In 1824 Carnot published a paper entitled *Reflexions sur la Puissance Motrice du Feu,* which is fundamental in the history of thermodynamics. In it he introduced the conception of a cycle of operations and proved that the most efficient thermodynamic engine is one in which all the operations of the cycle are reversible. His proof is erroneous because of his assumption of the materiality of heat. The principle is true, as was proved later by Clausius and Lord Kelvin, and when Carnot was able to use it without introducing the materiality of heat the conclusions which he drew from it were correct. In Carnot's notebooks from which extracts were published in 1878 there are passages which show that he had begun to doubt the truth of the doctrine of the materiality of heat and that he was planning experiments similar to those of Joule with a view of testing it. The translation by W. F. Magie appears in Harper's *Scientific Memoirs.*

The Motive Power of Heat

The production of motion in the steam-engine is always accompanied by a circumstance which we should particularly notice. This circumstance is the re-establishment of equilibrium in the caloric—that is, its passage from one body where the temperature is more or less elevated to another where it is lower. What happens, in fact, in a steam-engine at work? The caloric developed in the fire-box as an effect of combustion passes through the wall of the boiler and produces steam, incorporating itself with the steam in some way. This steam, carrying the caloric with it, transports it first into the cylinder, where it fulfils some function, and thence into the condenser, where the steam is precipitated by coming in contact with cold water. As a last result the cold water in the condenser receives the caloric developed by combustion. It is warmed by means of the steam, as if it had been placed directly on the fire-box. The steam is here only a means of transporting caloric; it thus fulfils the same office as in the heating of baths by steam, with the exception that in the case in hand its motion is rendered useful.

We can easily perceive, in the operation which we have just described, the re-establishment of equilibrium in the caloric and its passage from a hotter to a colder body. The first of these bodies is the heated air of the fire-box; the second, the water of condensation. The re-establishment of equilibrium of the caloric is accomplished between them—if not completely, at least in part; for, on the one hand, the heated air after having done its work escapes through the smoke-stack at a much lower temperature than that which it had acquired by the combustion; and, on the other hand, the water of the condenser, after having precipitated the steam, leaves the engine with a higher temperature than that which it had when it entered.

The production of motive power in the steam-engine is therefore not due to a real consumption of the caloric, but to its transfer from a hotter to a colder body—that is to say, to the reestablishment of its equilibrium, which is assumed to have been destroyed by a chemical action such as combustion, or by some other cause. We shall soon see that this principle is applicable to all engines operated by heat.

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At this point we naturally raise an interesting and important question: Is the motive power of heat invariable in quantity, or does it vary with the agent which one uses to obtain it—that is, with the intermediate body chosen as the subject of the action of heat?

It is clear that the question thus raised supposes given a certain quantity of caloric and a certain difference of temperature. For example, we suppose that we have at our disposal a body, *A*, maintained at the temperature 100 degrees, and another body, *B*, at 0 degrees, and inquire what quantity of motive power will be produced by the transfer of a given quantity of caloric—for example, of so much as is necessary to melt a kilogram of ice—from the first of these bodies to the second; we inquire if this quantity of motive power is necessarily limited; if it varies with the substance used to obtain it; if water vapor offers in this respect more or less advantage than vapor of alcohol or of mercury, than a permanent gas or than any other substance. We shall try to answer these questions in the light of the considerations already advanced.

We have previously called attention to the fact, which is self-evident, or at least becomes so if we take into consideration the changes of volume occasioned by heat, that wherever there is a difference of temperature the production of motive power is possible. Conversely, wherever this power can be employed, it is possible to produce a difference of temperature or to destroy the equilibrium of the caloric. Percussion and friction of bodies are means of raising their temperature spontaneously to a higher degree than that of surrounding bodies, and consequently of destroying that equilibrium in the caloric which had previously existed. It is an experimental fact that the temperature of gaseous fluids is raised by compression and lowered by expansion. This is a sure method of changing the temperature of bodies, and thus of destroying the equilibrium of the caloric in the same substance, as often as we please. Steam, when used in a reverse way from that in which it is used in the steam-engine, can thus be considered as a *means of destroying the equilibrium of the caloric*. To be convinced of this, it is only necessary to notice attentively the way in which motive power is developed by the action of heat on water vapor. Let us consider two bodies, *A* and *B*, each maintained at a constant temperature, that of *A* being higher than that of *B*; these two bodies, which can either give up or receive heat without a change of temperature, perform the functions of two indefinitely great reservoirs of caloric. We will call the first body the source and the second the refrigerator.

