

# Irreversible Thermodynamics of James Watt

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## Abstract

James Watt's thermodynamic works belong to the field of irreversible thermodynamics. In order to reduce heat dissipation from the steam engine to the environment, he devised and applied a method that essentially enabled reversible heat transfer. With this idea Watt paved the way for the next generations of scientists, but he is not credited in the literature as its creator. In recent papers the author has presented the James Watt's formulation of the first law of thermodynamics. An inspection of the energy conversion equation according to the first law shows that Watt simultaneously formulated also the second law. His results claim that heat cannot be fully converted into work.

## Keywords

James Watt, Irreversible Thermodynamics, Energy Conservation and Conversion, Thermal Efficiency, First Law, Second Law of Thermodynamics

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*“We narrow the reputation of Mr. Watt if we consider him only as a great practical mechanic; I believe him to be a profound philosopher and subtle chemist”.*

Sir Michael Shaw-Stewart, in 1836,  
and his grandson, Sir Hugh Shaw-Stewart, in 1936  
*Nature*, Vol. 137, pp. 131-133 (1936)

## 1. Introduction

In 1763, James Watt (1736-1819) was requested to repair a model of the Newcomen heat engine that consisted of a water boiler and a steam cylinder, equipped with a movable piston. In operation, the cylinder was used alternating also as a steam condenser. Watt repaired the model but he did not succeed to set it satisfactorily in operation. Subsequent Watt's analysis of the model that encompassed all energy losses, like mechanical friction and thermal losses of water boiler and the steam-condenser cylinder, revealed that only 25% of the steam

generated in the boiler were economically used in the engine, while 75% were wasted (Mitrovic & Smyk, 2021; Mitrovic, 2022a; Mitrovic, 2022b). Watt's analysis dealing with energy dissipation and heat losses is apparently the first work of this kind in the history of (irreversible) thermodynamics. Note that the terms energy, irreversibility and thermodynamics had not existed at that time.

On the basis of this analysis, Watt obtained in 1769 a patent which demonstrated fundamental knowledge on thermodynamics that he acquired and created since 1763 (Watt, 1769). William Rankine was apparently familiar with Watt's skills. In 1869, a century after Watt's patent, Rankine described some constructions of steam engines stressing their empirical nature. He introduced the time period of James Watt, stating (pp. XX-XXI, Rankine (1869)):

*...Then came the time when science was to effect more in a few years than mere empirical progress had done in nineteen centuries. In 1759, James Watt had his attention directed by Robison to the subject of the steam engine, and for a few years afterwards made various experiments on the properties of steam. In 1763 and 1764, Watt, while engaged in the repair of a small model of Newcomen's engine (belonging to the University of Glasgow, and since preserved by that University as the most precious of relics), perceived the various defects of that machine, and ascertained by experiment their causes. Watt set to work scientifically from the first. He studied the laws...*

Watt's 1769 patent is largely unknown in thermodynamic circles (Mitrovic, 2022a). His title is less informative for historians of thermodynamics and, in addition, it was not supported by patent law at that time, as Goodeve (Goodeve, 1888) reports, p. 22:

*...Now it is a maxim of the law that there cannot be a patent for a principle, and accordingly the property in an invention which revolutionized the mechanical industry of the whole world was nearly shipwrecked on the technical objection that the method claimed was a principle and not a manufacture, and it was only after a long struggle that the question was determined in favour of the inventor. ...the objection was finally disposed of by the strong common sense of Lord Kenyon, C.J., who observed:*

*I have no doubt in saying that this is a patent for a manufacture, which I understand to be something made by the hands of man.*

In the present paper I shall discuss some points Watt stated in the 1769 patent which are important for the development of thermodynamics. These are:

- a) The powers of steam that drive the engine,
- b) The range of the working temperature of steam engine,
- c) Watt's understanding of the laws of thermodynamics.

Points a) and b) show that Watt applied various measures to reduce energy dissipation and heat losses, thus trying to lessen the process' irreversibility. Also, an experiment will be mentioned where Watt realised conditions for a reversible heat transfer. Point c) is an extension of the discussion in Mitrovic (2022a, 2022b) where I have presented Watt's formulation of the first law of thermodynamics. The aim now is to include Watt's view of the second law into the discussion. An

appropriate interpretation of the expression reported in [Mitrovic \(2022a\)](#) as the Watt's formulation of the first law reveals also the roots of the second law of thermodynamics. As will be shown, the formulations of the second law by Rudolf Clausius and William Thomson (Lord Kelvin) in 1850s are contained in Watt's patent (1769) and his works on steam engine of 1770s.

