Chapter 8a

The first law of thermodynamics:

1. Kelvin’s relationship with Joule

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Abstract

A concise account is given for the gradual transition of William Thomson, Lord Kelvin, from acceptance of Carnot’s theory of indestructible caloric to the dynamical theory of heat.

1 Introduction

One may say that William Thomson (Lord Kelvin) was destined to study the phenomena of heat. Being a child prodigy, in 1834, at the age of 10, he matriculated at the University of Glasgow where his father James was a professor of mathematics. In 1840, the teenage William read the famous book *Analytical Theory of Heat* by Jean Baptiste Joseph Fourier. This event to a large extent formed his career as a mathematical physicist.

Fourier showed that one could develop the theory of heat without committing oneself on the issue of the nature of heat. He laid out his program in the first two sentences of the first chapter of his book.

‘The effects of heat are subject to constant laws which cannot be discovered without the aid of mathematical analysis. The object of the theory which we are about to explain is to demonstrate these laws; it reduces all physical researches on the propagation of heat, to problems of the integral calculus whose elements are given by experiment’ [1].

Thomson was impressed by the fact that Fourier’s theory was not based on hypothetical entities such as caloric which at that time was accepted by practically every physicist. Fourier’s work served as a model for Thomson in his further studies.

2 William Thomson’s fascination with Carnot’s theory of heat

The evidence is that the first acquaintance William Thomson had with the radical theory of Sadi Carnot (1796–1832) was third hand. The overall historical sequence appears to be as follows. In 1824 Carnot, still only a young engineer, wrote the original booklet [2], entitled *Réflexions sur
la puissance motrice du feu et sur les machines propres a développer cette puissance (Reflections on the motive power of heat and on machines capable of developing that power). As explained in this volume’s chapter Engineering Thermodynamics and the Carnot Cycle, Carnot’s original publication had a cold reception in Paris. It was really revived only by Emile Clapeyron’s 1834 paper entitled ‘Memoire sur la puissance motrice du feu’[3], in which the author gave a quantitative analysis of the work produced by a steam engine based on Carnot’s analysis. In expounding the famous doctrine familiar to every engineer under the name of Carnot’s Cycle, Clapeyron was the first, and possibly the only one, of Carnot’s compatriots to recognise its significance. So far, then, the story was French and in the French language but from then on it would become English. Three years later, Richard Taylor (who was to join with William Francis in 1852 to form the publishing company Taylor and Francis) republished Clapeyron’s paper in English [4] in the first volume of his Scientific Memoirs Selected from the Transactions of Foreign Academies of Science.

It was this third publication that apparently attracted William Thomson’s attention. Smith and Wise, in their exhaustive biography of Kelvin, Energy & Empire, explained in detail [5, p. 289] how in their correspondence the brothers Thomson started to discuss the matter. In a letter to William in 1844, James referred to ‘the paper you mentioned to me’. Smith and Wise comment that ‘This paper was almost certainly the 1837 translation for Taylor’s Scientific Memoirs of Clapeyron’s ‘Memoir on the motive power of heat’. They conclude that the 1844 letter of James’s is ‘… the earliest record of implicit references to Clapeyron and Carnot by the Thomsons’ since it showed ‘a considerable understanding of the basic principles involved in Carnot’s theory’ (all quotes from [5, p. 289]).

It is on the grounds of this ‘considerable understanding’, then, that Smith and Wise use the expression ‘almost certainly’ for their interpretation of the Thomson brothers’ link with Carnot’s original publication. Two aspects should be noted. Most importantly, James used the expression ‘whatever gaseous substances are acted on’. The independence of the Carnot cycle on working substance was a key concept and barely something James could have referred to without the knowledge of Carnot’s work. Also ‘James exhibited his familiarity with the waterfall analogy employed by Carnot’. In all, James Thomson had a sure grasp of ‘the fundamental principles of Carnot and Clapeyron’. By including Clapeyron, Smith and Wise are, of course, identifying Clapeyron’s paper as the source. (All quotes are from [5, p. 289/290].)