If we desire to produce motive power by the transfer of a certain quantity of heat from the body *A* to the body *B* we may proceed in the following way:

1. We take from the body *A* a quantity of caloric to make steam—that is, we cause *A* to serve as the fire-pot, or rather as the metal of the boiler in an ordinary engine; we assume the steam produced to be at the same temperature as the body *A*.

2. The steam is received into an envelope capable of enlargement, such as a cylinder furnished with a piston. We then increase the volume of this envelope, and consequently also the volume of the steam. The temperature of the steam falls when it is thus rarefied, as is the case with all elastic fluids; let us assume that the rarefaction is carried to the point where the temperature becomes precisely that of the body *B*.

3. We condense the steam by bringing it in contact with *B* and exerting on it at the same time a constant pressure until it becomes entirely condensed. The body *B* here performs the function of the injected water in an ordinary engine, with the difference that it condenses the steam without mixing with it and without changing its own temperature. The operations which we have just described could have been performed in a reverse sense and order. There is nothing to prevent the formation of vapor by means of the caloric of the body *B*, and its compression from the temperature of *B*, in such a way that it acquires the temperature of the body *A*, and then its condensation in contact with *A*, under a pressure which is maintained constant until it is completely liquefied.

In the first series of operations there is at the same time a production of motive power and a transfer of caloric from the body *A* to the body *B*; in the reverse series there is at the same time an expenditure of motive power and a return of the caloric from *B* to *A*. But if in each case the same quantity of vapor has been used, if there is no loss of motive power or of caloric, the quantity of motive power produced in the first case will equal the quantity expended in the second, and the quantity of caloric which in the first case passed from *A* to *B* will equal the quantity which in the second case returns from *B* to *A*, so that an indefinite number of such alternating operations can be effected without the production of motive power or the transfer of caloric from one body to the other. Now if there were any method of using heat preferable to that which we have employed, that is to say, if it were possible that the caloric should produce, by any process whatever, a larger quantity of motive power than that produced in our first series of operations, it would be possible, by diverting a portion of this power, to effect a return of caloric, by the method just indicated, from the body *B* to the body *A*—that is, from the refrigerator to the source—and thus to re-establish things in their original state, and to put them in position to recommence an operation exactly similar to the first one, and so on: there would thus result not only the perpetual motion, but an indefinite creation of motive power without consumption of caloric or of any other agent whatsoever. Such a creation is entirely contrary to the ideas now accepted, to the laws of mechanics and of sound physics; it is inadmissible. We may hence conclude that the maximum motive power resulting from the use of steam is also the maximum motive power which can be obtained by any other means. We shall soon give a second and more rigorous demonstration of the law. What has been given should only be regarded as a sketch.

It may properly be asked, in connection with the proposition just stated, what is the meaning of the word maximum? How can we know that this maximum is reached and that the steam is used in the most advantageous way possible to produce motive power?

Since any re-establishment of equilibrium in the caloric can be used to produce motive power, any re-establishment of equilibrium which is effected without producing motive power should be considered as a veritable loss: now, with little reflection, we can see that any change of temperature which is not due to a change of volume of the body can be only a useless re-establishment of equilibrium in the caloric. The necessary condition of the maximum is, then, that in bodies used to obtain the motive power of heat, no change of temperature occurs which is not due to a change of volume. Conversely, every time that this condition is fulfilled, the maximum is attained.

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We shall give here a second demonstration of the fundamental proposition stated on page 224 and present this proposition in a more general form than we have before.

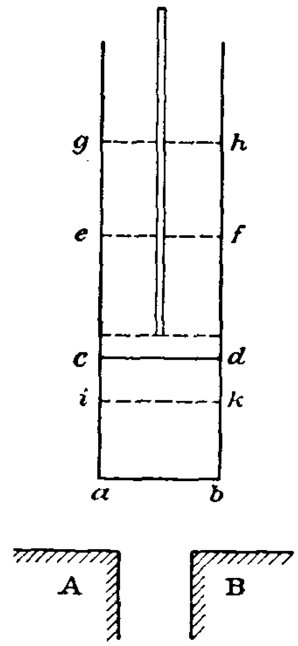

FIG. 42.

When a gaseous fluid is rapidly compressed its temperature rises, and when it is rapidly expanded its temperature falls. This is one of the best established facts of experience; we shall take it as the basis of our demonstration. When the temperature of a gas is raised and we wish to bring it back to its original temperature without again changing its volume, it is necessary to remove caloric from it. This caloric may also be removed as the compression is effected, so that the temperature of the gas remains constant. In the same way, if the gas is rarefied, we can prevent its temperature from falling, by furnishing it with a certain quantity of caloric. We shall call the caloric used in such cases, when it occasions no change of temperature, caloric due to a change of volume. This name does not indicate that the caloric belongs to the volume; it does not belong to it any more than it does to the pressure, and it might equally well be called caloric due to a change of pressure. We are ignorant of what laws it obeys in respect to changes of volume: it is possible that its quantity changes with the nature of the gas, or with its density or with its temperature. Experiment has taught us nothing on this subject; it has taught us only that this caloric is developed in greater or less quantity by the compression of elastic fluids.

