try," on "Fruit Culture in Japan," and on "The Art of Flower Arrangement," as well as others of special interest to all who study things Japanese. Altogether, the magazine makes very good reading, and if it maintains the standard of the issue which we have been considering it will take a high place among publications on the Far East. H. D.

RADIATION FROM HEATED GASES.[1]

On the Radiation from Gases.

In the first and second reports of the committee reference was made to the part played by radiation in the cooling of the products of an explosion, and to its bearing on the measurements of volumetric and specific heat with which those reports were principally concerned. The general question of radiation from heated gases has, however, from the point of view of the committee, an interest and importance of its own which are sufficient to justify a detailed study of it in its wider aspects. Radiation plays a part comparable with that of conduction in determining the heat-flow from the gas to the cylinder walls in the gas engine, and it is this flow of heat which is the most important peculiarity of the gas engine, and to which are chiefly due the leading characteristics of its design. Even to the uninstructed eye the most obvious features about large internal-combustion engines are the arrangements for cooling, and the great size and weight for a given power which is necessitated mainly by those arrangements. The difficulties which the designer has to meet are due in the main to the stresses set up by the temperature gradients which are necessary to sustain the flow of heat. In the present state of the art it is probable that the most important service which science could render to the gas-engine constructor would be to establish definitely the principles upon which depends the heat-flow from hot gases into cold metal with which they are in contact, and thus to enable him to predict the effect upon heat-flow of changes in the temperature, density, or composition of the charge, and in the state of the cylinder walls.

The committee does not propose in this report to deal with the whole of this large question, but will confine its attention to one important factor in heat-flow, namely, radiation. The subject is a wide one, which has excited much attention among physicists and chemists, and on several important points agreement has not yet been reached. No attempt will therefore be made to do more than state shortly the experimental facts, and to define the issues which have been raised in regard to the explanation of these facts.

Practical Effects of Radiation.

It is believed that the first instance in which radiation from a flame was used in an industrial process, with knowledge of its importance, was the regenerative glass furnace of Frederick Siemens, which he described at the Iron and Steel Institute in 1884. Here the combustible gas was burnt in a separate chamber, and the hot products of combustion were led into the furnace. The objects to be heated were placed on the floor of the furnace out of contact with the stream of flame which flowed above them. They would therefore receive heat only by radiation, and it was supposed that this radiation came in a large measure from the flame. Siemens, however, was of opinion (in 1884) that the radiation was due to incandescent particles of carbon, and that there was little radiation from a non-luminous flame.[2]

In 1890 Robert von Helmholtz measured the radiation from a non-luminous coal-gas flame 6 mm. diameter, and found it to be about 5 per cent. of the heat of combustion.[3] The radiation from a luminous flame was greater, but not very much greater—rising to a maximum of 11½ per cent. for an ethylene flame. Discussing the Siemens furnace in the light of these results, R. von Helmholtz calculated that radiation from the flame in the furnace could only account for a small fraction of the actual heat transmission. He pointed out, however, that a large flame would probably radiate energy at a greater rate than a small one. But while admitting that for this reason gaseous radiation might play a part in the heat transmission, he suggested that a more important agent was radiation from the roof of the furnace, which received heat by direct contact with the hot gas, and so reached a very high temperature. He showed by calculation that a comparatively small excess of temperature in the roof over that of the floor would cause a sufficient flow of heat.

But though the discussions on the Siemens furnace and the work of Helmholtz show that the idea that a flame, even if non-luminous, might radiate large amounts of heat, was a familiar one to many people twenty years ago, its possible importance in causing loss of heat during and after a gaseous explosion, and in determining the heat-flow in a gas engine, does not appear to have been appreciated until quite recently. Prof. Callendar was probably the first to direct attention to its significance in this connection. In the discussion on a paper about explosions, read before the Royal Society in 1906, he said that he had found a non-luminous Bunsen flame to radiate 15 to 20 per cent. of its heat of combustion, and expressed the opinion that the loss from this cause in a closed-vessel explosion would be of the same order.[1]

