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Is the Term Latent Heat a Misconception?

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Abstract

The term latent heat was coined by Joseph Black in 1762. The well-known scientist-engineer, James Watt, precisely determined its value of water by experiments 250 ago, with an accuracy that is comparable to our modern experiments. However, Rudolf Clausius, one of the founders of modern thermodynamics, stated in 1850 that this quantity not only is hidden (latent) but does even not exist. In this paper, we present Black's model of latent heat, describe Watt's experiments and shed some light on the motivation behind Clausius's statement.

Keywords

Phase Transition, Latent Heat, Energy Conversion, Joseph Back, James Watt, Rudolph Clausius

1. Introduction

The term *latent heat* appears in context with phase change, like condensation of vapours and evaporation of liquids. Joseph Black (1728-1799) coined the term and explained its meaning in 1762 (Williams, 2012). When a phase change starts and the new, daughter phase, grows, usually thermal equilibrium is supposed to establish at the contact surface of the two phases. Despite of heating/cooling of the phases at constant pressure a thermometer placed in this surface would not sense a temperature change, the heat remains concealed. This has motivated Black to term the heat supplied in the process the latent heat (Black, 1803: p. 343). He did not mean by this term that it was a different kind of heat from the heat which expands bodies, but merely that it was concealed from our sense of heat, and from the thermometer. The third edition of the *Encyclopædia Britannica* 1798 (Vol IV, p. 379, No. 35 left column) informs the reader:

Dr. Black is of opinion that heat, which he seems to make synonymous with fire, exists in two different states; in one of which it affects our senses and the *thermometer, in the other it does not. The former therefore he calls sensible heat, the latter latent heat. On these principles he gives the only satisfactory explanation of the phenomena of evaporation and fluidity that has yet appeared.*

This quote does not fully account for Black's vision of latent heat. On p. 168 Black (1803) explained the latent heat on the basis of an evaporation process:

It is unnecessary to add anything more to the preceding facts, to prove that the interruption in the calorific process, in the conversion of fluids into elastic vapour in the act of ebullition, is perfectly similar to that in the process of liquefaction; and I flatter myself that we may now take it as a point fully established, that, when a fluid body is raised to its boiling temperature, by the continual and copious application of heat, its particles suddenly attract to themselves a great quantity of heat and, by this combination, their mutual relation is so changed, that they no longer attract each other, gathering into drops and forming a liquid, but avoid each other, separating to at least ten times their former distance, (for a cubic inch of water forms much more than a thousand cubic inches of vapour), and would separate much farther, were they not compressed by the weight of the atmosphere; and in short, they now compose a fluid, elastic, and expansive, like air.

Black mentions the constancy of the temperature as interruption of heating (*calorific process*) and explains the state of steam in comparison to liquid water.

Black also worked experimentally. He conducted experiments on the latent heat using water and ice, and performed some measurements with evaporating water, Black (1803: p. 151), West (2014). Emeis (2004) provides several important details on the discovery of latent heat. He mentions the effort of James Watt (1736-1819) regarding the priority of Black's model on latent heat.

Black frequently mentioned James Watt in his lectures (Black, 1803). Watt actually made a significant contribution to understanding of latent heat. Watt's studies of latent heat were motivated by his interest in the design and construction of steam engines. However, relatively little attention has been paid to his works in literature. Fleming (1952) is one of the rare researchers who name Watt in context with latent heat, but his paper does not mention the most important results Watt obtained.

The present paper focuses on the latent heat as physical property mainly from a historical point of view. We explain the Watt's notion on and the experimental determination of the latent heat of steam. As is shown below, Watt obtained this property experimentally 250 years ago with an accuracy that is comparable with the reliability of our modern experiments. Subsequently we show why Rudolf Clausius (1822-1888), in 1850, considered the latent heat to be a misconception.

2. James Watt's Experiments on the Latent Heat of Steam

Independently of Joseph Black, James Watt realized that heat consumption or production occurred during the phase change, particularly with water evaporation and steam condensation. As mentioned above, Watt was interested in latent heat of steam in context with his steam engine (Watt, 1818). Next, we present Watt's understanding and his experimental determination of the latent heat of steam.

