Sadi Carnot: His Life and Achievements. Against the Historical Period—a Short Bibliographical Sketch

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Abstract: The life and work of Sadi Carnot are presented against the historical and political background existing in Europe before and after his birth. His achievements are analyzed and shown to reflect the influence that his family and education had on his development as a scientist, engineer, and military officer. In spite of his short life, the scientific consequences of his work have set the foundations of thermodynamics as we know it today.

Historical Background

The late eighteenth century, including the period of the French Revolution, is an outstanding example of the impact of science on society and the impact of social change upon the work and thought of scientists [1]. This great period of French scientific leadership overlaps the Age of the Revolution, and, in spite of the extreme events that took place in those days, French science emerged without much damage. At the dawn of the revolution politics had already infiltrated the scientific community. For example, on July 4, 1789, two weeks before the revolution, the members of the Academy of Sciences congratulated the astronomer Bailly on the manner in which he had performed as President of the National Assembly, and on the day following the taking of the Bastille, the academy held a regular meeting in the Louvre where technical papers were presented with no mention of the violent events taking place outside.

In order to understand the place and significance of science in the 18th century, it is important to compare the origin of two parallel institutions, the Royal Society in England and the Académie des Sciences in France, and learn about the structure of the latter. The Royal Society in London was founded in 1666 by the initiative of men of science who went to the crown and asked for a charter. The society received little more than moral support from the crown; its members had to pay dues to support the activities and had about 500 fellows by the end of the 18th century. In Paris it was otherwise. Jean Baptiste Colbert, comptroller general of finance of Louis XIV, aware of the foundation of the Royal Society, decided to formalize under royal patronage the periodic private meetings in Paris of a group of men of science that included Descartes, Pascal, and Gassendi. The Académie Royal de Sciences was given state support and in 1699 transferred to the Louvre. The adjective "royal" was added to confer to the institution the proper authority. The creation of the *académie* was a step towards materializing the dream of world domination, developing science as a tool for this purpose. The king becomes the motor and protector of the institution. A painting of Henri Testelin (1667, Museum of Versailles) entitled *Colbert Presenting the Members of the Académie to Louis XIV* gives a powerful picture of the alliance between scientists and royalty and the political power assigned to science. Not surprising then, the *académie* had the characteristics of the regime: monarchical, hierarchical, prescriptive, and privileged [2]. Twelve honorary members (*honoraires*) habitually chosen from the nobility and the magistracy formed its highest class, and their function was to be patrons and ornaments. They were the only ones eligible to be elected president and vice-president. Most of these notables seldom attended the sessions of the Academy and left the day-to-day management of the institution to the *pensionnaires*, eighteen in number. The latter were normally highly qualified scientists, elected for life and assigned a stipend. Although the academy functioned as a scientific body, it did also sponsor and supervise other activities. For example, in 1714 it instituted its annual prize competition, which usually addressed some object of public utility, like the problem of producing saltpeter, methods of lighting the streets (won by Antoine Lavoisier, 1765), friction in cordage (Charles Coulomb and Lazare Carnot), etc. The academy continued this practice of an annual prize until mid-1793 when it was abolished. The subject proposed for its last year of existence is particularly interesting: "The best theoretical analysis of the operation of steam engines with a discussion of methods for their improvement"; no prize was actually awarded although it was again announced in 1793 for the year 1795, no memoirs having been received. The problem was finally attacked for the first time a generation later by Sadi Carnot [2].

On August 8, 1793, the Jacobin Convention abolished the Académie de Sciences and other learned institutions, like École des Ponts et Chaussées, École des Mines, and Collège de France, because they represented an aristocratic remnant of the past, a "school of servility and falsehood," and were incompatible with the spirit of the new republic. The fall of these institutions was part of a chain reaction that resulted in the liquidation of the entire historical structure of French science [3]. Coulomb, Prieur de la Cote-d'Or, and Delambre were removed from the Committee of Public Safety because they were not worthy of confidence by their republican virtues and hatred of kings. Scientists like Bailly and Lavoisier were killed at the guillotine. After the downfall of Robespierre and the Jacobins, the new authorities amended the scientific damage by reviving some of the closed institutions (e.g., École des Mines, Collège de France) or creating new ones like École Normale, École Polytechnique, and Institut de France. The École Polytechnique counted among its staff men of the stature of Lagrange, Laplace, Monge, Berthollet, Carnot (Nicholas), and Prony.