There are, in fact, several points about the behaviour of gas engines which suggest the importance of radiation as a cooling agent. The particular matter which attracted Callendar's attention was the effect of speed on thermal efficiency. His experiments showed that a part of the loss of efficiency in an internal-combustion motor, as compared with the corresponding air-cycle, was independent of the speed at which the engine was run. The loss of heat per cycle could, to a first approximation, be represented by an expression of the type $A+B/n$, where n is the number of revolutions per minute and A and B are constants. The term A represents a constant loss of heat per explosion, and among the many causes contributing to this constant loss of heat, radiation from the flame is probably important.[2]

Another phenomenon which is difficult to explain, except as the result of radiation, is the effect of strength of mixture on heat-loss. The following table shows some results which were obtained by Hopkinson upon a 40 horse-power gas engine[3]:—

Percentage of gas in cylinder contents	8·5	11·0 per cent.
Total heat-loss per minute	1510	2300 B.Th.U.
Total heat-loss as percentage of total heat-supply	29	34 per cent.
Temperature of piston	300° C.	430° C.

It will be observed that the proportion of heat-loss to the walls increases very materially as the strength of mixture is increased. If the transfer of heat were wholly due to conduction it might be expected, apart from the disturbing influence of speed of ignition, which in this case was not very important, that the percentage of heat-loss would rather diminish with increase of charge, because the temperature with the stronger mixture should be relatively less on account of the increase of volumetric heat. The increased temperature of piston and valves would work in the same direction. The existence of radiation, however, which increases more rapidly in proportion to the temperature, would account for the increased heat-flow. The practical importance of questions of this kind is illustrated by these figures, from which it appears that the piston is 50 per cent. hotter, though the charge of gas is only increased 30 per cent.

More direct evidence of the importance of radiation is furnished by experiments on the effect of the surface of the walls. In the second report of the committee reference was made to the belief, which is widely spread among those who are concerned with the practical design and operation of gas engines that polishing the interior of the

[1] From the Third Report of the British Association Committee, consisting of Sir W. H. Preece (Chairman), Mr. Dugald Clerk and Prof. Bertram Hopkinson (Joint Secretaries), Profs. Bone, Burstall, Callendar, Coker, Dalby, and Dixon, D. Glazebrook, Profs. Petavel, Smithells, and Watson, Dr. Harker, Lieut.-Col. Holden, Capt. Sankey and Mr. D. L. Chapman, appointed for the Investigation of Gaseous Explosions, with special reference to Temperature. Presented at the Sheffield meeting of the Association, 1910.

[2] Capt. Sankey has prepared an abstract of papers relating to the Siemens furnace.

[3] "Die Licht- und Warmestrahlung verbrennender Gase," Robert von Helmholtz. (Berlin, 1890.)

[1] Hopkinson, Proc. Roy. Soc., A. vol. lxxvii., p. 400.

[2] Proc. Inst. Automobile Eng., June, 1907.

[3] Proc. Inst. C.E., vol. clxxvii. (1909).

© 1910 Nature Publishing Group

combustion chamber tends to increase efficiency. Some experiments were also quoted in which it was found that lining an explosion vessel with bright tinfoil perceptibly retarded the cooling of the products. More recently an explosion vessel has been plated with silver on the inner surface, and the results have been compared after exploding identical mixtures, first when the lining was highly polished, and secondly when it was blackened over with lamp-black. It was found that by highly polishing the interior of the vessel the maximum pressure reached could be increased 3 per cent., and the subsequent rate of cooling during its earlier stages reduced by about one-third. These experiments leave no doubt of the reality and of the practical importance of radiation as a factor in determining the heat-loss in the gas engine.[1]

Reference may also be made to the part played by radiation in determining the heat-flow in a boiler. Attention was directed to this by Dalby in a recent report to the Institution of Mechanical Engineers.[2] The circumstances in this case are widely different from those usually obtaining in the gas engine, but the instance serves to emphasise the importance to the engineer of the questions which will be discussed in this report.

Amount of the Radiation from Flame.

