The Question of Temperature and Efficiency of Thermal Radiation

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II. *The Question of Temperature and Efficiency of Thermal Radiation.* By JAMES SWINBURNE.*

ARGUMENT.

It is generally supposed that some surfaces can radiate light more economically than others. Twenty years ago the author inferred from Kirchhoff's and others' work that efficiency depended on temperature alone. This theory has been contradicted repeatedly. Evans's experiments do not support this theory. Explanation of his results. Professor Bottomley's results misleading owing to absence of photometric measurements. Lummer and Jahnke show little difference between platinum and a black body. Theories as to the thorium mantle. Explanation of phenomena.

It has long been known that at the same high temperatures some bodies, for instance those with black surfaces, radiate more energy per unit surface than white or polished surfaces; but it is now generally held that certain surfaces at a given temperature have a convenient property of selective radiation, in virtue of which they can give out radiation on the whole of a higher refrangibility than that given out by a black body at the same temperature.

As this question is of great importance in technology, I may be allowed to refer to incandescent lamps and mantles.

More than twenty years ago, when engaged on electric-lamp making, I worked on the theory that radiant light efficiency depends on the temperature only, and is independent of the nature of the surface; and that the colour of the light is therefore a test of the temperature. In those days, the work of Balfour-Stewart, Kirchhoff, Prévost, and Provostaye and Desains were available to the technologist. The perfectly black body had not been invented, and the perfectly black gas was not even a familiar idea. It appeared to me that, if a grey or white body at a given temperature could radiate energy corresponding to a black body at a higher temperature, the two bodies might be enclosed in a reflecting case, and the grey surface would be in equilibrium with a black surface at a higher temperature. If the temperature of the black body were reduced a little, so as still to be higher than that of the grey body, the grey body would radiate and the black absorb,

* Read November 10, 1905.

so that heat would move from a body to a hotter body. Experience agreed with this reasoning. Carbons that were made grey by "flashing" did not last any longer than black carbons of the same material and density, when run at the same efficiency; in fact, the flashed carbons were less durable, probably because they were not homogeneous.

I was not aware at that time that the opposite opinion was generally held among scientific men, though it was then widely spread among specialists in incandescent lamps. The statement has been repeatedly contradicted during the last twenty years, but without meeting the arguments, or production of good evidence.

I am thus to some extent compelled to act as a controversialist on the defensive. To take recent examples, Prof. Bottomley * quotes me, and brings forward experiments he has made to disprove my assertions. Mr. M. Solomon † also quotes me from a discussion, and brings forward arguments to show that bodies at the same temperature can have different efficiencies.

As I have also been frequently represented as saying various curious things, such as, that all surfaces have the same emissivity, it will be well to state the alleged law clearly and definitely, and then to leave it for discussion, so that if wrong, it may be cleared away as soon as possible. It is, "In the case of pure temperature-radiation, the light-efficiency is a function of the surface temperature only." Light is taken to mean, not only what affects the eye, but what includes ultra-violet radiation also. If this is the case, the colour of the light of a thermally radiating body depends on its temperature only.

The prevalent opinion that high efficiencies can be obtained at given temperatures from special surfaces is largely based on a paper by Mr. M. Evans ‡. The curious thing is that there is nothing in this paper to support the proposition it was written to maintain.

Before dealing with this paper, let us first consider what the effect of "flashing" an incandescent lamp is. Imagine a black carbon thread of a certain superficial area, and a

* Phil. Mag. Nov. 1902.

† 'Nature,' 1902.

