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Sadi Carnot and the Thermodynamics of James Watt

Jovan Mitrovic

Stuttgart, Germany
Email: mitrovic@tebam.de

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Abstract

A comparison of Carnot's thermodynamic statements, published in his Reflections, with the Watt's thermodynamic ideas shows that Carnot used Watt's thermodynamics, but he did not understand it properly. For instance, he did not realize the Watt's idea that production of work in the steam engine requires a consumption of heat. Also, instead of the pressure difference boiler-to-condenser, Carnot used the temperature difference to be the direct quantity for the transport of caloric in the engine. Many of Carnot's statements are shown to express Watt's ideas in other wording. Watt realized the reversible heat transfer in experiment several decades prior to Reflections. In addition, Carnot's analogy of steam engine and water fall, published 1824, has been invalidated, long before its birth, by the Watt's formulation of the first law in 1774. Despite these facts, James Watt is banished from the history of thermodynamics.

Keywords

Thermodynamics, James Watt, Sadi Carnot, Rudolf Clausius, Analogy Steam Engine-Waterfall

1. Introduction

In 1824 Sadi Carnot (Carnot, 1897) published the memoir *Reflections on the Motive Power of Fire* aiming at formulation of a general theory of heat engines. The work contains his thermodynamics and links numerous novel ideas into a coherent whole, which has led some authors to consider the publication year of the Reflections as the birth of modern thermodynamics. However, Carnot did not provide any State of the Art and the reader is required to consider him as the true creator of these ideas.[1]

James Watt published his ideas on thermodynamics, mostly using technical language, over a long period of time, beginning in 1763. Watt's works belong to the foundations of thermodynamics. He created several ides among them the first versions of thermodynamic laws in 1770s. Since Watt's works were completed before the Carnot's Reflections, they were considered to be part of "prehistory" of thermodynamics and have not been mentioned in the literature, even by historians of thermodynamics.

The Reflections (Carnot, 1897) names several scientists who have contributed to the development of steam engine but emphasized only one as *famous*, namely, *James Watt* (p. 42). In Appendix B (Carnot's Foot-Notes, p. 253), he makes additional references to Watt's work:

Watt, to whom we owe almost all the great improvements in steam-engines and who brought these engines to a state of perfection difficult even now to surpass, was also the first who employed steam under progressively decreasing pressures. …

From these quotations we may conclude that Carnot was very familiar with the Watt's thermodynamic works (Mitrovic, 2022a). In addition, Carnot was aware of the contributions made by English engineers (Wilson, 1981). Actually, he is credited with numerous ideas in thermodynamics, including the traces of the second law. Many historians of thermodynamics consider him the father of modern thermodynamics. Ernst Mach (Mach, 1894) supported this view in 1894:

Technical interests and the need of scientific lucidity meeting in the mind of S. Carnot led to the remarkable development from which thermodynamics flowed.

Since neither Carnot nor any other researcher studying Carnot's thermodynamics provided a state of knowledge prior to the Reflections, readers were forced to accept Carnot as the sole originator of all ideas presented in his publication. I exemplify this point by quoting (Bryant, 1973), who discusses the fundamental concept of the mutual convertibility of heat and work, including the idea that when heat is converted into work, it disappears as heat and appears as an equivalent amount of work. Bryant notes that this conversion was not immediately obvious in 1850 but was readily absorbed by engineers and presented little difficulty after approximately 1860 (p. 163-164):

The other set of essential ideas was much more troublesome: Carnot's principle that only a certain fraction of the heat supplied to an engine can be converted into work, and that this fraction depends on the temperature range through which the cycle works and not on the working medium. (Emphasis added.)

