ON THE

COMBUSTION OF GAS

FOR

ECONOMIC PURPOSES.

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[*A Lecture delivered before the British Association of Gas Managers, at St. Martin's Hall, London, on Wednesday, May* 23, 1866.]

From the JOURNAL OF GAS LIGHTING, &c., June 12, 1866.

Mr. President and Gentlemen,—At the close of the last lecture which I had the honour of delivering to this association at the meeting in Birmingham, I referred very briefly to the general phenomena of gaseous combustion, and to the principles of the economic use of coal gas. It was my intention, indeed, to have entered fully into this matter; but so much time was occupied in the examination of the chemical and physical properties of the most important constituents of coal gas, that little was left for the consideration of this part of our subject. I have therefore been requested to make it the especial subject-matter of this evening's lecture; and in order that you may follow me through the various details of the inquiry, it will be necessary to pursue it from the beginning.

The phenomena of visible combustion are always the results of energetic chemical action; and the heat and light which characterize it are the consequences of the violent collisions and rapid trembling of the combining atoms. When this collision occurs by the showering down, as it were, of gaseous atoms upon a solid, as you here see in the combustion of carbon and of iron in oxygen gas, and of antimony in chlorine, there may be a very intense ignition of the solid, but there is no flame. On the other hand, when the conflict is entirely among the particles of gaseous or vaporous matter, or matter in a finely divided and mobile condition, the phenomena are altogether different; for although, as before, the atoms or molecules of the burning body are intensely heated, yet from their mobility they give rise to that appearance called flame.

In all cases, therefore, we must regard flame as gaseous, or vaporous, or very finely divided matter intensely heated. That the particles of the gas or vapour must be themselves bodily and intensely heated to produce flame is evident from this—that when I burn hydrogen, or coal gas, or the vapour of ether, or alcohol by means or a finely divided solid, as I do here with a rosette of fine platinum wire, you see how the wire glows; but there is no flame, for the combustion is limited to the thin layer of gaseous matter which immediately surrounds the metal, and the temperature of the combustion is comparatively low. But if I raise it to a higher temperature, as will sometimes happen of itself, then the whole mass of escaping gas or vapour is thrown into a state of ignition, and it bursts into flame.

Let us pause for awhile to study the complicated nature of this phenomenon. Whenever a gas or vapour burns in an atmosphere of another gas or vapour, as we here see in the flame of the burning gas and candle, the phenomena are very complicated. At the points of contact which are now at the outside of the flame, the collision of the particles, because of their rapid chemical union, is most violent; and here, therefore, we have the highest temperature; but as a portion of the outer atmosphere penetrates for some distance into the burning gas, it extends the conflict into the body of the flame, and there finding itself in the presence of complex particles, it closes with those whose energies are most active. In this manner the hydrogen of the hydrocarbon is burnt first, and the liberated carbon, standing for a while in an ignited state, forms the luminous shell of the flame; and within, waiting for the presence of air, or rather passing out to take part in the conflict, is the unchanged gas or vapour. Every common flame, therefore, consists of at least three parts—the inner layer of unchanged gas or vapour, next the shell or cone of luminous matter, and lastly the outer shell of perfect combustion. That there is always an inner portion of gas or combustible vapour in every common flame may be proved by drawing it out with a glass tube and burning it at the end. See how I do it here with the flame of burning ether, and the same may be done with all other flames.

And now we are prepared to ask why it is that different substances burn with such different degrees of luminosity. The answer is clearly to be found in the circumstance that different substances contain, or evolve, or produce different amounts of solid particles. In all these flames of hydrogen, and sulphur, and carbonic oxide, there are no solid particles to be heated; but in this gas, and candle, and paraffin lamp, the particles of soot or carbon are very numerous; and if it so happens that the products of the combustion are also solid particles, the intensity of the light is so much the greater. Look at the splendid combustion of phosphorus in oxygen, and of magnesium in air. In both cases you will notice that the products are a white powder, every particle of which at the moment of its formation is intensely heated. It follows from this that every circumstance which increases the number of solid particles, within a reasonable limit, or which prolongs the time of their ignition, or which exalts the temperature of it, increases the light of the flame, and conversely everything which destroys the particles or lowers their temperature will also destroy the light.

If I throw the solid particles of lime into this almost invisible flame of oxygen and hydrogen, you will notice how vividly I bring out the light; and so also if I give the vapour of a hydrocarbon as benzole, which is rich in carbon, to the hydrogen by merely passing it through a tube packed with tow and moistened with naphtha, you observe how brightly the hydrogen burns. In the same way we can increase the illuminating power of coal gas by passing it into a chamber containing naphtha; and experiment shows that with common 13-candle gas the illuminating power is increased about 4·5 per cent. by every grain of naphtha to the cubic foot.

