Sadi Carnot and the Second Law of Thermodynamics

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The second law of thermodynamics is one of the enigmatic laws of physics. Sadi Carnot, a French engineer played an important role in its discovery in the 19th century. We recount here how he proposed the basic postulates of this law although he did not fully understand the first law of thermodynamics.

Introduction

A major revolution in physics in the 19th century was the discovery of the two laws of thermodynamics. Thermodynamics is a subject concerned with the interaction of energy with matter. The first law of thermodynamics states that energy can neither be created nor destroyed. The first law established the equivalence of heat and work interactions. The second law of thermodynamics states that it is not possible to convert all heat (or thermal energy) to work in a continuous process. The second law of thermodynamics, as stated above, has never been violated so far although the first law of thermodynamics has to be modified if there is a nuclear reaction. Most of you may be surprised to learn that the basic ideas related to the second law of thermodynamics were discovered earlier and the first law of thermodynamics was discovered much later! Sadi Carnot, who discovered the basic ideas that lead to the discovery of second law of thermodynamics, was a brilliant French military engineer. This genius lived for just 36 years and wrote only one important paper but this paper laid the foundation for one of the most enigmatic laws of physics. The second law of thermodynamics is both enigmatic and profound because it indicates the arrow of time.

Sadi Carnot, the eldest son of Lazare Carnot was born on 1st

June 1796 in Paris. Lazare Carnot named his son Sadi after the famous Persian poet and philosopher Sadi of Shiraz. Sadi Carnot grew up during a time when French politics and science were going through tumultuous times. Sadi Carnot's father was a famous general and was a minister of war under Napoleon Bonaparte. Lazare Carnot was known for his work in engineering mechanics. In 1807, he withdrew from politics and concentrated on teaching mathematics, science, languages and music to his son. Sadi Carnot went to Ecole Polytechnique at the age of 16. He studied under eminent faculty such as Gay-Lussac, Poisson and Ampere. His contemporaries were eminent scientists such as Navier and Coriolis. After spending some years in the army, he concentrated his efforts on study and research.

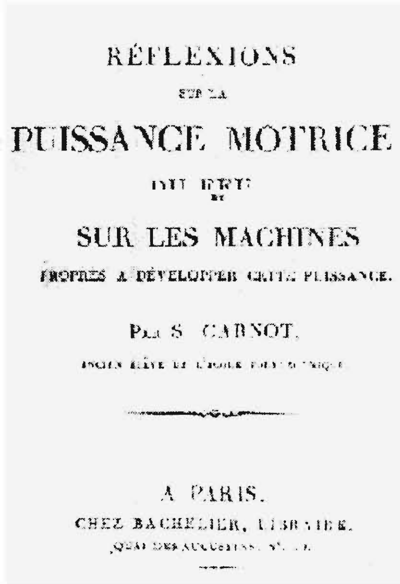
RÉFLEXIONS
PUISSANCE MOTRICE
SUR LES MACHINES
PAR S. CARNOT,
A PARIS,
CHEZ BACHELIER,

Figure 1.

Sadi Carnot was fascinated by the steam engine because it had a profound impact on the industrial revolution in England. He wanted to popularize the use of steam engines in France. In 1824, he wrote a monograph entitled 'Reflections on the motive power of fire and on machines fitted to develop that power'. This monograph was concerned with the theoretical as well practical issues related to the conversion of thermal energy to mechanical energy. This monograph begins with the following statement:

"Every one knows that heat can produce motion. That it possesses vast motive power no one can doubt, in these days when the steam engine is everywhere so well known. The study of these engines is of great interest, their importance enormous, their use is continually increasing, and they seem destined to produce a great revolution in the civilized world".

Caloric Theory

In 1824, the law of conservation of energy (i.e., the first law of thermodynamics) was not known. Most scientists assumed that heat can neither be created nor destroyed. Heat was considered

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to be an invisible fluid without mass that moved from one body to another when heat was transferred. This fluid was called 'caloric' by the famous French chemist Lavoisier. The caloric theory of heat reigned supreme for hundreds of years. It was assumed that caloric was neither created nor destroyed. Hence the amount of caloric in the universe was finite. The major limitation of the caloric theory was the assumption that mechanical energy cannot be converted to heat. In 1798, Count Rumford had demonstrated categorically that mechanical energy was converted to heat during the boring of a cannon. His experiments did not convince the believers in the caloric theory because he was not able to quantify the relationship between mechanical and thermal energy. Later, Robert Mayer, a medical doctor, proposed that thermal and mechanical energy were different forms of the same energy but his ideas were not accepted. Robert Mayer had obtained a rough estimate of the relationship between work (measured as force times distance) and heat measured in calories. This remarkable result was not understood for a long time because Mayer, being a doctor, adopted a line of reasoning that was alien to the physicists and chemists of those times. To overthrow the caloric theory that was accepted by most physicists and chemists at that time required a good experiment that would quantify the relationship between mechanical energy and heat. James Prescott Joule and Lord Kelvin (formerly William Thompson) performed a series of elegant experiments between 1850 and 1860 to obtain a quantitative relationship between mechanical and thermal energy. This led to the demise of the caloric theory by the close of the 19th century.