The Bryant's statement is incorrect: the fact is, Carnot never promulgated such a principle. James Watt, and not Sadi Carnot, is the true creator of this principle

[1]The importance of the State-of-the-Art has been stressed already in 1810 by the German philosopher and poet Johann Wolfgang von Goethe (Theory of Colours, English translation Charles Lock Eastlake, JOHN MURRAY, 1840, Preface to the First Edition1810, pp. XXIV/XXV):
As we before expressed the opinion that the history of an individual displays his character, so it may here be well affirmed that the history of science is science itself. *We cannot clearly be aware of what we possess till we have the means of knowing what others possessed before us. We cannot really and honestly rejoice in the advantages of our own time if we know not how to appreciate the advantages of former periods.*

of thermodynamics. In 1765, Watt conceived and developed a steam engine with a separate condenser that shall liquefy the steam the heat of which has not been consumed to produce work in the steam cylinder (Mitrovic, 2022a). Watt's great idea was to split the heat in the steam cylinder into useful work and wasted heat in the 1760s and 1770s, leading him to formulate the first law of thermodynamics. Rudolf Clausius presented this Watt's idea in the 1850 paper as his own concept, see the Appendix. However, neither Bryant nor Clausius mention Watt's name in this context. Further details on Watt's thermodynamics are provided in the references (Mitrovic, 2022a, 2022b, 2022c).

In publications we often find the statement: *Carnot formulated the second law although the first law was unknown*. This statement is doubly wrong. Carnot did not formulate the second law, nor was the first law unknown in Carnot's time. The assessment of Carnot's Reflections by (Truesdell, 1980) deserves particular attention (Carnot, 5. Act II, Dissipationless Work, p. 79):

…*Little of any consequence regarding this subject was then known. Anyone skeptical here need not resort to the writings of engineers, inventors, and constructors. Just eight years before Carnot's work was published, a leading physicist of the day (J. B. Biot) could give his readers in a whole chapter on steam engine no more than an illustrated description of the machines, embellished by a few scientific terms and some numerical data regarding them, followed by a sketch of their evolutions during the preceding* 111 *years, and finish with the discussion of how much work a horse of mean strength can do in a day.*

Truesdell's text allows the conclusion that thermodynamics did not exist before Carnot's reflections and that Carnot would formulate this discipline as a science from nothing.

The aim of the present work is not the thermodynamics of Sadi Carnot itself. His thermodynamic is well-known from the original publication and from numerous secondary sources, e.g. (Barnett, 1958; Dias et al., 1995). What is indeed missing regarding the Carnot's work is the state of the art prior to the Reflections. The aim of the present work is, therefore, to compare some of the statements accessible in the Reflections (Carnot, 1897) with the ideas which really come from James Watt (**Figure 1**). Many of Carnot's statements are shown to express Watt's ideas in modified wordings. Watt accomplished the reversible heat transfer in experiment several decades prior to Reflections. In addition, Carnot's analogy of steam engine and water fall, published in the Reflections, has been invalidated by the Watt's formulation of the first law in 1774, long before its birth. To a certain extent, the present paper can be considered as a late State of the Art missing from the Carnot's work.

2. Some of Carnot's Most Important Statements

In the reflections, Carnot presented the steam engine as an energy conversion device and presented his complete thermodynamics. In the introduction, he called for a universal theory of the generation of motion by heat, which should not be limited by the design or properties of the heat engine.

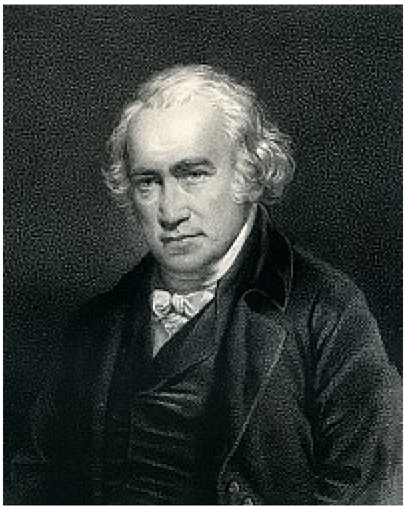

Figure 1. James Watt, 1736-1819. The Scottish Engineering Hall of Fame, James Watt (https://engineeringhalloffame.org/profile/james-watt). Genius whose thermodynamics was ignored or not understood for 250 years.

Carnot's program. On p. 43 Carnot explains his program (Carnot, 1897):

The principle of the production of motion by heat must be considered independently of any mechanism or any particular agent. It is necessary to establish principles applicable not only to steam engines but to all imaginable heat-engines, whatever the working substance and whatever the method by which it is operated.

Carnot calls for principles of heat engines that should be universally applicable regardless of mechanisms, kind of working substance, etc. However, considering that Watt established the first and second law of thermodynamics in the 1760s/1770s and applied in practice ever since, we can conclude that Carnot did not understand James Watt's thermodynamics, see references (Mitrovic, 2022b, 2022c).

