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Some Ideas of James Watt in Contemporary Energy Conversion Thermodynamics

Jovan Mitrovic

Stuttgart, Germany
Email: mitrovic@tebam.de

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Abstract

James Watt contributed significantly to the development of the thermodynamics of energy conversion as a science. Several of his ideas are now integral part of thermodynamics, but Watt as their creator is not mentioned. This paper presents some of Watt's concepts of energy conversion, including his thermodynamic analysis of the Newcomen steam engine that marks the beginning of thermal engineering. The analysis illuminated the causes of the enormously high heat losses in the installation and showed the ways for their reduction. This led him to a new conception of the steam engine with a separate condenser. Not less important was Watt's determination of some physical properties of water and steam used as the working substance. In the experiments he observed the decrease of the latent heat of steam with increasing temperature and its disappearance at very high temperature led him to postulate the existence of a thermodynamic critical state of water. He introduced the work associated with volume change into thermodynamics and illustrated it graphically. Several of Watt's numerous ideas deserve to be included into the history of the thermodynamics of energy conversion but they are rarely mentioned in the scientific literature. Arguably the most important is the First Law of Thermodynamics, which he introduced in his 1769 patent and related works in 1774 and 1778.

Keywords

Thermodynamics, Energy Conservation and Conversation, Mechanical Equivalent of Heat, James Watt, Volume Work, First Principle of Thermodynamics, Latent Heat, Steam Expansion and Condensation

1. Introduction

In trying to understand the coal consumption of the Newcomen steam engine as a function of its power, James Watt (1736-1819) believed that he had first to understand how the engine worked. This step was impossible, however, without an understanding of the processes involved in energy conversion and the knowledge of the physical properties of water and steam, used in the engine as the working substance. On pp. 7-8 [1] Watt summarized the state of knowledge regarding steam and the steam engine at the time he started his work on a model of Newcomen's engine, sometime prior to 1765. In particular, he mentions steam condensation in contact with, and heat communication to, cold bodies. Watt knew that water can boil at temperatures below 100˚F (≈37.8˚C) and that evaporation causes cooling of an unheated evaporating liquid and the bodies in contact with it. In addition, Watt himself conducted experiments to determine the specific heats of some substances in relation to that of water, the quantity of water which could be evaporated by consumption of a given quantity of coal, the steam pressure at different temperatures, and so on (see also pages 311 & 395 in Farey [2]). Of particular importance for the modification of the engine were knowledge of the elasticity of steam and the steam pressure at various temperatures.

In a thermodynamic analysis of the Newcomen engine[1] Watt arrived at the conclusion that heat losses caused useless condensation of saturated steam and have to be prevented in an economically conceived installation. He turned his attention to the boiler and especially to the steam cylinder. The steam cylinder was last stage in the conversion of heat into mechanical work, which served alternately as a steam condenser. The heat losses of the steam cylinder were therefore of central importance for Watt.

General aspects of Watt's thermodynamics have been considered in [3], including a discussion of why Watt has generally been excluded from the history of thermodynamics (as opposed to mechanical engineering). In the present paper we analyze some of Watt's ideas about the thermodynamics of energy conversion. Many of these ideas were actually published by Watt in his patents or as drawings. The content of these publications has generally been ignored by those who did not consider technical drawings and sketches to be a means of imparting knowledge. This is not the case in the present paper. To fully understand the meaning of Watt's drawings our present knowledge will be involved. However, the paper must not be qualified as the Whig history.

Our analysis will encompass the most important of Watt's ideas on the conversion of one energy form into another (particularly of heat into mechanical work), energy conservation, the separate condenser, the interpretation and determination of physical quantities, (particularly the latent heat of steam by using mass and heat balances), and the work associated with change of volume (during the expansion of the steam within the cylinder). We also sketch his formulation of the **First Law of Thermodynamics**. In the Appendix, Conversion of mechanical energy in heat, the attention is focused on Robert Boyle as the pioneer (1675) of energy conversion.

[1]When we speak of the Newcomen engine, we mean its model.

The topic of the present work limits its scope in a way that a comprehensive overview of the literature is neither necessary nor possible. In addition, James Watt's science is considered prehistoric. This, however, does not justify his firm exclusion from the History of Thermodynamics which actually created a gap in the development of this science. Of many works devoted to the history of thermodynamics, the recently published paper by W. M. Saslow [4] discusses several important details. The content of the present paper is limited to the Watt's historical ideas.

2. Watt's Thermo-Energetic Analysis of the Steam Engine

For much of the 18th century, the Newcomen steam engine was the main facility for converting heat into mechanical work. Its poor thermomechanical characteristic aroused Watt's interest in this machine. Watt thoroughly analysed the thermodynamics of a model of the engine and uncovered the reasons for its low performance. We next summarize the results Watt deduced from the analysis because they provide insight into the state of knowledge prior to Watt.

2.1. Actual-to-Minimum Steam Consumption

Watt modified the construction of the steam boiler and determined the amount of steam leaving it ([2], Chap. V, p. 309). This gave him the total production of steam. In the next step he determined the amount of steam required to run the engine which he assumed to be the amount of steam required to fill the cylinder with one stroke of the engine.

Denoting the mass of steam leaving the boiler by $M_S = \rho_S V_S$ and the steam quantity required for filling the cylinder by $M_{Smin} = \rho_S V_{CYL}$, Watt found

$$\frac{M_S}{M_{Smin}} = \frac{V_S}{V_{CYL}} = 4, \tag{1}$$

where M and V denote, respectively, the mass and volume of steam (subscript S) and the subscript CYL refers to the steam cylinder.

According to Equation (1) the mass of steam generated in the boiler was 4 times larger than the minimum mass required. In other words, only 1/4 of the steam leaving the boiler was effectively used to perform work while 3/4 had been wasted. On the basis of this relationship, Watt estimated the potential saving of coal or the "increase" in coal energy to be 75%. From this result he concluded that any useless vapour condensation had to be prevented. Being the cause of this condensation, heat losses in the entire engine's installation had to be avoided. This insight was important, not only for the further development of steam engines, but also for the economy of coal consumption.

2.2. Causes of High Steam Losses

<u>1) Geometric similarity</u>

Watt found that the boiler of the model Newcomen engine could not supply the cylinder with sufficient steam to keep the engine in operation. In order to understand the enormous waste of steam, Watt compared the geometries of the model and the real steam engine [5], p. 99. He calculated, in both cases, the ratio of the surface area A to the volume V of the cylinder occupied by steam. Watt did not state any formula he used, but his description suggests the following expression,

$$A/V = (4/d) + (2/L) \sim 1/d \,, \quad L \gg d \,, \tag{2}$$

where d is the diameter and L is the length of the cylinder. The ratio A/V may be viewed as the area of heat transfer surface per unit volume of steam occupying the cylinder. Watt's calculation showed that the model (small d) possessed much larger ratio A/V than the real engine, and the two cylinders were not geometrically similar. (It is not clear whether Watt actually had the geometric similarity criterion in mind when he compared the steam cylinders). The geometric disproportion was unfavorable for the model regarding fuel (coal) economy. Taking the other parameters to be the same, a cylinder with a smaller diameter d provides a larger ratio A/V and withdraws more heat from the steam per unit volume, thus causing a relatively larger heat loss.

2) Material properties

In addition to the geometric disproportion, Watt also considered the effects of the material properties of the cylinder on the heat losses. The cylinder of the model was made of brass, a material with thermal conductivity, approximately double that of the cast iron used in large engines. Relatively larger heat losses across the cylinder wall of the model engine were thus unavoidable. In this context the large mass density of the cylinder materials (metal) should also be mentioned. Watt tried to use other materials for the cylinder, like wood, but the disadvantages outweighed the advantages and the idea was not pursued further.

3) Mode of operation

In the Newcomen engine, the steam cylinder was alternately heated and cooled, and Watt realised that this was the main, though not the only, reason for the high heat losses and wasted steam condensation. In addition, he also realised that the heat supplied to the cylinder was partly transferred across the cylinder wall to ambient as a heat loss. For this reason, he enveloped the steam cylinder of the engine that he developed later with a layer of saturated steam. This measure reduced the heat losses almost completely.

