Joule's experiment: An historico-critical approach

Author: Marcos Pou Gallo Advisor: Enric Pérez Canals
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Abstract: We present the result of the historical analysis of Joule's paper "The mechanical equivalent of heat" (1849). We give a brief but close examination of his measurements of the mechanical value of a calorie, as well as their influence in the birth of thermodynamics.

I. INTRODUCTION

Heat, temperature and energy belong to different scales, such as the motion of microscopic particles and the thermal state a certain body. In the 19th century these concepts were widely discussed. The discoveries and the experiments of those years changed physics and its way of explaining reality. Among the involved scientists, James Prescott Joule stands out with his famous measurement of the mechanical equivalent of heat.

Joule's experiment had a big influence and was one of the most relevant results around the emergence of the principle of conservation of energy. His ingenious experiment and extraordinary precision (considering the technical possibilities of the time) changed (or confirmed) the way scientists understood heat, and contributed to the birth of modern thermodynamics. Our aim in this paper is to examine this experiment very closely and analyze every step Joule followed in order to give his exact value for the "mechanical equivalent of heat". We have repeated Joule's calculations and scrutinized any possible source of error.

We will begin by introducing the historical context in which Joule published his paper (Section II), in order to understand his motivations and possible influence. As we will see later (Section III), Joule pretends to obtain the exact proportion that relates heat to mechanical work. Therefore we will focus first on the antecedents that made Joule understand heat as a mode of motion instead of as an imponderable kind of fluid.

II. HEAT AS A MODE OF MOTION

2.1 Historical Context

In the beginning of the nineteenth century "vis viva" (from the Latin for "living force") was the common concept used to talk about the properties of motion. Later, it became the concept that Helmholtz and others used and re-defined as "kinetic energy". The new "accidental" experimenters of those days, the industrial engineers, developed their own concepts to define the properties of machines (such as efficiency or work)[1, 2]. Some of these engineers even dared to hypothesize the physical causes to all these phenomena and some also wrote scientific papers exposing their conclusions. By then, scientists were much more interested in electric and magnetic phenomena, and thermodynamics as we know it today wasn't even born.

The study of heat and temperature yielded a great number of contradictions to resolve. Concepts like "heat" or "temperature" were confused and usually misunderstood. In the eighteenth century these ideas had been widely discussed, but we want to emphasize the work by Joseph Black. The fact that heat had a kind of capacity to increment an object's temperature by contact made him think that fire (for instance) had "something" that passed to other objects [3]. Other experiments suggested to Black that heat was not created or destroyed; it simply changed "location". The temperature that a body gain when heated would be proportional to its mass, the quantity of heat injected, and a constant that he called "heat affinity". Thanks to his experiments related to the evaporation of water, he observed that the amount of heat that was absorbed or lost in these processes was the same.

Some scientists were convinced of the substancial nature of heat, but others proposed a new revolutionary way of understanding it. They spoke of heat like an "excitation of molecules", that is, some kind of communication of internal motion. In fact, all the experiments that were made to find "the weight of heat" (measuring the weight of different bodies before and after being heated) came to be insignificant. This kind of behavior convinced Black about the conservation of heat [3].

Still, other experiments confirmed Black's considerations. Heating by friction and hammering seemed to demonstrate that heat, as Rumford would say, "is in essence movement and nothing else" [3]. Even Davy, recognized that "heat is some kind of peculiar movement of the particles in bodies" [3]. Davy considered the "rubbing ice pieces" experiment, and the well proved fact that the capacity of ice for heat is much less than that of water, to say: "the immediate cause of the phenomenon of heat is motion, and the laws of its communication are precisely the same as the laws of the communication of motion" [4]. Since then the new way of understanding heat as "motion" began to find his place.

But how did Helmholtz formulate the principle of conservation of energy the same century that magnetism, thermodynamics or electric properties were being discovered? According to Kuhn [5], because of Naturphilosophie (philosophical current that influenced some German scientists of the nineteenth century), the industrial revolution (the machinery revolution), and the interconversion experiments.

In fact, light, heat, electricity and magnetism, were in those days considered "imponderable" and unrelated agents. However, several and very relevant studies and experiments changed this conception: Laplace's mathematic theory of intercorpuscular forces, Fourier's studies of heat, Fresnel's studies of undulation properties, Oersted and Faraday's experiments, and Joule's "mechanical equivalent of heat", among others. Volta's experiments with electricity conservation showed that electric current could be obtained thanks to chemical affinity, and that electrical current could produce heat and, in good conditions, even light. After that, Oersted demonstrated the magnetic effects of the electric current. Later, Faraday described the induced currents, and Melloni identified light as radiated heat. All these phenomena suggested a last and unified proportion and order in reality, and so different fields of science became closer to each other [2].