Lazare Carnot

The father of Sadi Carnot, Lazare Carnot, deserves some special attention because his scientific and political activities were crucial in determining the destiny of his surviving two sons, Sadi and Hippolyte. Lazare Nicolas Marguerite Carnot was born on May 13, 1753, his father was a lawyer and a notary in the town of Nolay (Burgundy). Lazare Carnot was one of the most outstanding men of his generation. He was the man who appointed Napoleon to his first independent command, who organized the armies that conquered Europe, and who at Antwerp remained the only one of Napoleon's generals to be undefeated. In addition, he was an excellent mathematician and mechanical engineer and wrote several books on rational mechanics. In one them, *Fundamental Principles of Equilibrium and Movement* (1803), which discusses the efficiency of machines, the concepts of conservation of mechanical energy and the impossibility of perpetual motion are tacitly implied [4]. These conclusions seem trivial today but not in the days when the First Law of Thermodynamics was yet to be enunciated. L. 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. Hippolyte's memoirs attribute to Lazare Carnot and his countryman, Prieur de la Cote-d'Or, the conception of *École Polytechnique* founded by the Convention in 1795. The purpose of this new engineering school was to combine military and civil engineering into a single profession and to carry the momentum imparted to war production by the Committee of Public Safety into civil engineering.

In the early days of the revolution, Lazare Carnot was the leading member of the Directory of the French Republic, the executive power of the state. He was displaced from power in 1797 by a *coup d'etat* and sent to voluntary exile until 1800 when he returned to be appointed Minister of War by Napoleon. In 1815, during the Hundred Days, he served again under Napoleon, as his last Minister of the Interior. After the defeat of Napoleon, he went into exile, first to Warsaw and then to Magdeburg, until his death in 1823. The Third Republic consecrated Lazare Carnot as the "Organizer of Victory," and when his grandson, Sadi Carnot (son of Hippolyte), was President of the Republic, the ashes of Lazare were put in the Panthéon in Paris.

The Life of Sadi Carnot

Into this world in turmoil Nicolas Leonard Sadi Carnot was born on June 1, 1796, in the Palais du Petit-Luxembourg. He was the eldest son of Sophie Dupont de Moringhem and Lazare Nicolas Marguerite Carnot. His godfathers were Leonard Dupont (the grandfather) and Celestine Joseph Colignon. At the time of Sadi's birth his father was a member of the Directory, the French revolutionary government that lasted four years from November 1795 to November 1799. Birembaut [5] indicates that the election of the name Sadi comes from an episode in the military career of Lazare Carnot. In the year 1786, when Lazare was stationed as an engineer captain in Arras, he was admitted to the Rosati Society, whose founders in 1778 had adopted as its name the anagram of the province of Artois. In their reunions, the Rosati celebrated the beauty of roses with readings of light poetry followed by the tasting of good wine. In remembrance of those days Lazare picked for his first two sons (the first died at the age of 13 months) the name of the Persian poet and moralist Saadi Musharif ed Din (1184–1280); the French translation of his work *Gulistan ou l'Empire des Roses* had been recently reprinted in Paris.

Until the age of 16, Sadi Carnot was educated by his father, who taught him mathematics and science as well as languages and music. He was first sent to the Lycée Charlemagne in Paris to prepare him for the examinations for admittance to the École Polytechnique in Paris. In 1812 at age 16, the minimum age possible, Carnot entered the École Polytechnique, where Poisson, Ampère, and Arago were among his teachers. Chasles was in the same class as Carnot and their friendship lasted throughout Carnot's life [4]. Carnot graduated from the École Polytechnique in 1814 but, before he graduated, Carnot and other students from the École Polytechnique volunteered to fight (unsuccessfully) with Napoleon to defend Vincennes. After graduating, Carnot completed his training with two additional years of study of military engineering at the École du Génie at Metz.

The military career of Sadi Carnot was not easy; it reflected the political ups and downs of his father and caused him to be reserved, introverted, and almost taciturn. Things were particularly difficult when his father was in exile; he was transferred from place to place and given jobs of inspecting fortifications and drawing up plans and writing reports. Disturbed at his lack of promotion and continuous denial of a job that allowed him to make use of his training, in 1819 he sat and passed the examinations to join the recently formed General Staff Corps in Paris [4]. After a few months he took leave on half pay, but he remained on call for army duty. In 1827 the General Staff Corps in Paris was reorganized and he was recalled to full-time duties. He served for less than one year as a military engineer, being posted first to Lyon and then to Auxonne. Afterwards, he retired permanently from the army and returned to Paris. S. Carnot was strongly republican as his father had been and pleased with the direction taken by France after the July 1830 revolution. At that time he became interested in public life, particular in improving public education.

