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MOTION AND HEAT.

THE term "Mechanical Equivalent of Heat" does not present a perfectly accurate concept of the determinations of Dr. Joule and others. The great work actually done was the determination of the "Heat Equivalent of Molar Motion."

"The Mechanical Equivalent of Molar Motion" is the amount of mechanical work that it will do; and when the whole energy embodied in a given molar motion is converted into heat, the units of heat thus developed may again be converted into molar motion capable of doing the same work. Hence the term "Mechanical Equivalent of Heat" is accurate enough for purposes of calculation.

But the true equation is that molar motion is equivalent to so much mechanical work; molar motion may be converted into heat capable of the same amount of mechanical work that the molar motion could do before its conversion into heat, and therefore we have the "Mechanical Equivalent of Heat." This use of the consequence, that is, the mechanical work which molar motion can do, for the motion itself, tends to obscure the concept of the real relation between heat and molar motion.

The primal work of the energy, or force, which constitutes molar motion is to transfer a mass from one place, or part of space, to another, and so long as this work is continued and unresisted, no heat is developed. A body moving through space entirely unresisted, whatever may be its mass or velocity, develops no heat. It is only when the movement is resisted by impact or friction of some kind that the energy of motion assumes the form of heat; and it is only when thus resisted that this energy of motion can do mechanical work. To the extent that the energy embodied in resisted molar motion is expended in mechanical work it cannot be converted into heat.

Mechanical work consists in counteracting some other force, generally gravitation or cohesion. The force or energy embodied in a ball thrown upwards from the earth's surface develops no heat except such as may result from the friction of the air; and if at its precise point of highest elevation it lodges on the top of a house or some other support, none of the energy is thereby converted into heat. The ball has acquired what Mr. Balfour Stewart calls energy of position; and when this potential energy again becomes dynamic by the ball's falling to the earth, no heat is developed except by the friction of the atmosphere, until the ball strikes the surface of the earth. If the phenomena occurred in vacuum neither the energy of motion in the ball, while doing the work of lifting the ball to its highest elevation, thus counteracting gravity, nor the potential energy rendered dynamic by its fall, would develop any heat whatever until its impact against the earth's surface. Here, according to the law of conservation of energy, it would do work or develop heat equivalent to that expended in its upward projection.

But to the extent that the energy of the impact itself does mechanical work, that is, counteracts cohesion in the work of molar deformation, it develops no heat. If an egg and a metal ball of the same shape, size, and weight are dropped from the same height on a hard pavement, the heat developed by the two impacts cannot be the same if the egg is smashed. If the heat developed by the impact of the metal ball is X, that developed by the impact of the egg must be X minus the kinetic energy required to smash the egg.

One of the occupations of my boyhood was to attend a mill for grinding corn, and one of the first things learned in that business was that if the moving stone was properly balanced and a sufficiency of corn supplied, the meal came out very little heated; but if the stones came into contact from lack of having corn to grind or from want of proper adjustment or levelling of the moving stone, heat was developed rapidly.

It is for this reason that hard substances like flint and steel more readily develop by friction the heat necessary for combustion than softer substances; the energy of motion in the friction of softer substances is expended to a greater or less extent in molar deformation, and it is only the residue not thus expended that is available for conversion into heat.

This principle is constantly applied in practical mechanics to develop heat from friction when it is required, and to prevent its development when not wanted. Except for igniting combustibles, heat from friction is not generally wanted for practical use; but Dr. Mayer mentions an instance in which a manufactory used a surplus of water power to revolve two large iron disks against each other to develop heat by friction to warm the establishment. The very general object in mechanical work is to prevent the conversion of the energy of motion into heat by friction, and this is done both by diminishing the frictional resistance, and also by the use of solid lubricants whose molar deformation will furnish work for the energy unavoidably lost in friction, and thus prevent the development of heat and the local injury from the energy in that form.

Hence it was that Dr. Joule and others, in making the determinations of the so-called "Mechanical Equivalent of Heat," made use of substances in which there was no work or very little work of molar deformation for the energy, the heat equivalent of which was measured.

It seems, therefore, that two propositions may be stated:—

First, that molar energy, that is, the kinetic energy of a moving mass without friction, develops no heat while doing its primal work of transferring the mass from one place, or part of space, to another.