On the other hand, if I destroy the solid particles by hastening their combustion, the light of the flame is diminished. Here, with a common Argand burner, I merely increase the flow of air to the gas by lengthening the glass chimney, or by enlarging the central aperture, or by driving the gas by great pressure through small openings, and you see how I destroy the light; and worse still if I mix air with the gas, so that the particles of carbon find themselves at once in the presence of atmospheric oxygen—there is no light at all. Let me blow out the gas-flame from this Argand burner, and put a piece of wire gauze upon the top of the glass chimney. The gas will now draw in the air and mix with it before it reaches the top of the chimney, and see how the light is destroyed. The same is the case with this burner of Professor Bunsen. It is a metal tube of 5 or 6 inches in length and from ½ to 1 inch diameter; the gas is admitted through a small aperture at the bottom of the tube, and just below this point there are four or five openings for the admission of air. As the gas issues from the jet and passes up the tube, it draws in the air, and this, mixing with the gas, burns at the top of this tube without any light, but with great heat. This indicates to us the disadvantage of allowing air, even in small proportion, to get into the gas; in fact, experiment shows that with common 12-candle gas the loss of light with different proportions of air will be as follows:—

Loss of Light from Air in Gas.

Per cent. Air.	Loss per cent.	Per cent. Air.	Loss per cent.
1	6	8	58
2	11	9	64
3	18	10	67
4	26	15	80
5	33	20	93
6	44	30	98
7	53	40	100

The practical conclusions from these inquiries are, that gas must be burnt with such a proportion of air as that, on the one hand, the particles of carbon shall be intensely heated, and shall remain as long as possible in an ignited state, and, on the other hand, they must not escape unburnt.

The difficulties in arriving at these results are almost insuperable, for every illuminating agent has its own particular conditions, and requires its own especial appliances to bring out the fullest effects.

Take, for example, the effect of different kinds of burners, each burning at its best, with the same gas (13 candle).

Relative Luminosity of different Burners, calculated for the same Consumption.

Kind of Burner.	Pressure at Burner.	Relative Value per Foot Gas.
Single jet	0·50	100
Fishtail	0·25	146
Bat's-wing	0·18	153
Argand	0·17	198
Bengel	0·13	214

Again, the same kind of burner, but of different sizes, will give different values.

Relative Luminosity of Jets of different Sizes, calculated for the same Consumption.

Size of Jet, Inch.	Pressure at Burner.	Relative Value per Foot Gas.
0·040	0·87	100
0·056	0·35	120
0·083	0·12	136
0·100	0·04	150

Fishtails.

Size of Jet, Inch.	Pressure at Burner.	Relative Value per Foot Gas.
0·036	0·47	100
0·045	0·39	194
0·056	0·24	293
0·062	0·39	319

Bat's-wings.

Size of Jet, Inch.	Pressure at Burner.	Relative Value per Foot Gas.
0·008	1·19	100
0·012	0·49	184
0·016	0·24	232
0·020	0·16	293
0·024	0·11	313
0·028	0·09	322
0·032	0·07	316
0·036	0·04	310
0·040	0·03	307

Argands of 15 Holes and 7-inch Chimney, consuming 5 Cubic Feet of Gas per Hour.

Size of Inner Hole.	Pressure, Inch.	Relative Value per Foot Gas.
0·70	0·66	100
0·57	0·46	108
0·48	0·17	117
0·44	0·17	120
0·43	0·17	115
0·42	0·17	110

And, again, the same burner with different pressures, and therefore different rates of consumption, will give different values, when calculated for the same quantity of gas.

Relative Luminosity of the same Jet (0·04 *in.*) *at different Pressures, calculated for equal Consumptions.*

Consump. per Hour, Cub. Ft.	Pressure, Inch,	Relative Value per Foot Gas.
0·88	0·28	100
1·31	0·43	156
1·80	0·87	195
2·33	1·38	240
2·83	1·97	264
3·53	2·68	270
Fishtails (0·03 *in. holes*).		
2·00	0·17	100
3·00	0·34	109
4·00	0·50	111
5·00	0·74	110
6·00	1·00	95
Bat's-wings (0·015 *in. slit*).		
2·00	0·13	100
3·00	0·21	109
4·00	0·29	135
5·00	0·45	128
6·00	0·53	122
7·00	0·68	121
Sugg's Argand 15 *Holes* (0·45 *Internal Diameter; Hole* 0·05 *in*).		
2·0	0·04	100
3·0	0·08	143
4·0	0·12	183
5·0	0·17	202
5·5	0·18	201
6·0	0·19	196

And so, also, with cannel gas, although in many cases the variations are not so great as with common gas, yet they are sufficiently considerable to be serious. This is seen by the following table, which I have drawn up from the experiments of Mr. King, of Liverpool:—

Relative Illuminating Power of Cannel Gas, when burnt from different Burners and in different Quantities from the same Burner.

Power in sperm candles (120) per foot of gas.