In addition to his formal education, Sadi Carnot attended courses at various institutions in Paris, including the Sorbonne and the Collège de France. He became interested in industrial problems; visited factories and workshops; studied the latest theories of political economy; and, in particular, began to study the theory of gases. Beyond this, his activity and ability embraced mathematics and the fine arts (his brother Hippolyte claimed that he was an excellent violin player). In June 1832 Sadi became ill and had not fully regained his health when the cholera epidemic of 1832 hit Paris. Although only 36 years of age, it is said he died within a day of contracting cholera. Almost every publication that gives details regarding the death of Carnot (August 24, 1832) quotes the version given by Hippolyte Carnot that he was a victim of the cholera plague that affected parts of France that year. Contrary to this version, Birembaut [5] claims that Sadi Carnot actually passed away in an insane asylum for rich people (maison de santé du Dr. Esquirol, located in Ivry-sur-Seine) and that Carnot's brother tried to hide this fact. The death notice supplied by Hippolyte

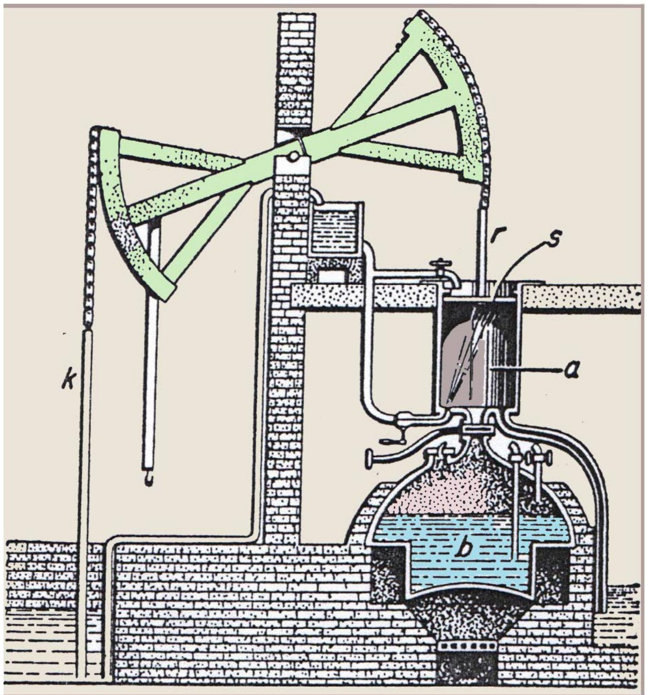

Figure 1. Schematic drawing of the Newcomen steam engine.

Carnot did not indicate the date or the place where the funeral would take place. In the same manner, the press news published on August 26, 1832, suggested that the cause of death was the cholera plague that afflicted Paris at the time. Birembaut claims that the probable cause of death was gastroenteritis and not cholera because, as the medical records show, the plague did not affect Ivry.

The Steam Engine

Before discussing the significance of Sadi Carnot's work, it is necessary to review the history of the steam engine and its development [6]. Thomas Savery patented the first commercially successful steam-driven device in 1698. His apparatus depended on the condensation of steam in a vessel, creating a partial vacuum into which water was forced by atmospheric pressure. The Savery apparatus was first used to pump out the flooded coalmines of Cornwall and eventually in other places of Europe having the same problem. The Savery development was another in a long series of machines in which steam acted either by its momentum alone or by exerting pressure on the surface of water. Denis Papin is supposed to have proposed a different scheme where steam acted against a piston that, in turn, activated a mechanism. The Papin engine provided the basis for the first commercially successful steam engine developed by Thomas Newcomen and patented in 1712 (Figure 1). Basically, in the Newcomen scheme steam was generated in a boiler, *b*, and admitted to a steam cylinder, *a*. A counterbalanced beam raised a piston, *s*, and rod, *r*, at one end and lowered a pump rod, *k*, at the other end. A water spray was injected *into* the steam cylinder, condensing the steam and creating a partial vacuum. In a further development, condensation was produced by water cooling the *outside* of the cylinder. The Newcomen engine was robust and unsophisticated, capable of 10 to 16 strokes per minute and was always used for pumping water. Further