Watt's first, rather crude, experiments were performed in 1765 (Watt, 1818: p. 10, footnote), and these were followed by more precise measurements in 1781 (Watt, 1818: 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, as noted by Farey (1827: 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 experimental method is best illustrated if we neglect thermal losses in the experiments and repeat once his evaluation. Assuming isobaric conditions in the experiments, the following energy balance:

$$m_S h_{vl} = m_W c_{pW} \Delta T_W \tag{1}$$

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 (1) in the calculations.

Using Watt's experimental data,

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

and the NIST (US National Institute of Standards and Technology) value[1] for the specific heat capacity of water, $c_{pW} = 4200.0\,\text{J}/(\text{kgK})$, Equation (1) 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 the 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 raise of the liquid phase in degrees Fahrenheit (˚F) which would be caused by the absorption

[1]In (Watt, 1818) Watt mentions the specific heat of some metals in comparison to water; for water, he set $c_{pW} = 1$ (thermal units) as a reference value, and measured the latent heat in degrees Fahrenheit.

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 the saturation of 70˚F (Watt, 1818: pp. 6-7). Note that (degree F) means the temperature raise of water corresponding to latent heat, $h_{vl} = c_{pW} \Delta T_W$, $\Delta T_W = (\text{degree F})$.

It is instructive to compare Watt's experimental method with that used by Joseph Black. Three years prior to Watt's experiments, in 1762, Black (1807) 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; the results he obtained were affected by the condition of heat transfer to the heated and evaporating water. In Black's experiments not only the driving temperature difference and the heat transfer surface but also the mechanisms of heat transfer in the water changed in the course of the experiments. Consequently, the heat transfer conditions for heating the subcooled water were not the same as for the evaporating water, which affected the times used by Black for calculation of the latent heat. Compared with 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. The Total Heat of Saturated Steam

Using the latent heat, Watt[2] defined the *total heat* of steam as the sum of the sensible heat, $c_{pW}(T_S - T_R)$ required to raise the water temperature from the reference value (e.g. 32˚F) to the saturation temperature at the prevailing pressure, and the latent heat, h_{vl}, required to evaporate the water at that pressure. For an easier discussion of the property thus composed, we shall express this idea analytically.

Denoting the total heat of saturated steam by h_S, we can write the equation:

$$h_S = c_{pW}(T_S - T_R) + h_{vl} \tag{2}$$

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, $T_R = 0^\circ\text{C} = 32^\circ\text{F}$). Today, Equation (2) defines the specific enthalpy of saturated steam; in Watt's time it was known as *Watt's law of latent heat*; see e.g. Cardwell, (1971) and Miller (2004). 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 the pressure variation covered by his experiments.

Watt's Equation (1) is valid only if the originally subcooled water is heated up to the saturation temperature T_S. Its validity can be extended to any tempera-

[2]It is not clear from the literature who is the true originator of this idea: James Watt or Joseph Black. Watt used it in his heat balances.

ture $T_1 < T_S$ by using the total heat of steam according to Equation (2). The mass and heat balances then give:

$$m_S\left(c_{pW}\left(T_S - T_1\right) + h_{vl}\right) = m_W c_{pW}\left(T_1 - T_W\right) \tag{3a}$$

or

$$h_{vl} = \left(\left(m_W / m_S\right)\left(T_1 - T_W\right) - \left(T_S - T_1\right)\right) c_{pW} \tag{3b}$$

The change in the total heat of steam (left hand side of Equation (3a)) covers the heating of the subcooled water m_W from T_W to T_1. For $T_1 = T_S$, Equation (3a) becomes identical to Equation (1). Setting $c_{pW} = 1$, as Watt actually did, Equation (3a) expresses Watt's original scheme for calculating the latent heat (Watt, 1818: p. 7) in this case, Equation (3b) becomes identical to the equation Capecchi (2020) deduced from the Watt's calculation table.

4. Watt's Understanding of Latent Heat

The Watt's perception of the term latent heat is best described in his own words (Watt, 1818: p. VII):

I had measured the quantity of cold water required in every stroke to condense the steam in that cylinder, so as to give it a working power of about 7 lb. on the inch.

Here I was at a loss to understand how so much cold water could be heated so much by so small a quantity in the form of steam, and applied to Dr. Black, and then first understood what was called Latent Heat.

Watt observed that steam was a huge reservoir of heat; Joseph Black explained him the cause of that heat and termed it the latent heat.

