Tuesday, January 2, 1849.

Dr CHRISTISON in the Chair.

The following Communications were read:—

1. An Account of Carnot's Theory of the Motive Power of Heat,* with Numerical Results deduced from Regnault's Experiments on Steam.† By Professor William Thomson, of Glasgow.

The questions to be resolved by a complete theory of the motive power of heat, are the following:—

I. What is the precise nature of the thermal agency by means of which *mechanical effect* is to be produced, without effects of any other kind?

II. How may the amount of this thermal agency necessary for performing a given quantity of work be estimated?

I. On the nature of Thermal Agency, considered as a Motive Power.

The whole theory rests on a principle generally admitted as an axiom, which Carnot expresses in the following terms:‡—

"In our demonstration, we tacitly assume that after a body has experienced a certain number of transformations, if it be brought identically to its primitive physical state as to density, temperature, and molecular constitution, it must contain the same quantity of heat as that which it initially possessed; or, in other words, we suppose that the quantities of heat lost by the body under one set of operations, are precisely compensated by those which are absorbed in the others. This fact has never been doubted; it has at first been ad-

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* Published in 1824, in a work entitled, "Réflexions sur la Puissance Motrice du Feu," by Mons. S. Carnot. An account of Carnot's theory is also published in the *Journal de l'Ecole Polytechnique*, vol. xiv., 1834, in a paper by Mons. Clapeyron.

† An account of the first part of a series of researches undertaken by Mons. Regnault, by order of the late French Government, for ascertaining the various physical data of importance in the theory of the steam-engine, has been recently published in the *Mémoires de l'Institut*, of which it constitutes the twenty-first volume (1847). The second part of the researches has not yet been published.

‡ The passage quoted in the text is translated from a note to p. 37, in Carnot's Treatise.

mitted without reflection, and afterwards verified in many cases by calorimetrical experiments. To deny it would be to overturn the whole theory of heat, of which it is a fundamental principle. It must be admitted, however, that the chief foundations on which the theory of heat rests would require a most attentive examination. Several experimental facts appear nearly inexplicable in the actual state of this theory."

Since the time when Carnot thus expressed himself, the necessity of a most careful examination of the entire experimental basis of the theory of heat has become more and more urgent. Especially all those assumptions depending on the idea that heat is a *substance* invariable in quantity, not convertible into any other element, and incapable of being *generated* by any physical agency ; in fact, the acknowledged principles of latent heat, would require to be tested by a most searching investigation before they ought to be admitted, as they usually are, by almost every one who has worked on the subject, whether in combining the results of experimental researches or in reasoning *à priori*.

The extremely important discoveries recently made by Mr Joule, of Manchester, that heat is evolved in every part of a closed electric conductor, moving in the neighbourhood of a magnet ;* and that heat

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* I cannot omit this opportunity of correcting an expression which I made use of in a note published in the Philosophical Magazine (vol. xxxiii., p. 315), in alluding to the *generation* of heat by such operations, which I inadvertently asserted to have been proved by "*known experiments,* adduced by Mr Joule." It is true that the *evolution* of heat in a fixed conductor, through which a galvanic current is sent from any source whatever, has long been known to the scientific world ; but it was pointed out by Mr Joule that we cannot infer, from any previously published experimental researches, the actual *generation* of heat when the current originates in electro-magnetic induction, since the question occurs, *Is the heat which is evolved in one part of the closed conductor merely transferred from those parts which are subject to the inducing influence?* Mr Joule, after a most careful experimental investigation, with reference to this question, finds that it must be answered in the negative. (See a paper "On the Calorific Effects of Magneto-Electricity, and on the Mechanical Value of Heat; by J. P. Joule, Esq. ;" read before the British Association at Cork, in 1843, and subsequently communicated by the author to the Philosophical Magazine, vol. xxiii., pp. 263, 347, 435.)

Before we can finally conclude that heat is absolutely generated in such operations, it would be necessary to prove that the inducing magnet does not become lower in temperature, and thus give compensation for the heat evolved in the is *generated* by the friction of fluids in motion seem to overturn the opinion commonly held that heat cannot be *generated*, but only produced from a source where it has previously existed, either in a sensible or in a latent condition. In the present state of science, however, no operation is known by which heat can be absorbed into a body, without either elevating its temperature or becoming latent, and producing some alteration in its physical condition; and the fundamental axiom adopted by Carnot may be considered as still the most probable basis for an investigation of the motive power of heat; although this, and with it every other branch of the theory of heat, may ultimately require to be reconstructed on another foundation, when our experimental data are more complete. On this understanding the author of the present paper refers to Carnot's fundamental principle, as if its truth were thoroughly established.

