of the geometry of the surfaces, his attempts to explain the phenomena were based on a static view of matter. Liquids at rest, whether in a capillary tube or not, were clearly in equilibrium, so that attractive forces in it must be balanced by repulsive forces. Laplace assumed that the repulsive forces could be replaced by an internal or intrinsic pressure that acted throughout an incompressible liquid and that the main curvature C of the free surface was proportional to the pressure change across the surface. Hence, by the laws of hydrostatics this curvature was given by $C = uRr/2s$ where u was the height of the meniscus, R the radius of the tube, and r and s the density and surface tension of the liquid, respectively.

Using elegant and very clear mathematical derivations Petit proceeded to analyze different capillary setups and reached the following conclusions:

(a) For tubes submerged in the same liquid, the elevation of the liquid was proportional to the perimeter of the base of the tube and inversely to the area of the same. For a cylindrical tube of constant section (radius R) this meant that the height was proportional to 2/R, (b) The elevation was independent of the angle of the tube with respect to the surface of the liquid, that is, the rise would be the same if the tube was vertical or inclined, (c) if two concentric tubes were immersed in a liquid, then the elevation was equivalent to that of a circular tube with a radius equal to the difference of the radii of the two tubes.

Petit extended the latter result to the case of two parallel planes (corresponding to each cylinder having infinite radius) and deduced that for this situation the rise would be inversely proportional to the distance between the two planes and equal to one-half the elevations that would take place if the two walls were built of one material or of the other. Finally, he concluded that the liquid would rise in the capillary if the force of attraction between the wall and the liquid was at least twice the force of attraction of the liquid with itself. If this was not so, the liquid would descend instead of rising. For the case where both forces were equal there would no change in the height of the liquid.

Petit went on to determine the shape of the surface of the liquid contained in a capillary and derived the differential equation that described the same. To do so he took first the same approach as Laplace, that is, a static force balance, and then made a balance of the forces acting on a molecule. Both approaches yielded the same differential equation that was impossible to integrate, except for particular situations. For example, if the capillary tube was a cylinder of constant section, then the free surface would correspond to a spherical shape. If a flat surface was submerged perpendicular to the surface of the free liquid then the horizontal place of the liquid was asymptotic to the surface of the elevated liquid.

Petit also derived the following equation relating the force that the capillary wall exerted on the liquid (H) and the force the liquid exerted on itself (H')

$$H = H' \cos^2 (\varpi/2) \tag{1}$$

where ϖ represented the angle between the free surface and the wetting fluid.

Interesting enough, Petit made no mention of a 1805 paper by Young [Young, 1805]; today a classical paper] supporting the view that in an equilibrium configuration in the absence of frictional resistance to motion along the boundary walls, the fluid met the bounding walls in a constant angle, depending only on the materials and in no way on the shape of the boundary of the surface.

Mention should also be made of Van der Waals' thermodynamic theory of capillarity, which in its basic form first appeared in 1893 [Van der Waals, 1894]. Van de Waals questioned the analysis of Laplace and Gauss who assumed the phenomena to be strictly in the domain of statics. According to Van der Waals the theory on the nature of heat assumed that the molecules were in rapid movement everywhere, not only in the bulk of the fluid but also in the boundary layer. Thus the phenomenon should be analyzed on the basis of thermodynamics using the concepts of dynamic equilibrium. Gibbs had previously analyzed the phenomenon assuming a sudden transition of the density of the fluid into that of the vapor, while Van der Waals claimed the existence of a gradual, though very rapid, change of density at the boundary layer between liquid and vapor. Eventually, experiments concerning the phenomena in near the critical temperature decided in favor of Van der Waals' ideas.

Theory of machines

For a better understanding of Petit's contribution in this area it is necessary to give some background information on the theories regarding the nature of heat and light, current at his time. Ideas like the mechanical equivalent of heat and conservation of energy (First law of thermodynamics) were yet to be defined and accepted. During the first quarter of the 18th century the caloric theory of heat was prevalent although under increasing attack. The question of what was the nature of heat was explained postulating the existence of a fluid, called *caloric*, whose only properties were heat and the ability to pass from one body into another by contact. Its concentration was measured by the thermometer and, as any fluid must, it flowed from higher to lower concentration. The great advantage of this concept of heat was that it permitted quantitative statements. Caloric was conceived as a type of rather all-pervading, imponderable, highly elastic fluid the particles of which were attracted by matter and repelled by one another. When two bodies at different temperature came into contact, it was supposed that caloric flowed from the hotter to the colder body until equilibrium was established in the two systems of material and caloric particles. When expansion resulted from heating, the expansion was attributed to the mutual repulsion of the caloric particles that entered the bodies when heated.

Similarly, as explained in the next section, light was assumed to be composed of particles (corpuscular theory).