It was thanks to Carnot father that the technical concept of work ($force \cdot distance$) came into common use. And it is thanks to his influence in others like Navier, Coriolis or Poncelet that "vis viva" was redefined by adding a 1/2 factor, our actual idea of "kinetic energy". Helmholtz became aware of both Joule and Mayer's contributions and he used them to publish in a definitive way the principle of conservation of energy. Joule is now known for both the Joule effect and the parameter that relates work, energy and heat in any field of physics [6]. We will return to him in Sect. III.

2.2 Key concepts and questions

Before focusing on Joule's experiment, we want to summarize the most relevant and urgent questions about the properties of heat, work and energy, which were discussed when he published his paper in the mid-nineteenth century:

-Heat is a "property" that can be measured by the use of a thermometer.
-Consequently, temperature can be defined as the amount of heat that a certain body has as the result of heating, which is independent of its capacity of communicating it.
-An increment of temperature can be caused by friction (the contact of a moving surface). This property applies to solids and liquids.
-Heat can change matter status, like evaporation of water. Those processes need a supplement of heat.
-A body in motion doesn't suffer a variation of its temperature (if it is isolated).
-Heat transmitted is proportional to matter and to a different constant that depends on the material used.
-As mechanical work (with friction) can cause heat, heat is able to do mechanical work (steam engine).
-Some of the heat lost in some processes can not be used in an inverted way. However,
-If heat is the communication of motion, how does it communicate it?
-In what proportion does vis viva heat a body?
-Could we develop some kind of "microscopical motion" but prevent "macroscopical motion"?
-If heat is another manifestation of energy, can we talk about conservation of heat?

As we will see, Joule was not im general interested in these questions, but his research strongly influenced the answers given by others.

III. JOULE'S EXPERIMENT

3.1 Introducing James Prescott Joule: Before "The mechanical equivalent of heat"

James Prescott Joule (14 December 1818 - 11 October 1889) was born in Lancashire and lived in Manchester. He was familiar with industry machinery. When he was just a child, the revolution of steam machines and the construction of the railway were in its peak. He and his brother received lessons from Dalton himself, who influenced very much Joule's way of doing research. Soon he began to experiment with all sort of things, mostly related to electricity. He became famous for his accuracy in experimental studies [1].

Count Rumford had also a big influence in Joule's life. He inspired Joule's studies related to heating by friction. Rumford had observed in Munich in 1797 the frictional heat that boring a cannon generates. Reading such paper fostered Joule's interest in the possibility of understanding heat as mechanical work. Before publishing his famous "The mechanical equivalent of heat", he wrote several papers related to friction with magnets. He published some of those results in *"On the caloric effects of magneto-electricity and on the mechanical value of heat"* [7]. He soon became more and more interested in experiments that proved his conviction: "the natural agents can't be destroyed, and no matter how the mechanical force is, you always obtain the exact equivalent of heat".

The most important determinations of the heat equivalent made by other scientists prior to Joule are [8]: (1 $lb = 0,453\ Kg$)

- In 1798 Rumford 1034 lb
- In 1830 Carnot 674 lb
- In 1842 Mayer 665 lb
- In 1843 Colding 638 lb

Results are given for an increase of 1 $Fahrenheit$ in 1 lb (pound) of water, developed with a mechanical force represented by the fall of a certain weight through the space of one $foot$. These are the weights found.

3.2 Joule's experiment: first analysis

Joule finished his paper in Oak Field, near Manchester, in June 4th of 1849. We could outline Joule's experiment as follows: he used the work needed to move a viscous fluid through a cylinder to measure energy losses and temperature changes of the cylinder and the surrounding air. This was a simple way of proving the energetical nature of heat with an ingenious instrument.

Joule recognizes the originality of Rumford's *"An inquiry concerning the Source of Heat which is excited by friction"*. According to Rumford, the heat required to raise 1 $Fahr$ a $pound$ of water would be equivalent to the force represented by 1034 $foot - pounds$ [4], 5,56 $Joules$ in current units. Joule attributes the difference between his result and Rumford's (262 $foot-pounds$) to the fact that Rumford did not consider "the heat accumulated in the wooden box, nor that dispersed during the experiment" [4]. Joule's method and apparatus allowed a much more isolated experiment.