Carnot himself used ideal fluid thus eliminating the fluid friction; in addition, he eliminated the mechanical friction and inertia of moving parts of the engine. This changed his original, enthusiastic program considerably but he did not inform the reader explicitly about the consequences of these simplifications which cannot be realized in practice.

Main processes in the steam engine. On p. 45 (Carnot, 1897) describes the main processes taking place in the engine:

The caloric developed in the furnace by the effect of combustion transverses the walls of the boiler, produces steam, and in some way incorporates itself with it. The latter carrying it away, takes it first into the cylinder, where it performs some function, and from thence into the condenser, where it is liquefied by contact with the cold water which it encounters there. Then, as a final result, the cold water of the condenser takes possession of the caloric developed by the *combustion*.

Taking caloric to represent heat, Carnot describes the steam engine process that James Watt devised some 60 years earlier, patented in 1769 and realized in practice for several decades prior to Carnot's Reflections (Mitrovic, 2022a). According to Carnot, caloric is transported from the boiler (hot body) to the condenser (cold body) and the cause of this transport is the imbalance in the caloric of the considered bodies; this imbalance is the temperature difference in Watt's explanations. In the process, the caloric is—according to Carnot—neither produced nor consumed; the quantity of the caloric that enters the condenser is exactly the same as the one that leaves the boiler. This violates the first principle! Carnot emphasized (p. 46):

The production of motive power is then due in steam-engines not to an actual consumption of caloric, but to its transportation from a warm to a cold body.

The remark by (Barbour, 2020: p. 7), on this statement underlines its content:

Carnot's italicized words bid fair to be the most fruitful false statement in the history of science.

Splitting of heat in the steam cylinder. From the given citations, we could conclude that Carnot may not have been aware of James Watt's establishment of the first and second laws of thermodynamics, which demonstrated the splitting of thermal energy, delivered by boiler, into two streams in the steam engine. One stream was the work the engine performs, the other one the low temperature heat that is wasted in the separate condenser (Mitrovic, 2022b, 2022c). Carnot's above statement and his understanding of the conservation of heat, or "caloric", came from his analogy of a steam engine and a waterfall. As shown below, this analogy is physically incorrect.

Necessity of hot and cold reservoirs. Carnot (Carnot, 1897) emphasized, as his crucial idea, the necessity of not only a hot reservoir but also a cold reservoir with a lower temperature in order to produce motive power by heat, p. 46. However, he omitted to mention that James Watt had already introduced the separate condenser, which acted as a cold reservoir, in his 1769 patent and had been using it in practice. Watt had conceptualized and realized steam engines based on the interaction of water boiler and steam condenser for decades prior to the publication of Carnot's Reflections. Hanlon (Hanlon, 2020) states some of Watt's early steps towards the founding of thermodynamics.

Motive power at any temperature difference. Carnot maintains (p. 48):

Wherever there exists a difference of temperature, wherever it has been possible for the equilibrium of the caloric to be re-established, it is possible to have also the production of impelling power, which immediately follows from Watt's drawings of the steam engine that includes water boiler and steam condenser (Mitrovic, 2022a). Watt's experiments with water in 1760s have demonstrated an increase in steam pressure with the increase in temperature causing a motive pressure force in any non-isothermal two-phase system. Being educated engineer, Carnot was—most probably—able to read and interpret Watt's technical language.

The maximum of motive power. Regarding the maximum of the motive power, Carnot demands in 1824, means that (useless) establishment of caloric equilibrium, without change of volume of working substance, would be a loss of motive power. Compared with Watt's terminology, this is another wording for suppression of heat losses Watt described in the 1769 patent (Mitrovic, 2022a). Finally, this is suppression of thermal irreversibility and we recognize here the old Watt's idea (1769),

$$\text{Heat losses minimum} \rightarrow \text{motive power maximun}\,,$$

as the original Carnot's concept.[2]

Carnot did not precisely specify the conditions for the maximum of the motive power. His idea can be stated thus: the lower the heat losses and the irreversibility, the higher the motive power. This, however, follows immediately from the Watt's 1769 patent and his formulation of the First Law (1774); the motive power changes inversely to heat losses, reaching maximum when the irreversibility becomes zero, which is impossible under real conditions.

