THE TEMPERATURE OF THE SURFACE OF THE SUN

IT will be recollected that Messrs. M. E. Vicaire and Sainte-Claire Deville read some papers before the Academy of Sciences at Paris last January, showing that the temperature of the solar surface does not exceed that produced by the combustion of organic substances. Their reasoning being based on the law of radiant heat established by the investigations of Dulong and Petit. I have in the meantime instituted a series of experiments on a comparatively large scale, in order to test the correctness of the said law. Accordingly, the dynamic energy developed by the radiation of a mass of fused iron weighing 7,000 pounds raised by "overheating" in the furnace to a temperature of 3,000° F., has been carefully measured.

Sir Isaac Newton assumed that the quantity of heat lost or gained by a body in a given time is proportional to the difference between its temperature and that of the surrounding medium. Some eminent scientists, however, accepting Dulong's conclusions and formula, assert positively that the stated assumption is incorrect. In so doing they apparently overlook the conditions inseparable from the Newtonian doctrine, namely, that the conducting power of the radiating body should be perfect; that at every instant the temperature pervading the interior mass should be transmitted to the surface.* It needs no demonstration to prove that if the conducting power of a body be so perfect that the temperature of the centre is at all times the same as that of the surface; in other words, that the fall of temperature at the centre, occasioned by radiation, is as rapid as the fall of temperature at the surface, the rate of cooling of such a body will be very different from that observed by Dulong and Petit. The investigation instituted by those experimentalists has in reality established only the degree of conductivity of the radiators employed, under certain conditions, but by no means their true radiant energy at given temperatures. M. E. Vicaire and Sainte-Claire Deville, therefore, commit a serious mistake in assuming that the *quantity* of heat transmitted by the radiation of incandescent bodies at high temperatures has been determined. It may be observed that the relation between the time of cooling and the *quantity* of heat transmitted by radiation which Dulong and Petit established, also misled Pouillet regarding the temperature of the solar surface, which he computed at 1,461° C., or at most 1,761° C. It will be well to bear in mind that Pouillet had himself ascertained with considerable accuracy the temperature produced by solar radiation on the surface of the earth; and also the retardation suffered during the passage of the rays through the terrestrial atmosphere. He was therefore able to demonstrate that the dynamic energy developed by solar heat amounts to nearly 300,000 thermal units per minute for each square foot of the surface of the sun. Considering the imperfect means employed by Pouillet, his "pyrheliometre," the exactness of his determination of solar energy is remarkable. The truth is, however, that the near approach to exactness was somewhat fortuitous, the eminent physicist having underrated the energy of radiant heat on the surface of the earth, while proportionately over-estimating the retarding influence of the terrestrial atmosphere. The true dynamic energy developed by radiation at the surface of the sun, exclusive of the absorption of the solar atmosphere—no doubt exceedingly small—determined by the solar calorimeter mentioned in a previous article, is 312,500 thermal units per minute upon an area of one square foot. It will be proper to notice that this amount is not a mean result of a number of observations, but the greatest energy developed at any time during observations continued upwards of three years, namely February 28, 1871. It will be proper to add that this result has been withheld from publication until it could be verified by a second observation indicating an equal energy. Fortunately the sky at noon, March 7, 1872, proved to be as clear as on the previous occasion referred to, the indicated energy differing only a few hundred units from that developed February 28, 1871.

Temperature being a true index of molecular and mechanical energy, conclusively established by the exact relation between the degree of heat and the expansive force of permanent gases under constant volume, it is surprising that Pouillet did not perceive that an intensity of 1,461° C. or 1,761° C., could not possibly develop on a single square foot of surface the enormous energy represented by 300,000 thermal units per minute. M. Vicaire, adopting like Pouillet Dulong's formula, states in the paper presented to the French Academy that "an increase of 600° is sufficient to increase the radiation a hundred fold;" and that Pouillet has verified Dulong's law to more than 1,000°. "Supposing," he observes, "that beyond this temperature the law ceases to be true, it cannot be absolutely remote from the truth for the temperatures of from 1,400° to 1,500° which we deduce by adopting the law." Sainte-Claire Deville concludes his essay on solar temperature thus:—"In accordance with my first estimate I believe that this temperature will not be found far removed from 2,500° to 2,800°, the numbers which result from the experiments of M. Bunsen, and those published long ago by M. Debray and myself." The French *savans* then agree that the temperature of the surface of the sun does not exceed the intensity produced by the combustion of organic substances, their grounds for this assumption being, as we have seen, Dulong's formula relating to the velocity of cooling at high temperatures. But Dulong and Petit did not carry their investigations practically beyond the temperature of boiling mercury; hence their formula relating to high temperatures is mere theory, the soundness of which we have now been enabled to test most effectually by measuring the radiant power of a mass of fused metal raised to a temperature of 3,000° F., 30 inches in depth, presenting an area of 900 square inches.