R. von Helmholtz appears to have been the first to attempt the accurate measurement of the radiation emitted by a flame. He found that a "solid" flame 6 mm. diameter, burning coal-gas, radiated about 5 per cent. of the total heat of combustion. A carbon monoxide flame radiated about 8 per cent., and a hydrogen flame about 3 per cent. On account of the smallness of the flame his experiments have not much application to the problem of the gas engine. The size of the flame affects the matter in two ways. In the first place, a large flame radiates more per unit of area than a small one, because a flame is to a great extent transparent even to its own radiation, so that radiation is received, not only from molecules at the surface of the flame, but also from those at a depth within it. This matter will be further dealt with in another section of the report. The second point is that the cooling of the gas is slower in a large flame than in a small one. The radiation originates in the vibration of the CO_2 and steam molecules, and the life of one of these molecules as a radiating body extends from the moment of its formation to the time when its vibrational energy has been destroyed by radiation and by collision with colder molecules, such as those of the air surrounding the flame. The smaller the flame the more rapid will be the extinction of the vibrations, and the less, therefore, the total amount of radiation per molecule. The products of explosion in a closed vessel or in a gas engine differ considerably in this respect from any open flame, however large, which it is possible to produce, for they are not subject to cooling by mixture with the outside air. Moreover, the density of the gas is very much greater.

Callendar has repeated some of Helmholtz's experiments on a larger scale, and has found that the radiation in a non-luminous coal-gas flame 30 mm. in diameter may amount to 15 per cent. of the whole heat of combustion. Further reference will be made to Callendar's work under the heading of "transparency."

Hopkinson has recently made measurements of the radiation emitted in the course of an explosion in a closed vessel and subsequent cooling. A bolometer made of blackened platinum strip was placed outside a window of fluorite in the walls of the explosion vessel. The electrical resistance of this bolometer was recorded by means of a reflecting galvanometer throwing a spot of light on a revolving drum, and an optical indicator traced simultaneously a record of the pressure on the same drum. He found that the total heat radiated during an explosion of a 15 per cent. mixture of coal-gas and air, and the subsequent cooling, amounted to more than 22 per cent. of the whole heat of combustion. The radiation which had been received at the moment of maximum pressure amounted to 3 per cent., and it continued, though at a diminishing rate, for a long period. Radiation was still perceptible half a second after maximum pressure, when the gas-temperature had fallen to 1000° C.[1]

[1] Hopkinson, Proc. Roy. Soc., A., vol. lxxxiv. (1910), p. 155.
[2] Proc. Inst. Mech. Eng., October (1909).

Nature and Origin of the Radiation from Flames.

In the gas-engine cylinder and in explosion experiments we are usually concerned with flames in which there is some excess of air. A mixture of similar composition burnt at atmospheric pressure would give an almost non-luminous flame; in the gas engine there is more luminosity on account of the greater density. There is, however, no reason to suppose that the radiation in the gas-engine cylinder differs materially as regards its quality or origin from that emitted by an open flame.

A very complete analysis of the radiation from different kinds of flame was made by Julius, and his experiments leave no doubt that the radiation is almost wholly due to the CO_2 and steam molecules. He examined the spectrum of the flame by means of a rock-salt prism, and he found that in all flames producing both CO_2 and steam most of the radiation was concentrated into two bands, the wave-lengths of which are, respectively, 4·4 μ and 2·8 μ. In a pure hydrogen flame the 4·4 band disappears completely, but the other remains; and in the pure CO flame the 2·8 band disappears, the other remaining. These results are independent of the nature of the combustible gas, the spectrum depending solely on the products of combustion.[2]

A confirmation of the statement that the radiation from these flames originates in the CO_2 and H_2O molecules only was furnished in the course of the work by R. von Helmholtz, to which reference has been made above. He measured the amount of radiation per litre of gas consumed, emitted by flames of given size burning, respectively, hydrogen, carbon monoxide, and certain compound gases, such as methane, giving both CO_2 and steam. The supply of air was adjusted in each case so that the flame was just non-luminous. His results are best given in his own words, but it should be stated that he worked with a small flame about 6 mm. diameter and measured the radiation with a bolometer, taking the steady change of its resistance as a measure of the amount of radiation falling upon it:—

"According to the experiments of Julius described in the first chapter, the *quality* of the radiation of flames depends only on the nature of the burnt and not on that of the burning gases. It is relevant to inquire whether the *quantity* of radiation is also dependent on the mass of the products of combustion. I have calculated in the second and third columns below how many litres of H_2O and CO_2, respectively, arise theoretically from each litre of combustible gas. I then assume that for every litre of water produced as much radiation is sent out as corresponds to the radiating power of a hydrogen flame—for this gas yields one litre of H_2O per litre of combustile—and that in a corresponding way the radiation from one litre of carbonic acid would be determined by the radiating power of the carbonic oxide flame, and I can then calculate the radiation from the non-luminous flames of methane, ethylene, and coal-gas.