In conclusion, Watt realized the heat losses of the Newcomen engine to be decisive regarding the useless consumption of fuel whereas the mechanical losses (friction and inertia) were of less importance for the economy of the engine. He tried to reduce the heat loss by insulating the engine parts, an idea that later proved to be very fruitful. In our terminology, Watt's ideas on heat losses are synonymous with a reduction of thermal irreversibility of the system. Sadi Carnot used the temperature difference in his theoretical discussion of thermal reversibility. According to Newton's law of cooling, the heat flow (loss) across the system boundary is proportional to the temperature difference, so Carnot would have arrived at the same results if he had worked in terms of the heat loss instead. The notion that Watt's ideas were included in Carnot's analysis, cannot be ruled out.

3. Physical Properties of Water and Steam

3.1. The Latent Heat of Steam

The term latent heat was introduced by Joseph Black (1728-1799) who was, apparently, the first to recognize that heat is consumed or released during the change of phase of a substance even though the temperature remains constant. For example, the conversion of water to steam at constant pressure consumes heat that cannot be detected by a thermometer but is regained when the phase transition is reversed and the steam condensed. With respect to temperature, the action of the heat remained ***hidden*** and Black referred to it as ***latent heat***. Independently of Black, James Watt also realized that heat consumption or production occurred during the phase change, particularly with water evaporation and steam condensation. Here we discuss Watt's understanding and his experimental determination of the latent heat of steam.

Watt's first, rather crude, experiments were performed in 1765 ([1], p. 10, Footnote) and these were followed by more precise measurements in 1781 ([1], p. 6, Experiment I). In the experiments, Watt used the method of direct condensation of saturated steam in initially subcooled water of known mass and temperature. He introduced into the subcooled water a stream of saturated steam which, according to Farey, [2], p. 312,

… *mixed with*, *and condensed in*, *that water*, *which received all the heat of the steam*, *till it became boiling hot*, *and could condense no more* : *the water in the jar was then found to have gained about one-sixth part of its weight*, *by the addition of the condensed steam*; *whence it appeared that one pound of water*, *in the state of steam*, *can heat six pounds of water from 52 deg. to 212 deg.*

Due to the steam condensation both the mass and the temperature of the water increased and this allowed Watt to calculate the latent heat. Watt's method is best illustrated if we neglect thermal losses in the experiments and repeat his evaluation. Assuming isobaric conditions in the experiments, the following energy balance:

$$m_S h_{vl} = m_W c_{pW} \Delta T_W \tag{3}$$

holds, where m denotes the mass of initially subcooled water (subscript W) and saturated steam (subscript S) condensed in the water; c_{pW} is the average specific heat capacity of the water in the temperature range ΔT_W (52˚F to 212˚F) covered by the experiments, and h_{vl} is the specific latent heat of steam condensation. Watt did not write the energy balance using symbols, but effectively applied Equation (3) in his calculations.

Using Watt's experimental data,

$$m_W / m_S = 6\,, \quad \Delta T_W = (212 - 52)^{\circ}\mathrm{F} = 160^{\circ}\mathrm{F} = 88.89^{\circ}\mathrm{C}\,,$$

and the NIST (US National Institute of Standards and Technology) value[2] for the

[2]In [1] Watt mentions the specific heat of some metals in comparison to water; for water, he set c_{pW} = 1 as a reference value, and measured the latent heat in degrees Fahrenheit.

specific heat capacity of water, $c_{pW} = 4200.0\ \text{J}/(\text{kg}\cdot\text{K})$, Equation (3) gives,

$$h_{vl} = (m_W/m_S)c_{pW}\Delta T_W = 6\times 4200.0\times 88.89 = 2240.0\ \text{kJ/kg}.$$

This value Watt obtained 250 years ago from a simple but ingenious idea is only 0.77% smaller than the actual standard (NIST) value of 2257.4 kJ/kg. The deviation is most probably caused by heat losses to the surroundings and to the pan containing the water in Watt's experiments. The remarkable agreement underlines the depth of Watt's investigative ability and the rigour of his analysis.

Watt adopted Joseph Black's method for expressing the latent heat of evaporation (equal to latent heat of steam condensation) as the temperature rise of the liquid phase in degrees Fahrenheit (˚F) which would be caused by the absorption of that heat without evaporation. This method follows from Equation (3). Watt obtained a latent heat of 950 (degree F) at a saturation temperature of 212˚F and of 1000 (degree F) at a saturation of 70˚F ([1], pp. 6-7). Watt therefore concluded that the latent heat decreases with increase of temperature.

It is instructive to compare Watt's method with the one used by Joseph Black. Three years prior to Watt's experiments, in 1762, Black [6] conducted experiments on the latent heat of evaporating water. He heated and evaporated a quantity of water in an open pot and measured the time required to heat the subcooled water from the initial to the boiling temperature and also the time needed to completely evaporate the saturated water. From a comparison of these times, he obtained the latent heat of boiling water. Black did not use any heat balance and his method is affected by the condition of heat transfer to the heated and evaporating water. Compared to Watt's experiments of 1765 and 1781, Black's method was not scientifically rigorous. This is possibly the reason why Watt did not use it in his experiments. Watt was therefore the first scientist to determine precisely the latent heat of water.

3.2. The Total Heat of Saturated Steam

Using the latent heat, Watt defined the total heat of steam as the sum of the sensible heat required to raise the water temperature from the reference value (e.g. 32˚F = 0˚C) to the saturation temperature at the prevailing pressure and the latent heat required to evaporate the water at that pressure. For an easier discussion, we shall express this idea analytically.

Denoting the total heat of saturated steam by h_S, we can express Watt's idea by the equation,

$$h_S = c_{pW}(T_S - T_R) + h_{vl} \tag{4}$$

where the subscripts R and S refer, respectively, to the reference and the saturation state of water; (T_R is usually taken to be zero, $T_R = 0^\circ\text{C}$). The first term that results from the temperature difference is sensible heat, since it can be detected by a thermometer; h_{vl} is the latent heat. Today, Equation (4) defines the specific enthalpy of saturated steam. In Watt's time Equation (4) was known as ***Watt's law of latent heat***; see e.g. [7] and [8]. Watt was inclined to believe that the total heat of steam h_S was independent of pressure which was an acceptable approximation given the range of pressure variation covered by his experiments.

Watt's Equation (3) is valid only when the originally subcooled water is heated up to the saturation temperature T_S. Its validity can be extended to any temperature $T_1 < T_S$ by using the total heat of steam according to Equation (4). The mass and heat balances then give:

$$m_S\left(c_{pW}\left(T_S - T_1\right) + h_{vl}\right) = m_W c_{pW}\left(T_1 - T_W\right), \tag{5a}$$

or

$$h_{vl} = \left(\left(m_W / m_S\right)\left(T_1 - T_W\right) - \left(T_S - T_1\right)\right)c_{pW}. \tag{5b}$$

The change in the total heat of steam (left hand side of Equation (5a)) covers the heating of subcooled water m_W from T_W to T_1. For $T_1 = T_S$, Equation (5a) becomes identical to Equation (3). Setting $c_{pW} = 1$, as Watt actually did, Equation (5a) results in Watt's original scheme for calculating the latent heat [1], p. 7; in this case, Equation (5b) becomes identical to the equation Capecchi [9] deduced from the Watt's calculation table.

3.3. The Thermodynamic Critical State of Water

The interaction of the sensible heat and latent heat as parts of the total heat of steam was important for Watt regarding the coexistence of the two phases (steam and liquid). Watt understood these components to undertake reciprocal alterations (at constant total heat) when the pressure is varied; an increase of pressure decreases the latent heat. He linked the coexistence of the phases (water and steam) along the saturation line with the latent heat, and from his experiments he observed a decrease of latent heat with increasing pressure. At a sufficiently high pressure, he expected the latent heat to disappear while water underwent some remarkable changes. Accordingly, Watt specified in 1782 a new state of the steam-water system, today known as the *thermodynamic critical state*, [10], p. 5, see below. The temperature and pressure at which the latent heat becomes zero determine a point that is now known as the *critical point*, and which we might also call the Watt's point.