If we consider any case in which mechanical effect is obtained from a thermal origin, by means of the alternate expansions and contractions of any substance whatever, and follow a perfectly rigorous process of reasoning indicated by Carnot, we arrive at the following conclusion, by which the first proposed question is answered :—

The thermal agency by which mechanical effect may be obtained, is the transference of heat from one body to another at a lower temperature.

II. On the measurement of Thermal Agency, considered with reference to its equivalent of mechanical effect.

The criterion of what may be called *a perfect thermo-dynamic engine* is thus stated :—

A perfect thermo-dynamic engine is such, that, whatever amount of mechanical effect it can derive from a given thermal agency, if an equal amount be spent in working it backwaxds, an equal reverse thermal effect will be produced.

Any two perfect engines, however different in their constructions,

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conductor. I am not aware that any examination, with reference to the truth of this conjecture, has been instituted; but in the case when the inducing body is a pure electro-magnet (without any iron) the experiments actually performed by Mr Joule render the conclusion probable, that the heat evolved in the wire of the electro-magnet is not affected by the inductive action otherwise than through the reflected influence, which diminishes the strength of its own current.

or in the physical media employed, must derive the same equivalent of mechanical effect from a given thermal agency. Carnot describes a steam-engine and an air-engine, each of which satisfies the criterion laid down above (the construction being however in each case, practically impossible); and he shews how, with certain physical data, with reference to steam in one case, and with reference to air or any gas in the other, the equivalent of mechanical effect, derivable from a given thermal agency, may be calculated. Thus, if M denote the amount of mechanical effect due to the *descent* of H units of heat (or *caloric*) from a body A at the temperature S, through the medium of a perfect engine of any kind, to a body B at the temperature T, we find, by Carnot's method of reasoning,

$$\mathrm{M} = \mathrm{H}\int_{\mathrm{T}}^{\mathrm{S}} (1-\sigma)\,\frac{\frac{dp}{dt}}{k}\,dt = \mathrm{E}\,p_0 v_0 \int_0^{\mathrm{H}} \int_{\mathrm{T}}^{\mathrm{S}} \frac{1}{v}\frac{dv}{dq}\,dt\,dq$$

In the first expression, deduced by the theory of the steam-engine, p denotes the pressure, σ the density, and k the latent heat of a unit of volume of saturated vapour from any liquid, at the temperature t. In the second, deduced by the theory of the air-engine, E denotes the coefficient of expansion (·00366, if the centigrade scale of the air-thermometer be adopted) of a gas; p_0 the pressure of a given mass of gas when reduced to the freezing point of temperature, and to the volume v_0; p the pressure of the same gaseous mass when occupying the volume v, at the temperature t; q the quantity of heat which must be added to the same mass to raise its temperature from 0 to t, when its volume is at the same time changed from v_0 to v; and $d\,q$ the heat absorbed by the gas when, with its temperature kept at t, its volume is augmented from v to $v + d\,v$.

Hence the mechanical effect to be obtained by the *letting down* of a unit of heat from a body A, to a body B at a lower temperature t, if the interval between their temperatures be an extremely small quantity τ, will be, according to the first expression:

$$(1-\sigma)\,\frac{\frac{dp}{dt}}{k}\,\tau,$$

and, according to the latter,

$$\frac{\mathrm{E}\,p_0 v_0}{\mathrm{H}}\int_0^{\mathrm{H}} \frac{1}{v}\,\frac{dv}{dq}\,dq\,.\,\tau$$

If H be taken infinitely small, the latter expression becomes

$$\mathrm{E}\, p_0 v_0 \frac{1}{v} \frac{dv}{dq} \cdot \tau.$$

Hence, if $\mu\tau$ denote the mechanical effect due to the descent of one unit of heat from A at the temperature $t+\tau$ to B at the temperature t, we have

$$\mu = (1-\sigma)\frac{\frac{dp}{dt}}{k} = \mathrm{E}\, p_0 v_0 \,\frac{1}{v}\frac{dv}{dq}.$$

The value of μ (" Carnot's coefficient"), which is independent of the nature of the liquid or gas employed, may be determined for an assigned temperature, by means of observations upon any gas, or any liquid and its vapour. The most complete series of experiments from which the values of μ at different temperatures may be deduced, are those by means of which Regnault has determined the latent heat of a given weight, and the pressure, of saturated steam, at all temperatures between 0° and 230°. Besides these data, however, the density of saturated vapour must be given, in order that k, the latent heat of a unit of volume, may be calculated from Regnault's determination of the latent heat of a given weight. Between the limits of 0° and 100°, it is probable, from various experiments which have been made, that the density of vapour follows very closely the simple laws which are so accurately verified by the ordinary gases;* and thus it may be calculated from Regnault's table, giving the pressure at any temperature within those limits. Nothing as yet is known with accuracy as to the density of saturated steam between 100° and 230°, and we must be contented at present to estimate it by calculation from Regnault's table of pressures; although, when accurate experimental researches on the subject shall have been made, considerable deviations from the laws of Boyle and Dalton may be found.