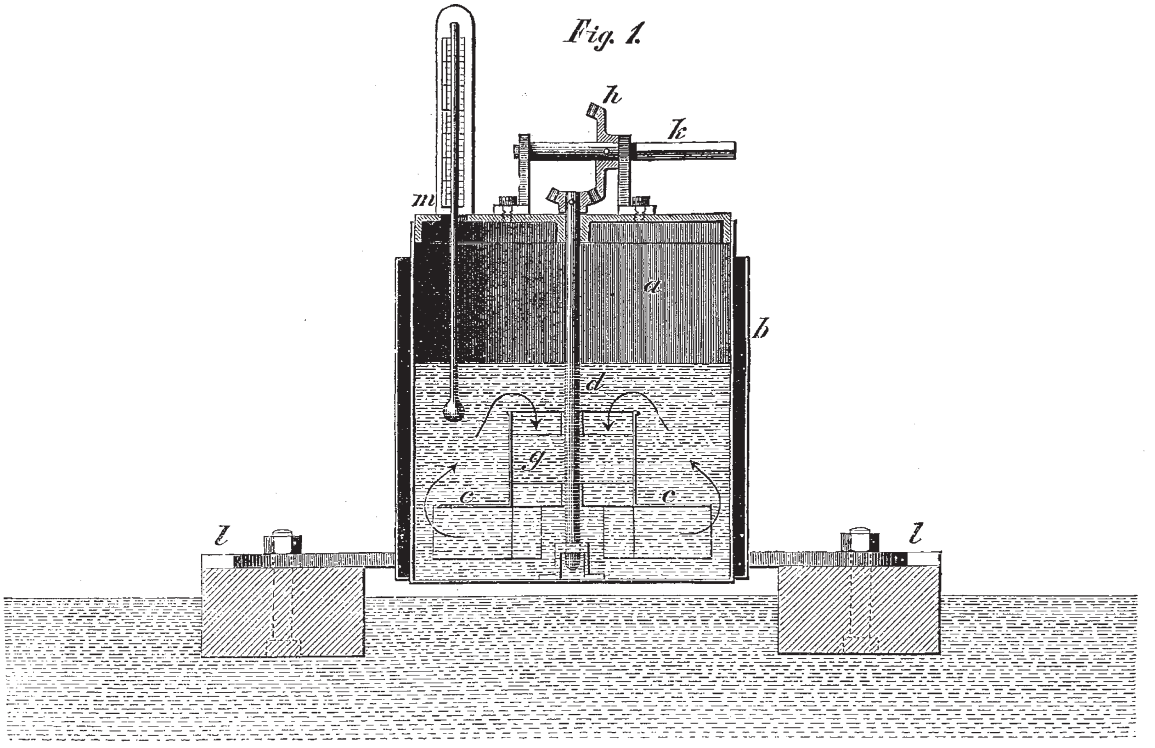
Before describing the means which have been employed in measuring its radiant power, let us briefly consider the condition of the fused mass during the experiments. In the first place, the temperature has been sufficiently high to produce an intense white light, luminous rays of great brilliancy being emitted by the radiant surface during the trial; (2) the bulk of the fused mass being adequate, the intensity of radiation has been sustained without appreciable diminution during the time required for observation; (3) the temperature being higher than that which the French investigations assign to the surface of the sun, while the bulk, as stated, is sufficient to maintain the temperature of the fused mass, it may be reasonably asked, why an area of one square foot of our experimental radiator should not emit as much heat in a given time as an equal area on the solar surface, if its temperature be that assumed by Pouillet? It may be positively asserted, moreover, that an increase of the dimensions of our radiator to any extent, laterally or vertically, could not augment the intensity or the dynamic energy developed by a given area. Again, Dulong's formula, as applied by scientists, shows that the emissive power of a *metallic* radiator raised to a temperature of 3,000°, reaches the enormous solar emission computed by Pouillet.