Watt stated this idea in a letter to J.-A. De Luc (Jean-André De Luc, Swiss-English scientist, 1727-1817), dated 13 December 1782. In an extract from this letter ([10], p. 4), we read:

Dr. Priestley has made a most surprising discovery, which seems to confirm my theory of water's undergoing some very remarkable change ***at the point where all its latent heat would be changed into sensible heat****, which must follow from the diminution of the latent heat, as the sensible heat increases, probably at or near 1200° of Fahrenheit.* (emphasis added).

The letter was written at a time when the composition of water was still being discussed. Watt was involved in this discussion and his letter, printed in Muirhead book: *Correspondence of the Late James Watt on his Discovery of the Theory of the Composition of Water* [10], could actually be associated with the constitution of water. However, based on Watt's experiments on the "common" latent heat of steam that decreases as the pressure and temperature increase, the quotation is concerned with the vapour-liquid phase transition. Watt stated the total heat of steam at which the latent heat would disappear to be nearly 1200 (degree F), independent of pressure. According to his own experiments at atmospheric pressure, (Watt [1], p. 7, Miller [8], Capecchi [9]), the total heat of steam should lie between 1134 (degree F) and 1177 (degree F) which is very near to the value he estimated earlier. His Equation (4), too, gives for the total heat of steam ($c_{pW} = 1$ and $h_{Vl} = T_R = 0$) the value $h_S = 1200$ (degree F), approximately. In 1853 Charles Siemens [11] published a review paper stating the total heat of water at the critical point to be 1180 (degree F), which is only 20 (degree F) below the value of 1200 (degree F) which Watt had estimated seven decades earlier, in 1782. These additions support the notion that Watt was referring to the critical state of the steam-water system, and not the state of thermal decomposition of steam at much higher temperature.

Watt explained the decrease and disappearance of latent heat in a letter of 13th December 1782 sent to Dr. Black, stating ([10], p. 5)

… *that, as steam parts with its latent heat as it acquires sensible heat, or is more compressed, that when it arrives at a certain point it will have no latent heat, and may, under proper compression, be an elastic fluid nearly as specifically heavy as water; at which point I conceive it will again change its state and become something else than steam or water. My opinion has been that it would then become air;* …

This quote refers to a steam-water system below the critical temperature where the latent heat is finite and decreases as the critical point is approached, whereupon it disappears. Watt's comparison of water at this point with air could be interpreted as the decomposition of water into its constituents. Actually, however, the comparison seems to be symbolical. Watt chose air for comparison to emphasise the dramatic changes in the state of water at the critical point which, according to Watt, was neither steam nor ordinary liquid. He mentions a large steam elasticity which he did not expect at such a large steam density. Today we can express Watt's idea on elasticity at the critical point by the relationship $\partial p/\partial v = 0$, which implies that a small variation of pressure p causes a very large variation of the specific volume v.

Some authors ascribe the detection of the critical point to Cagniard de la Tour, who in 1822/3 published two papers dealing with critical phenomena. Berche *et al.* [12] mention James Watt's decrease of the latent heat with increasing temperature, but not its disappearance at a certain (critical) temperature. Nonetheless, the above facts show conclusively that Watt's idea on the critical state of water preceded the works of Cagniard de la Tour by four decades.

Figure 1 illustrates the position of the Watt (critical) point in a T, p-diagram; its coordinates for water are approximately: $T_{CR} \approx 647.0\ \text{K}$, $p_{CR} \approx 22.0\ \text{MPa}$. Along the Watt-curve the two phases exist in equilibrium, while in the supercritical region, $T > T_{CR}$ and $p > p_{CR}$, the system is in a kind of single-phase

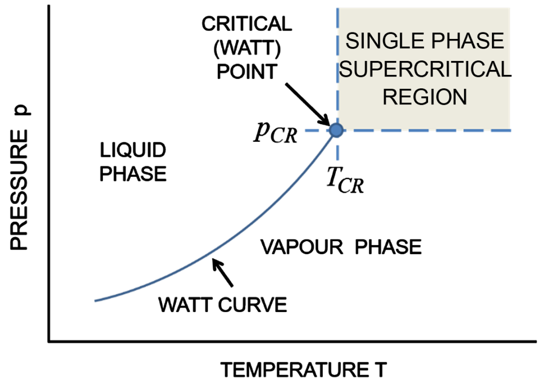

Figure 1. Position of the thermodynamic critical (Watt's) point of a pure fluid substance in the *T*, *p*-diagram. Starting at low values of *p* and *T*, the latent heat decreases along the curve, vanishing at the temperature $T = T_{CR}$.

state. In this region the system shows remarkable changes, as stated by Watt in 1782. Watt's experiments extended from a pressure of 0.15 inches of Hg to 22 inches of Hg and from 30 inches of Hg to 82 inches of Hg and hence only covered a small region of the whole pressure range.

4. Watt's Energy Conversion Principle

4.1. Watt's Patent of 1769: The Separate Condenser

With this patent Watt devised and introduced a separate condenser and substantially changed the conception of the Newcomen steam engine.[3] Here we provide a short explanation for the need of the condenser which Watt himself formulated in his patent of 1769 [13] [14]. Watt states in the first paragraph of the patent (the letters a), b) and emphasis added):

__First__, that vessel in which __a) the powers of steam are to be employed to work the engine__, which is called the cylinder in common fire engines, and which I called the steam vessel, must during the whole time the engine is at work kept __b) as hot as the steam that enters it__, first, by enclosing it in a case of wood or any other materials that transmit heat slowly; secondly, by surrounding it with steam or other heated bodies; and, thirdly, by suffering neither water or any other substance colder than the steam to enter or touch it during that time.

According to Watt, a), the power of steam drives the engine; he does not mention any heat explicitly in this context because the first energy conversion step has been completed by the steam production in the boiler. In addition, he was not convinced that the word heat alone would adequately encompass the ability of steam to do work. He sought to include also the pressure into considerations, but first without much success. Watt's idea is understandable: a multiplication of the pressure by the specific volume of the fluid, shifts the physical property

[3]In 1974 A. J. Pacey [15] stated the invention of the Newcomen atmospheric steam engine (1712), the patent of James Watt for a condenser separate from the engine's cylinder (1769), and Watt's further patent for the expansive use of steam (1782) to be the outstanding events of the eighteenth century for the historian of thermodynamics. These Watt patents are important for the development of thermodynamics as a science.

pressure to a higher quality, namely energy. Watt's intuition turned out to be justified by his invention of the pressure indicator.

Watt required, b), the steam cylinder to be kept at the same temperature as the steam entering it throughout the whole time the engine is at work. This means the complete thermal decoupling of the cylinder from the surroundings and the avoidance of all heat losses. He also specified the ways how this could be achieved.

Watt's patent does not allow for any temperature changes in the cylinder wall, neither temporally nor spatially. This condition also excludes the alternating heating of the cylinder (filling with saturated steam) and its cooling with water (steam condensation) as in Newcomen's engine. Consequently, the whole of Newcomen's conception of the steam engine collapses with the Watt's patent.

Watt's formulation was not an ***ad hoc*** statement but was based on a thermodynamic inspection of the Newcomen engine and a detailed analysis of the heat losses, starting with the boiler. According to Watt's ideas, the first step of energy transformation in his cycle occurs with water evaporation in the boiler where the heat is mostly consumed for steam production (increase of total heat, Equation (4)) at constant pressure. Thence heat is partly transformed in mechanical (potential) energy of steam, $p\left(v_S - v_L\right)$, and partly dissipated to ambient as heat loss. Watt seemingly understood the product pv_S as the power of the steam in his patent of 1769, which would justify his attempt to include the pressure in the thermodynamic analysis of the engine.