Lazare Carnot (1753-1823) had written his book on rational mechanics, *Fundamental Principles of Equilibrium and Movement* (1803), where he discussed the efficiency of machines (pulleys and inclined planes), and the concepts of conservation of mechanical energy and the impossibility of perpetual motion were tacitly implied. Carnot selected for his analysis the conservation of live force (*vis viva* or, in today's terms, kinetic energy) and chose the product of force times distance (*moment of activity*) as the measure of the efficiency of a machine. Today we use the term *work*, proposed by Gustave Coriolis in 1829 [Gillispie, 1971].

A more sophisticated contribution to the literature of applied mechanics was a memoir of 1818 by Petit [Petit, 1818] where he discussed the use of the principle of live force for calculating the yield of an engine. As stated by Petit, live force furnished in any particular case the most natural evaluation both of the motor and the effect produced, so that the equation determining the relation between these two quantities would furnish the direct solution of the problem. Following Marie-Riche Prony (1755-1839) and Hachette, Petit considered that the fundamental function of a motor was to overcome resistance. During the initial stage the velocity of the motor increased from zero to a steady state, where movement was uniform. The applied forces produce results that are different depending on whether the engine is in equilibrium (rest) or in movement. In the equilibrium state it was necessary to consider only the intensity of the forces, while when in action, it was necessary to also consider the distance traveled. For example, when the particularly engine was a weight, then at equilibrium the effect was measured by the supported weight (Mg) when the engine was in movement the effect depended both on the weight and the height of its elevation (H). For a falling weight the velocity acquired (V) was given by $V^2 = 2gH$ and $MgH = MV^2/2$ (today these relations seem obvious, but they must be examined on the light of what was known then about energy conversion).

In an first example of the application of his reasoning Petit compared the live force that a given quantity of heat could produce, if it was employed to vaporize water or to heat a mass of air. In the first case one gram of water at 0°C was vaporized to produce steam at 100°C and atmospheric pressure. It would then occupy approximately 1,700 cm^3 [today, (22400/18)(273.15/273.15)] and exert a pressure equivalent to that of a column of water ten meters high. If it was then completely condensed, the live force developed would be capable of raising the weight of the 1,700 cm^3 to a height of 10 meters (or raising a mass of 17 kg one meter). The same amount of heat would heat 666 g of water through 1^0; or taking Bérard-Laroche value for the specific heat of air of 0.267, it would heat 2,500 g of air at a pressure equal to that of a column of water of 10 meters. The elasticity of the air would then increase by 0.0375 meters, and the ive force produced would lift to a height of 0.0375 meters the weight of a volume of water equal to that occupied by the 2,500 grams of air. That volume was 1,925 cubic decimeters, so that reducing everything to the same units, the live force was sufficient to raise a weight of 72.2 kg to a height of one meter-more than quadruple the live force in the first case.

Petit when on then to apply his ideas to the different types of water wheels operating in his time and a firing cannon. For the latter, he wrote that his equations allowed calculating the amount of charge (black powder) that would produce the maximum effect for a given bullet and recoil velocities. The live force produced by the combustion gases was equal to were M and u were the mass and velocity of the bullet, and M' the mass of the cannon.

Sadi Carnot (1796-1832) in his famous monograph [Carnot, 1824], discussed the possible superiority of air over steam engines and further on he cited Petit memoir after demonstrating that it makes no difference whether steam, air, or alcohol vapor be employed; what determines the motive power of a heat engine is temperature differential. Carnot attributed Petit's erroneous conclusion to an "imperfect method of considering the action of heat" [Carnot, 1824, footnote on page 44]. Contrary to Petit, Carnot thought of heat engines in terms of reversible processes instead of overcoming resistance.

In the same year Henry Navier (1785-1836) published a paper in which he stated that he wanted to give a more thorough historical note review of the history of the live-force principle on the theory of machines, in order to restate procedures and results that seemed to have been forgotten [Navier, 1818].

Refractive power

By the end of the 17th century Newton represented light as formed by very light particles emitted by the source and projected as a straight line through vacuum or air, at a very high speed. According to this emission theory reflection was explained by the elastic collision of the particles with the surface of a mirror while refraction was considered the result of an attracting force between a transparent material and light. To interpret refraction it was necessary to admit that the velocity of light was larger in water than in air. Experience did not support this supposition, the speed of light was less the larger the refractive index of the medium. At the beginning of the 18th century the materiality of light was in little doubt, the results were given in terms of the refractive power p and not the refractive index m. Laplace had retained Newton's concept of a refractive force, equal to (m^2-1), as the measure of the force of attraction that a body exerted on incident particles of light. The magnitude of this force was proportional to the increase in the square of the velocity of these particles, the increase was supposed to occur according to the standard laws of dynamics. The force was conceived as gravitational in nature and to vary proportionally to the density of the material. According to Newton and Laplace, the refractive power, i.e., the refracting force divided by the density, $(m^2 - 1)/r$, yielded the quantity more closely related to the true nature of the substance and characteristic of it alone. The interference phenomena discovered at the beginning of the 19th century also seemed unexplainable using a corpuscular theory.