	Litres		F	
	H_2O	CO_2	Observed	Calculated
Hydrogen	1	0	74	—
Carbon monoxide	0	1	177	—
Marsh gas	2	1	327	325
Ethylene	2	2	510	502
Coal gas	1·2	0·5	181	179

"The correspondence between the calculated numbers with the radiation from a flame which has just been rendered non-luminous surprised me the more since the latter is conditioned, in some measure, by the volume of air mixed with the gas, and this is very different for the three non-luminous flames. On this account it cannot be asserted that this agreement is not accidental. Moreover, the number of observations is much too small. Nevertheless, the experiment seems worthy of record and will be followed up further."

[1] Proc. Roy. Soc., A., vol. lxxxiv. (1910), p. 155.
[2] "Die Licht- und Wärmestrahlung verbrannter Gase," Dr. W. H. Julius. (Berlin, 1890.)

© 1910 Nature Publishing Group

With regard to the last remarks, it is to be noted that the fact that the flame was just rendered non-luminous shows that the air was in each case in approximately the proportion required for complete combustion. The heating value of such a mixture is much the same for all the gases in the above table, and the temperatures of the flames would be still more nearly the same, the higher heating value of a CO mixture being partly neutralised by the high specific heat of the products. The agreement is certainly more than a coincidence. W. T. David, from a comparison of the radiation emitted in the steam and CO bands, respectively, in a coal-gas and air explosion, infers that CO_2 radiates about $2\frac{1}{2}$ times as much as steam per unit of volume. This result, which was obtained in ignorance of Helmholtz's estimate, agrees with it almost exactly.

Cold CO_2 shows a strong absorption band at the same point of the spectrum as the emission band given by a flame in which CO_2 is produced, and water vapour powerfully absorbs the radiation from a hydrogen flame.

As stated above, it is most probable that the radiation in an explosion also consists almost entirely of the same two bands as are emitted by the Bunsen flame. A complete analysis of the radiation from an explosion has not been made, but Hopkinson and David found, using a recording bolometer, that the radiation is almost completely stopped by a water-cell, and that it is largely stopped by a glass plate. It follows that the luminosity of the flame in an explosion or in a gas engine accounts for but little of the energy which it radiates.

Molecular Theory of Radiation from Gases.

Much difference of opinion exists as to the physical interpretation of the facts described in the preceding sections. The issues in this controversy can conveniently be stated in terms of the molecular theory, and it is therefore desirable to give a short account of this theory. But it will be apparent that the issues are not merely of theoretical interest, but are in large measure issues of fact capable of being tested by experiment, and that the answers to important practical questions may depend on the manner in which they are settled.

According to the kinetic theory, the energy of a gas must be referred partly to translational motion of the molecules as a whole and partly to motions of some sort internal to the molecules. The translational motion is that which causes the pressure of the gas, and in the case of gases for which pv/θ is constant (with which alone we are concerned in this discussion), the translational energy per unit of volume is equal in absolute measure to $1\frac{1}{2}$ times the pressure. This part of the energy may conveniently be called "pressure energy." It amounts to nearly 3 calories per gram molecule, or to 12 feet lb. per cubic foot per degree centigrade.

The other part of the energy produces no external physical effect except radiation, and at ordinary temperatures, when there is no radiation, its existence and amount are inferred from the fact that when work is done or heat put into the gas the corresponding increase in pressure energy amounts to only a fraction of the whole. The internal motions to which this suppressed energy corresponds may be pictured as of a mechanical nature, such as the vibrations of spring-connected masses or as rotation about the centre of gravity of the molecule, but there is not the same reason as exists in the case of the transitional energy for supposing that they are really of this character. They may be, and indeed probably are, electrical phenomena, at any rate in part. Any radiation from the gas must take its origin in this internal motion, and so much of that motion as gives rise to radiation must be of a periodic character and have a frequency equal to that of the radiation emitted. It will be convenient to call the whole energy which is internal to the molecule "atomic energy," and that part of it which gives rise to radiation may be called "vibrational energy." The vibrational energy may be imagined as due to high-frequency vibrations within the molecule, and the rest of the atomic energy as due to slower movements—perhaps rotations of the molecule as a whole—which do not produce any disturbance in the æther. This remaining energy may conveniently be called "rotational," it being understood that the motion to which it corresponds is not necessarily a physical rotation, but is some internal motion which gives no external physical effects.