At the end of the introduction, Joule sets his aim: "Subsequently, in 1845 and 1847, I employed a paddle-wheel to produce the fluid friction, and obtained the equivalents 781.5, 782.1 and 787.6, respectively, from the agitation of water, sperm-oil and mercury. Results so closely coinciding with one another, and with those previously derived from experiments with elastic fluids and the electro-magnetic machine, left no doubt on my mind as to the existence of an equivalent relation between force and heat; but still it appeared of the highest importance to obtain that relation with still greater accuracy. This I have attempted in the present paper."[4].

As we can see, Joule doesn't pose a scientific discussion or demonstration on the real nature of heat and energy, on the contrary his own experiments and many others had clearly convinced him that there is an exact proportion that relates heat and work ("a force capable of"). In other words, he was more concerned in finding the exact proportion of the phenomenon.

3.3 Experimental procedure

Joule uses 3 thermometers with a precision of calibration of 0,01 $Fahr$. He also used another instrument which embraced both the boiling and freezing point. Once Joule explains the calibration process he considers the precision in the temperature measure. He claims he is able to measure by naked eye (thanks to practice) a $1/20th$ of a division. That, considering the scale of the three thermometers would give measures of a precision of 1/200 $Fahr$.

As we can appreciate in the vertical and horizontal figures 1 and 2, Joule's apparatus employed for producing the friction of water consisted on a brass paddle-wheel. A series of circulating paddles had the function of shaking the water while fixed sections prevented the generation of a fluent current. Once the paddles had made the full movement in the cylinder the water recovered the static status. The water was contained in a copper vessel into which the revolving apparatus was firmly fitted. There were two necks into which the rotational axis was fixed and occasionally the thermometer for measurements. The whole experiment was protected by wooden pieces, in order to protect the vessel from the radiated heat that could come from the experimenter, or in order to avoid any loss of heat from the vessel by contact.

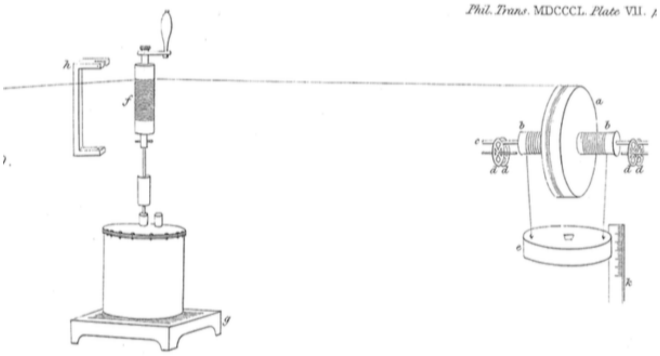


FIG. 1: Graphical front view of the apparatus.

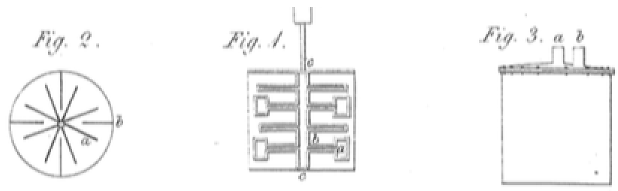


FIG. 2: Graphical description of the cilynder that contained the water.

The method of experimenting was as follows: The temperature of the frictional apparatus having been ascertained and the weights wound up, the roller was fixed to the axis. "The weights made a fall of about 63 inches. The roller was then removed to the stand, the weights wound up again, and the friction renewed" as Joule describes [4]. This was repeated twenty times and the experiment was concluded with a new measurement of temperature. Immediately before or after making the experiments, Joule made a trial of the effect of radiation and conduction of heat from the atmosphere by measuring the temperature of the water and the surrounding air. He concludes the description of the experimental procedure as follows: "In these trials the position of the apparatus, the quantity of water contained by it, the time occupied, the method of observing the thermometers, the position of the experimenter, in short everything, with the exception of the apparatus being at rest, was the same as in the experiments in which the effect of friction was observed".

3.4 Results

In the first series of experiments (friction on water), the velocity of the weights descending was 2,42 $inches$ per second (0,061 m/s), and the time spent in each experiment 35 min. Joule presents a table in which we can appreciate: The number of experiment (and type), the full quantity of inches covered by the falling weights, the mean temperature of air, the difference between the temperature of apparatus (a mean between the initial temperature and the final temperature), and the gain or loss of temperature during the experiment. Joule measured the temperature of the water after every 20 descents to obtain how much the temperature increased due to friction. He also measured temperature variations in the room where the experiment was done and compared them to that of the water to consider temperature increases due to radiation. After 40 repetitions, and after making some corrections on the temperature increases, Joule presents the following mean temperature variations: 0,57250 *deg* of gain for friction measures, and 0,012975 *deg* for radiation measures.