On the basis of his experiments Watt concluded that the latent heat decreases with increase of temperature and a state of the system will be reached where the latent heat disappears. Denoting in this state the system temperature $\left(T_S\right)$ by T_C, Equation (2) becomes:

$$h_S = c_{pW}\left(T_C - T_R\right), \quad h_{vl} = 0. \tag{4}$$

The disappearance of the latent heat, $h_{vl} = 0$, shows that in the system only one phase is present and its total heat consists of the sensible heat. The state of a system that satisfies this condition is known as the thermodynamic critical state. Consequently, the disappearance of the latent heat defines the Watt's criterion for the existence and position of the thermodynamic critical point of the system in appropriate coordinates. This criterion is not mentioned in literature as an idea of James Watt. Some details on this point are given in Mitrovic (2022) and Mitrovic & Smyk (2021).

5. Objection by Rudolf Clausius

The idea of Rudolf Clausius (1850) on latent heat put forward in 1850 (1867) is important for understanding the principle of steam engine. In his explanation Clausius answered the question, which he did not ask explicitly: What occurs in a process of phase change? According to Clausius a phase change, e.g. evaporation of a liquid, results not only in the change of phase but also simultaneously in a conversion of energy. The heat q supplied to evaporating liquid is at least partly transformed in mechanical energy or the expansion work, $(v_S - v_L)p$, which Clausius termed external work. Hence, for evaporation at constant pressure, p,

$$q \to (v_S - v_L)p. \tag{5}$$

Here v_S and v_L denote the specific volume of steam (subscript S) and liquid (subscript L). Note that Clausius also considered the internal work which could be understood as expansion work of the mother phase prior to observable phase change.

Relation (5) visualizes the *interruption of the calorific process* stated above in the Black's quote. If $p = const$, also T is constant, $T = const$, and we need other quantities to express the physical state of the system undergoing evaporation, as is shown in Equation (5).

Discussing the conversion of water into steam and the heat involved, Clausius explained (Clausius, 1850; Barbour, 2020):

…, so unterscheiden wir in der Wärmemenge, welche dem Wasser bei seinen Veränderungen mitgeteilt werden muss, die freie und latente Wärme. Von diesen dürfen wir aber in dem gebildeten Dampfe nur die erstere als wirklich vorhanden betrachten. Die letztere ist nicht bloß, wie der Name andeutet, für unsere Wahrnehmung verborgen, sondern überhaupt nicht vorhanden; sie ist während der Veränderungen zu Arbeit verbraucht.

…, we distinguish in the quantity of heat imparted to the water during the change the sensible heat and the latent heat. Only the former of these, however, must we regard as present in the produced steam; the latter is not only as its name imports, hidden from our perceptions, but has actually no existence; during the alteration it has been converted into work.

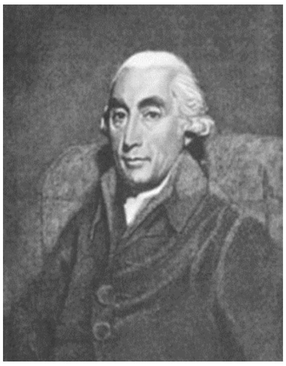
For Clausius the term latent heat is a misconception, because this heat is not only hidden but it does not exist; it is transformed into work. This is correct. However, the term *latent* heat is justified if we understand this term to mean a form of an energy that can be converted into sensible heat. This is the case with the mechanical work.

The Clausius idea about the non-existence of latent heat is not entirely new. As early as his 1769 patent, Watt stated that powers drive the steam engine without mentioning any heat in this context. Today, the Watt's powers stand for the mechanical energy of the steam.

6. Conclusion

Latent heat is a physical property of processes that accompany a phase change. The term was coined by Joseph Black more than 250 years ago. According to Black and James Watt the latent heat represents heat required to perform a phase change. Watt determined this quantity of saturated steam amazingly precisely; he defined the total heat of saturated steam as the sum of sensible and latent heats. If considered as independent of pressure, this sum was known as Watt's law of latent heat.

Rudolf Clausius objected that the latent heat not only is hidden, but it does not exist. Clausius argued that heat supplied to an evaporating liquid is converted into work and does not exist as heat; his objection helps to understand the principle of steam engine. Clausius' concern about the meaning of latent heat is understandable, especially if the physical interpretation of this quantity is considered. Considering that potential heat is in question, the term latent heat is adequate.



Joseph Black (1728-1799)

James Watt (1736-1819)

Rudolf Clausius (1822-1888)

Conflicts of Interest

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

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