According to Watt's analysis, the latent heat of steam was irrelevant for the conception and introduction of the separate condenser. Consequently, unjustified are also speculations in the literature linking the role of Joseph Black and his doctrine of latent heat of steam with Watt's invention. Watt's guiding idea for the conception of a separate condenser was not the latent heat but the suppression of all unintended heat losses which caused useless steam condensation and a reduction of the power delivered.

Figure 2 shows a drawing of the steam engine as described in Watt's patent of 1769. The steam cylinder (a), enveloped by a layer of steam, is connected to the boiler (not shown in the drawing). This construction almost completely prevented heat losses to the environment. The separate condenser (h), situated below the steam cylinder, is immersed in cooling water. In comparison to Newcomen's installation, the Watt's arrangement increased the performance of the engine substantially. The figure contains all the important details of the working principle of a steam engine and can be read like a book on thermodynamics. In this respect it is comparable to the Galileo's book of nature.

4.2. The Equivalence of Heat and Work

For some 40 years, around the transition from the 18th to the 19th century, Watt's steam engine was the main industrial facility for converting thermal energy (heat) into mechanical work. Watt practised this kind of energy conversion several decades before the "official" development of thermodynamics began in the first half of the 19th century. On page 337 John Farey [2] states (see also p. 330):

In 1778, when Mr. Watt first established his engine, his proposals were to raise 500,000 cubic feet of water 1 foot high by the consumption of one hundred weight (=112 lbs) of Wednesbury coals.

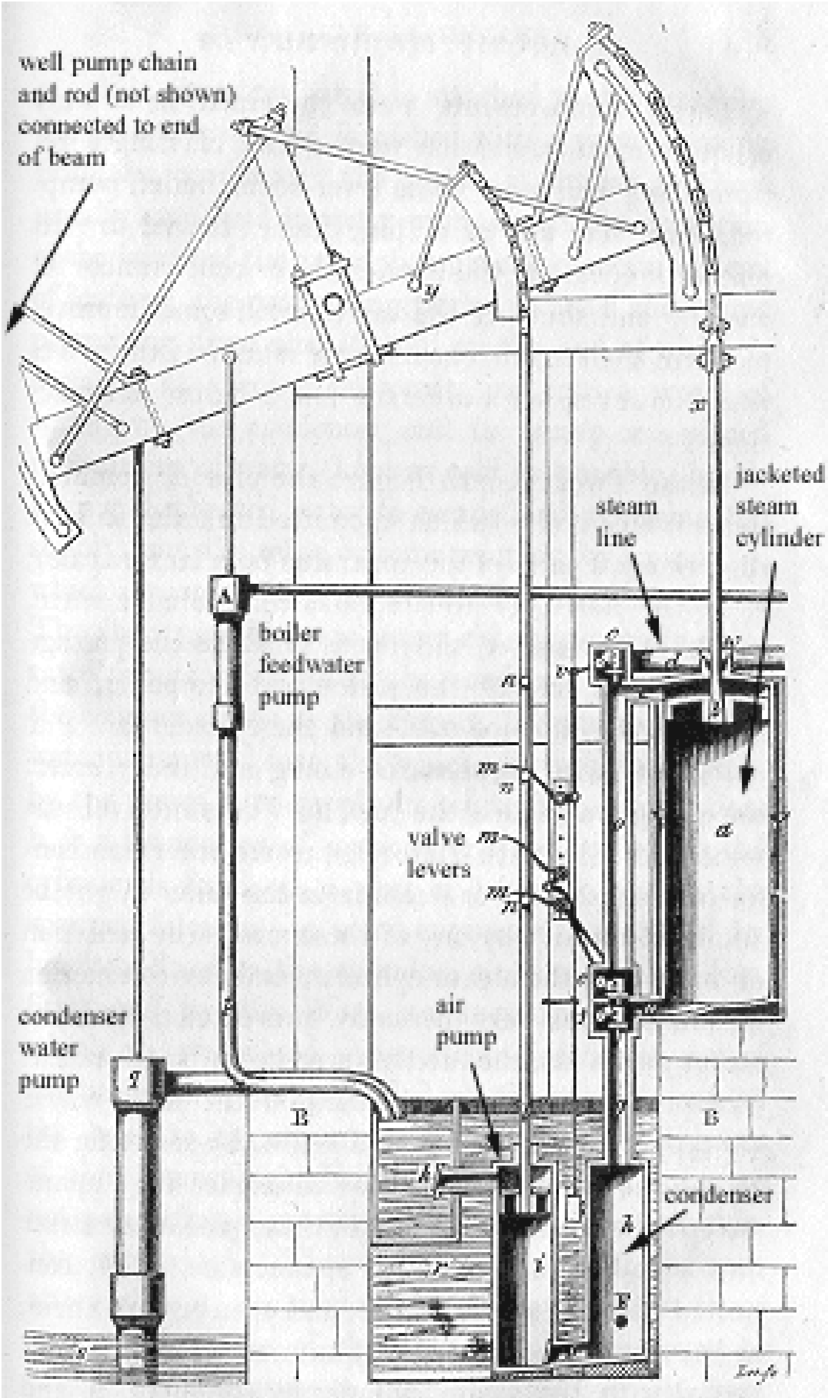

Figure 2. Watt's steam engine with separate condenser (h) as described in his patent of 1769, built 1774; the water boiler is not shown in the drawing. The drawing in Stuart's book ([5], p. 114) is without text; C. Lyra, Michigan State University, presents the figure with text but without mentioning the author,
https://www.egr.msu.edu/~lira/supp/steam/wattengine.htm.

This proposal is important for understanding the equivalence and mutual convertibility of different energy forms. Its greatest value consists in showing the profound connection between heat that disappears and reappears as work. This interconnection became later a pillar of the foundation of the dynamical theory of heat. In order to easier overview the proposal's content, we shall reduce it to a relation of physical quantities, assuming the term consumption to mean the burning of coal and the production of heat. Watt's proposal then expresses the energy balance of a set of real processes spanning three modes of energy conversion (chemical energy of coal → heat → mechanical energy of steam → useful mechanical work), taking into account all the energy losses of the engine's installation.

Multiplying the mass, M, of coal consumed in the reaction by the heat of this reaction, H, Watt's proposal can be cast in the quantitative energy equation:

$$H \cdot M = V \cdot \rho \cdot g \cdot h + E_{loss} \tag{6}$$

(Heat = Work + Losses)

(V-volume, ρ-mass density, h-elevation height of water,
g-acceleration of gravity, E_{loss}-sum of all energy losses).

Equation (6) specifies the quantity of heat (coal) required to produce a quantity of mechanical work by using Watt's steam engine. The quantity E_{loss} encompasses all losses of the energy conversion process, *i.e.*, friction and heat losses, including also the heat of steam condensation in the condenser. Consequently, Watt's proposal not only states the equivalence of heat and work but also measured the heat in mechanical units.[4] The conversion of energy from one form into the other, does not contradict to the idea of its conservation, hence the Watt's proposal expresses also the principle of energy conservation. On its basis Cardwell [16] guessed that a given amount of heat must correspond to a given amount of work. Because of the statement's clarity, it is possible that later investigations into the mechanical equivalent of heat, such as those of Joule [17], have been motivated by the Watt's proposal.

4.3. The First Law of Thermodynamics

Equation (6) leads to an important relationship of thermodynamics if the energy (heat) losses are assumed—as is usually done in publications—to arise only from steam condensation in the condenser and set, $E_{loss} = Q_C$, where Q_C denotes that wasted heat. The product $H \cdot M$ is equal to the heat Q_B, the working substance receives in the boiler. Denoting, in addition, by W the elevation work, $V \rho g h = W$, Equation (6) takes the form

$$Q_B = W + Q_C. \tag{7}$$

The heat Q_B is converted in the steam cylinder into the work W and wasted heat Q_C. This equation is well-known from literature as the ***First Principle of Thermodynamics***. It's formulation by James Watt in 1778 preceded by more

[4]Equation (6) does not contain the coefficients of energy equivalence which would be necessary if the terms were measured in different units.

than 6 decades the next generation of similar works, starting with R. Mayer and J. P. Joule in the 1840s. Collins [18] names it *the Mayer-Joule Principle*. The meaning of the terms Q_B and W are mentioned in the Watt's proposal, while the term Q_C follows from the fact that steam engine was used for energy conversion. In his 1769 patent, Watt described the principle of the steam engine and identified the heat of condensation of the steam Q_C as wasted heat [3].