For terms used but not explained in the present paper I recommend the publication by [Saslow \(2020\)](#) who gives a broad general overview on the history of the thermodynamics. For biography of James Watt, the papers by [MacLeod and Tann \(2007\)](#) and [Tann \(2004\)](#) are recommended.

## 2. The Powers of Steam and Watt's 1769 Patent

Watt introduced his patent as a principle, stating: *My method...consists of the following principles*, and explained in the first line of the first paragraph the working mode of the steam engine:

***First, that vessel in which 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 be kept 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,*** (emphasis added).

What was the intention of this demand?

According to Watt, **heat is used to generate the powers of steam which drive the engine**. Under Watt's term *powers*, the potential energy of steam is meant that can be expressed as product of its pressure and the volume. Watt understood that the first energy conversion process occurs in the boiler where heat is converted into the mechanical energy of steam. Rudolf Clausius provided in 1850 a discussion on steam generation as a process of conversion of heat into mechanical energy; see [Mitrovic \(2022c\)](#).

***The second part of the paragraph, ...the steam vessel shall be kept as hot as the steam that enters it,*** requires an absolute isolation of the steam cylinder from the surroundings and prevention of heat losses which would cause losses of steam power. Watt knew that heat losses cause useless steam condensation thereby reducing engine's power and increasing coal consumption. Steam condensation is a process of conversion of mechanical energy of steam into heat. Watt possessed a profound knowledge of the effect of different materials on heat losses. To reduce these losses, he recommended protection heating and insulation of the cylinder. In the end, the measures Watt specified would mean realisation of ***adiabatic conditions in the cylinder***, ...by enclosing it with steam of the same temperature, [Mitrovic \(2022b\)](#).

Watt's measure of suppression of heat losses by enclosing the cylinder with a layer of steam is very important for the development of thermodynamics because it is for the first time that conditions for a reversible heat transfer in the steam cylinder could be realised in experiment. These conditions can be stated as

product of two quantities, one tending to zero, the other to infinity:

$q \cdot \tau \rightarrow 0 \cdot \infty$ . The quantity  $q$  is the net heat flux across the contact surface, the other,  $\tau$ , is the time. If the product happens to become finite, however small, the heat transfer is considered to be reversible.

Such a process can occur within thermodynamic fluctuations in a macroscopic system at equilibrium. Sadi Carnot based his thermodynamics on reversible heat transfer without mentioning Watt as the originator of this idea. Despite this fact James Watt was the first to provide conditions in experiment for a reversible process in 1769. Norton (2016) calls the *Thermodynamic Reversibility the Impossible Process*, <https://doi.org/10.1016/j.shpsb.2016.08.001>.

### 3. The Temperature Range of the Working Substance

Watt paid particular attention to technical safety of the steam engine installation and limited the operating parameters so that explosion of the installation could be excluded. The 2nd paragraph of his 1769 patent provides some information on that point:

**Secondly**, in engines that are to be worked wholly or partially by condensation of steam, ***the steam is to be condensed in vessels distinct from the steam vessels or cylinders***, although occasionally communicating with them; these vessels I call condensers; and, ***whilst the engines are working, these condensers ought at least to be kept as cold as the air in the neighborhood of the engines, by application of water, or other cold bodies***, (emphasis added).

Watt's second vessel later became known as the *separate condenser*. *With its introduction, Watt patented a generally applicable energy conversion method*. Thus, the patent is not—as is usually stated in the literature—merely an improvement of the steam engine, but a comprehensive process of energy conversion that is still in use (Mitrovic, 2022a).

Watt's idea to separate the steam cylinder and the steam condenser marks a turning point in the history of thermal engineering and gives thermodynamics the status of science. His idea is based on a detailed thermodynamic analysis of conversion and transport of thermal energy, including its losses to the surrounding and dissipation within the engine. The conception of the steam engine with two heat reservoirs of different (high and low) temperatures is repeatedly stated by S. Carnot in the 1824 memoir as his own idea. This is not in agreement with the history of thermodynamics. The roots of Carnot's idea immediately follow from Watt's 1769 patent where the steam generator and the steam condenser represent two heat reservoirs of different temperatures.