Second Law

Sadi Carnot had, however, formulated the basic ideas relevant to the second law of thermodynamics at a time when the caloric theory of heat was reigning supreme. Sadi Carnot somehow managed to formulate the second law of thermodynamics correctly although he did not understand the first law of thermodynamics. He arrived at the basic postulates of the second law of thermodynamics through his knowledge of hydraulic turbines. His father, Lazare Carnot was well versed with the design of water wheels to extract kinetic energy from the potential energy of falling water. Sadi Carnot proposed that the simplest heat engine would be one between two thermal reservoirs. A heat engine is a device that works in a cycle and converts thermal heat to work. A water wheel receives water from a hydraulic reservoir at a higher level and discharges water to a hydraulic reservoir at a lower level. Hence it converts a part of the potential energy of the falling water to kinetic energy of the water wheel. In the water wheel the potential energy available in the water can be extracted as kinetic energy without any loss of water. Sadi Carnot argued that, like the water wheel, a heat engine receives heat from a thermal reservoir at a higher temperature and conducts heat to a thermal reservoir at a lower temperature (*Figure* 2). Since he believed in the caloric theory of heat he assumed that heat is not lost in the process.

In his own words, "*The production of motive power is then due in steam engines not on actual consumption of the caloric but to its*

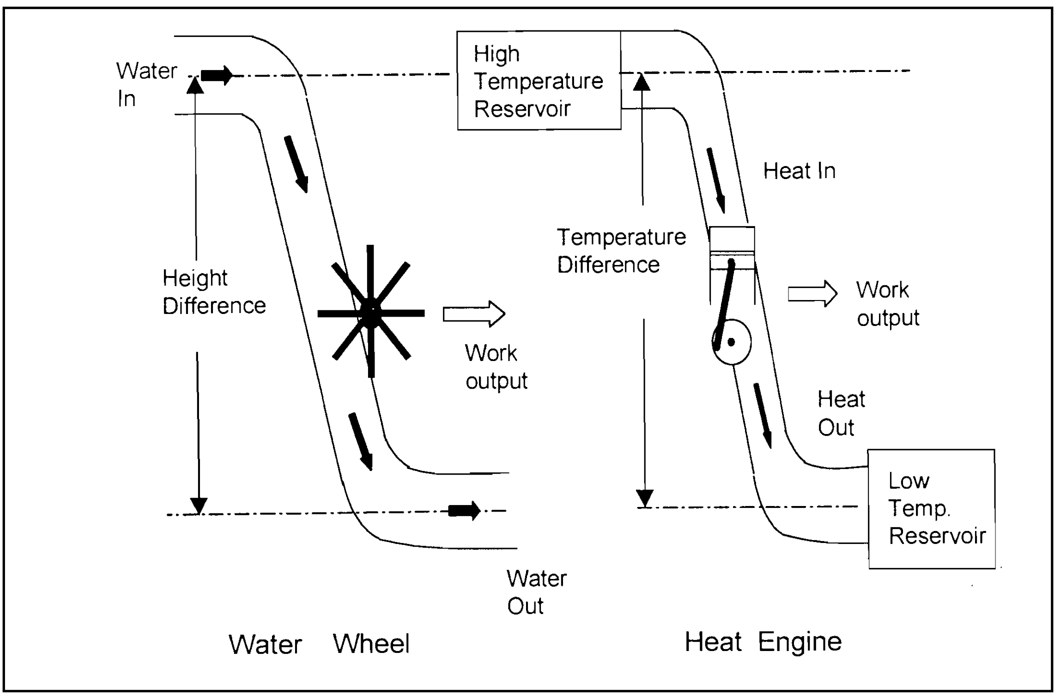

Figure 2. Hydraulic analogy of a heat engine according to Carnot.

Although mechanical energy can be converted to heat easily the reverse is not so easy! Sadi Carnot tried to find out what fraction of heat (or thermal energy) can be converted to mechanical energy in a cyclic process.

transportation from a warm body to a cold body". We now know that this is not true from the first law of thermodynamics. Although Sadi Carnot did not apply the first law correctly, he postulated that a heat engine cannot convert all heat to work in a cyclic process. Carnot, like many geniuses, was able to arrive at the correct postulate for the second law of thermodynamics because he was guided by his intuition. It is truly remarkable that Carnot was able to discover the second law of thermodynamics without understanding the first law of thermodynamics!