This preliminary idea having been stated, let us imagine an elastic fluid—atmospheric air, for example—enclosed in a cylindrical vessel *abcd* (Fig. 42) furnished with a movable diaphragm or piston *cd*; let us assume also the two bodies *A*, *B*, both at constant temperatures, that of *A* being higher than that of *B*, and let us consider the series of operations which follows:

1. Contact of the body *A* with the air contained in the vessel *abcd* or with the wall of this vessel, which wall is supposed to be a good conductor of caloric. By means of this contact the air attains the same temperature as the body *A*; *cd* is the position of the piston.

2. The piston rises gradually until it takes the position *ef*. Contact is always maintained between the air and the body *A*, and the temperature thus remains constant during the rarefaction. The body *A* furnishes the caloric necessary to maintain a constant temperature.

3. The body *A* is removed and the air is no longer in contact with any body capable of supplying it with caloric; the piston however, continues to move and passes from the position *ef* to the position *gh*. The air is rarefied without receiving caloric and its temperature falls. Let us suppose that it falls until it becomes equal to that of the body *B*; at this instant the piston ceases to move and occupies the position *gh*.

4. The air is brought in contact with the body *B*; it is compressed by the piston as it returns from the position *gh* to the position *cd*. The air, however, remains at a constant temperature on account of its contact with the body *B*, to which it gives up its caloric.

5. The body *B* is removed and the compression of the air continued. The temperature of the air, which is now isolated, rises. The compression is continued until the air acquires the temperature of the body *A*. The piston during this time passes from the position *cd* to the position *ik*.

6. The air is again brought in contact with the body *A*; the piston returns from the position *ik* to the position *ef*, and the temperature remains constant.

7. The operation described in No. 3 is repeated, and then the operations 4, 5, 6, 3, 4, 5, 6, 3, 4, 5, and so on, successively.

In these various operations a pressure is exerted upon the piston by the air contained in the cylinder; the elastic force of this air varies with the changes of volume as well as with the changes of temperature; but we should notice that at equal volumes—that is, for similar positions of the piston—the temperature is higher during the expansions than during the compressions. During the former, therefore, the elastic force of the air is greater, and consequently the quantity of motive power produced by the expansions is greater than that which is consumed in effecting the compressions. Thus there remains an excess of motive power, which we can dispose of for any purpose whatsoever. The air has therefore served as a heat-engine; and it has been used in the most advantageous way possible, for there has been no useless re-establishment of equilibrium in the caloric.

All the operations described above can be carried out in a direct and in a reverse order. Let us suppose that after the sixth step, when the piston is at *ef*, it is brought back to the position *ik*, and that, at the same time, the air is kept in contact with the body *A*; the caloric furnished by this body during the sixth operation returns to its source—that is, to the body *A*, and the condition of things is the same as at the end of the fifth operation. If now we remove the body *A* and move the piston from *ef* to *cd*, the temperature of the air will fall as many degrees as it rose during the fifth operation and will equal that of the body *B*. A series of reverse operations to those above described could evidently be carried out; it is only necessary to bring the system into the same initial state and in each operation to carry out an expansion instead of a compression, and conversely.

The result of the first operation was the production of a certain quantity of motive power and the transfer of the caloric from the body *A* to the body *B*; the result of the reverse operation would be the consumption of the motive power produced and the return of the caloric from the body *B* to the body *A*; so that the two series of operations in a sense annul or neutralize each other.

The impossibility of making the caloric produce a larger quantity of motive power than that which we obtained in our first series of operations is now easy to prove. It may be demonstrated by an argument similar to that used on page 224. The argument will have even a greater degree of rigor; the air which serves to develop the motive power is brought back, at the end of each cycle of operations, to its original condition which was, as we noticed, not quite the case with the steam.

We have chosen atmospheric air as the agency employed to develop the motive power of heat; but it is evident that the same reasoning would hold for any other gaseous substance, and even for all other bodies susceptible of changes of temperature by successive contractions and expansions—that is, for all bodies in Nature, at least, all those which are capable of developing the motive power of heat. Thus we are led to establish this general proposition:

The motive power of heat is independent of the agents employed to develop it; its quantity is determined solely by the temperatures of the bodies between which, in the final result, the transfer of the caloric occurs.