In the second part of this paragraph Watt requires the temperature of steam condensation (and thus the pressure in the separate condenser) to be kept as low as possible. For safety reasons (explosion of water boiler) Watt limited the maximum steam pressure in the boiler (not mentioned directly in the patent) slightly above the atmospheric pressure. The corresponding temperature of the steam was obtained from the steam pressure curve which Watt himself determined ex-

perimentally. Watt thus defined not only the temperature range but also both the highest temperature and pressure in the installation.

Some 60 years later, in 1824, Sadi Carnot defined the temperature range in the steam engine. Without mentioning James Watt and his safety requirements Carnot actually adopted the Watt's definition. For Carnot, however, only the temperature difference from boiler to condenser is significant, but for Watt also the height of the steam temperature and pressure in the boiler. Due to its failure to comply with safety requirements, Carnot's definition is an inappropriate simplification of Watt's method. Indeed, Watt was correct on the limitation of the maximum steam pressure, because in 1830 there were almost 60 explosions of boilers on the American's steamships, killing more than 300 people. (R. Fox: Anmerkungen, p. 70 in S. Carnot, Betrachtungen über die bewegende Kraft des Feuers, Translation W. Ostwald Leipzig 1892 and J. Sommer, Vieweg, Braunschweig, 1988.)

Statements taken from Watt's 1769 patent are sufficient to place his works in the field of irreversible thermodynamics. His guiding idea also in later works was always reduction of the irreversibility of real processes, and from this point of view his works can be associated with a law that became, almost a century later, known as the second law of thermodynamics. Next, we provide evidence that Watt actually worked experimentally according to this law, several decades prior to any formulation of the law in written. In other words, the second law of thermodynamics immediately follows from Watt's experiments.

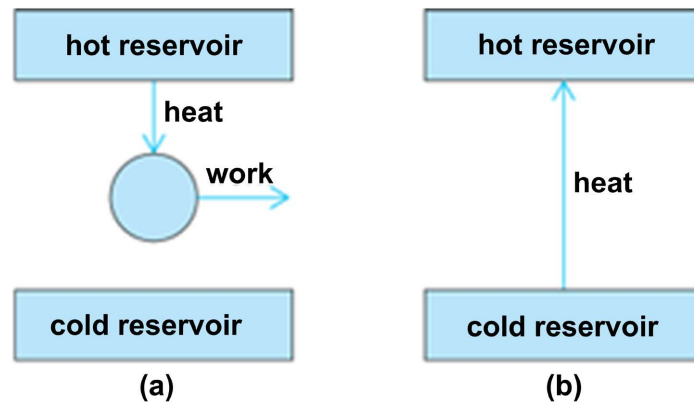
## 4. The Second Law of Thermodynamics

### 4.1. The Statements of the Law

There are numerous, more or less equivalent, statements of the second law in the literature; see for example Saslow (2020), Uffink (2001). Its basic scientific formulation is commonly credited to William Thomson (Lord Kelvin) and Rudolf Clausius. Representing various formulations, I mention here only the versions given by P. W. Atkins, *Thermodynamic principles*, Last reviewed: May 2019, <https://doi.org/10.1036/1097-8542.690700> Atkins (2019). Atkins presents this law as follows, **Figure 1**:

- (a) W. Thomson: *no cyclic engine operates without a heat sink,*
- (b) R. Clausius: *heat does not transfer spontaneously from a cool to a hotter body.*

These formulations can be extracted from works by James Watt, who used drawings to convey his ideas instead of ordinary language. Obviously, Watt was familiar with these restrictions, formulated around 1850, when he conceived his steam engine in 1765 and described in his patent of 1769. Interestingly the authors of the statements, Lord Kelvin and Rudolf Clausius, given by Atkins (2019) do not mention James Watt, but they choose Watt's processes of the steam engine as well-established thermodynamic foundations suitable for illustration of novel ideas. Both statements deny processes opposite to the processes of



**Figure 1.** Statements of the second law of thermodynamics by (a) William Thomson (Lord Kelvin) and (b) by Rudolf Clausius. The sketches show systems that cannot be operated in practice because of the contradiction to the second law. (Taken from Atkins (2019))

the steam engine illustrated in **Figure 2**, verifying that Watt's engine was well-studied, see also Mitrovic (2022a).