Jean-Baptiste Biot (1774-1862) and Arago [Biot and Arago, 1806] maintained that the smallness of the light particles by comparison with the distance between the particles of ponderable matter would diminish any effect that a change in volume during a reaction might have. The refractive power of a compound would be determined in a wholly predictable way by those of its constituents, except in the cases were very great decreases in volume occurred. Biot and Arago also contended that since the attractive force exerted by any body on the particles of light was proportional to its mass, the respective reactants would contribute to the refractive power of the resulting compound in a manner proportional to the weights in which they combined, as well as their affinities for light. On this basis it was possible to establish a conservation law in which the refractive power of reactants and compound were closely related. The law was expressed as

$$p = \sum p_i m_i \tag{2}$$

where p_i and m_i were the refractive power and mass of component i.

The refractive power was the expression of the force per unit mass of matter taken that attracted the light molecules in the emitting system. At first view it seemed that this force ought to be constant for a given substance, independently of its state of aggregation because it was based on the same amount of mass, making it thus independent of the changes in density. It was already recognized that this constancy was not true in the case of elements that became part of a compound. Arago and Petit found that the constancy did not exist when the substance was heated and changed its state of aggregation. For example, and in general, the refractive power of a vapor was less than that of the liquid from which it originated. Unfortunately Arago and Petit did not report actual values or the method they used.

Arago and Petit concluded (a) that the emission system on which the calculation of the attraction was applied, did not have reality or, (b) that it was necessary to assume that a given mass did not exert always the same attraction. Nevertheless, it could be said (in spite of the little that was known about the intimate constitution of matter) that it was impossible to know how the attractive properties of material particles were modified by imponderable principles such as electricity and caloric. It was not known how these principles distributed themselves among the particles and were retained in different amounts by matter. Did they contribute by themselves to the refraction that proved the existence of the light rays?

When Arago and Petit [Arago and Petit, 1816] reexamined the matter in 1815, they could find no justification for a simple relationship as expressed by equation (2) and, largely as a result of this conclusion, they cast grave doubts on the corpuscular theory of light. Arago and Petit's were intent on verifying if the action of a given body upon light was always proportional to its density. Their experimental method consisted in the direct measurement of the deviation experienced by light experienced when crossing a prism, first empty and then filled with an elastic fluid. One of their most important results was that for a given elastic fluid the increase in velocity of light when passing from vacuum through the gas (or its diminution if the wave hypothesis was assumed) was proportional to the density variation.

In their publication Arago and Petit interpreted their experimental results on the refraction of gases in a way that appeared irreconcilable with the corpuscular theory of light. Afterwards, Petit openly rejected the corpuscular theory and become one of the earliest supporters of the wave theory, which had just been revived in France by Augustine-Jean Fresnel (1788-1827).

In a paper published after Petit's death, Dulong [Dulong, 1826] reasoned that since it was very easy to increase or decrease the density of a gas, it would be always possible to find a density where the speed of light would be the same as in air. Thus, knowing the densities of the gas and the air that satisfied this condition, a simple ratio would give the increase in velocity when both fluids had the same density. Dulong believed that in this manner it would be possible to verify Arago and Petit's conclusion regarding the relation between the speed of light and density, and also to determine if there was a relation between the refractive power of a compound and that of its constituents (similar to Dulong-Petit's law for the specific heats). To do so, Dulong took particular care in assuring the purity of the gases as well as eliminating the sources of error that were clearly present in the method used by Arago and Petit. He then went on to measure the diffractive power of twenty-two gases, some of them simple (chlorine, nitrogen, oxygen, hydrogen), and others compounded (like HCl, NH_3, CO, CO_2, NO, H_2S, C_2N_2, etc.), and concluded that there was no clear relation between the refractive power of a gas and its density, nor that of a compound gas and its constituent elements. The only generalization he found was that the refractive power was greater than the sum of the powers of the components when the compound was neutral or alkaline, and less when the compound was acid. He also indicated that the difference in the speed of light in different gases was dependent on *l'etat electrique* (electrical state) of the molecules in each substance.

A suitable closing remark on the theme of refraction relates to the prize proposed in 1817 by the Académie on the subject of diffraction of light. This prize was proposed at a crucial point on the arguments between the corpuscular and wave theory. The commission appointed by the Académie to judge the prize consisted of Biot, Arago, Laplace, Joseph-Louis Gay-Lussac (1778-1850), and Poisson. Laplace, Biot and Arago were committed to the corpuscular theory, Arago as sympathetic to a wave theory and Gay-Lussac the least committed. The fact that the prize was awarded to Fresnel in 1819 for work which contradicted the Laplacian view may be seen as a decline in Laplace's influence, the triumph of a superior theory, or a vindication of the standards of impartiality of the Academy [Crosland, 1978].

Conclusion

Petit was one of the most outstanding French scientists of his period. A precocious child of innate mathematical ability, he lived a very short life but made substantial contributions to many areas in the physical sciences. His most important achievements were obtained in collaboration with Dulong, where his mathematical skills were critical.

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Notes

1. One consequence of the freedom of the public to attend lectures of the Faculty was that a lecturer's course notes could be copied and sold.