Equation (7) is suitable for quantifying the consequence of the idea that heat is transported from the boiler to the condenser without consumption, $Q_B = Q_C$, as S. Carnot and W. Thomson (Lord Kelvin) (and apparently also R. Clausius) originally thought; in this case no work is won, $W = 0$. If the work W is supplied to the system instead of Q_B, then with $Q_B = 0$, the Watt's Equation (7) becomes $W + Q_C = 0$, expressing the energy balance of the Joule's padlewheel experiment where Q_C represents the change of the internal energy of the fluid.

For other formulations of the first law of Thermodynamics, Equation (7), the reader is referred to common books on Thermodynamics. Here we only show the version with the internal energy which was motivated by an anonymous reviewer. We consider a cylinder filed with gas that is enclosed with a movable piston and take Q_B to be the heat supplied to the gas, W is the work done by the gas (expansion). Then Q_C is not wasted as in the steam engine but it remains in the gas representing the change of internal gas energy, $Q_C = \Delta U$. Hence: $Q_B = W + \Delta U$.

Energy splitting in the steam engine: The energy splitting is an important step of the energy conversion process. This step is illustrated in **Figure 3**. It shows a section of **Figure 2** surrounding the steam cylinder. The splitting of the energy Q_B according to Equation (7) takes place on the piston as it moves down the cylinder. Literally, the piston acts as a permeable device, allowing only the mechanical energy $p\mathrm{d}V$ of the steam to leave the cylinder and do the work W, $W = \int p\mathrm{d}V$.

The transfer of the work from the piston to the water pump q takes place via the vertical rod x, **Figure 2**, and the massive rocker (beam), which can perform small angular movements in the plane of the drawing around its suspension point. The heat Q_C leaves the cylinder mainly as latent heat of steam; after the condensation in the separate condenser, it becomes absorbed by cooling water and wasted as sensible heat.

4.4. Flow Sheet of Watt's Energy Conversion Process

The drawing of Watt's installation in **Figure 2** is too complex for a quick overview of the whole energy conversion process. On the basis of this drawing and Watt's patent of 1769, a simple flow sheet, shown in **Figure 4**, will be used for a brief description. The main elements are the water boiler, the steam cylinder, the separate condenser and the feed pump. These components constitute the Watt's cycle. The working substance changes its potential (state) mainly in the boiler and in the steam cylinder; the changes in the feed pump and the condenser are

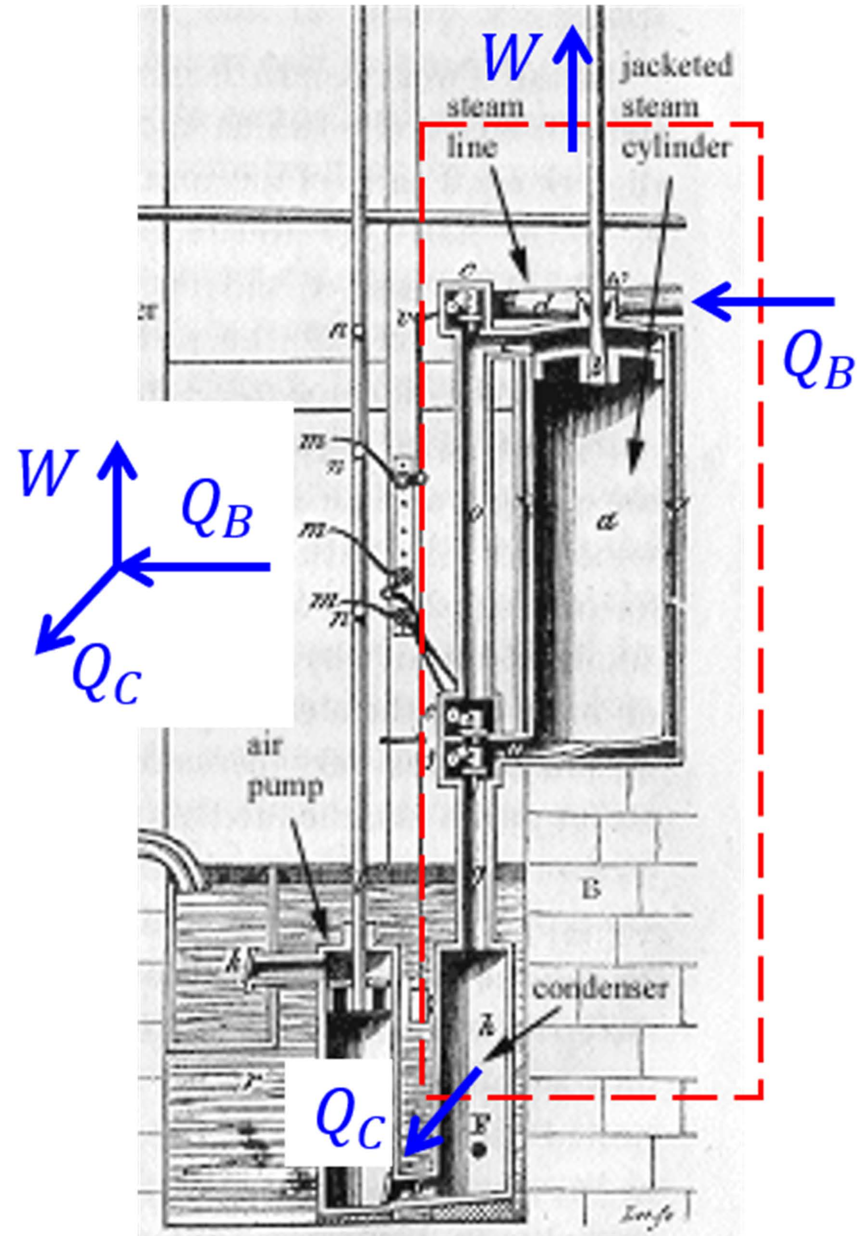

Figure 3. Watt's illustration of the first law of Thermodynamics as energy splitting in the steam engine (supplemented section of **Figure 2** surrounding the steam cylinder).

not separately illustrated. With this assumption the change of potential in the boiler is equal and opposite to that in the steam cylinder. The term potential used here shall account for Watt's idea stated in his patent of 1769 that the power of steam drives the engine [3].

The conversion of energy in the Watt's cycle is best illustrated by the Newton analogy. Newton studied the interaction of elementary particles of matter in terms of forces, assuming that the interaction force is repulsive at one particle distance but attractive at the other. The change in force is continuous as the distance changes continuously. Using his algebra, Newton said [19]:

… And as in Algebra, where affirmative Quantities vanish and cease, there negative ones begin; so in Mechanicks, where Attraction ceases, there a repulsive Virtue ought to succeed. …

If we replace the positive and negative quantities in Newton's algebra by different forms of energy, we can conclude that where one form of energy decreases and disappears, the other form of energy emerges and increases, while the total energy of the systems remains conserved.

The flow sheet of the Watt's stem engine in Figure 4 constitutes the skeletons of several modern energy conversion plants. For instance, replacing in Watt's installation the steam cylinder by a steam turbine with an electric-generator, it becomes identical to the flow sheet of a contemporary power plant operating with saturated steam. The flow sheet (on the left) not only shows the implementation of Equation (7) but also the temperature range covered by the steam engine. The steam has the highest temperature in the boiler and the lowest in the condenser. Watt recommends keeping the temperature in the condenser as low as possible (depending of cooling water). He did not limit the temperature in the boiler directly, but for safety reasons (boiler explosion) via the steam pressure, which he determined himself as a function of the temperature. Because of $T = f(p)$ he clearly defined the temperature of the working substance in the boiler and thus also the temperature range of the steam engine. This temperature range Watt defined corresponds exactly to the definition that Sadi Carnot published in his 1824 dissertation. Carnot's definition is known in the literature as Carnot's postulate, while James Watt is never mentioned as the originator of this idea. Further details are given in [3].