Second, that when the movement of the mass is resisted, the heat developed is the equivalent of only so much of its energy as is not expended in molar deformation or other mechanical work.

There is obviously another cause which may prevent the kinetic energy of molar motion from development into heat, and that is its conversion into the molecular motion of expansion. When expansion occurs, there is necessarily an enlargement of the intermolecular spaces or of the molecules themselves, or a movement of the molecules; and while we have as yet no such demonstration as is possible in molar phenomena, we can assert, without fear of scientific denial, that the phenomenon of expansion is a manifestation of molecular motion.

It is usual to regard expansion as the work of heat, and it is undoubtedly the work of the same energy which is embodied in molar motion, and which causes an elevation of temperature; which passes from one body to another by conduction, and from one body to another and from bodies into space by radiation.

But this energy, while doing the work of molecular motion in expansion, develops no more heat than while it is moving an unimpeded mass through space. The impact of moving masses free to expand from the instant of impact could develop no perceptible heat; that is, only so much of the energy as was not expended in the work of molecular motion of expansion would be available for the development of heat. If the bodies brought into impact were liquid ammonia, and this was set free in the atmosphere by the impact, not only the entire energy of the impact (unless the molar motion was almost beyond calculable velocity) would be expended in the work of expansion, but energy in the form of heat would be withdrawn from surrounding bodies to finish the work.

It is resistance to the molecular motion of expansion that develops heat when expansion occurs as the primal work, that is, which causes an elevation of temperature, and converts the energy or force into the other well-known phenomena of heat.

This resistance may be from cohesion in the matter to which the energy or force is imparted, from chemical affinity, from the walls of a containing vessel or other environment, or from a piston or other compression. In every case the development of heat, that is, the elevation of temperature, and the other phenomena indicating the conversion of the force or energy into the form of heat, is determined by the intensity of the molecular motion set up by the force or energy imparted to the body, and the resistance to it.

Hence, in the experiments to determine the so-called "Mechanical Equivalent of Heat" where expansion was used, means were provided for its perfect resistance. Here again the term does not express an accurate concept of the determination actually made; it was really the "Heat Equivalent of Molecular Motion." As in the other case, the expression is accurate enough for purposes of calculation, because the mechanical equivalent of molecular motion, that is, the mechanical work it will do, is the same as the mechanical equivalent of the heat developed by its perfect resistance.

It is not the motion in either case that is converted into heat, but it is the force or energy causing the motion which ceases to move the mass or molecules and causes an elevation of temperature and the other phenomena of heat.

It seems, therefore, that we can state two other propositions, namely:

Third, that so much of molar motion as is converted into molecular motion by impact or friction cannot be directly converted into heat; and,

Fourth, that the molecular motion set up by molar impact, friction, or otherwise, and manifested by expansion, can be converted into heat only by resistance to expansion.

This force, or energy, is dynamic when causing motion or when causing elevation of temperature and the other phenomena of heat; but it becomes potential, or "energy of position," when a ball is thrown up and lodged on the roof of a house, or when radiant and dynamic heat becomes the latent heat of liquefaction and evaporation, or when the dynamic radiation from the sun is stored up in the molecular structure of the hydro-carbons of vegetable and animal organisms by chemical affinity and the vital forces; and it becomes partly potential when heat is absorbed.

This force, or energy, is directly subject to observation only when dynamic; it apparently disappears when a ball thrown up lodges on the roof of a house, or when heat becomes latent in liquefaction and evaporation, and when heat and light are stored up in the molecular structure of vegetable organisms. But we know that by appropriate means it can be rendered again dynamic, with its full integrity and with the qualities it possessed before its imprisonment, including the equivalence of its different forms. It becomes dynamic in the form in which it was rendered potential; in the ball loosed from its perch the energy becomes dynamic as molar motion; in liquids and gases subjected to pressure the latent heat of liquefaction and evaporation becomes again dynamic as heat; and in the combustion of vegetable organisms the sun's energy becomes again dynamic substantially as it was locked up.

Light is undoubtedly a division of the heat form of this force, or energy. It is rendered potential in vegetable organisms, and becomes dynamic as heat, not as light, when the combustion of the organism occurs slowly and at a low temperature. It not only results from intense heat, but Professor Tyndall has demonstrated that heat rays, after they leave the body which sends them forth, may be concentrated into light rays. It will therefore be sufficiently accurate for our present purpose to consider both heat and light as together constituting a single form of this force, or energy.