‡ Proc. Roy. Soc. No. 243, 1886, p. 207.

certain resistance, the resistance varying with the temperature. At a certain temperature this filament gives, let us say, 20 candles measured in a given direction, and takes, say, 80 watts. Now imagine the filament coated with something not nearly so black as the original carbon; for instance, let it be "flashed" so that it is coated with a light steely-grey carbon. It is then found that with the same expenditure of power the lamp gives much more light, while if run at the same candle-power as before, it takes less electrical power. From this it has been argued that the lamp is more efficient after flashing, and that it is a good thing to have a grey surface rather than a black, because at a given temperature and expenditure for a given power, it gives more light. The idea appears to be that the grey surface gives a higher efficiency at a given temperature, and is therefore more durable. To quote the paper just mentioned—"The same filament at 3 watts per candle, when black, had to give off 31 candles, equal to 270 candles per square inch of its surface, while in its polished state it required to give only 18 candles to equal 3 watts per candle, and its surface was strained only to the extent of 155 candles per square inch. It is certain, therefore, that its lasting power with its surface bright would be many times greater at the foregoing expenditure of energy than in its black condition." This is not very clear; but unless it means that the carbon was at a higher temperature when giving 31 candles in the black state than when it was giving 18 in its grey, the whole paper has no point. Evans's paper is quoted as it is apparently the foundation of the theory that "flashing" improves the efficiency of a carbon. Professor Bottomley has made other experiments of his own.

It is generally admitted that a black body is a good absorbent when cold, and a good radiator when hot, and that a white body absorbs less and reflects or diffuses more when cold, and emits less when hot. Returning to the carbon filament, when black it is a good radiator. Let it be run at 0.3 candles per watt, and give 31 candles. It is then at such a temperature that, with its emissivity it can just radiate energy at the rate of 93 watts. If the power is kept at 93 watts, and the emissivity or power of radiation increased, the temperature will fall. The greater the emissivity the

greater the power radiated at a given temperature; or if the power is kept constant, the greater the emissivity the lower the temperature necessary to radiate at 93 watts. On the other hand, if the emissivity is reduced and the power kept constant, the temperature must rise until the increased temperature compensates for the decreased emissivity. If the filament is flashed, it will become grey or whitish, so that its emissivity may be expected to be less, not greater; as it reflects well and absorbs badly when cold. Assume its emissivity is less. Then if run at 93 watts it must get to a higher temperature before it can radiate at 93 watts. If, instead of running it up to 93 watts, it is run at 31 candles: as the emissivity is less the light at a given temperature is less, and in order to give the same light, 31 candles, as when black, the filament must be at a higher temperature. At the same candle-power the grey carbon is therefore hotter than the black, otherwise it cannot give the same light with reduced emissivity. Now run it at 0.3 candles per watt. It gives 18 candles. It is therefore colder than when it was giving 31 candles, and much colder than when it was taking 93 watts. There is no reason to suppose, however, that it is colder than when giving 31 candles with a black surface. At 18 candles the grey filament is at the same efficiency as the black at 31 candles, namely 0.3 w.p.c. There is no reason yet to suppose they are at the same temperature. If they are, when the grey is raised to 31 candles it will be at a higher temperature and higher efficiency, taking less than 93 watts. If raised to take 93 watts the temperature and efficiency are very much higher still. There is thus nothing in Evans's experiments to show that a grey carbon is at a lower temperature than a black when running at the same efficiency; the whole of the results are explained amply on the ground that a body that is black when cold has a higher emissivity (and a higher absorption) than a grey or white body.

Suppose, instead of flashing the black filament, it had been shortened by nearly half. It might then give 18 candles at 0.3 candles per watt, instead of 31; and if run at 31 candles it would take less than 93 watts, and at 93 watts would give much more than even 31 candles. From this it might have been argued on the same lines that a small carbon is much

more efficient than a large one. It is, if run at the same candle-power or same electrical power, but it is obviously at a higher temperature. It might be said that this is not a fair illustration, because in the case of the flashed and unflashed surface, the fact that the unflashed gives much more light per unit surface at a given efficiency shows it is at a higher temperature. But such reasoning is obviously fallacious. Imagine the flashed and unflashed filaments not heated electrically, in an enclosure kept at the temperature corresponding to 0.3 candles per watt for the black filament. Both are equally hot; but a black body, under such circumstances, radiates and absorbs much more heat than a grey or white one, which reflects a large proportion of the incident radiation, and therefore only absorbs the remainder, and radiates what it absorbs. That a black carbon at the same efficiency radiates more per unit surface than a grey or white, is not a proof that it is hotter: it is a necessary result of their being at the same temperature, and therefore no proof of their difference.