4.5. Watt's Patent of 1782: The Steam Expansion

In this patent, titled Certain New Improvements Upon Steam Or Fire Engines…, Muirhead [20], we consider only the specification No. 1:

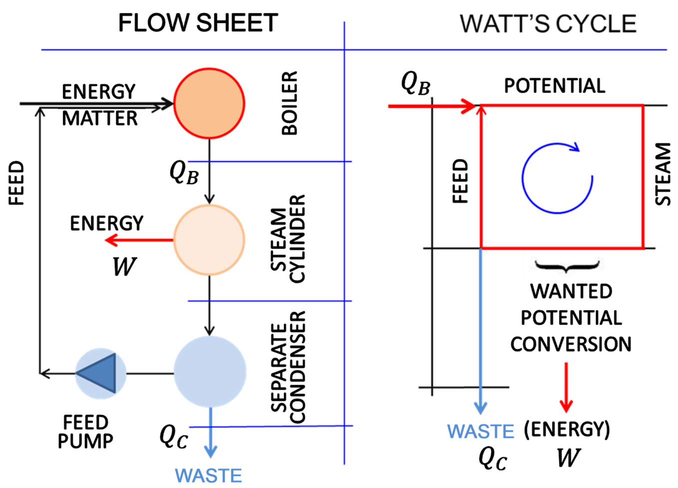

Figure 4. Simplified flow sheet of Watt's energy conversion process. For the meaning of Q_B, W and Q_C see Equation (7).

The use of steam on the expansive principle: *together with various methods or contrivances*, (*six in number, some of them comprising various modifications*), *for equalising the expansive power*.

Preparing the reader for an easier understanding of the expansive action of steam in the cylinder, Watt described in the patent first the effect of a constant steam pressure acting on the top of the piston moving downwards. He denoted this effect as the power of the elastic steam force. Watt's reasoning resulted in the definition of a new important quantity; the work done by the steam due to change of volume; next we illustrate some steps of Watt's idea.

1) The work due to change of steam volume at constant pressure

Watt states that, if the power of the elastic steam force were employed to act upon the piston through the whole length of its stroke, and to work a pump connected to the stroke as is usual in steam engines, it would raise through the whole length of its stroke a column of water whose weight should be equal to several pounds per square inch of the area of the piston, besides overcoming all the friction and inertia of the water and the parts of the engine. Watt utilized the increase of volume of steam in the cylinder at constant pressure to perform work. The later became known as the volume work of steam.

Following Watt's description, the steam pressure p acting on the piston, multiplied by the piston area A determines the force F acting on the piston,

$$p \cdot A = F \text{ ,} \tag{8}$$

which, multiplied by the length L of the stroke, gives the work W performed by the steam,

$$W = F \cdot L = p \cdot A \cdot L = p \cdot V \text{ ,} \tag{9}$$

$V = A \cdot L$ being the volume of the steam in the cylinder. If the piston travels a small distance dL, the work done by the steam is

$$\mathrm{d}W = p \cdot \mathrm{d}V \text{ , } \quad \mathrm{d}V = A \cdot \mathrm{d}L \text{ .} \tag{10}$$

These expressions were known to Watt; the last one is important when calculating the work of expanding steam. Thus far the volume work of steam at constant pressure according to Watt's idea.

2) The expansion work at constant temperature

For calculating the work of steam expanding at constant temperature, Watt devised a thought experiment which consisted in cutting off the steam filling the cylinder at certain point, before the whole cylinder becomes full of steam, and allowing the supplied steam to expand in the cylinder. **Figure 5** illustrates the core of the Watt's idea which was included into the patent specification of 1782. It shows the calculated pressure distribution along the cylinder length if cutting off of the steam supply occurs at the steam volume occupying 1/4 of the cylinder volume. The supplying steam is nearly at atmospheric pressure.

Watt showed in the patent that the specific power of the steam engine is not reduced if the steam admitted into the cylinder does not fill its entire volume. The subsequent steam expansion was described by equation of an ideal gas. The

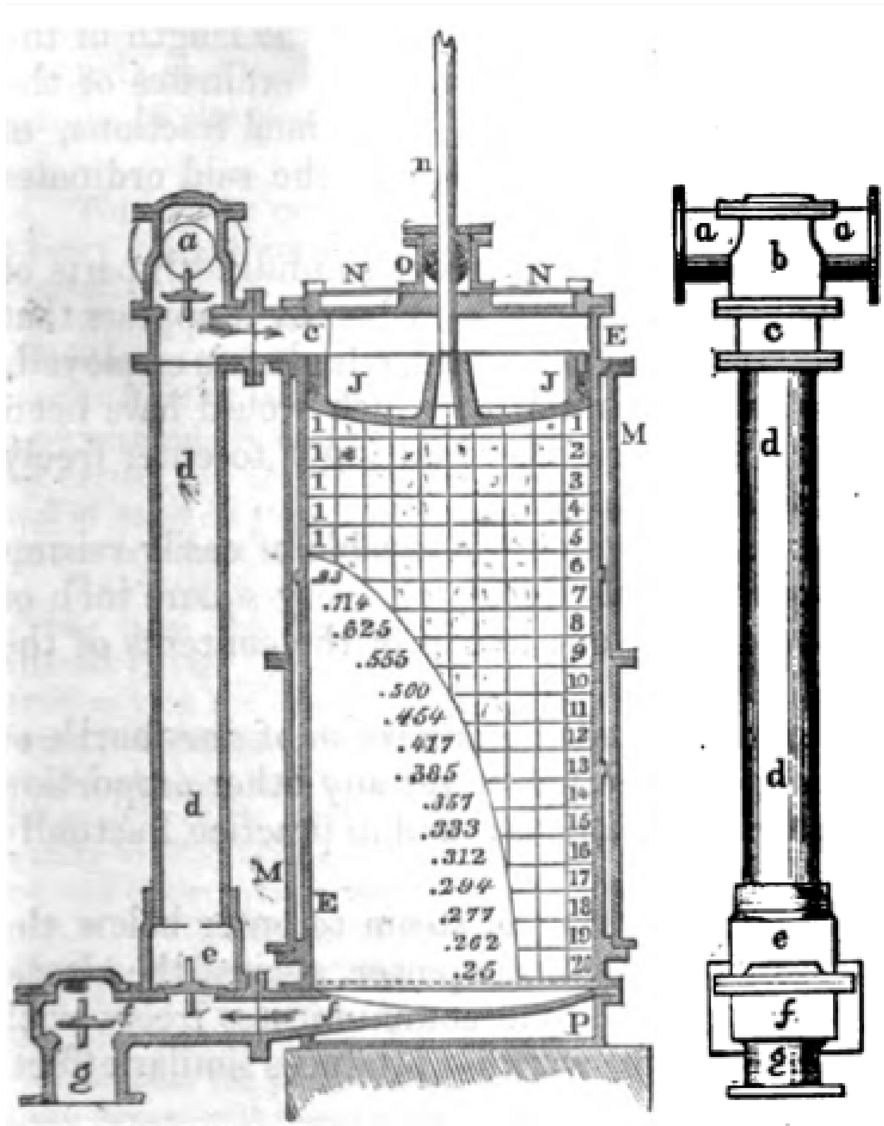

Figure 5. Isothermal steam expansion according to Watt's calculations as part of his patent specification of 1782. Pressure distribution along the cylinder when steam admission cut-off occurs at a steam volume in the cylinder equal to 1/4 of the cylinder volume, Farey [2], p. 347.

curve in Figure 5 corresponds to this equation, the numbers along the curve represent the calculated pressure divided by the pressure of supplied steam prior to expansion. Every two neighboring horizontal lines symbolize circular surfaces which together with the cylinder circumference define an element of steam volume V_k, the index k referring to the k-th element (of total 20 identical elements). The volume work W_k of the k-th element is given by

$$W_k = p_k \cdot V_k, \tag{11}$$

which is basically the Equation (10). Since the volume V_k of the elements does not change along the cylinder, we can write

$$V_k = l_k \cdot A_k = l \cdot A = const$$

$$W_{exp} = \sum W_k = \sum \left(p_k \cdot V_k \right) = l \cdot A \cdot \sum p_k \tag{12}$$

Setting in Equation (12) $l = L/K$, whereby K (=20) denotes the total number of compartments, and L the length of the stroke, **Figure 5**, we get the expansion work

$$W_{exp} = L \cdot A \cdot \left(\sum p_k \right) / K = V_{CYL} \cdot p_{av} \tag{13}$$

$$p_{av} = \left(\sum p_k \right) / K$$

Equation (13) expresses the Watt's calculation of the volume work of expanding steam. Its derivation coincides with the description Watt gave in his patent. Of the equations reported here he mentions only the sum of pressures of expanding steam, $\sum p_k$. Obviously, Watt applied the numerical integration to evaluate the expansion work. Farey's book provides some details of Watt's calculations, which are not given in the original patent of 1782, Farey [2], p. 341.