If expansion is resisted by cohesion, chemical affinity, mechanical pressure, or otherwise, the temperature of the body rises in proportion to the increments of the force, or energy, received; radiation increases with rise of temperature, and if the resistance is sufficient, incandescence and the more intense radiation in the form of light, begin.

It may be impossible from lack of power in any machine which man can construct to compel by compression of expanded matter incandescent radiation. But when heat becomes radiant as it does from compression, it is only a question of intensity whether the matter radiating heat will become red hot and radiate light also.

In the combustion of hydrocarbons it is evidently the resistance to expansion which causes heat radiation, and as this resistance becomes more intense, light radiation also. In the vegetable or animal organisms which constitute the hydrocarbons a new molecular structure has been built up, in which force, or energy, coming dynamic from the sun has been stored up and rendered as completely potential as the energy of a ball lodged on the roof of a house, or as dynamic heat when it becomes the latent heat of liquefaction or evaporation. This force, or energy, thus stored up by chemical and vital action in the new molecular structure and rendered potential, is set free and again rendered dynamic by the chemical reaction of combustion, and the material elements return substantially to the condition in which they were before.

The force, or energy, thus set free by the chemical reaction at once begins the work of dynamic energy; and if the matter in which the reaction occurs is free to expand, the energy is expended in the molecular motion evidenced by expansion.

But if expansion is resisted by cohesion, chemical affinity, or mechanical compression, there is an elevation of temperature and the other phenomena of heat.

As resistance to expansion increases, heat becomes more intense; and when heat radiation is unable to carry off the energy as rapidly as it is set free, the matter becomes incandescent, and the more intense form of light radiation begins.

The graphic description of ordinary combustion in Dr. Josiah P. Cooke's "New Chemistry" leaves no doubt that this is what actually occurs, and that "the light comes from the incandescent solid particles," because they are more persistent in resistance to the molecular motion evidenced by expansion. The moment these particles are converted into carbonic dioxide, and aqueous vapor, and thus become free to expand, the matter ceases to be incandescent.

If we could provide some means in ordinary combustion for retaining the carbonic dioxide and aqueous vapor, with the molecules concentrated as they are in the carbon particles, the matter would doubtless continue incandescent after the reaction; and undoubtedly the energy expended in the expansion of the carbon dioxide and aqueous vapor, could be converted into radiant heat by sufficient compression of those gases.

The phenomena of explosions demonstrate even more clearly than ordinary combustion that the development of heat results from resistance to molecular motion. Loose gun-cotton exploded, will not develop heat sufficient to ignite gun-powder in contact with it; but if the gun-cotton is confined, its combustion develops heat sufficient to ignite gunpowder, and substances far more refractory. It is said that the reason for this peculiar result of the explosion of loose gun-cotton, is that there is not time to develop the heat. But the true reason undoubtedly is that the molecular motion set up is so intense, as compared to the resistance of the atmosphere, that the entire force or energy of the explosion is expended in that work, and there is little or no necessity for elevation of temperature or radiation.

In firing a gun, the energy developed by the explosion is divided into three parts: that which by reason of resistance to molecular motion causes elevation of temperature and radiation in the barrel; that which imparts molar motion to the projectile (which we know may also be converted into heat); and, third, the residue of molecular motion which is dissipated in the atmosphere at the muzzle of the gun, and neither develops heat in the barrel nor adds to the molar motion of the projectile.

If the foregoing inductions are sound, the heat developed by an explosion is determined by the resistance to the molecular motion exerted by the force or energy set free and rendered dynamic by the chemical reaction. This resistance consists of cohesion and chemical affinity in the matter in which the reaction occurs, and in the environment. If the whole force or energy set free and rendered dynamic is d, and the whole resistance is r, and x the units of heat developed, then $x = \frac{d}{r}$.

This explains why the attempts made to determine the energy of explosives by the units of heat developed in their explosion have resulted in unmitigated nonsense.[1]

This has doubtless been a source of error in determining the heat evolved or absorbed in chemical processes. The energy converted into heat by resistance to molecular motion, and afterwards lost by radiation or conduction, is estimated or otherwise taken into the account, but that which slips away in the form of unresisted molecular motion is not counted.