When the gas is in a steady state the various kinds of energy will bear definite ratios to one another, dependent on the temperature and pressure. It may be expected, however, that after any sudden change of temperature or pressure the gas will not at once reach the steady state of equilibrium corresponding to the new conditions. For instance, it may be that in the rapid compression of a gas the work done goes at first mainly to increasing the translational energy. If in such case the compression be arrested, and if there be no loss of heat, this form of energy will be found in excess; and a certain time, though possibly a very short time, will elapse before the excess is transformed by collisions into atomic energy and the state of equilibrium attained. This change would be manifest as a fall of temperature or of pressure without any change of energy.

If, on the other hand, the gas be heated by combustion, the first effect is undoubtedly an increase in the energy of those molecules, and of those only which have been formed as the result of the combustion; and it is probable that in the first instance the energy of the newly formed molecules is mainly in the atomic form. Before equilibrium can be attained there must be a process of adjustment, in the course of which the energy of the new molecules will be shared in part, with inert molecules, *e.g.* the nitrogen in an air-gas explosion, while the translational form of energy will increase at the expense of the atomic energy. The final state of equilibrium reached will be the same at the same temperature, whether the gas was heated in the first instance by combustion or by compression; the assumption that this is the case is involved in any statement of volumetric heat as a definite physical quantity. The pressure energy in the final state of equilibrium is certainly shared equally between the different kinds of molecules, but the atomic energy is not necessarily equally shared. It is known, for example, that the steam molecules, after an explosion of hydrogen and air, carry, on the average, more energy than the nitrogen molecules, though the pressure energy is the same.

The process of attaining equilibrium after an explosion, which has just been described, would (if heat loss were arrested) result in a rise of temperature, and in the ordinary case of rapid cooling it would retard the cooling. It would, therefore, be indistinguishable as regards pressure or temperature effects from continued combustion or after-burning.

Stated in terms of the molecular theory, the first question as to which there is difference of opinion is whether the radiation from a flame arises from gas which is in equilibrium or whether it comes from molecules which still possess a larger share than they will ultimately (in the equilibrium state) be entitled to of the atomic energy which resulted from their formation. If the products of combustion of a non-luminous Bunsen flame were heated, say, by passing through a hot tube—to the average temperature of the flame (taken to be equal to that of a solid body of moderate extent immersed in it), would they emit substantially the same amount of radiation? In order to clear the ground for the discussion of this question it will be convenient, first, to state two or three points about which there will probably be general agreement. First, there is here no question of the origin of luminosity, for the luminous part of the radiation from the flame possesses practically no energy. Secondly, the radiation, whether in the heated gas or in the flame, arises almost entirely from the compound constituents CO_2 and H_2O; in neither case does any come from the molecules of nitrogen or of excess oxygen. And, thirdly, the powerful absorption of cold CO_2 for the radiation from a CO flame, and of water vapour for that from a hydrogen flame, will probably lead all to admit that these gases when heated will emit *some* radiation of the same type. The only question is, how much?

R. von Helmholtz was of opinion that the radiation in a flame comes mainly from molecules which have just been formed, and which are, therefore, still in a state of vigorous vibration. Pringsheim, Smithells, and others take the same view. This is practically equivalent to saying that this radiation, like the radiation of higher

© 1910 Nature Publishing Group

frequency which gives luminosity, is due to chemical action and not to purely thermal causes. On the other hand, Paschen and some others have maintained that the radiation from a flame is purely thermal, or that it arises from gas which has attained the normal or equilibrium state, and is substantially the same as that which would be emitted if the products of combustion were heated.