Let us now briefly examine the calorimeter constructed

* The writer has just completed a set of experiments with a spherical radiator, 2·75 in. in diameter, composed of very thin hammered copper, charged with water kept in motion by a wheel applied within the sphere, revolving at a rate of 30 turns per minute, the centrifugal action of which brings the particles of the central portion of the fluid so rapidly in contact with the thin spherical shell, that the apparently absurd condition of perfect conductivity has been practically fulfilled. The result of carefully conducted experiments with this radiator, enclosed in an exhausted vessel kept at a constant temperature, has established that Newton's law relating to radiant heat, up to a differential temperature of 100° Fahr. (beyond which the investigation has not extended), is rigorously correct. The subject will be fully discussed in a future article.

for ascertaining the mechanical energy developed by the radiation of the fused mass under consideration. Fig. 1 represents a vertical section, and Fig. 2 a perspective view. *a* is a cylindrical boiler, having a flat bottom, composed of thin sheet-iron 0·012 inch thick, coated with lamp-black. The cylindrical part of this boiler is surrounded by a concentric casing *b*, the intervening space being filled with a fire-proof non-conducting substance. A horizontal wheel, *c c*, provided with six radial paddles, is applied within the boiler, attached to a vertical axle, *d*. An open cylindrical trunk, *g*, is secured to the perforated disc which supports the paddles. The vertical axle passes through the top of the boiler, a conical pinion being secured to its upper termination. By means of a vertical cog-wheel, *h*, attached to the horizontal axle *k*, and geared into the conical pinion, rotary motion is communicated to the paddles. The centrifugal action of the latter will obviously cause a rapid and uniform circulation of the water contained in the boiler—indispensable to prevent the intense radiant heat from burning the bottom. The boiler and mechanism thus described are secured to a raft, *l l*, composed of fire-bricks floating on the top of the fluid metal. By this means it has been found practicable to keep the bottom of the boiler at a given distance, very near the surface of the fused mass, while by moving the raft from point to point, during the observation, irregular heating resulting from the reduction of temperature of the surface of the metal, under the bottom of the calorimeter, has been prevented. The radiant heat being too intense to admit of the axle *k* being turned directly by hand, an intervening shaft, eight feet long, provided with a crank handle at the outer end, has been employed for keeping up the rotation of the paddle-wheel during the trial. It is scarcely necessary to observe that, the intervening shaft should be coupled to the gear work by means of a "universal joint," to admit of the necessary movement of the raft. The experiment, repeated several times, has been conducted in accordance with the following explanation. The boiler being charged,

Fig. 1.



the paddle wheel should be turned at a moderate speed while observing the temperature of the water, the thermometer employed for this purpose being introduced through an opening, *m*, at the top of the boiler. The temperature being ascertained, the instrument should be quickly placed on the raft, and the time noted. As soon as vapour is observed to escape through the opening at *m*, the instrument must be instantly removed, the time again noted, and the temperature of the water within the boiler ascertained. It will be well to keep the paddle-wheel in motion until the last observation has been concluded.

The temperature of the fused metal having been as high during our experiments as that of the solar surface computed by Pouillet and his followers, while the thin substance composing the bottom of the calorimeter has been brought almost in contact with, and consequently received the entire energy transmitted by, the radiant surface, the reader will be anxious to learn what amount of dynamic energy has been communicated in a given time, on a given area. The desired information is contained in the following brief statement:—The necessary corrections being made for heat absorbed by the materials composing the paddle-wheel, &c., the instituted test shows that the temperature of a quantity of water weighing 10 pounds avoirdupois has been elevated 121° F. in 164 seconds (2·73 minutes), the area exposed to the radiant heat being 63 square inches. Hence a dynamic energy $\frac{10 \times 121}{2{\cdot}73} \times \frac{144}{63} = 1013$ thermal units per minute, has been developed by the radiation from one square foot of the surface of the fused metal maintained at 3,000° F., against 312,500 units developed by the radiation of one square foot of the solar surface, the temperature of which, agreeably to the calculations of the French *savans*, is less than that of our experimental radiator.

Having thus ascertained practically the amount of dynamic energy developed by the radiation of a metallic body raised to the high temperature of 3,000°, we have only to show in a similar manner the amount of energy developed by a metallic radiator of a low temperature, to be enabled to demonstrate the correctness or fallacy of Dulong's formula. Numerous experiments have been made for this purpose with apparatus of different forms, the results having proved substantially alike. The device most readily described consists of a spherical vessel charged with water, suspended within an exhausted spherical enclosure kept at a constant temperature. Repeated trials show that, when the differential temperature is 65°, the enclosure being maintained at 60°, while the sphere is 125°, the dynamic energy transmitted to the enclosure by a sphere the convex area of which is one square foot, amounts to 5·22 thermal units per minute. The accuracy of this determination is confirmed by the fact that during the summer solstice at noon, when the sun's differential radiant intensity is 65°, the solar calorimeter indicates a dynamic energy of 5·12 units per minute on one square foot of surface.