Such are the experimental data on which the calculation of the mean values of μ, for the successive degrees of the air-thermometer from 0° to 230°, at present laid before the Royal Society, is founded.

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* This is well established by experiment, within the ordinary atmospheric limits, in Regnault's *Etudes Météorologiques*, in the *Annales de Chimie.*

The unit of length adopted is the English foot; the unit of weight, the pound; the unit of work, a "foot-pound;" and the unit of heat, that quantity which, when added to a pound of water at 0°, will produce an elevation of 1° in temperature. In making the calculation, the factor σ, in the expression for μ, which for all temperatures between 0° and 100° is less than $\frac{1}{1700}$, is neglected. The mean value of $\frac{dp}{dt}$ for any degree of the scale is found to a sufficiently high degree of approximation by merely taking the difference, the pressures given by Regnault at the temperatures immediately above and below it; and, to complete the calculation on the same system, the denominator of the fraction is taken as the mean value of k for that degree. The amount of mechanical effect due to the descent of a unit of heat through the nth degree of the scale, will be simply the nth value of μ in the table thus calculated.

The following abstract of the table, exhibits the sum of the first twenty values of μ, of the second twenty, of the third twenty, and so on; as well as the first value, the twenty-first, the forty-first, &c.

Mean values of μ for Cent. degrees of the Air-thermometer.		Sums of values of μ for intervals of 20°.	
No. on the scale.	Ft. lbs.		Ft. lbs.
1	5·12	From 1 to 20	99·8
20	4·85	... 21 ... 40	94·2
40	4·57	... 41 ... 60	88·8
60	4·31	... 61 ... 80	83·9
80	4·09	... 81 ... 100	79·7
100	3·90	... 101 ... 120	76·2
120	3·73	... 121 ... 140	73·3
140	3·60	... 141 ... 160	70·7
160	3·48	... 161 ... 180	68·5
180	3·37	... 181 ... 200	66·7
200	3·30	... 201 ... 220	65·2
220	3·23		
230	3·19		

As an example of the usefulness of these tables, let it be required to find the amount of mechanical effect produced by a steam-engine working with perfect economy, for each unit of heat which, after entering the water of the boiler, is *let down* through the engine to the condenser, and there evolved. The "thermal agency" here is a unit of heat let down from a body at the temperature of the water in the boiler to another at the temperature of condensation, and the "mechanical effect," therefore, cannot be determined, unless those temperatures be given. Let us suppose then, in a particular engine, that the water of the boiler is at 120°, and the condenser at 40°, during the working of the engine. The required mechanical effect, calculated by adding the "sums" in the preceding table for all the intervals from 40° to 120° is found to be 328·6 foot-pounds.

2. Theoretical Considerations on the Effect of Pressure in lowering the Freezing-Point of Water. By James Thomson, Esq., jun., Glasgow. Communicated by Professor W. Thomson.

At the commencement of this paper the two following propositions are laid down :

I. That water at the freezing-point may be converted into ice by a process solely mechanical, and yet without the final expenditure of any mechanical work.

II. That the freezing-point of water must become lower as the pressure to which the water is subjected is increased.

The first of these is given as being interesting in itself, and as having been the original means of suggesting the second to the author. It may be deduced directly by the application to the freezing of water of the principle developed by Carnot, that no work is given out when heat passes from one body to another without a fall of temperature ; or rather by the application of the converse of this, which, of course, equally holds good,—namely, that no work requires to be expended to make heat pass from one body to another at the same temperature. The first being established, the reasonableness of the second will readily be admitted ; because the ordinary supposition of the freezing-point being constant, would involve the absurdity of a perpetual motion (or, more strictly, a perpetual source of mechanical work) being possible. For if a quantity of water were enclosed in a vessel with a moveable piston and frozen without the expenditure of work, the motion of the piston consequent on the expansion being resisted by pressure, mechanical work would be given out ; and there would be no expenditure of any thing whatever to serve as an equivalent for this mechanical work given out, because