The thermal efficiency of steam engine. James Watt expressed the performance of his steam engine as the ratio of work it performs and the quantity of coal it consumes. Work was obtained as the product of the amount of water (in pounds) and the height of its lift (in feet). This ratio was called *duty*, if the lift height was one foot and the quantity of coal consumed one bushel (84 pounds). The unit duty thus defined was (pound water x foot)/(pound of coal). This unit takes into account all of the impurities contained in the coal (like ash, water etc.) which is acceptable, to some extent, from the practical point of view. The unit thus defined was dependent on the geology and the location of coal mine. However, Watt was aware that only the heat of coal combustion performs work; multiplying the amount of coal consumed by the heat of its combustion gives the energy (heat) supplied to the engine in the boiler. Denoting the energy (heat) the working substance receives in the boiler by Q_B and the work performed by W, we obtain the final expressions for the thermal efficiency of steam engine η,

$$\eta = \frac{W}{Q_B} = 1 - \frac{Q_C}{Q_B} < 1\,,$$

where Q_C stands for the heat absorbed in the condenser (Mitrovic, 2022b). This is the basic expression for η due to James Watt, which is independent of the geology (origin) of coal. Today, it can be easily stated in terms of temperatures, $\eta = 1 - \left(T_C / T_B\right)$. Watt introduced the unit *duty* for the thermal efficiency of the steam engine sporadically from 1763 to 1775, some 6 decades prior to Carnot's Reflections (1824). It is therefore incorrect to credit Sadi Carnot with the definition of thermal efficiency as occasionally done in publications.

[2]Watt's idea on the irreversibility was the first of this kind in science and most likely has been forgotten over time. Because, about 170 years later, in 1938, F. Bosnjakovic, without mentioning James Watt, took up the fight against irreversibility and called on researchers to support his program. (Bošnjaković, F., 1938, *Kampf den Nichtumkehrbarkeiten* (*Fight against irreversibility*), publ. in Arch. Wärmewirtsch. Dampfkesselwesen 1938, **19**, 1-2, in German).

3. The Thermodynamic Reversibility

As follows from Watt's drawings, the Carnot's steam engine cycle is actually the James Watt steam engine cycle exposed to Carnot's assumptions about heat transfer and changes of the working substance. One of the assumptions is the *heat transfer at zero temperature difference*. This assumption reduces the irreversibility and simultaneously the kinetic of the heat transfer process to zero; in other words, it renders the process not realizable and the cycle not feasible. Carnot did not mention any reference in this context. Note that Watt was the first scientist to introduce the complete cyclic flow of working substance in general, not Sadi Carnot.

For the heat transfer rate to become finite at zero temperature difference, some other conditions have to be met, for instance the heat transfer surface and/or the process time have to be infinite. These additional conditions render Carnot process non-feasible.

Jacketing of steam cylinder. At this point it is instructive to compare the Carnot's reversible heat transfer (1824) with the James Watt idea (1769) of suppression of heat losses. To reduce the heat losses and thermal irreversibility, Watt required in the 1769 patent that the steam cylinder be kept at the same temperature as the steam that enters it. To realize the idea and achieve the goals, he *encased the steam cylinder in a layer of saturated steam* produced in the boiler. Figure 2 displays an experimental realization of the Watt's idea in 1774. The outer surface of the steam jacket was insulated. The arrangement kept the cylinder largely isothermal with the results of an insignificant heat transport across the cylinder wall.

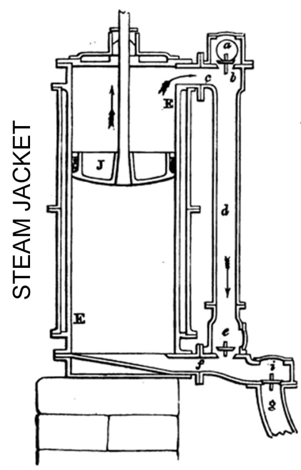

Figure 2. James Watt's type of steam cylinder jacketed by a layer of saturated steam, 1774. Due to the equal steam temperatures inside the cylinder and in the jacket, Watt ideally suppressed heat losses from the cylinder to surroundings. The steam jacked did not diminish the rapidity of the processes taking place inside the cylinder. Figure: John Farey, A Treatise on the Steam Engine: Historical, Practical, and Descriptive (London: *Longman, Rees, Orme, Brown, and Green, 1827*), p. 333.