It will readily be seen that the difference between the two opinions really turns on the question of the time taken by a gas which is not initially in, or has been disturbed from, the equilibrium state to attain that state. All will concede that the CO_2 or steam molecule will radiate more powerfully just after its formation than at any other time. If, as R. von Helmholtz contended, the greater part of the radiation which it gives out in the course of its life is to be ascribed to this early period of its history, we must suppose that that period is sufficiently extended to give time for the emission of a considerable amount of energy with a rate of radiation which, though greater than that of the gas in its ultimate equilibrium state, is at least of the same order of magnitude. In other words, we must suppose that the process, which may indifferently be called attainment of equilibrium or continued chemical action, must go on in the gases as they pass through the flame for a time of the order perhaps of one-tenth of a second. For if it be supposed that equilibrium is reached in an excessively short time, say in 1·1000 second or less, then the radiation, if ascribed to that short period, must be supposed to be of corresponding intensity—there must be a sudden and violent flow of energy by radiation just while combustion is going on, and very little radiation after it is complete. This is, however, negatived by the bolometer measurements made during an explosion, which show that radiation goes on for something like half a second after maximum pressure. Those who hold that the radiation emitted by CO_2 and steam is mainly due to continued combustion must be prepared to admit that such combustion goes on for a long period after the attainment of maximum pressure in an explosion. The issue involved here is, in fact, the same as that in the controversy about "after-burning."

The principal argument advanced by R. von Helmholtz in support of his view is the experimental fact discovered by him that the radiation of a flame is diminished by heating the gas and air before they enter the burner, in spite of the fact that the temperature of the flame must be raised. This he explains by the acceleration of the approach to the state of equilibrium which would be brought about by the more frequent collisions between the newly formed compound molecules and their neighbours.

The question of the velocity with which a gas approaches its normal state after a disturbance has been much discussed in connection with the kinetic theory. Immediately after an explosion we have an extreme case of such a disturbance, the atomic energy being, at any point which the flame has just reached, in considerable excess. The transformation of this energy into the pressure form will proceed at a rate diminishing with the amount remaining to be transformed and, in the final stages of the process at all events, proportional thereto. The slowness of approach to the state of equilibrium may be measured by the time required for the reduction of the untransformed energy in any specified ratio. It is usual to take $1/e$ as this ratio, and, following Maxwell, the corresponding time may be called the "time of relaxation." Estimates of this time, based on the kinetic theory of gases, may be made in various ways, but they all involve hypotheses as to the nature of the action between the molecules, and must be regarded as little more than speculation. It will be well, however, to indicate the general character of the arguments on which they are based. By methods which need not be considered in detail here, it is possible to calculate the number of collisions with its neighbours which the average molecule undergoes per second. This calculation can be approached in various ways, based on different kinds of data, but they all lead to the same result, at any rate as regards order of magnitude, namely, that a molecule of air at normal temperature and pressure collides, on the average, 3×10 times per second with other molecules. At every collision the energy distribution in the colliding molecules is modified, both as regards the manner in which it is shared between the two and the relative proportions due to vibration and translation in either. It is argued that after every molecule has suffered a few thousand collisions, which will happen in a millionth of a second, the gas must have reached a steady average state. This argument would, however, be upset if the interchange of energy as between vibration and translation at each collision were sufficiently small. It is only necessary to suppose that a vibrating molecule loses less than one-thousand millionth part of its vibratory energy at each collision to raise the time of relaxation to something of the order of a second. Any objection to this supposition must be founded on some hypothesis, which cannot be other than entirely speculative, as to the mechanism of a collision. The kinetic theory, therefore, can give no information about the absolute value of the time of relaxation, though it provides valuable suggestions as to the way in which that time is affected by the temperature and density of the gas.

There is plenty of physical evidence, however, that in ordinary circumstances the time of relaxation is excessively short. The phenomena of the propagation of sound shows that compressions and rarefactions of atmospheric air may take place many thousands of times in a second without the gas departing appreciably at any instant from the state of equilibrium. The experiments of Tyndall, in which an intermittent beam of radiant energy directed through the gas caused variations of pressure sufficiently rapid to give sounds, show that the transformation of vibrational into pressure energy under the conditions of his experiments is a process far more rapid than any with which we are accustomed to deal in the gas engine or in the study of gaseous explosions. The departure from equilibrium which follows combustion is, however, of a special kind, and it may be that the gas is slower in recovering from it than when the disturbance is that produced by the propagation of sound at ordinary temperatures.