James’s letter was sent to William during his 4 years, 1841–1845, in Cambridge. In the latter part of 1845, William Thomson went to Paris (Smith and Wise [5, p. 300/301]) and in the laboratory of Victor Regnault he learned about heat as a source of motive power. Thomson, while being evidently fascinated by Clapeyron’s account had no direct knowledge of Carnot’s work. Being in Paris gave him the opportunity to look for an ‘original Carnot’.

However, Carnot’s booklet was exceedingly rare, very few copies having been printed. Thomson inquired for it in the Library of the College de France. No one could tell him even where a copy might be seen. Years afterwards, he narrated how in 1845, when in Paris, he sought in vain for this work.

‘I went to every book-shop I could think of, asking for the Puissance motrice du feu, by Carnot. ‘Caino ? Je ne connais pas cet auteur’. With much difficulty I managed to explain that it was ‘r’ not ‘i’ I meant. ‘Ah ! Ca-rrr-not ! Oui, voici son ouvrage,’ producing a volume on some social question by Hippolyte Carnot; but the Puissance motrice du feu was quite unknown’ [6].
Thomson was gripped by the French scientist’s argumentation. In his analysis of the motive power of heat Carnot believed, as was commonly assumed at that time, that heat is a substance, a subtle fluid named caloric. Then, he also employed the analogy between the fall of water from a higher to a lower level and the ‘fall’ of caloric from higher to lower temperature:

‘According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a waterfall. Each has a maximum that we cannot exceed, whatever may be, on the one hand, the machine which is acted upon by the water, and whatever, on the other hand, the substance acted upon by the heat. The motive power of a waterfall depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made’ [7]. It is worth pointing out here that water power was a key contributor to the industrial, especially the textile, scene. Cardwell describes the water-steam rivalry in Chapter 3 of Ref. [8]. It was logical, therefore, for Carnot to use such an analogy. James Thomson did exactly the same – [5, p. 289/290]).

After a detailed analysis of what we now call Carnot’s cycle, Sadi Carnot concluded in his work that ‘The production of motive power is then due in steam-engines not to an actual consumption of caloric, but to its transportation from a warm body to a cold body, that is, to its re-establishment of equilibrium – an equilibrium considered as destroyed by any cause whatever, by chemical action such as combustion, or by any other. We shall see shortly that this principle is applicable to any machine set in motion by heat’ [9].

3 Enter James Prescott Joule

William Thomson was unaware that in the 1840s there were other people studying the problem of heat. James Prescott Joule (1818–1889) from Manchester was educated at home, partly by the famous John Dalton. He was quite well-off because of the prospering family brewery and built himself a small laboratory at home. There he performed various experiments on the production of heat by mechanical actions.

Joule read his first paper on the mechanical equivalent of heat on 21 August 1843, during the annual meeting of the British Association for the Advancement of Science (BAAS) at Cork, in southern Ireland. He presented it to the Chemistry Section because the Physics Section was full. Joule’s conclusion was that ‘By a dynamometrical apparatus attached to his machine, the author has ascertained that …. a quantity of heat, capable of increasing the temperature of a pound of water by one degree of Fahrenheit’s scale is equal to a mechanical force capable of raising a weight of about 838 pounds to the height of one foot’ [10].

Joule’s paper attracted little attention. He, however, continued experiments. In 1845, at the BAAS meeting in Cambridge, he presented the results of his next experiment in which a pair of falling weights drove, by means of two light cords, a vertical drum mounted on a shaft at the lower end of which was a brass paddle. This rotated in a copper drum full of water. The weights fell through 36 feet at a speed of one foot per second. The mechanical equivalent of heat determined from the rise of the temperature of water and the easily calculable expense of the potential energy of the weights was found to be between 774 and 890 foot×pounds. Joule’s presentation again did not attract attention.
William Thomson met James Joule for the first time during the BAAS meeting in Oxford, in 1847. On Thursday 24th June, Joule presented his paper on the new theory of heat. He was told by the chairman to be brief in his presentation because it was late in the day and the subject was not interesting to the audience. Joule reported again on experiments with his paddle-wheel apparatus. He gave 781.5 and 782.1 foot-pounds for the mechanical equivalent of heat measured using water and sperm oil, respectively. Joule’s presentation would have passed without notice but a young man at the back of the lecture hall asked some penetrating questions about it. That created an interest in the paper. The young man was William Thomson, then 22 years old, who later presented another version of the incident, saying that he remained seated and put his questions to Joule after the meeting. Whichever version was true, this encounter marked the beginning of a life-long friendship between the two great scientists.