What was the Carnot's method? Carnot allows the working substance to change its state to reach approximately the temperatures of the heat sink and heat source. The interaction of the working substance with the heat reservoirs has to occur at the same time in the whole volume of the working substance which is due to finite size of the volume impossible. Regarding the heat transfer at negligible small temperature difference, the effect is the same in both cases (Watt and Carnot). The big difference, however, is the fact that Watt reduces the heat losses and the irreversibility of the process thus increase the efficiency of the steam engine, while Carnot reduces the main process quantity—the heat flow rate—and the irreversibility. On the contrary, the Carnot's method renders the process non feasible.

The Watt's idea on the reversible heat transfer can actually be viewed as the origin of Carnot's reversibility. With this notion, the Carnot's reversible heat transfer is not a novel idea but a thought realization of the Watt's old one. In this context, I cite Watt from (Thatcher, 1907: p. 309):

On reflecting further, I perceived that, in order to make the best use of steam, it was necessary first, that the cylinder should be maintained always as hot as the steam which entered it; and, secondly, that when the steam was condensed, the water of which it was composed, and the injection itself, should be cooled down to 100˚, *or lower, where that was possible*. (˚ means ˚F, present paper.)

Carnot provides similar wording in the Reflections.

The *best use of steam*, in Watt's understanding, means suppression of heat losses and thermal irreversibility of the steam engine. Carnot used a very similar definition as his own idea in the Reflections more than 60 years later.

The *reversible heat transfer* is a "philosophical" term, because it shall occur at zero temperature difference, that is at equilibrium, with zero gradients of the system's coordinates. Norton (2016) provides a detailed, in-dept discussion on Thermodynamic Reversibility, linking the Sadi Carnot's thermal reversibility to the mechanical reversibility dealt with by his father, Lazare Carnot (1808). See also the discussion by (Valente, 2019). Actually, James Watt provided much earlier all the information on reversible heat transfer needed from a thermodynamic point of view.

Thermodynamic system. Some authors ascribe to Carnot the idea of thermodynamic system. This is not correct! James Watt treated in his patent 1782 the expansion of steam in the cylinder using the equation of ideal gas. Keeping the gas temperature T constant, he calculated the pressure p of expanding steam as function of volume V and presented the results in a (V, p)-diagram. The function

$$f\left(p,V,T\right)=0 \qquad (1)$$

represents the equilibrium states and constitutes the thermodynamic (Watt's) system.

Another example for thermodynamic system is the Watt's model of steam engine and its thermodynamic analysis around 1765. Watt treated the steam engine models as thermodynamic systems. Also, the Watt's pressure indicator (around 1780) belongs to the family of thermodynamic systems. However, Watt did not coin the term thermodynamic system.

4. The Carnot's Analogy

Driving force for flow of steam in the engine. In order to present the processes of the steam engine in a more understandable way, Carnot compared the steam engine to a waterfall. We call this comparison the *Carnot's analogy*. He sets the heat flow from the boiler to the condenser analogous to flow of water in the water fall from the higher to the lower reservoir, thereby assuming the hight of water column to correspond to the difference in the steam temperatures (boiler to condenser) in the engine. The motive power of the waterfall—the pressure gradient—is proportional to the hight of water column. The actual driving force in the steam engine, is not the temperature difference, as Carnot states, but the difference of steam pressure. Since the steam pressure does not linearly depend on the steam temperature, this analogy was not physically correct. Further details are given below.

Note that Watt stated in his 1769 patent that the powers of steam drive the engine. The term power means the pressure of steam or the product of pressure and the piston area, or the volume of generated steam.