Transparency.

The radiation from hot gas is complicated by the fact that the gas is to a considerable extent transparent to its own radiation. The radiation emitted, therefore, depends upon the thickness of the layer of gas, instead of being purely a surface phenomenon, as in the case of a solid body. This property, besides being of great physical interest, is important from the point of view of the committee because upon it depends, or may depend, the relative magnitude of radiation losses in engines or explosion vessels of different sizes.

The transparency of flames is well illustrated by some experiments which Prof. Callendar has been making, and which he showed to the committee. The radiation from a Mêker burner (which gives a "solid" flame without inner cone) was measured by means of a Fery pyrometer, the reading of which gives a measure of the radiation transmitted through a small cone intersecting the flame and having its vertex at this point of observation (see Fig. 1). Callendar proposes to give the name "intrinsic radiance" to the radiation of a flame measured in this way, divided by the solid angle of the cone. When a second similar flame was placed behind the first in the line of sight, it was found that the reading recorded by the pyrometer was considerably increased, but not doubled; the first flame appeared to be partly, but not completely, transparent to the radiation emitted by the second. A third flame placed behind the first two contributed a further but smaller addition to the radiation, and as the number of flames in the row was increased the radiation received from each fell off according to an exponential law. The total radiation from the whole row (which is that recorded on the pyrometer) tends to a finite limit as the number of flames is increased. The radiation from a depth of 12 cm. is about half, and that from a depth of 100 cm. is within half per cent. of that emitted by an infinitely great depth.

The general result of Callendar's experiments is to show that flames of a diameter of 3 centimetres or less burning at atmospheric pressure emit radiation approximately in proportion to the volume. If the diameter be increased beyond that figure the radiation will also increase, but not in proportion to the volume of the flame. The radiation from very large flames would tend to become proportional to the surface, but no certain inference as to the diameter

© 1910 Nature Publishing Group

of flame for which this would be substantially true can be drawn from Callendar's experiments, because he was looking along a thin row of flames in which there was but little lateral extension.

The flames met with in a gas-engine cylinder or in explosion vessels differ from open flames such as can readily be produced in the laboratory, both in respect of the lateral extension which has just been mentioned and also in respect of density. In both these particulars the difference is rather great, the least dimension of the mass of flame in a gas-engine cylinder being only in the smallest sizes comparable with the diameter of the Mêker burner flame, while the density of the gas just after firing in the gas engine is from twenty to thirty times that of the burner flame gases. It does not seem possible from theoretical considerations to determine the effect of these two factors with sufficient accuracy to enable any quantitative inference as to radiation in the gas engine to be drawn from laboratory experiments on flames, but it is useful to discuss their probable qualitative effects.

In Fig. 1, P is the point of observation at which the pyrometer is placed, as in Callendar's experiments, and the portion of the flame from which the radiation is measured is that intercepted by the small cone. If a second similar flame B is placed behind A at a considerable distance, but so that it is intersected by the cone, then the radiation recorded by the pyrometer will be increased, say, by 50 per cent., showing that of the radiation emitted by B and falling on A 50 per cent. is absorbed and the remainder is transmitted to the pyrometer. The absorbed energy is, of course, not lost, but must result

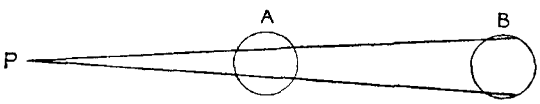

FIG. 1.

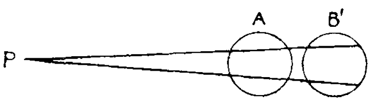

FIG. 2.

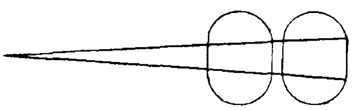

FIG. 3.

in slightly increased radiation from A in all directions. The flame A appears to be a little hotter because of the proximity of B. Thus the increase of radiation absorbed at the pyrometer is due, not only to the radiation transmitted from B, but also to an increase in the intrinsic radiance of A. If the two flames are a considerable distance apart, the latter part is negligibly small, since the flame A does not then receive much radiation from B, and what it does receive is dissipated in every direction. But when flame B is pushed close up to A into the position of B[1] (Fig. 2) this effect may be considerable, and it is obvious that it will be greatly enhanced if the two flames are extended laterally as in Fig. 3. For in such case flame A must get rid of the energy which it is receiving by radiation from B[1], mainly by an enhanced radiation in the direction of P. It may therefore be expected that the effect of lateral extension will be to make the flame apparently more transparent.