Though there is nothing in Evans's experiments to prove his own case, the greater emissivity of black compared with grey does not in itself show that bodies radiating at the same efficiency are at the same temperature.

Professor Bottomley's experiments consist of running two similar platinum wires under similar conditions in the same exhausted vessel. One is blackened with lampblack, the other is polished. The electrical measurements are carefully and no doubt accurately made, but no photometric measurements are made at all. The human eye is used to judge whether two wires of the same size, one of which is giving out more than four times the power of the other, are giving off an equal amount of light. Of course the eye is hopelessly inadequate for such a purpose.

Professor Bottomley seems to think that if bodies have different emissivities they must have different radiating efficiencies, and that proving one is proving the other. He says:—"In 1887, together with Mr. Mortimer Evans, I pointed out the marked difference in emissivity between a polished metallic-like surface and a dull sooted surface." But it was known long before this that black bodies had

higher emissivities than polished or white. I remember in my early schooldays reading why a polished silver tea-pot kept hot. That certainly was not the point of Mr. Evans's paper : it was, that a grey surface gave a given efficiency at a lower temperature than a black. Professor Bottomley goes on :—" I think it is now generally admitted that such a difference does really exist ; but at the time, my conclusions were controverted." He then quotes a passage of mine in which I controvert, not the statement that black is more emissive than grey, but that it is less efficient. Professor Bottomley, in a footnote, adds that a speaker in a discussion " expressed the view that incandescent-lamp makers do not find any difference between flashed and unflashed filaments. I venture to think, however, that this is incorrect. . . . I believe that all first-class makers are now fully alive to a difference in economy between a brightly flashed and a dull unflashed filament." Of course' all lamp-makers know that a flashed filament has less emissivity, and at a given efficiency makes a lamp of less candle-power ; but that is quite different from its being more economical. It is possible that Prof. Bottomley uses the word emissivity in some other sense. I have heard people say, for instance, that the emissivity of a carbon is increased by flashing. Prof. Bottomley's experiments show that the emissivity of a black surface is nearly 8 times that of polished platinum at 444° , the difference decreasing until at 895° it is over 4 times. He makes no photometric measurements, but trusts to the judgment of a skilled assistant to say whether the strips give an equal amount of light. The experiments show what would be an extraordinary result, though there is no remark on it. The strips always give equal amounts of light at the same temperature ; though the theory is that in each case the blackened wire gave light of lower average frequency. The eye is a physiological instrument, and is only useful photometrically by null methods. No one who has not tried it has any idea of the inaccuracy of the eye in looking at lamps of different sizes run at different efficiencies. Professor Bottomley says that bodies at the same temperatures with widely different emissivities give the same amount of light, though one radiates four times the power of the other. Mr. Evans, on

the other hand, argues that because one carbon radiates about twice the power another does, it must be hotter. I submit that Prof. Bottomley's experiments are inaccurate as to the light. If his two platinum wires were put in a closed hot chamber and examined through a small hole, they would be at the same temperature. The black one would be emitting and absorbing four times the power of the bright one. They would both receive the same radiation, but the black would absorb most of what it received and reflect the rest. The bright would reflect a much larger proportion of the radiation falling upon it. If Professor Bottomley were right, the black and bright body would only emit the same light; but as the bright body reflects very much more, it would appear enormously brighter in the hot enclosure. It is quite well known that all such bodies in a hot enclosure look equally bright.