"Although these values," says Dr. Cooke in his "Chemical Philosophy," "are undoubtedly as fundamental constants of chemistry as the atomic weights, yet they have not been as yet so fully confirmed or so thoroughly collated as to enable us to present an entirely consistent system. Hence the table here given [of heat evolved or absorbed in different chemical actions] must be regarded as provisional, and as serving only to illustrate the principles of the subject.[2]

It is not necessary to the present inductions to determine whether the molecular motion evidenced by expansion, and which, when resisted, results in elevation of temperature and other phenomena of heat, is molecular vibration as supposed in the kinetic theory, or a rectilinear projection of the molecules, as I have tried to prove.[3] All we need to know is that this molecular motion, whatever may be its character or direction, is work done, and, as in the case of molar motion, the energy embodied in it cannot be converted into heat except by resistance.

Elevation of temperature, which is the first phenomenon of heat, seems to be a preparation for the flight of radiation, the flight becoming more rapid or intense as the temperature rises; but energy will not make the preparation nor begin the flight from the matter in which it is embodied, unless its work of molar or molecular motion is resisted or hindered.

Whether heat absorbed by matter is energy rendered partially potential by the partial counteraction of cohesion, or whether it continues fully dynamic in the work of increased molecular vibration as supposed in the kinetic theory, it is not necessary for our present purpose to determine. We know certainly that heat is absorbed by matter, and the phenomena of the atmosphere demonstrate that the capacity of matter to absorb heat diminishes by some as yet undetermined ratio with increase of tenuity. This diminution of capacity to absorb heat doubtless results from the smaller number of molecules to which motion can be imparted; and taken in connection with the induction that energy becomes radiant as heat and light when molecular motion is resisted, or hindered, it furnishes a very simple explanation of the intense heat and brilliant incandescence which small increments of energy develop in highly exhausted tubes.

The work of molecular motion being restricted by the paucity of the molecules, the small increments of energy, finding no sufficient work in moving them, elevation of temperature and incandescence follow, for substantially the same reason as in other cases where greater increments of energy are applied.

It seems to make no specific difference whether the increments of energy are imparted by the direct conduction or radiation of heat, or by resistance to a current of electricity.

Mr. Crookes, by concentrating increments of energy in a highly exhausted tube on iridio-platinum alloy, one of the most refractory metallic compounds, not only raised it to a white heat, but actually melted it: while the same measurable increments of energy applied to the same substance in the atmosphere, or in some other medium not more tenuous, would have caused hardly an appreciable elevation of temperature. The energy, in such case, would be expended in

[1] The true measure of the energy of explosions must be the amount of energy set free by the chemical reaction, and this is determined by the number of molecules put in motion (quantity of matter, etc.) and their velocity.

[2] "Chemical Philosophy," revised edition (1891), p. 174.

[3] "Molecular Motion in the Radiometer," etc. N. D. C. Hodges, New York, 1891.

molecular motion in the surrounding medium. And the brilliant incandescence in Geissler, Crookes, and Tyndall tubes from minute increments of energy are well known.

This increase of temperature and radiation from small increments of energy in highly tenuous matter seems to be what we ought to expect from the phenomena of this force or energy when it is in the form of molar motion. We then measure it by the mass and velocity of the moving body; that is, by its momentum, and this momentum is what is convertible into heat when the movement is resisted.

Increase in velocity compensates for decrease in mass, and hence a small projectile, at high velocity, will do the same work as a larger projectile at lower velocity; and the momentum, in each case, can be converted into the same units of heat. For obviously the same reason, the intense velocity imparted to the gaseous products of an explosion of dynamite enables this highly tenuous matter to do precisely the same work on a hard rock, as a hammer of a million times the mass, but moving with only one-millionth of the velocity.

But there is necessarily a limit to this substitution of velocity for mass; and this limit is in the capacity of matter to embody the energy; and when the force of energy is applied to matter in the form of heat we ought to expect to find the same limit. This application in the form of heat may be made by conduction, when the whole energy imparted is absorbed; or by radiation when only so much as is not reflected, is absorbed; but the resulting phenomena are the same, whatever may be the process by which the absorption is accomplished.