The drawing on **Figure 2**, right, expresses is Kelvin's statement (a): *A cyclic operation of a steam engine is impossible without a heat sink (condenser). The steam pipe in Watt's drawing of 1774 is cut off after the cylinder, picture 2 on the left, and closed adiabatically. A cyclic flow of working substance is thus impossible, as is the case in Figure 1(a).* Obviously, Watt knew the consequences which would result if the condenser would not be included into the installation as heat sink.

Clausius's statement (b), **Figure 1** right, asserts: *heat does not transfer spontaneously from the condenser (lower temperature) to the boiler (higher temperature) in a running steam engine, neither along the steam line nor along the feed line.* Watt was aware also of this impossibility and installed a feed pump in the feed line to bring the condensate from the condenser into the boiler at higher pressure and temperature, see detail A, **Figure 1** in Mitrovic (2022a).

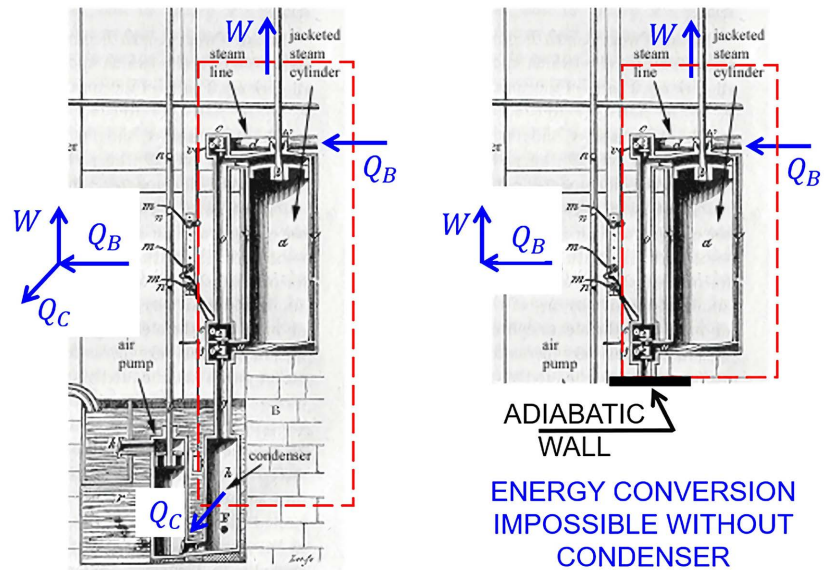
The above formulations by Lord Kelvin and Rudolf Clausius are well-known from the literature. They allow the following, somewhat unusual conclusion: *To express the second law, Kelvin and Clausius "damaged" the Watt's functioning steam engine installation just to demonstrate that it cannot be operated in the damaged state.*

The second law of thermodynamics can be formulated without any removal of the engine components (thus rendering it inoperable), by looking more closely at its operating equations. This is the last, perhaps the most important task of the present paper.

#### 4.2. Watt's View of the Second Law

Based on Watt's patent of 1769, his proposal of 1778 and his drawings of steam engines, the James Watt's formulation of the first law of thermodynamics has been sketched in Mitrovic (2022a, 2022b). The final outcome is the balance equation





**Figure 2.** Parts of steam engine according to Watt's drawing, built 1774, Mitrovic (2022a, 2022b). Left: Splitting of energy in the cylinder as stated by the first law; on the right the same engine without heat sink (condenser).

$$Q_B = W + Q_C \quad (1)$$

where  $Q_B$  denotes the heat that the working substance absorbs in the boiler,  $W$  the work performed by the engine, and  $Q_C$  the heat wasted in the engine's condenser. The heat  $Q_B$  is split in the steam cylinder into the work  $W$  and wasted heat  $Q_C$ , see **Figure 2**, left.

Equation (1) expresses simultaneously

- The energy conservation and
- The energy conversion.

In the first case the energy  $Q_B$  prior to splitting is equal to the sum of energies,  $W$  and  $Q_C$ , after the splitting, which is the core of the first law of thermodynamics.