To a first approximation it may be expected that the radiating and absorptive powers of a gas at a given temperature will be proportional to its density. That is to say, two geometrically similar masses of flame, in which the temperatures at corresponding points are the same, and the densities in inverse proportion to the volumes (so that the total masses are the same), will radiate in the same way and to the same total amount. It would seem that this must be so, so long as the vibrations of the radiating molecules are the same in character and amplitude in the two cases. For there will then be the same number of molecules vibrating in exactly the same way and arranged in the same way in the two cases. The only difference is in the scale of the arrangement, and this can only affect the matter if the distance between molecules is comparable with the wave-lengths of the radiation emitted, which is not the case. It is only, however, within moderate limits that the molecular vibrations are independent of density. Angström found that the absorption of the radiation from a given source in a tube of CO_2 at ordinary temperature and atmospheric pressure was reduced by increasing the length and diminishing the pressure [1] in the same proportion so as to keep the mass of gas constant. Schäfer found that on increasing the pressure the absorption bands of this gas were widened, so that the curve connecting intensity of radiation and wave-length did not remain of the same shape.[2] These experiments were made at low temperatures, and at the higher temperatures, in which the committee are more particularly interested, there has been but little work. There is no reason to doubt, however, that the character and amount of the radiation from CO_2 and steam at high temperatures will change with the density.

From the point of view of the molecular theory, such a change might be anticipated from either of two causes. An increase of density implies a proportionate increase in the frequency of molecular collisions, and this would result in greater facility of interchange between the translational and atomic types of energy. It is possible that the equilibrium proportion of the two types might be different in consequence. The denser gas may conceivably possess, with a given amount of translational energy, more atomic energy, and therefore radiate more strongly at a given temperature. It is certain that there would be a more rapid attainment of equilibrium in the gas after an explosion or a rapid expansion. Another possible cause is a direct interaction between the molecules, apart from collisions. Two molecules at a sufficient distance apart will vibrate practically independently, each behaving as though the other was not there, except that there will be a tendency for them to vibrate in the same phase. But if the two are close together they react on one another so that the natural period or periods of the two together will not be the same as those which each would have if it were isolated.

Such direct measurements as have been made of the radiation after a closed-vessel explosion suggest that the flame is more transparent than might be inferred from the experiments on open flames. According to information given to the committee by Prof. Hopkinson, W. T. David has found that the radiation received by a bolometer placed outside a fluorite window in the cover of a cylindrical explosion vessel 30 cm.×30 cm. is greatly increased by highly polishing that portion of the opposite cover which can be "seen" by the bolometer. This implies that a thickness of 30 cm. of flame in these circumstances can transmit much of the radiation which it emits. The density of the gas in this case was atmospheric, and the 30 cm. thickness in the explosion vessel would be equivalent to perhaps 150 cm. of open flame if absorption were simply proportional to density. According to Callendar's experiment, such a thickness would be almost completely opaque. It is possible that the lateral extension is sufficient to account for this result. The open flame should be a cylindrical mass of dimensions 150 cm.× 150 cm., instead of a long strip with a cross-section of 3 cm., in order to make the two cases strictly comparable. It will be remembered that in the discussion above it appeared that the laterally extended flame would seem to be more transparent.

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

CAMBRIDGE.—The Walsingham medal for 1910 has been awarded to A. V. Hill, of Trinity College. A second medal has been awarded to J. C. F. Fryer, of Gonville and Caius College.

The following have been elected to the Clerk Maxwell scholarship:—R. D. Kleeman and R. T. Beatty, both of Emmanuel College.

At a meeting of the Fitzwilliam Museums syndicate, held

1 Ark. for Mat. Astron. och Fysik, Stockholm, vol. iv., No. 30, p. 1.
2 Ann. der Physik, vol. xvi. (1905), p. 93.

© 1910 Nature Publishing Group