After the meeting, Thomson wrote to his father from Cambridge on 1 July 1847. He described the meeting as ‘delightful’ and wrote: ‘I am going to write to James [his brother] about [Joule’s paper on the dynamical theory of heat] and enclose him a set of papers I have received from Joule, whose acquaintance I made…. Joule is, I am sure, wrong in many of his ideas, but he seems to have discovered some facts of extreme importance, as for instance, that heat is developed by the friction of fluids…’ [11].

The meeting with Joule marked the beginning of Thomson’s very slow conversion to the dynamical theory of heat. Still, in 1848 he published a paper [12] explaining how Carnot’s theory [9] may be used to define an absolute temperature scale.

At the end of 1848 Thomson obtained a copy of Carnot’s booklet from Professor Lewis Gordon. He realised that Carnot’s wordy discussion can be expressed better with the use of mathematics. Thus, he wrote a paper [13] in which he presented an improvement of Carnot’s calculations by using more precise experimental data obtained by Regnault. Joule was disappointed and surprised that Thomson still adhered to Carnot’s heat theory.

4 Rudolf Clausius finds the solution

Meanwhile, another important player appeared on the scene. The German physicist Rudolf Clausius (1822–1888) was only 2 years older than William Thomson. He received his doctorate at the University in Halle in 1847 and was teaching at the Royal School of Artillery and Engineering in Berlin. He did not know Carnot’s booklet but learned about his ideas from Clapeyron [2] and Thomson [13].

In an important paper ‘On the moving force of heat’ [14] published in 1850 Clausius realised that, contrary to Thomson’s belief, there was no need to make a choice between Carnot’s statement that a loss of heat never occurs in the production of heat by heat engines, and Joule’s experimental finding of the equivalence between heat and mechanical work.

Clausius argued that Carnot’s and Joule’s ideas could be reconciled if it was assumed that in the production of work a certain portion of heat was consumed and a further portion transmitted from a warm body to a cold one. He further proposed that both portions stand in a certain definite relation to the quantity of work produced. Thus, Clausius stated two important principles, the equivalence of heat and work, and the principle that heat always shows a tendency
to equalise temperature differences and therefore pass from hotter to colder bodies. He obtained an explicit form of the first law of thermodynamics and also formulated the second law.

5 William Thomson’s answer

Thomson read Clausius’ paper and regretted that he did not see this point earlier. Then he wrote his own version of the solution of the motive power of heat.

‘The whole theory of the motive power of heat is founded on the two following propositions, due respectively to Joule, and to Carnot and Clausius.

Prop. I (Joule) – When equal quantities of mechanical effect are produced by any means whatsoever from purely thermal sources, or lost in purely thermal effects, equal quantities of heat are put out of existence or are generated.

Prop. II (Carnot and Clausius) – If an engine be such that, when it is worked backwards, the physical and mechanical agencies in every part of its motions are all reversed, it produces as much mechanical effect as can be produced by any thermo-dynamic engine, with the same temperatures of source and refrigerator, from a given quantity of heat’ [15].

In the same paper Thomson also proposed his own version of the second law of thermodynamics. This paper marked the final conversion of William Thomson to the dynamical theory of heat.

6 Concluding remarks

It is worth remembering that in the middle of the nineteenth century force had not been clearly distinguished from what is now called energy. Thus, for example, Hermann Helmholtz’s important treatise on the conservation of energy was entitled ‘Über die Erhaltung der Kraft’ (On the conservation of force). Helmholtz was speaking about living force (Lebendige Kraft) and tension force (Spannkraft).

Thomson first used the terms ‘statistical energy’ and ‘dynamical energy’. The terms ‘potential’ (hidden) energy and ‘actual’ (visible) energy were introduced by W.J. Macquorn Rankine. Finally, in 1867 William Thomson and Peter Guthrie Tait introduced ‘potential’ energy and ‘kinetic’ energy in their famous textbook ‘Treatise on Natural Philosophy’ [16].

References