Today many students find it much easier to understand the first law of thermodynamics than the second law of thermodynamics. This is not surprising! The law of conservation of mechanical energy is well-known and easy to understand. The first law merely extends this notion to the conservation of mechanical and thermal energy. The great scientists of the 18th and 19th centuries were however wedded to the concept of heat as a material fluid and hence were unable to see the fact that mechanical energy can be easily converted to heat through friction. Although mechanical energy can be converted to heat easily the reverse is not so easy! Sadi Carnot tried to find out what fraction of heat (or thermal energy) can be converted to mechanical energy in a cyclic process. The concept of cyclic processes is central to the various postulates of Sadi Carnot. This is natural since Sadi Carnot's primary concern was with the devices such as steam engines that work in a cycle and convert heat to work. The thermal efficiency of steam engines (i.e., the ratio of work done to heat added) was less than 5% during the 18th century. Hence there was a strong incentive to find ways to increase the efficiency of these steam engines. Sadi Carnot postulated the existence of an ideal heat engine whose efficiency was independent of the working fluid used and dependent upon the temperature of the hot and cold thermal reservoirs. This postulate was truly the creation of an inspired genius. In his own words:

"*The motive power of a waterfall depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used and on what may be termed the height of its fall,* *that is to say, the difference of temperature of bodies between which the exchange of caloric is made. In the waterfall the motive power is exactly proportional to the difference in level between the high and low reservoirs. In the fall of the caloric the motive power undoubtedly increases with difference in temperature between the warm and cold bodies".*

The basic postulates proposed by Sadi Carnot form the basis of the derivation of the second law of thermodynamics in all modern books on engineering thermodynamics. The monograph published by Sadi Carnot in 1824 was not really understood and appreciated during his lifetime. This was partly on account of the fact that his ideas were well ahead of his time and also because the caloric theory that he had adopted was attacked by many scientists. Emil Clapeyron recognized the importance of Carnot's monograph and extended his ideas further by displaying the ideal heat engine in thermodynamic diagrams. Kelvin completed this task by showing that an ideal heat engine can be used to define an absolute temperature scale. Rudolf Clausius, who was professor of physics at Berlin, developed the second law of thermodynamics without appealing to the caloric theory of heat. He defined an important property called entropy that emerges directly from the basic postulates of Sadi Carnot.

Rudolf Clausius developed the second law of thermodynamics without appealing to the caloric theory of heat. He defined an important property called entropy that emerges directly from the basic postulates of Sadi Carnot.

After the publication of his monograph in 1824, Sadi Carnot examined the caloric theory further and began to entertain doubts about the caloric theory. He died on 24th August, 1832 in Paris in a cholera epidemic. Many of his unpublished papers were buried with him. Hence we will never know whether Sadi Carnot had reformulated the second law without using the concepts from caloric theory. On account of the premature death of Sadi Carnot, the correct formulation of the first and second law of thermodynamics was not achieved till 1865. In 1865, Clausius stated the first and second laws of thermodynamics in an elegant way.

1. The energy of the universe remains a constant.
2. The entropy of the universe tends to a maximum.

Can we say that Sadi Carnot discovered the second law of thermodynamics? Most scientists will consider entropy to be the cornerstone of the second law of thermodynamics and hence Sadi Carnot will not be considered as the discoverer of the second law of thermodynamics. The monograph that he published in 1824 represents the first attempt to address the issues related to the efficiency of conversion of heat to work in a cyclic process. Without Sadi Carnot's original and revolutionary ideas the discovery of the second law of thermodynamics may have taken much longer.

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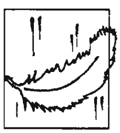
Suggested Reading

[1] ***The Second Law of Thermodynamics***, **Ed. J Kestin, Dowden, Hutchinson and Ross Inc., 1976.**

[2] **D S L Cardwell, *From Watt to Clausius*, Cornell Univeristy Press, Ithaca, NY, 1971.**

[3] **C C Gillispie, *Lazare Carnot Savant*, Princeton University Press, Princeton, NJ, 1971.**



An Ancient Indian Proof of the Riemann Hypothesis ?!

It has come to light that the famous Riemann hypothesis which is thought to be as yet unsolved, was actually already solved by and known to the ancient Indians in their monumental work 'Ramayana'. The name 'Riemann zeta function' is actually a corrupted version of the 'Raman Sita function'. The reason the name 'Sita' became 'Zeta' on reaching Germany is clear as the German pronounciation of the letter 'S' is similar to the English pronunciation of the letter 'Z'. What the western world calls the 'critical line' is already known to the ancient Indians as the 'Lakshman Rekha'. Having been drawn by Lakshmana, a half-brother of Raman, the critical line is also known at times by the name of 'half-line'. Sita vanished precisely when she stepped on the critical line.

It is not clear whether this proof did reach the western world although there are reports that the name of Vashishta did reach Germany. Unfortunately, they could make nothing of it and forgot the whole thing after merely quipping 'Was ist?'

Hanuman's character came to be known to the western world where it came to be identified as one with super powers who often flew over mountains and oceans in a cape rescuing damsels in distress. Of course, gradually, 'Hanuman' became 'Hanu Man' and following that it became 'Simian Man' which finally ended up as a big 'S'. (Another version has it that due to his attribute of scattering largesse to the multitude, he himself became a large 'S'.

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