Professor Bottomley's results are also contradicted by the well-known experiment of electrically heating a strip of platinum with a spot of ink on one side. The spot looks brighter than the platinum round it; but the other side of the platinum strip shows a dull spot where the ink is, showing that the spot, though giving more light, is really colder than the rest.

Elaborate tests on the emission of the perfectly black body and polished platinum have been made by Lummer and Jahnke. Lummer has treated the question of emission very fully in his *Die Ziele der Leuchtechnik* (Oldenburg, Munich and Berlin, 1903). He gives (p. 69) a set of curves of a black body. He does not merely measure the light with a photometer; he measures the power radiated at each wavelength. The curves are taken for seven different temperatures, and each curve shows the individual observations and calculations, and they agree and give smooth curves. On p. 79 similar curves are given for seven different temperatures for polished platinum. These curves are particularly interesting as they are taken apparently with great care and thoroughness, and Dr. Lummer is a strong believer in the higher efficiency of special surfaces. There is one black-body curve for 1646° and a polished-platinum for 1689° . The platinum curve is much lower, as the ordinates represent the power per unit

surface for the wave-length represented by the abscissæ. As the emissivity of platinum is very much smaller than that of the black body, we ought to increase the surface of the platinum till it radiates the same power, by increasing the ordinates in proportion till the areas of the platinum and black radiation-curves are equal. If my theory is correct,

Fig. 1.

Curves of Radiation for perfectly black body (full lines) and polished platinum (broken lines).

however, it will do as well to raise all the ordinates till the tops of the curves correspond. In the figure the platinum curves are raised, so as to allow roughly for their higher temperatures, and are shown dotted, while the perfectly black body's curves are shown in full lines. All the curves are in the heat region, where $\lambda > 1\mu$. The curves in the

original have been distorted in reproduction, and the two sets are not to the same scale. The curves now produced are, however, accurate enough for the present purpose. They show the platinum to be somewhat more efficient than the black body. Of course the measurements may be wrong, as they are delicate, and the methods for the platinum and "black body" are different; but so much care has been taken that it seems more likely that there is a flaw in my reasoning. It must either prove absolutely equal efficiency at a given temperature, or break down altogether. Lummer's experiments seem to show a greater efficiency in the case of platinum. All the same, considering that the platinum is in each case at a higher temperature, and that the difference in efficiency is comparatively small, though polished platinum and a "black body" are very far apart, it may still be open to say the selective emissivity of platinum is "not proven." Nichols, in the 'Physical Review,' gives results according to which grey carbon is more efficient than black.

There is, however, another consideration. A body may be supposed to have selective emissivity, so that at a given temperature it gives out the same rays as a black body at a higher temperature; but it might be said that the efficient radiator did not do this, that it gave out the same radiation as a black body at that temperature as far as short wavelengths go, but did not emit long waves in the same proportion. The curious thing about such a theory as this is that it would not at all lead to grey carbon or platinum being efficient; quite the reverse. If the body is to radiate light well when hot, it should be absorbent when cold, that is to say black. It should be a bad absorber of heat when cold; so that to a large animal, with an optical mechanism worked by what we call heat rays, it would look white or polished, while to us it would look black. It does not follow rigidly that a good absorber when cold is necessarily a good emitter when hot. Platinum appears to get blacker when hot. This seems to be Lummer's idea of an economical source of light, yet he apparently expected platinum to be economical. The idea seems generally to be that white bodies are economical, such as grey rather than black carbons, and the white