Transport of the caloric. Regarding the transport of the caloric by steam from boiler to the condenser, Carnot explains (Carnot, 1897: p. 45):

The latter (steam) *carrying it* (caloric) *away, takes it first into the cylinder, where it performs some function, and from thence into the condenser, where it is liquefied by contact with the cold water which it encounters there. Then, as a final result, the cold water of the condenser takes possession of the caloric developed by the combustion. … The steam is here* (in the steam engine) *only a means of transporting the caloric.*

Obviously, the transport of caloric in the steam engine occurs by convection at the steam velocity. This mode of heat transport is not governed directly by the temperature difference, as Carnot assumed, but by the pressure difference, produced by the temperature difference boiler-to-condenser. As noted above, James Watt stated in the 1769 patent that *powers of steam drive the engine* (Mitrovic, 2022a). Hence, the temperature difference is not the direct quantity that governs the motive power of the steam and thus not analogous quantity to the pressure difference in the water fall. If we accept the temperature difference as the driving force of steam flow in the engine, we must reject the Carnot's assumption that the driving force is independent of the nature of the working substance.

Carnot's justification of the analogy. Carnot wrote (pp. 60/61), Reflexions (Carnot, 1897):

According to established principles at the present time, we can compare with *sufficient accuracy the motive power of heat to that of a waterfall. …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, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made. In the waterfall the motive power is exactly proportional to the difference of level between the higher and lower reservoirs. In the fall of caloric the motive power undoubtedly increases with the difference of temperature between the warm and the cold bodies; but we do not know whether it is proportional to this difference*. (Emphasises added.)

An answer to the last question follows from Watt's works. It was known since Watt's experiments (around 1763) that vapor pressure increases more than linearly with the temperature and the driving force (fluid flow) cannot depend linearly on the temperature difference. This, but not only that, renders Carnot's analogy inapplicable.

Carnot's General proposition. Carnot considered his own ideas to be infallible and put forward the following general theorem (p. 68, Reflexions 1824):

The motive power of heat is independent of the agents employed to realize it; its quantity is fixed solely by the temperatures of the bodies between which is effected, finally, the transfer of the caloric.

Carnot assumed the working substance to be ideal and the results he obtained contain implicitly this restriction. On p. 94/95 (Reflexions 1824) he explicitly stated the motive power to be independent of the temperature niveous. He obtained this result under the assumption of a very small temperature difference (much less than 1˚C) at two different temperature levels, one at 100˚C to (100˚C - h˚C), the other at 1˚C to (1˚C - h˚C), h being indefinitely small quantity, and found his idea confirmed. Below we will assume a larger temperature difference and estimate the corresponding pressure differences.

Other deficiencies of the analogy. Regarding the physics, validity, and consequences, our analyse reveals certain deficiencies of Carnot's model. Taking heat in the steam engine and water in waterfall to be analogous quantities, as Carnot did, and considering the Watt's formulation of the First Law of Thermodynamics in 1760s/1770s, the heat undergoes a splitting in the steam cylinder (Mitrovic, 2022a) but water amount in the waterfall remains conserved. A further inconsistency, already stated above, arises from the Carnot's assumption that the temperature difference (boiler-to-condenser) directly governs the steam engine processes. According to James Watt's notion (Watt's 1769 patent), the steam power (pressure difference) governs directly the engine's power and its kinetic. In this context also the expansion of steam in the steam cylinder shall be mentioned, whereas an expansion of water in the waterfall is insignificant.

Implications of the Carnot's analogy. A specified temperature difference determines the pressure difference that governs the steam flow from the boiler to the condenser. In order for the steam flow to be the same at the same temperature difference but different temperature levels, pressure difference has to be nearly the same. This pressure difference is quantified in the following by using the *Clausius-Clapeyron* (*C-C*) equation, which did not exist at Watt's and Carnot's time, although Watt measured (1760s) the steam pressure at different temperatures and obtained a steam pressure curve.

The C-C equation. The application of the (C-C) equation is justified by the fact that steam flowing from the boiler to the condenser is saturated and contains some condensate. This permits the application of the (C-C) equation:

$$\frac{\mathrm{d}p}{\mathrm{d}T} = \frac{h_{VL}}{T\left(v_V - v_L\right)} = f\left(T\right) \tag{2}$$

where $f\left(T\right)$ represents the slope of the p- curve in the (T, p)- diagram.