The final contribution in temperature because of friction (after making some corrections related to the apparatus mean temperature and its capacity of absorbing heat in different temperatures) is 0,5632. This is the true mean increase of temperature due to the friction of water. Now Joule aims to obtain the exact value of the temperature gained by the whole apparatus, to calculate its "capacity of heat". For such operation he has to consider all the materials implied considering the proportion between the heat capacity for water and the heat capacity for each material. For example 25541 *grs* of Copper $\cdot\, 0,09515 = 2430,2\ grs$ of Water. Considering the brass stopper used to prevent the contact of air with water (and "not considering the temperature of the thermometer because it was always brought to the expected temperature before immersion" [4]) the entire capacity of the apparatus is as follows (the parenthesis term refers to my own calculations with actual SI values): ($1\ grs = 0,065\ gr$)

- Water 93229,7 *grs*
- Copper as water 2330 (2350,2) *grs*
- Brass as water 1810,3 (1784,5) *grs*
- Total 97470,2 (97364,4) *grs*

Hence, the total heat was 0,5632 in 97470,2 *grs* (grains) of water, or 1 *Fahr* in 7,8422 *lbs* of water.

If we reproduce Joule's calculations with SI units (also referred to 1 *Fahr*) and modern tabulated values yield:

$$\frac{1\ Fahr}{0,5632\ Fahr} = 1,77553\ proportion \tag{1}$$

Therefore:

$$\frac{97470,2\ grs}{15,432\ (grs/gr)} = 6315,962\ gr \tag{2}$$

$$\frac{6315,962\ gr}{453,592\ (gr/lb\ of\ water)} = 13,924\ lb, \tag{3}$$

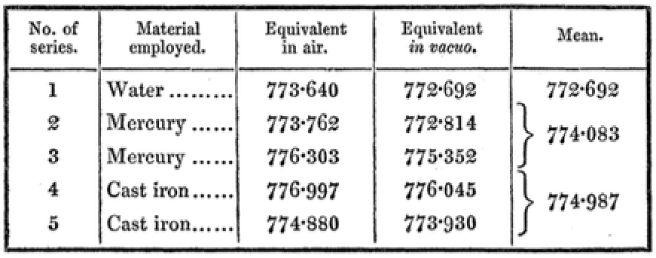
that divided by our previous proportion for 1 *Fahr* gives us the value of 7,8423. This value coincides very precisely with the value that Joule offers, and so, the error related to capacity calculations is quite negligible.

Joule also finds the force applied considering the weight and subtracting the friction arising from the pulleys and the rigidity of the string. Considering the friction of the roller, he finds 2837 *grs* as the amount of friction in the experiments; subtracted from the leaden weights leaves 403325 *grs* as the "actual pressure applied". As we can appreciate, Joule was very careful in considering all posible force dissipations, even if they are 1/200 th part of the force of the falling weights (such as this case).

A last correction needs to be done considering the velocity with which the leaden weights came to the ground. It is a force that is instantly "lost" once the weights impact the floor. Joule considers the force lost in such process and calculates it considering conservation of mechanical energy, obtaining what would be the height acquired if they moved in the opposite direction. The "extra height" that needs to be subtracted from the initial height found by Joule (and considering the 20 repetitions) is 0,152 *inches*. Such result matches perfectly with my own calculations considering the conservation of mechanical energy.

Finally, and after making some last corrections due to the elasticity of the string, Joule proudly announces the result of his first series of experiments like this: "Hence $6067,114/7,842299 = foot - pounds$, will be the force which, according to the above experiments on the friction of water, is equivalent to 1 *Fahr*, in a *lb* of water" [4].

Considering that the other experimental series (mercury and cast iron) give a less precise value for the mechanical equivalent of heat and that they follow the same procedure, we will not dwell on them. In fact, we can verify in Joule's paper, the rest of series have more error sources, due to the complexity of the apparatus used and the calculation of its heat capacity. Or, like Joule mentions referring to the two last series of experiments, "it is highly probable that the equivalent from cast iron was somewhat increased by the abrasion of particles of the metal during friction". Although these results are less precise, they are very similar between themselves and so are important to demonstrate that there is an exact "mechanical equivalent of heat" [4].



No. of series.	Material employed.	Equivalent in air.	Equivalent *in vacuo.*	Mean.
1	Water	773·640	772·692	772·692
2	Mercury	773·762	772·814	774·083
3	Mercury	776·303	775·352	
4	Cast iron......	776·997	776·045	774·987
5	Cast iron......	774·880	773·930	

FIG. 3: Joule's results (table IX in his paper).