oxides used in the Nernst electric and the Welsbach mantle. Electric lamps are now made of osmium and tantalum. If bodies with selective emissivity can exist, whose economy depends on their failing to give out low frequency radiation, we may also have bodies which fail to give out high frequency radiation. They would be less efficient than the perfectly black body. It may be argued that such bodies are quite possible thermodynamically. Thus, suppose as an extreme case we have an economical body L which at a given temperature gives out visible light and omits to emit heat, while B is a black body, and H gives out nothing but heat. In a reflecting enclosure of a high temperature it may be said, L gives out and absorbs the same light, and therefore keeps at the same temperature as B. It may reflect some of the light that falls on it. It reflects all the heat that falls on it and gives out none. Against this it may be argued that a thermodynamic radiation-engine, such as is used in proving Boltzmann's, and dealing with Wien's laws, may be used which will take radiation from L, get work out of it, and return it degraded into heat to H; which would be absurd. Again, imagine a block of H radiating heat only at a temperature at which L and B are luminous. Imagine H surrounded by a very thin vessel whose inner side is lined with H, while the outer is coated with L. This shell will then take in energy as heat, and give it out as light; in other words, it may be said to fluoresce rays of higher refrangibility than it receives, which may be impossible.

A great deal has been written about the incandescent gas-mantle, and all sorts of theories have been evolved. It is generally assumed that the temperature of the flame in the region where the mantle is hung is measurable with a platinum thermocouple, and therefore below the melting-point of platinum. The oxides are therefore said to be endowed with the power of selective radiation, performing an office analogous to Maxwell's demon, but dealing with the radiation from them, instead of with the molecules. There seems to be a sort of attractive mystery about the rare earths. Erbium is stated to give a discontinuous radiation spectrum. Cerium has two oxides, and it has been urged that it takes in oxygen and then parts with it again to the gas, thus

producing a higher temperature than that of the direct combination. The energy developed is obviously the same with or without ceria. If by intervention of the cerium oxides, with the same final energy liberation we get a higher temperature, we must have produced energy. Putting the matter another way, ceria cannot add energy continually, so the final temperature of combustion cannot be altered by any rapidly alternating changes of the ceria. Apart from such reasonings, there is no ground for supposing such change of oxidation, as oxides of metals with single valencies will do instead of ceria.

The matter admits of very easy explanation on the ground that white bodies have less emissivity than black. In the first place, the part of the flame at the mantle is much above the melting-point of platinum, as a small wire is fused instantly. As a melting wire is absorbing heat from the hot gases and radiating rapidly, it must be much below the temperature of the gases. The gases are much above the melting-point of platinum, and any temperature determinations made with thermocouples are necessarily entirely wrong. If a comparatively large wire, such as used for a thermocouple, is put into the flame, it radiates so well, in proportion to the heat it can get, that it keeps comparatively cool. While a bunsen will only heat a two-inch ball to a low red heat, it will heat a thermocouple yellow-hot, and it will melt fine platinum and volatilise it rapidly if still finer. We may therefore take it that the active zone, at least, of a bunsen is at a very high temperature. If a small body is immersed in it, it will get hotter until it radiates as much as it takes in. The rate at which it takes in heat depends on the difference of the temperatures of the body and the gas and the flow of gas past it. The rate at which it radiates depends on its emissivity and its temperature. Suppose the emissivity is increased, the body, if left at the same temperature, would radiate more, and would need a greater intake of heat; but this would demand a greater difference of temperature between it and the gas, the temperature of the body would thus fall, increasing the intake of heat, and decreasing the radiation, until they balanced at some lower temperature. A body with no emissivity would be

at the temperature of the flame, and would of course give no light. If the emissivity is very small, it will be nearly as hot as the flame, and will give a little light. This will be of high average refrangibility. If the emissivity is increased a little more, the light will increase but will be redder because the body must fall to a temperature at which the intake of heat is enough. As the emissivity is increased the radiation increases, but gets redder, till it is no longer luminous. A black mantle is only red-hot; and a mantle of "perfectly black" material would be duller still. As the temperature of the flame is not high enough to give a light much whiter than that wanted from the mantle, there is not much margin. As soon as the mantle is made emissive enough to give a reasonable amount of light in proportion to the gas consumed, the luminous part of the radiation begins to decrease, so there is very little margin. Pure zirconia, or thoria, or alumina gives very little light. Zirconia was therefore mixed with a little oxide of the yttria group, thus introducing a trace of coloured oxide so as to increase the emissivity. Thoria again has ceria introduced. It is not because ceria has any special properties due to there being two oxides. Any coloured body would do as far as emissivity goes; but what is needed is an emissive body that will not volatilise. Any coloured additions that will stay at all will give the light as long as they are there, but they evaporate. Platinum, for example, evaporates very quickly. Alumina was largely used in conjunction with chromium oxide. At first the chromium oxide, being free, makes a mantle that is quite green when cold and very emissive. It therefore gives a useless red light. The chromium oxide soon combines with the alumina, or goes into solution, forming a very light pink ruby. The fall of emissivity lets the mantle get hot enough to give a good light.