The quantities  $W$  and  $Q_C$  in Equation (1) are positive,

$$W, Q_C > 0. \quad (2)$$

Considering the expression (2), Equation (1) delivers:

$$Q_B > W \text{ and } Q_B > Q_C. \quad (3)$$

The expression (3) states:

***The energy (heat)  $Q_B$  the working substance absorbs in the boiler cannot be completely converted into the work  $W$ , a part of it,  $Q_C$ , must be wasted in the cycle of steam engine.***

While work can be completely converted into heat, the wasted heat  $Q_C$  limits the conversion of the heat  $Q_B$  into the work  $W$  and makes the conversion processes  $W \rightarrow Q$  and  $Q \rightarrow W$  asymmetrical and irreversible. This is an addition to the first law that can be viewed as another, distinct law of thermodynamics. Being deduced solely from the Watt's works it seems reasonable to call it

the Watt's formulation of **the second law of thermodynamics**. However, Watt did not number or count the thermodynamic laws, but he built steam engines according to these laws.

The formulation of the second law uses physical quantities to express the boundary of a possible, real process. As long as the heat  $Q_B$  in Equation (1) satisfies the first law, this heat can be converted into the work  $W$ , not completely, but only partially. This explanation of Watt's results is reasonable because the second law requires the knowledge about the energy convertibility (equivalence) according to the first law to determine the boundaries of the process conversion. It connects the first and the second law in a logical sequence. Based on the first principle, the second law is formulated without any imaginary processes, as is done by Kelvin and Clausius. Expressions (2) are deduced from Watt's ideas, stated in 1760s/1770s. This simple formulation does not require additional limitations. In view of the Watt's thermodynamics, it is obvious that Carnot's demand for a cold heat reservoir in the steam engine installation was realized in practice by James Watt more than 50 years earlier.

The energy splitting in the steam cylinder follows from the paragraph 2 of Watt's patent (Watt, 1769) and his drawings of the steam engines in 1770s. Despite these facts it was only in 1850 that Rudolf Clausius (1850) recognized the work  $W$  as a part of the heat  $Q_B$  and corrected the notion of Sadi Carnot on the heat conservation in the steam engine. According to Carnot, no heat was converted into work in the process and remained conserved as heat. Clausius thus rendered Carnot's analogy (steam engine-waterfall) inapplicable. This analogy was also in contradiction to Watt's statement of the first law (in 1770s).

The second law according to James Watt represents the origin of several synonymous wordings. As example I mention only the formulation by Max Planck (1858-1947), *Treatise on Thermodynamics*, English by A. Ogg, Dover Publications Inc., 1910. In §108, Planck states that not every change which is consistent with the principle of the conservation of energy satisfies also the additional conditions which the second law imposes upon the processes, which actually take place in nature. ... Planck continues, we often find the second law stated as follows:

***The change of mechanical work into heat may be complete, but, on the contrary, that of heat into work must needs be incomplete, since, whenever a certain quantity of heat is transformed into work, another quantity of heat must undergo a corresponding and compensating change; e.g. transference from higher to lower temperature.***

... And in §116: The second fundamental principle of thermodynamics being, like the first, an empirical law, we can speak of its proof only in so far as its total purport may be deduced from a single self-evident proposition. We, therefore, put forward the following proposition as being given directly by experience:

***It is impossible to construct an engine which will work in a complete cycle, and produce no effect except the raising of a weight and the cooling of a heat-reservoir.***



A more precise wording of the Watt's expressions (3) stating the second law seems scarcely possible. This wording poses the question: Did Max Planck study and analyze the James Watt's thermodynamic ideas?

In context with Watt's view of the second law we can also understand other relationships he formulated. For instance, Watt must have had the left-hand side of expressions (3) in mind when he established the final form for the thermal efficiency  $\eta$  of steam engine,

$$\eta = \frac{W}{Q_B} < 1, \quad (4)$$

which he termed *duty*. Originally, it measured the work done by the engine on consumption of one bushel of coal (number of pounds of water raised one foot by consumption of one bushel of coal).

## 5. Conclusion

James Watt is well-known as a mechanical engineer for his construction, particularly, of steam engines. In the present paper I have discussed some Watt's ideas which make the scientific origin of the thermodynamics. Watt was the first to analyse heat losses and irreversibility of the steam engine. But he was also the first to establish the conditions for a possible reversible heat transfer. In an earlier paper, his formulation of the first law of thermodynamics has been illustrated. The present paper shows that all of his thermodynamic works belong to the field of irreversible thermodynamics where he illustrated the second law.

In the present paper I have not discriminated between the conversion and equivalence of energy. However, from the original Watt statement: *his steam engine could raise 500,000 cubic feet of water 1 foot high by the consumption of one hundred weight of coals*, follows the equivalence rather than the conversion of energy.

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## Conflicts of Interest

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

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