II.

THE ANIMAL AS A MACHINE AND A PRIME MOTOR.

13. The Animal as a Machine.—The engineer regards the animal system with peculiar interest, as a machine of singularly complicated structure, a heat-engine or other prime motor—he is not certain as to its classification—of extraordinary efficiency, and as the embodiment of scientific problems of the highest interest and greatest obscurity. In this curious machine, combustible matter in the form of the grains or other foods, is consumed, with resultant production of carbon dioxide and other chemical compounds of various degrees of oxidation, and there is thus made available thermal, mechanical, and probably electrical as well as vital energies, all of which energies find application in the processes of animal life, in the performance of work, external and internal, and probably in mental operations as well. Waste also occurs in the form of heat and the rejected potential energy of incomplete chemical action.

Considering the automatic system of the animal, apart from intelligence and will, it is, in the eye of the engineer, a self-contained prime mover, including its furnace, its mechanism of work and energy-development, and possessing mechanism of transmission of power peculiarly and exactly adapted to its purposes.

14. The Animal as a Prime Motor.*—Hirn was probably the first and the greatest of those who have sought to measure up the energies of living creatures, and to follow the transformations which occur in the processes of vital organization and animal exertion.†

The origin of heat in the bodies of living animals has been a matter awakening the greatest interest and curiosity from the earliest times. The ancients thought heat and light a part of the vital power, due to the creative act, and without immediate source in the processes of vital existence. They thought the act of breathing a necessary process of cooling and removal of excess of this spontaneously generated heat, due to the fact of life simply. Since the establishment of the principles of energy in modern times, however, the philosopher has only concerned himself as to the method of production of this heat, recognizing the fact that it must have its origin, as must all the exhibitions and expenditures of energy that accompany it in the living being, from the potential and latent energies of combustible substances subjected to the processes of digestion and assimilation in the body. The scientific man of later times sees in the vital processes a transformation of energies originating in a slow combustion at low temperature, with changes of form of the resulting energies which, though none the less certainly phases of the chain of vital phenomena which he studies, are not all fully understood, or as yet all detected and rendered evident by research. The chemical compositions of these combustibles are

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* From Cassier's Magazine, Feb., 1892; by R. H. Thurston.

† La Thermodynamique et l'Étude du Travail chez les Êtres vivants. G. A. Hirn, Paris. *Bureaux des Revues*, 1887.

known; the quantities of energy which may be obtained by their perfect combustion to carbonic acid and water are well ascertained, and it only remains to determine the exact nature of the processes by which it is possible to effect their combustion at the temperature of the animal system, and to utilize by transformation the resulting power through those intermediate forms of energy-change which remain as yet undiscovered, and, in that sense, mysterious. We do not yet know how to produce combustion at a temperature of 98° Fahr., that at which combustion certainly does occur in the human system; or at the still lower temperatures at which such chemical changes go on in the bodies of cold-blooded creatures; nor do we know how to secure transformation of heat into mechanical and other forms of energy without sensible change of temperature and with high efficiency. In all our uses of heat-engines the wastes are a much greater proportion of the available energy than in any animal system, except where, as in some cases of application of the heat-energy of steam, for example, the wastes of the engine are, as in the human body, utilized for heating purposes.

The muscles when doing work, and all the glands, every organ, in fact, while performing its legitimate function, is found to become warmer; indicating the final appearance of whatever form of energy may be operating in the system in the form of heat. Heat is produced, apparently, in all the organs of the body, but in different degree, accordingly as their action is intense or deliberate. Those veins which return blood from working organs bring it back slightly warmer than the average for the whole system; those coming in toward

the heart from the skin bring back colder blood from that constantly refrigerated system of capillaries. The mean temperature of the venous blood entering the heart is about one degree warmer, in man, than the average for the whole system; between one and two degrees warmer than the arterial blood. The temperature of the body, as a whole, is automatically regulated by the system of nerves studied by Bernard; which causes the flow of blood toward any part to be accelerated when that part is cold, and retarded when it is too warm.

In every mechanism endowed with animal life, heat is produced and work is performed. It by no means follows that the work is the result of thermodynamic transformation; in fact, it seems impossible, in view of the fact that we have in the animal system no differences of temperature such as characterize and limit the action of the thermodynamic engine, that there should be a thermodynamic transformation. The heat would seem to be either a "by-product" or to be produced simply to insure uniform and sufficient temperature to permit the continuous and steady action of the vital powers and the machinery of the body. All the alimentary substances are combustible; but it is not a necessary consequence that they should be oxidized by a heat-producing combustion within the animal system. On the contrary, the quantity of heat which would be thus produced, added to the quantity of work performed by the vital organs, in digestion, nutrition, circulation of the blood,—itself an enormous quantity,—though reproducing the energy thus expended, as heat, and thus, in one sense, costing nothing—and in brain-work, to say nothing of wastes by conduction and

radiation to surrounding objects, the total amount of heat produced by such combustion would vastly exceed the quantity discharged from the body in any given time. This discrepancy is greater in cold-blooded animals than in warm-blooded; and, in many instances, the heat given out is probably too small in amount to account for combustion of any important fraction of the aliment of the system. The animal machine is not thermodynamic in the usual acceptation of that term, even if it be in any sense.

Mon. J. Beclard was probably the first to attempt to measure the relation of quantity and of transformation, thermodynamically, if such energy-transformations actually occur, in the animal machine. But he reached no definite result. Herdenheim suceeded little better; but Hirn found ways of investigation which gave real quantitative results of importance. A certain correspondence was found between work performed and heat exhaled; but nothing in his experiments gave indications of the method of production of that heat; and it is still impossible to say whether the heat is the direct product of oxidation of food, the result of oxidation of worn muscular and other tissue, or due to a number of thermal and other interactions occurring within the body and as yet beyond the reach of scientific observation. The disappearance of heat unquestionably established by Hirn's researches may or may not have been due to thermodynamic transformations. Whatever form of energy-transformation characterizes the vital machine, the wastes of energy take the final form of heat, and its quantity would, in any case, be reduced by the production of mechanical energy and the performance of work within and without the body.

In 1856–57 Hirn experimented with men engaged in regular work and at rest, and found that when at rest they produced a quantity of heat almost exactly, if not precisely, proportional to the amount of oxidation, as measured by the quantity of oxygen absorbed by them and exhaled in carbonic acid.

This was not precisely the case when they were at work. The principle of equivalence of energies then takes effect, and the measure of all the energy produced by oxidation is found in the sum of the heat discharged from the system and that energy of work which stands for the parts converted into dynamic forms.*

Hirn found that the quantity of heat generated by the human body at rest, whether that of men of middle age, or youth of either sex approaching maturity, was substantially the same under the same circumstances: about 5 calories per gramme of oxygen inspired and exhaled as a minimum, 5.2 as a maximum, and usually the latter figure. The differences may be ascribed to variations in observations, rather than to real differences of fact. Precisely the same quantities of air were measured as exhaled as were measured as inhaled, in all cases. A singular and significant fact was, however. discoverable in the results, as reported by Hirn: The quantity of heat produced per unit of oxygen absorbed and converted into compounds exceeds by a third the amount computed upon the basis of the experiments of Favre and Silbermann. This result would seem to indicate other sources of heat than combustion with oxygen. It may be due to

* L'Équivalent mécanique de la Chaleur. G. A. Hirn, 1858.