Purely scientific, or non-technical writers on the theory of mantles often assume that the various blends are made with the light alone in view. This is not so: the makers have to consider toughness, durability, flexibility, absence of shrinkage and price. They sometimes have to consider one another's patents. It is found that the oxide must not be quite white,

and that if the threads are very fine they can take in heat relatively well, and can therefore stand more ceria and higher emissivity. On the other hand, they are then less durable, and the total radiating surface is less, unless the fine fibres are made more numerous, and they then tend to impede the flame, and cannot get their heat so well. The best practice in mantle-making is to get a good compromise. Fineness means that the mantle gets heat easily, and can therefore stand more ceria, without getting too cold to emit well. It also means less surface, greater fragility, and more rapid change with time. Too high a temperature means volatilisation of the ceria, and falling off of light. Too many fibres, or a fine mesh tend to check the gases, and prevent the rapid supply of heat to the mantle. The technical practice in making mantles, as far as I am acquainted with it—and it is a difficult subject—completely bears out the theory that oxides radiate merely because they are hot, and have a reasonable emissivity, the emissivity being raised and the temperature therefore lowered to the point which gives the maximum light. The maker has also to make sure that the mantle is tough and flexible, strong when cold, shapes well in seasoning, stands collodion, and can be made economically.

The Nernst lamp was at first supposed to give its high efficiency because the oxides used were specially efficient radiators, and this theory is, no doubt, held in some quarters; but there is no evidence to show that its efficiency is not due simply to its being very hot.

DISCUSSION.

The Secretary read a letter from Dr. J. T. BOTTOMLEY, in which he stated that the Author's paper seemed to be to a large extent an attack on his work on radiation. He could not see that Mr. Swinburne had made a single experiment in support of his proposition that "In the case of pure temperature-radiation, the light-efficiency is a function of the surface-temperature only." No amount of discussion such as the Author asked for could do anything to prove or disprove this proposition. He failed to see that the Author had worked out any logical proof of the proposition. The

Author had assumed that he (Dr. Bottomley) was incapable of matching the light-giving properties of two platinum strips placed side by side and properly arranged for this sort of comparison. The matching is exactly the same in principle as in shadow photometry, and in all the cases cited in the paper to which Mr. Swinburne takes exception, Dr. Bottomley's determinations agreed with those of his assistant, Mr. Evans.

Dr. J. A. HARKER expressed his interest in the paper, and said that the question of radiation was of practical importance in the measurement of high temperatures by electrical resistance methods. He asked if two platinum thermometers, one bright and the other blackened, but identical in other respects, were transferred from an ice-bath into a sulphur-bath, would the final temperatures of the two thermometers be the same, and also would the thermometers approach their final temperatures at the same rate? Dr. Harker also drew attention to some interesting experiments on black-body radiation by Messrs. Waidner and Burgess, published in the Bulletin of the American Bureau of Standards. They determined by means of a Holborn & Kurlbaum optical pyrometer the black-body temperature of a maldometer strip calibrated by known melting-points in the usual way, and from these experiments plotted curves showing the difference between the true and black-body temperatures of the strip over the range 700° – 1500° C. They also determined the black-body temperature for 1780° C., the value they assumed for the melting-point of platinum. The difference between real and black-body temperature at this point they found to be 239° , 203° , and 168° C. for three wave-lengths in the red, green, and blue respectively. By extrapolation of the maldometer experiments through 280° a second set of values for this difference at the platinum melting-point may be obtained, namely, 153° , 115° , and 90° respectively, numbers quite out of harmony with those just quoted. Dr. Harker pointed out that by taking instead of 1780° C. as the melting-point of platinum, the value obtained in his own recent determination, 1710° C., the discrepancy was reduced in each case to within the limits of error of such experiments.