The local hydrodynamic pressure $p\left(z\right)$ of flowing steam can be set equal to the local saturation pressure, hence

$$\frac{\mathrm{d}p}{\mathrm{d}z} = \frac{\mathrm{d}p}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}z} = f\left(T\right)\frac{\mathrm{d}T}{\mathrm{d}z} \tag{3}$$

where z denotes the coordinate along the steam flow.

These equations suffice to test the Carnot hypothesis by which the driving force of the steam engine depends only on the temperature difference of hot and cold reservoirs. From Equation (2),

$$\mathrm{d}T = \frac{1}{f\left(T\right)}\mathrm{d}p\,. \tag{4}$$

Integration for the substance, say a, gives:

$$\left(\int_{T_C}^{T_B} \mathrm{d}T\right)_a = \left(T_B - T_C\right)_a = \left(\int_{T_C}^{T_B} \frac{1}{f\left(T\right)}\mathrm{d}p\right)_a \tag{5}$$

where the subscripts B and C refer to the boiler and condenser, respectively. Adding the expression for a substance b, requires

$$\left(T_B - T_C\right)_a = \left(T_B - T_C\right)_b\,, \tag{6}$$

or

$$\left(\int_{T_C}^{T_B} \frac{1}{f\left(T\right)}\mathrm{d}p\right)_a = \left(\int_{T_C}^{T_B} \frac{1}{f\left(T\right)}\mathrm{d}p\right)_b \tag{7}$$

which has to be satisfied for the Carnot's hypothesis to be valid. Note that the temperatures T_B and T_C can be different for the substances a and b but their differences have to be equal. A trivial case follows for the substances having the same physical properties:

$$\left(f\left(T\right)\right)_a = \left(f\left(T\right)\right)_b\,. \tag{8}$$

On the basis of this results one can conclude that the Carnot's hypothesis is not generally satisfied.

The heat transport will be directly proportional to the temperature difference boiler-to-condenser $(T_B - T_C)$ only at a steady-state heat conduction in the steam of constant physical properties. Such conditions, however, are not met in the steam engine. Note that Carnot assumed the fluid to be ideal and excluded the flow resistances.

To quantify the Carnot's hypothesis, we consider water (real substances) in the states *a* and *b* instead of chemically different substances. The properties of water in the cases, (*a*) and (*b*), are listed in **Table 1** and shown in **Figure 3**. In the case (*a*) the boiler temperature is $t_B = 100^\circ\text{C}$ and in the condenser is $t_C = 50^\circ\text{C}$; in the case (*b*) $t_B = 110^\circ\text{C}$ and $t_C = 60^\circ\text{C}$; in both cases the temperature difference is $t_B - t_C = 50^\circ\text{C}$. By this example, the steam engine covers at different temperatures the same temperature difference $\Delta t = t_B - t_C$. As expected, the differences of the steam pressures at different temperature levels are different. In the case (*a*) the pressure difference is $\Delta p_a = p_B - p_C \approx 88$ kPa, while in the case (*b*) $\Delta p_b = p_B - p_C \approx 126$ kPa, more than 40% larger.

The pressure differences Δp_a and Δp_b result in different motive powers of the steam engine. In case (*b*) the motive power will be larger than in the case (*a*), despite the fact of equal temperature differences; this is in contradiction to the Carnot's hypothesis. As this example illustrates, the Carnot's analogy, expressing the similarities between the waterfall and the steam engine, is inapplicable. Note that we have used real substances instead of ideal, adopted by Carnot.

Table 1. Comparison of steam engine runs at same temperature difference and different temperatures; t in ˚C, p in kPa.

CASE	t_C	t_B	Δt	p_C	p_B	Δp
(*a*)	50	100	50	12	100	88
(*b*)	60	110	50	19	145	126

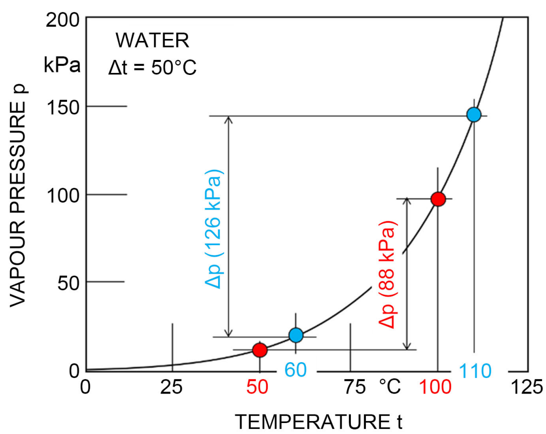

Figure 3. Effect of temperature level on the pressure difference at the equal differences of boiler and condenser temperatures. Different pressure differences render Carnot's analogy inapplicable.