According to Watt's calculations the product of the average steam pressure p_{av} and the volume of the cylinder V_{CYL} is less with, than without, the steam expansion. However, dividing these products with the masses of steam taken from the boiler gives a larger value with, than without, the steam expansion. In other words, the work of steam per unit of mass of steam consumed is greater with the steam expansion.

Watt's assumption of an isothermal steam expansion leads to the weakest pressure change and the maximum benefit of the expansion process. Watt was aware of this correlation and tried to realize the isothermal conditions in practice. He surrounded the steam cylinder by a layer of steam having the same temperature, **Figure 2**. As ingenious as this measure may seem with regard to the thermal insulation of the cylinder, it would not have been possible to achieve isothermal, but rather an adiabatic steam expansion.

The benefits of steam expansion have been studied by several authors aiming at optimization of cutting-off point of the steam admission to the engine working expansively. As example we mention the investigations by Clark [21], published in 1852. **Figure 6** taken from Clark's publication shows the indicator diagrams obtained at various process conditions. The experiment N°1 provides apparently the largest expansion work, corresponding to the largest indicator area.

Watt's patent on steam expansion (1782) is a logical extension of his patent of 1769, where he already used steam expansion in the working step of the engine. By connecting the working cylinder filled with steam to the separate, empty and cold condenser, **Figure 2**, the steam expanded and enabled the piston to descend. Regarding the acceptance of Watt's steam expansion method in engineering practice and its use, particularly by Sadi Carnot, the reader is referred to the publication by Fox [22].

4.6. Condensation of Expanding Steam

In addition to the improvement of the engine performance by steam expansion, we shall also notice an important Watt's contribution to the foundations of

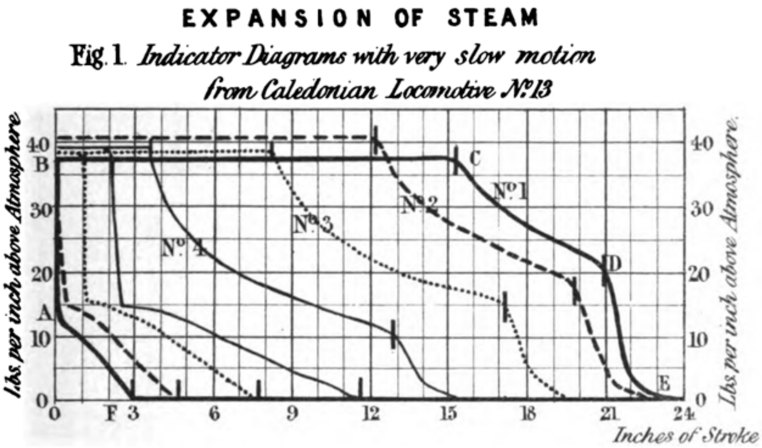

Figure 6. Effect of steam cut-off on the shape of the indicator diagram of expansively working steam engine: taken from Clark [21]. A—the *point of steam admission*; C—the *point of cutting-off, or suppression*; D—the *point of exhaust, or release*; F—the *point* of *compression*; also, the portion of the stroke described while the line AB is traced, is the period of *pre-admission*.

thermodynamics. Watt experimentally demonstrated the condensation of expanding steam in his laboratory at Soho, Birmingham. The occasion was the visit of Henry Cavendish and Charles Blagden on their "*Philosophical Tours*" in 1785. In this context, Miller [23] cites from the Cavendish's notebook:

Mr. Watt mentioned, that having found that some steam is condensed in the cylinder of the Steam engine, tho' surrounded with steam, he made an experiment to discover what happened. He threw steam into a Glass vessel close at the top (*By making it communicate with that part of the cylinder of this fire engine in which there is alternately Steam and Vacuum*) *and found that upon making the Vacuum some of the steam condensed on the sides of the Glass Vessel*; *and having heated the sides of this Vessel, so that none could condense upon them, he observed the condensation take place, so as to render the Steam visible in the middle of the Glass vessel* [...] *a cloud began to appear at each Vacuum* [...]

Since the condensation requires a steam cooling, Watt was the first to realize that **expansion of a steam causes its cooling**. The condensation occurred also in the steam bulk, without influence of a solid surface, which is today known as homogeneous phase transition. Formation of viable nuclei of the new phase (tiny water droplets) under such conditions requires certain metastability of mother-phase, which is measured in terms of steam subcooling. In 1788, three years after Watt's experiments, Erasmus Darwin [24] (grandfather of Charles Darwin) published a paper on air cooling by expansion. Next experiments in this area were performed by Joule [25] in 1845, more than 5 decades after Watt's experiments. Watt's name is neither mentioned in Darwin's nor Joule's paper, nor in any other publication on cooling of gases by expansion.

The pressure diagram of expanding steam in **Figure 5** did not satisfy its originator (Watt) because it does not provide any information on the expansion dynamics. The science at that time could not provide any information on this point and Watt was again required to devise a measuring device, this time a device that should indicate the steam pressure in the cylinder as function of the piston position. Thus, he later built and used in the experiments an instrument—the pressure indicator—for measurements of the pressure change in the steam cylinder.

4.7. The Watt's Indicator Diagram

In 1854 Rankine [26] published a paper and in 1859 a section in his book [27] (p. 301) on the expansive action of heat, including a *p, v*– diagram that corresponds to the famous diagram generated by the Watt's pressure indicator. The accompanying Rankine's text reads (1854):

The first application of a geometrical diagram to represent the expansive action of Heat was made by James Watt, when he contrived the well-known Steam-Engine Indicator, subsequently altered and improved by others in various ways. As the diagram described by Watt's Indicator is the type of all diagrams representing the expansive action of heat, its general nature is exhibited in ***Figure 1****.*

Figure 7 shows the shape of Watt's indicator diagram published as **Figure 1** by Rankine in 1854. Rankine states that the area encircled by the closed curve in the *p, v*-coordinates (**Figure 7**) represent the useful energy provided by steam, without clearly mentioning James Watt as originator of this idea, see Watt patent of 1782. Actually, Rankine is inclined to acknowledge Sadi Carnot and Emile Clapeyron as the originators of the *p, v*-diagram, but he hesitated to do this, because he did not accept their material notion of heat. However, Watt was the first to define the volume (expansion) work and to identify the encircled area in the *p, v*–coordinates as work performed by expanding steam in the cylinder, see **Figure 5**. With the *p, v*-diagram Watt introduced graphics into thermodynamics and provided a possibility to look in the steam cylinder and to visualize the energy conversion.

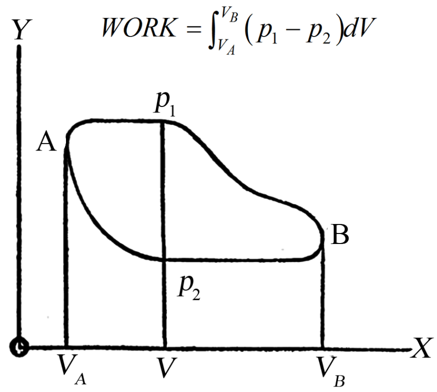

Figure 7. Rankine's sketch of Watt's indicator diagram (1854) supplemented by Watt's equation for expansion work, *Y* means pressure, *X* means the volume. (Rankine frequently stated the expression for calculating the expansion work but not clearly its origin. Already in his patent of 1782 Watt used such an expression, **Figure 4**. To show the details of his calculations, Watt expressed the integration by summation of elemental rectangles of the encircled area (numerical integration). We have included the integral form of Watt's expression as written by Rankine).