The fact developed in spectrum analysis, that incandescent matter absorbs the same rays of light which it emits, seems to be another illustration of the law that the capacity of matter to receive radiant energy is limited, and in this case by its capacity to radiate the energy received.

If the evolution of heat and elevation of temperature results from resisted molecular motion, it necessarily follows, that a single molecule, moving in unconfined space, whatever may be its velocity, would be at the absolute zero of temperature. But this is mere speculation of no scientific value, because we have no evidence that a molecule can become separated from other molecules, nor that it is possible to place it where it could move without resistance.

But there is another induction of practical importance in sustaining the assumption that we have just made. If the effect of heat imparted to matter by conduction or radiation is to set up the molecular motion evidenced by expansion, and this work of molecular motion must be resisted before radiation begins, it necessarily follows that the number of molecules in the body receiving heat, and to which motion can be imparted; in other words, the density of tenuity of the matter, must be an element, determining, in some measure, the capacity of the matter to absorb heat.

This explains why the atmosphere decreases in temperature with increase of tenuity, upwards from the earth's surface; and why we can assume absolute zero in space entirely unoccupied by ponderable matter, if there is any space thus entirely unoccupied, notwithstanding the presence of potential or dynamic energy, because it is only in conjunction with ponderable matter (resisted molar or molecular motion) that dynamic energy develops elevation of temperature, and the other phenomena of heat.

It is obvious that force or energy in the form of molar motion is being constantly converted by impact or friction into the form of heat. Taking the earth as a whole, during the period of human observation, this constant conversion of molar motion into heat has been compensated by a conversion of heat into molar motion, so that the equilibrium between the two forms of this force or energy has been preserved in terrestrial nature, and there has been no loss of motion nor increase of heat, since man began to observe nature and keep a record of his observations.

Resistance to movement, that is, to the work being done by the force or energy in molar motion, is necessary to convert the force or energy into the form of heat; and it may be that when this force of energy is applied to ponderable matter in the form of heat, and its proper work as heat is resisted, the surplus heat may be converted directly into molar motion.

It is certainly within the range of possibility, that, under certain conditions, a body of ponderable matter may receive increments of heat more rapidly than it can furnish work for it in the molecular motion of expansion, or discharge it by radiation or conduction; and, in such case, it seems inevitable that the body thus receiving more heat than it could furnish work for or discharge, if free to move, would be put in motion away from the source of heat, and that this motion would continue until a distance from the source of heat was reached, at which the heat received was not greater than could be employed in expansion or discharged in radiation and conduction.

Dr. Grove was inclined to the opinion that it was thus possible to convert heat directly into molar motion. He says, "There are, indeed, some delicate experiments which tend to prove that a repulsive action between separate masses is produced by heat. Fresnel found that mobile bodies heated in an exhausted receiver repelled each other to sensible distances; and Baden Powell found that the colored rings, usually called Newton's rings, change their breadth and position, when the glasses between which they appear are heated, in a manner which showed that the glasses repelled each other." [1]

But, however that may be, there is certainly a molar motion which always follows and evidences the molecular motion of expansion. The law that action and reaction must be equal and opposite, applies to molecular motion in a closed vessel. It is the operation of this law which secures uniform pressure in steam boilers, and other like devices for using gas expansion for mechanical purposes; and thus converts the molecular motion, evidenced by expansion, into molar motion.

DANIEL S. TROY.

(To be continued.)

[1] "Correlation and Conservation of Forces," p. 41. D. Appleton & Co. 1890.

LETTERS TO THE EDITOR.

**** Correspondents are requested to be as brief as possible. The writer's name is in all cases required as proof of good faith.*

On request in advance, one hundred copies of the number containing his communication will be furnished free to any correspondent.

The editor will be glad to publish any queries consonant with the character of the journal.

A Question in Physics.

CAN there be a crowding of the particles of a gas to a much smaller compass without its being markedly heated? Can a gas expand without being cooled? At first thought the answer would seem to be an emphatic *no* in both cases; but it would appear that these conditions may exist sometimes. *Science*, Vol. XV., p. 387, published the results obtained by direct determination of the heating of air when compressed by a pump connected by a long tube with the cylinder. A compression to ten inches above atmospheric pressure gave a heating of about 4° F., ignoring the heat lost to the sides of the cylinder. The corresponding expansion into the open air gave a cooling of about 4°, neglecting the