Prof. H. L. CALLENDAR, referring to Dr. Harker's questions,

stated that if the sulphur-bath was in an isothermal enclosure, the two wires would reach the same ultimate temperature, although the blackened one would reach it quicker. The difference, however, would be small. With fine wires the loss of heat by conduction through the gas was more important than the radiation loss. The loss by radiation was proportional to the surface but the loss by conduction was not, and it therefore became relatively more and more important with the fineness of the wire. With regard to the action of incandescent mantles, he thought the Author's theory was reasonable and satisfactory.

Mr. M. SOLOMON said that the Author's main contention was that there was no such thing as selective emissivity, but that all bodies at the same temperature radiated light of the same efficiency, and that any departure from this rule was inconsistent with the second law of thermodynamics and consequently with the theory of exchanges. This did not seem correct as selective emissivity existed in the case of incandescent vapours, and if it was consistent with the laws of thermodynamics in such a case, it could not be inconsistent in the case of an incandescent solid. There was no reason why two incandescent bodies both raised to the same temperature, one radiating as a black body the other selectively, should not coexist inside a perfectly reflecting shell. As regards the incandescent mantle, the explanation put forward by the Author did not seem satisfactory. It was difficult to believe that the very small differences in colour between a thoria, a thoria-ceria, and a ceria mantle could account for the enormous differences in their candle-powers. Mr. Solomon remarked that he thought catalytic action seemed a more reasonable hypothesis than that suggested by the Author, and he was inclined to think that the thoria-ceria mantle was actually at a much higher temperature than the flame. It was possible that the average temperature of the mantle was no higher than that of the flame, but that exceedingly high temperatures existed locally in the neighbourhood of the ceria particles. The problem was an extremely difficult one, and was complicated by the confusion which existed as to what constituted selective emission. If two bodies were at the same temperature, one might

radiate more light than the other because it was a better radiator, but the ratio of the energy radiated at any one position in the spectrum to that radiated at any other position might be the same in both cases. Of two such bodies, the one giving more light was a better emitter but it was not a selective emitter. It would only be selective if the ratio of the energy radiated at different positions in the spectrum was different from that for some particular body chosen as standard for comparison—"the perfectly black body."

Prof. W. E. AYRTON referred to experiments which he had carried out which tended to show that the temperature of a Bunsen flame was lowered by an incandescent mantle. He had also found that small pieces of mantle heated in a platinum boat to various temperatures just below the melting-point of platinum never looked brighter than the platinum. If, however, a small hole was made in the bottom of the boat and coal-gas passed in, the mantle immediately became brilliant.

Mr. SWINBURNE, replying to Dr. Bottomley, said that his main argument was that he had not made experiments. In the investigation of a question such as that considered in the paper, it was possible to prove much by means of experiment, but it was also possible to attack the problem by thermodynamic reasoning. He expressed his interest in the fact that Prof. Callendar had referred to his views as reasonable. As to Mr. Solomon's statement that incandescent vapours show selective emissivity, it required confirmation if he meant vapours heated by application of heat; if they were heated by degradation of work, for instance by electric discharge, they did not bear on the question. Catalytic action is sufficiently mysterious to be generally dragged in to explain anything, but catalysis is generally hastening an action that would otherwise go on slowly or not at all; it tends to produce equilibrium. To make the mantle at a higher temperature than the gas it is in involves supplying energy, a feat which catalytic action cannot perform.