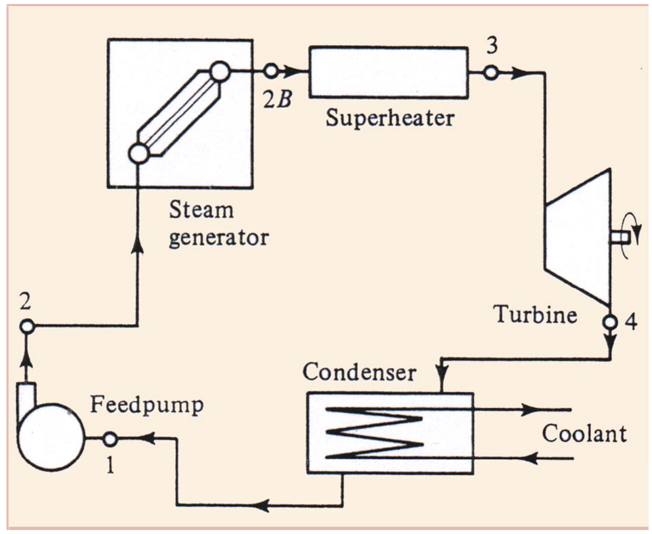

Figure 2. Flow sheet of a modern steam power plant.

improvements were minor until James Watt realized that the low efficiency of the available engines was due to the alternate cooling and heating of the cylinder walls. In the original Watt engine, patented in 1769, steam was introduced during the entire stroke of the piston and the action of the piston pulled the beam down. This first model consumed much less steam than the Newcomen engine, but still could be used only for pumping. In a second patent, granted to Watt in 1782, the steam was now admitted during part of the stroke, yielding more work per pound and permitting construction of a double-acting engine. In this engine the steam pushed alternately on both sides of the piston, permitting the production of work during each stroke, which doubles the output of a given size of engine. In this way, the early steam engines fulfilled one of the most pressing needs of British industry in the 18th century. Steam did not simply replace other sources of power; it transformed them. Figure 2 illustrates schematically a modern steam power plant.

A further improvement was the production of *rotary* motion, leading to the use of the steam engine as a prime mover in supplying power to a variety of machines for numerous applications. From their initial goal of pumping water from flooded mines, the applications of the steam engine went on to factories, textile workshops, metallurgy, and transportation (maritime and land-transport—the railways). The three basic engines described here can be best compared on the basis of kilograms of steam consumed per kilowatt-hour of work produced, about 180 for the Savery engine, 120 for the Newcomen engine, and 40 for the Watt engine. A more detailed analysis of the development of the steam engine shows that British engineers were way ahead of any other industrialized country in the conversion of heat energy, generated by burning coal, into mechanical energy. With time, steam became the characteristic and ubiquitous source of the British industrial revolution.

The Scientific Work of Carnot

According to Mendoza [7], the import into France of advanced engines after the war with Britain showed to Lazare and Sadi Carnot how far French design had fallen behind. It troubled Sadi, in particular, that the British had progressed so far through the genius of a few engineers who lacked formal scientific education. British engineers had also accumulated and published reliable data about the efficiency of many types of engines under actual running conditions and were able to compare the pros and cons of low- and high-pressure engines and of single-cylinder and multi-cylinder engines. It could very well be that this was the reason behind the decision of the Académie de Sciences for offering twice a prize for a theoretical essay on the analysis of the operation of steam engines with a discussion of methods for their improvement.

The importance that Sadi Carnot assigned to the supremacy of England in the use of the steam engine is already mentioned in the first pages of his monograph. Carnot writes: "To take away from England her steam engines would be to take away at the same time her coal and iron. It would be to dry up all her sources of wealth, to ruin all on which her prosperity depends, in short, to annhilate that colossal power."

Sadi Carnot visited his exiled father in 1821 in Magdeburg where the first steam engine had been installed already three years before. Lazare Carnot become very interested in the way of operation of the engine and had long discussions with his son on the theory of the same. The subject was so fascinating that Sadi Carnot left Magdeburg filled with enthusiasm to develop a theory for steam engines. According to E. Mendoza [7]: "The problem occupying Carnot was how to design good steam engines. Steam power already had many uses—draining water from mines, excavating ports and rivers, forging iron, grinding grain, and spinning and weaving cloth—*but it was inefficient*."