Our practical investigations, then, show that a differential temperature of 3,000° developes by radiation a dynamic energy of 1,013 thermal units per minute upon an area of one square foot; and that a differential temperature of 65° develops 5·22 units per minute upon an equal area. The ratio of radiant energy at the first mentioned intensity will therefore amount to $\frac{1013}{3000} = 0\cdot337$ units for each degree of differential temperature; while for the low intensity it will be $\frac{5\cdot22}{65} = 0\cdot080$ unit for each degree of differential temperature. Consequently, the ratio o the radiating energy will be $\frac{0\cdot337}{0\cdot080} = 4\cdot21$ times greater at 3,000° than at 65°. Now, M. Vicaire, on the authority of Dulong, states that the ratio will be a hundred fold greater for an increase of only 600°. According to Newton's theory, based on dynamic laws, the proportion between the differential temperature and the radiant energy of bodies is constant; while Dulong and Petit, basing their conclusions upon an erroneous estimate of the time of cooling, assert that the ratio of energy increases

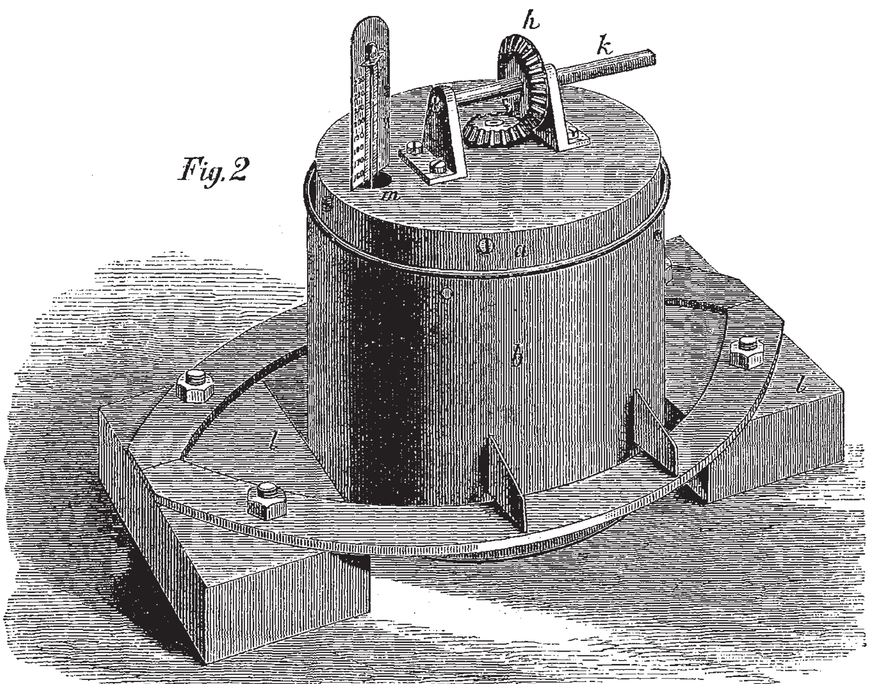


Fig. 2

several thousand times when the temperature is increased from 65° to 3,000°. Newton, then, as our experiments prove, is incomparably nearer the truth than the French experimenters; and possibly future research will prove that his law, when properly applied, will be found absolutely correct. It should be mentioned that the result of our experiments with the fused metal, compared with the result of other experiments with solid metals at various temperatures, show that the emissive power of cast iron is relatively greater in a state of fusion than when solid, or merely incandescent. This observed increase of emissive power, now being thoroughly investigated, will no doubt account for the deviation from the Newtonian law indicated by the preceding comparison, which, let us recollect, is based upon the difference of radiant energy of fused metal at 3,000°, and solid metal at 65°. Considering this extreme range of temperature, and the totally different conditions of the radiators, the observed discrepancy is not too great to admit of satisfactory explanation.

The fallacy of Dulong's formula relating to high temperatures having been conclusively shown, it will not be necessary to examine the calculations of Messrs. M. E. Vicaire and Sainte-Claire Deville, presented to the Academy of Sciences at Paris. Besides, the question of solar temperature cannot be properly investigated without considering the leading points connected with the propagation of radiant heat through space—a subject of too wide a range to be discussed in this article. It should, however, be mentioned that the result of the measurement of solar intensity March 7, 1872, before referred to, proves the correctness of our previous demonstrations, showing that the temperature of the surface of the sun is at least 4,036,000 F. J. ERICSSON

THE CYCLONE IN THE WEST INDIES

A CORRESPONDENT in your number of October 12, 1871, expresses a wish for an article to appear in your paper, on the Cyclone which passed over Antigua, and several other of the Leeward Islands in the West