The paper ends with a table of results (figure 3). Joule considers that the value presented for water is the most precise. However, due to the friction of fluids it was impossible to entirely avoid vibration and the production of a slight sound. That is why Joule says that it is probable that the above number is slightly in excess. Joule concludes enumerating what he considers that has been demonstrated by the experiments contained in this paper. 1. That the quantity of heat produced in both solid or liquid bodies is always proportional to the quantity of force expended, and 2. that the quantity of heat capable of increasing 1 $Fahr$ 1 lb of water (weight in vacuo and taken between 55 and 60) "requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lb through the space of one ft (foot)" [4]. In actual SI units:

$$\frac{772 \cdot 1,8 \frac{C}{Fahr}}{\frac{1\ joule}{0{,}7376\ ft-lb} \cdot \frac{1\ lb\ water}{453{,}6\ gr}} = 4,157\ J, \qquad (4)$$

that differs in a 0,006 % relative discrepancy with the actual established value: 4,186 *Joules*.

IV. FINAL REMARKS

Joule's "mechanical equivalent of heat" is probably the most influential paper for the birth of the first principle of thermodynamics. It analyzed adiabatic processes where the potential energy of the studied object remains constant and yet the system absorbs energy. The only possibility for understanding such process is some kind of conversion of energy. This energy, as we introduced before, is what Clausius will call later internal energy. Therefore, any variation of the internal energy is caused (in an adiabatic system) by a proportion of mechanical work added to the system. Since Joule's heating results can be done by heating with fire and controlling expansion or pressure increases, the difference between these two processes yield the definition of heat: $dU - W = Q$. Q and W are only involved when we change the initial state of any system through a particular process in which it can receive or lose heat (Q), and receive or perform work, (W). Hence, Q cannot be considered a state variable. According to modern views (not to Joule's) heat is not the instantaneous consequence of the work developed by the falling weights, but a variation of internal energy.

Joule's paper is a clear demonstration of the fact that there is a direct and proportional relation between internal energy and mechanical work. Without finding the exact proportion for heat, the first law of thermodynamics would have probably been established much later, and with more difficulties. That is why Joule's experiment deserves a special mention considering the precision of its results and the extremely ingenious apparatus he employed. In my opinion, the most meritorious fact concerning his experiment, is that Joule prevents the generation of a fluent current. Thanks to this important achievement, Joule allows a much more profound discussion about the nature of internal energy by distinguishing dynamical motion and internal energy.

On the other hand, Joule's technical approach is also far from revealing the nature of the concepts we have discussed. Macroscopic and microscopic "worlds" can easily be distinguished with intuition or natural perception by observing some phenomena, but in a theoretical way they are not so easily distinguished. After this study we can appreciate much better the origin of many of the ambiguities some physical concepts have. Many of the parameters and concepts come from intuitive or technical definitions, developed for a practical use. In fact, we have also seen how technique can have a big influence in physical knowledge providing measures, scales and even hypothesis. But a further interpretation is needed in order to recognize the structure of matter. Joule gave an important contribution to this discussion with his demonstration, but he did not clarify the real nature behind these processes. For instance, his device to perform work on a system without altering its pot. energy open some questions. What does the size or molecular structure have to do in the communication of heat? What is the size in wich we start considering something a dynamical motion of an object and not a thermodynamical state? These problems are not simple dialectic ambiguities, but open questions about the particular and concrete structure of reality.

Acknowledgments

I would like to thank my advisor for his patience and support, specially in making me have a much more critic and reasonable point of view. I would also like to thank my parents and my friends, specially J.M.García and M.Oliveira.

[1] D.S.L Cardwell, *James Joule, a biography*, (Manchester University Press, Manchester & New York, 1989).

[2] P.M Harman, *Energía fuerza y materia*, (Alianza Editorial, Madrid, 1990).

[3] J.B Conant & L.K Nash, *Harvard Case Histories in Experimental Science*, (Harvard University Press, Cambridge, 1957, pp. 117).

[4] J.P Joule, *Philosophical Transactions of the Royal Society of London, Vol. 140*, (The Royal Society, London 1850, pp. 61).

[5] M Clagett, *Critical problems in the History of Science*, (University of Wisconsin Press, Madison, 1959, pp. 321).

[6] J Forrester, *"Chemistry and the conservation of energy: The work of James Prescott Joule", Studies in History and Philosophy of Science*, 1975, 6, pp. 273.

[7] J.P Joule, *Scientific Papers of J.P Joule*, (Physical Society of London, London 1884).

[8] G.F Helm, *The historical development of energetics*, (Kluwer Academic, Dordrecht, 2000).