5. Conclusion

Sadi Carnot is considered to be the originator of several ideas in the development of thermodynamics and occupies one of the central positions in the history of this important branch of physics. For instance, not seldom do we encounter the statement in publications that Carnot managed to recognise the second law of thermodynamics, although the first law has not been established. This assertion is of pivotal importance for the history of thermodynamics, but it is incorrect. It, therefore, seemed important to pursue the question of whether Carnot borrowed some of James Watt's ideas without properly quoting Watt.

The present paper provides evidences that the origin of numerous Carnot statements is contained in the thermodynamic of James Watt. Carnot did not provide any State of the Art and the reader was forced to ascribe these ideas to the author of the Reflections. Today it is known, that James Watt formulated and used the laws of thermodynamics at least 5 decades prior to Carnot's Reflections. The splitting of heat in the steam cylinder is solely Watt's idea, today it is—incorrectly—ascribed to Rudolf Clausius. On the basis of Watt's work, we have concluded that the Carnot's analogy is ill posed. My earlier woks cited in this paper provide additional details on James Watt thermodynamics.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix

As is well known, Rudolf Clausius published a number of Papers on Thermodynamics. I have used here his first paper published in 1850:

Clausius, R. (1850) Über die bewegende Kraft der Wärme, und die Gesetze, welche sich daraus für die Wärmelehre selbst ableiten lassen. *Poggendorff's Annalen der Physik*, **79**, pp. 368–397, 500–524, 1850; English translation: On the Moving Force of Heat, and the Laws regarding the Nature of Heat itself which are deducible therefrom, *Philosophical Magazine* Series **4**, Vol. **2**, pp. 1–21, 102–119, 1851; DOI: 10.1080/14786445108646819.

It was not Rudolf Clausius who first (1850) came up with the idea of heat splitting in the cylinder of the steam engine, but James Watt in 1769, at the latest in 1774.

Clausius opens his first thermodynamic paper (1850, 1851) with a discussion of the equivalence of work and heat, mainly focussing on the Carnot's concept that heat remains unchanged in a heat-to-work conversion process in the steam engine. He explains, that the Carnot's theory is not opposed to the real fundamental principle, but to the Carnot's addition "*no heat is lost*;" he then states that the production of work may take place simultaneously with loss (consumption) of heat; a certain portion of heat may be consumed, and a further portion transmitted from a warm body to a cold one, like in a steam engine; and both portions may stand in a certain definite relation to the quantity of work produced. Clausius than provided the following statement regarding the equivalence of heat and work (p. 4):

In all cases where work is produced by heat, a quantity of heat proportional to the work done is expended; and inversely, by the expenditure of a like quantity of work, the same amount of heat may be produced.

This is the first important modification of the Carnot's idea. By this idea, the heat produced in the boiler reaches the condenser of the steam engine, where it becomes completely liquified; but on its way from the boiler to condenser the heat does not experience any changes, its quantity remains conserved. Contrary to Carnot, Clausius maintains now that the quantity of heat proportional to the work done is expended in the steam cylinder. In other words, the heat produced in the boiler of the engine is split in the steam cylinder.

The Clausius' idea has been accepted by the thermodynamic community as a fundamental statement of the classical thermodynamics. Its meaning raises the following question:

Was Rudolf Clausius the first who established the idea of heat splitting in the steam engine? Clausius mentions in his essay some works that have appeared after Carnot's reflection, but his paper does not contain any broader state of the knowledge. The author of the present paper has shown in earlier works that James Watt established the idea of energy splitting in the steam cylinder and realised in the operations of his steam engines, see reference (Mitrovic, 2022b). The question stated above can be answered as follows: James Watt is the true creator of the idea of energy (heat) splitting in the steam cylinder, not Carnot, not Clausius, … Watt developed this idea in his 1769 patent, 80 years prior to Clausius' publication.