A manuscript discovered in 1966, but never published, describes the ideas that by 1822 had already crystallized in Carnot's analysis of the problem. A provocative question that can be raised (and left unanswered!) is how much of the analysis and consequences correspond to the ideas of Lazare alone, and how much to the actual contribution of Sadi. Anyhow, by that time Sadi Carnot was intent in calculating how much work can be obtained from one kilogram of steam, and he had already made use of an adiabatic stage followed by an isothermal one. Eventually Carnot summarized all his ideas in a 64-page brochure, *Reflexions sur la puissance motrice du feu et sur les machines propres a developper cette puissance*, published in 200 copies on June 12, 1824, and sold for three francs. It was published by the bookstore Bachelier (today the publishing house Gauthier-Villars, Paris). Apparently, hardly anyone bought the book; a few years later booksellers had never heard of it [7]. On July 26 of that year Pierre Girard, a prominent engineer, gave a long review of it to the Académie des Sciences in Paris. Among the academicians present were Arago, Fourier, Laplace, Ampère, Fresnel, Legendre, Poisson, Cauchy, Dulong, and Navier. Pierre Girard's review was very positive and was published in the Revue Encyclopédique, a literary journal devoted to criticism of the most noteworthy works produced in the sciences, industrial arts, literature, and the fine arts. Perhaps the problem with the review was that, although it stated the theorems and the conclusions of Carnot's paper in full, it did not comment on the highly original reasoning that Carnot had employed to achieve his results. As mentioned before, Carnot's little treatise went practically unnoticed. No one seems to have been impressed by it or attracted to it; however, ten years later (1834), Émile Clapeyron published a paper in which he took up some of Carnot's discussions, formulated them in analytical terms [8], and drew for the first time Carnot's cycle, using the Watt indicator diagram, already familiar to engineers. Clapeyron emphasized the fact, already contained in Carnot's work, that the efficiency of a reversible engine depends only on the temperatures of the source and sink. In the introduction to his paper Clapeyron says that one of the basic ideas contained in Carnot's work is that "it is impossible to create motive power or heat out of nothing," and that from here one can conclude, for example, the difference in the heat capacities of a gas is the same for all gases, under all conditions. Later on, Lord Kelvin found and read Carnot's book during a visit to Paris in 1844 and declared it "the most significant scientific work ever published." As a side note, we can mention that Clapeyron was also a graduate of the École Polytechnique and that at some time went to teach and do construction work in Russia. Upon his return to France, he engaged in railroad engineering and specialized in the design and construction of steam locomotives.

In the very first pages of his work, Sadi Carnot points out that, notwithstanding the work of all kinds done by steam engines and the satisfactory condition to which they have been brought, their theory is very little understood, and the attempts to improve them are directed almost by chance. He then proceeds to ask the critical question: is the motive power of steam unbounded and is there a limit to the development of a steam engine. He argues that the principle for converting heat to work must be analyzed independently of the mechanical structure of the machine and of the agent used to perform the transformation. He comes first to the conclusion that the production of power is not due to a consumption of heat (caloric), but to its transportation from a warm body to a cold body. A temperature difference must be present to produce power. After discussing the physical implications, he comes to two crucial conclusions: (a) that the maximum motive power resulting from the employment of steam is also the maximum of motive power realizable by any means whatsoever (in other words, the maximum efficiency of the engine is independent of the energy carrier) and, (b) that the amount of motive power is fixed only by the temperatures of the bodies between which the heat is finally transported. Interestingly enough, when Carnot develops the physical steps that the heat engine must go through, he does not close the cycle, the stages are steam generation in a boiler, its expansion in a cylinder provided with a piston, and, finally, its condensation by contact with a cold source. Using this reasoning he comes also to the conclusion that it is impossible to build a perpetual-motion engine for motive power, that the investment of heat will produce cooling, and that the difference in specific heat is the same for all gases. We see here that Carnot sets the concepts of reversibility and the principles for building heat pumps, a much later development.

The understanding of the principles of converting heat into power stated by Sadi Carnot had deep repercussions throughout industry. The steam engine increased, first, the need for coal, and later, that of petroleum. Larger availability of coal reflected in new technologies for producing iron and steel and in using coal for producing a large number of chemicals. Steam power was now used to drive the machines involved in the textile industry, to develop massive systems of transportation, and in other trades. On the other hand, Carnot's statement of the refrigeration cycle would eventually give rise to techniques that, already in the second half of the 19th century, made it possible to convey meat from Argentina and Australia to European markets and encourage the growth of dairy farming and market gardening.

Conclusion

The life and work of Sadi Carnot are presented against the historical and political background existing in Europe before and after his birth. His achievements reflect the influence that his father and his education had on his development as a scientist, engineer, and military officer. Carnot is the product of an epoch in which a very large number of the most renowned French scientists were alive and one of the most turbulent political events of history was taking place. The conclusions achieved by Carnot in his epoch-making book would eventually lead Clausius to the statement of the Second Law of thermodynamics and the definition of entropy [9].

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