Watt used the pressure indicator and created several *p, v*–diagrams; from these he obtained the performance of his engines long before the next generation of scientists (including Carnot, Rankine, …) began to work in this field. As quoted above, Rankine acknowledges this too. Carnot also studied Watt's works and because of the clarity of Watt's ideas called him "***the famous Watt***" (Gillispie and Pisano [28]). Comparing Carnot's thermodynamics with Watt's thermodynamics, shown e. g. in **Figure 2**, we see that Carnot actually describes the process that Watt developed, published as drawings and used in practice for decades.

Lervig [29] extensively examined Sadi Carnot's studies of the works of James Watt, filling almost 50 pages. Attention was drawn to Carnot's involvement in calculating the steam engine's power. The heat of steam condensation was problematic because it wasn't clear whether to ignore or include it in the calculations. This is the quantity Q_C in our Equation (7) which gives an unambiguous answer: setting $Q_C = 0$ gives $Q_B = W$ and the heat Q_B would be completely converted into work, which is, however, thermodynamically impossible.

Based on Watts's contributions in the field of thermodynamics of energy conversion, one would expect his name to be at, or very close to, the central position regarding the history of thermodynamics. This is far from being the case! Watt is not mentioned in this context, and if the unit of power does not bear his name, James Watt, one of the originators of thermodynamics as a science, would long be forgotten.

5. Conclusions

James Watt's works associated with the development of the steam engines are at the origins of energy conversion thermodynamics. His patent of 1769, usually considered to be an improvement of steam engine, actually describes an energy conversion process of general validity. In this patent, Watt defined the range of steam temperature for running the engine, some 60 years prior to Sadi Carnot. The patent has brought thermal engineering to the scientific level. With the second, 1782 patent, Watt formulated and introduced the volume and expansion work of steam and enriched the general understanding of energy conversion.

Watt's works on latent heat of steam guided him to the conclusion that the latent heat of steam decreases with increasing temperature, becoming zero at certain temperature while the steam-water system assumes a new state which later was termed the thermodynamic critical state. Besides of latent heat of steam, he defined the total heat of steam, today known as the enthalpy of saturated steam. He was the first to observe condensation of expanding steam and to visualize energy conversion by using diagrams.

The most important Watt's contribution to the development of thermodynamics is probably his formulation of the first law of this discipline in 1778. However, the Watt's formulation went unrecognized and—as far as the author is aware—was first described in the present paper.

This paper supplements the previous work [3] and demonstrates the outstanding contributions of James Watt to understanding of the thermal processes. However, Watt's works were mostly considered to be prehistorical, which apparently motivated researcher to exclude him from the history of thermodynamics.

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A referee has carefully analyzed the content of the manuscript and stated several important questions.

Conflicts of Interest

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

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Appendix: Conversion of Mechanical Energy in Heat

The first artificial conversion of mechanical energy in thermal energy (heat) is thought to have been achieved with the creation of fire based on mechanical friction. Usually, Graf Rumford [30] (Benjamin Thompson, 1753-1814) is credited with the idea to be the first who conducted experiments in this area of energy conversion. In the experiments (… *boring of canon in the workshops of the military arsenal in Munich* …) conducted in 1798 he tried to answer the question: ***From whence comes the heat actually produced in the mechanical operation above stated?***

More than a century prior to Rumford, in 1675, Robert Boyle (1627-1691)[5] describes several methods of mechanical heat generation [31]. Despite the fact that Boyle's work provides excellent insights into the kinetic nature of heat, it is not mentioned in relevant publication. In Sect. II, p. 40, **Of the Mechanical Origin or Production of Heat,** Boyle notes:

… *the nature of heat consists mainly*, *if not only*, *in that Mechanical affection of matter we call Local motion mechanically modified*, …

On page 59, the experiment VI, he discusses the production of heat:

… *when a Smith does hastily hammer a nail or such like piece of iron*, *the hammer' d metal will grow exceeding hot*, *and yet there appears not anything to make it so*, *save the forcible motion of the hammer which impresses a vehement and variously determin' d agitation of the small parts of the Iron*; *which being a cold body before becomes* … *exceedingly hot*, …

Boyle recognized two important properties of heat:

1) Heat can be understood as motion of smallest parts of bodies,

2) Heat is produced by mechanical action (hammering of iron piece).

Consequently, heat cannot be of substantial origin, Boyle concluded, it is the magnitude of the process.

Boyle's work of 1675 precisely answers the Rumford's question stated in 1798. As follows from b), mechanical action produces heat. By incorporating the principle *cause equals effect* (G.W. Leibniz, 1646-1716): *There is neither more nor less power in an effect than in its cause* [32]), one arrives directly at a relationship between the mechanical work and heat, and Boyle could have determined the heat equivalent to the mechanical work that produced it from the following balance: Motion of gross body (kinetic energy of hammer) generates local motion (kinetic energy) of small parts of hammered piece. Identifying the kinetic energy of local motion as heat results in conversion of mechanical (kinetic) energy in heat.

The contacts of hammer and the piece of iron in Boyle's experiments can be viewed as a succession of inelastic impacts of two bodies. This immediately allows application of Leibniz's idea of conservation of energy – *vis viva* of 1692 in

[5]Robert Boyle was one of the founders of The Royal Society of London for Improving Natural Knowledge, established in 1660. The motto of the Society was: *Nullius in verba*, which could mean *Don' t take anyone' s words for granted*. The intention was to support experiments in scientific research.

an inelastic impact [33]. Since one body (hammered iron piece) is at rest, its kinetic energy (*vis viva*) is zero during the impact process. Also, the kinetic energy of the hammer after the impact is zero, which means that its pre-impact *vis viva* is completely transformed in local motion (heat) of iron during impact.

Actually, Leibniz assumed (in 1692) that *vis viva* in an inelastic collision is not conserved and that the apparent loss of this quantity is caused by its distribution among the small elements of impacting bodies, which is in agreement with the Boyle's experiment published in 1675, more than two decades earlier. This loss of *vis viva* is of local character and it is limited to the actual impact. Even in this case there is actually not a loss of *vis viva*, as Leibniz says: *For that which is absorbed by the minute parts is not absolutely lost for the total force of the concurrent bodies* [33], p. 144). Keeton provides a detailed discussion on the meaning of the terms conservation and conversion of energy [34].

In this context I shall mention a publication by Valenti of 1979 [35] which I happened to come across after the manuscript has been completed. Valenti states and credits Leibniz with the following balance equation:

$$\begin{aligned} &\text{vis viva consumed by machine} \\ &= \text{useful work}\left(\text{height a given quantity of wateris raised}\right) \\ &\quad + \text{heat lost in overcoming friction} \\ &\quad + \text{heat lost to superfluous cooling} + \text{other inefficiencies} \end{aligned} \tag{A1}$$

The equation expresses the equivalence of *vis viva* of fundamental elements of expanding steam and work done by steam in a steam engine. According to Leibniz, the work required to raise a heavy body to a certain height corresponds to the *vis viva* that the body acquires when falling from rest that height (Galileo's model). He suggested measuring the *vis viva* by the steam temperature, which thus also includes the vapor pressure into the balance. This equation shows the transformation of *vis viva* and its preservation (in other forms) in the whole process of the transformation. According to Boyle model sketched above, we can take the ***vis viva*** analogously to the heat of the steam; then the content of the Equation (A1) becomes identical to Equation (6) in the main text. However, Equation (A1) does not seem to exist in Leibniz's works which are accessible to the author of the present paper. Its existence does not emerge from Watt's works either. The actual author of Equation (A1) remains at present unknown.