Kind of Burner.	1 Foot per Hour.	2 Feet per Hour.	3 Feet per Hour.	4 Feet per Hour.	5 Feet per Hour.
Single jet	2·64	..	..	..	—
Lancashire fishtail (No. 2)	3·23	3·59	3·66	..	—
do. do. (No. 4)	3·59	3·95	4·11	4·0	—
London do. (No. 2)	3·49	3·61	3·89	3·85	—
Bat's-wing	3·09	3·76	4·05	4·11	4·16
Sixteen-hole Argand	0·26	1·74	2·48	3·53	3·68
Winfield 28-hole Argand	0·28	2·04	3·09	3·57	3·77

What, then, is to be done in the apparent confusion of all these facts, and can any useful generalization be made of them?

In the first place, we perceive that, of all kinds of burners, the single jet is the least effective.

Secondly, we notice that, although the bat's-wing and fishtail burners are not subject to so great variations in power as others, and are therefore best suited for common use, yet they require certain precautions to be fully effective. The best burners are those which consume from 3 to 5 cubic feet of gas per hour, and the slits and holes should be so graduated that the gas issues at a pressure of from 0·08 to 0·12 of an inch for very poor gas (12-candle), and from 0·20 to 0·40 for 14-candle gas, and from 0·4 to 0·6 inch for cannel gas.

Thirdly, we find that Argand burners are only fit for gas of less than 18 or 19 candle power. For very poor gas (up to 13-candle), the best form of Argand burner is the porcelain Argand of France (the Bengel), which has the following measurements:—

Bengel Burner (Argand) of 30 Holes.

Total height of burner . . .	3·150 inches.
From gallery rest to top . . .	1·220 „
External diameter	0·886 „
Internal do.	0·354 „
Diameter of circle of holes . .	0·650 „
do. of holes	0·024 „
Height of glass	7·87 „
External diameter of do. . . .	2·00 „

The flame is protected from currents of air by a cage or basket of porcelain below, which is pierced with 109 holes of the 0·118 of an inch in diameter. This burner requires a pressure of from 0·15 to 0·25 for the proper consumption of the gas, and the rate at which it burns never exceeds 3·5 cubic feet per hour. This is the standard burner for France, and, compared with the best English burners, the value of the light for 5 cubic feet of 13-candle gas is as 113 is to 100.

In this country the best form of Argand burner is the 15-hole steatite burner of Mr. Sugg. The measurements of it are as follows:—

Sugg's Steatite (Argand) of 15 holes.

Total height of burner . .	3·00 inches.
From gallery rest to top . .	1·10 „
External diameter . . .	1·10 „
Internal „ . . .	variable, according to quality of gas.
Diameter of circle of holes .	0·80 „
Diameter of holes	0·06 „
Height of glass	7·00 „
External diameter ditto . .	2·00 „

The flame is protected by a perforated metal disc placed under the gallery, the perforations being 0·08 inch in diameter, and 8 in the inch linear.

The diameter of the inner hole or air-channel should vary according to the power of the gas, thus:—

For 12-candle gas	0·44 inch.
„ 14 „	0·48 „
„ 16 „	0·55 „
„ 18 „	0·60 „

All these Argands have the holes the 0·06 of an inch diameter, and the pressure is only 0·07 of an inch instead of 0·17, as with the old Sugg of 0·04 diameter. Above 18 candles the bat's-wing is the best burner for educing the light, and it should be regulated from 4·5 feet to 4 feet, according to the richness of the gas. And now, before I leave this part of the subject, I will show you some of the contrivances which have been proposed for increasing the illuminating power of a poor gas.

You have already seen that the single jet gives proportionably less light than the double jet or fishtail, and this is because of the larger surface of the flame exposed to oxidation In this experiment, when I bring the jets together, you will notice how the light is at once increased, the proportion of increase being shown in the diagram.

Relative Illuminating Power of Jets separate and together.

Size of Jet, Inch.	Pressure, Inch.	Relative value per Foot Gas. Separate.	Together.
0·067	0·24	100	164
0·083	0·20	100	190
0·100	0·12	100	184

But the pressure may be such as to spread out the flame too much, and then it is over-oxidated. To check this there are the contrivances of

Hart, Williamson, and others, which are fishtail burners attached to a box stuffed with wool, or having a small aperture within, as compared with the aperture, without. This offers resistance to the flow of the gas, and by making it tail a little it thickens the flame and brightens the light; but the same effect would also be produced by altering the tap, provided the tap is placed, as it always should be, at a distance of about 18 inches from the burner: in fact, if it is nearer than this, as is generally the case, there is no space or chamber for the equalization of the pressure, and the gas always burns at a disadvantage.

Again, there are contrivances on the outside of the burners—as caps, and rings, and thickenings of the top of the jet—whereby the flow of air to the gas is checked and oxidation diminished.

Even with the Argand burner, if the gas is over-oxidated, as by burning it with too large an inner aperture, or with too high a chimney, or at too small a rate, the light is improved by checking the draught of air; and this may be done, as you see, by putting a cap of wire gauze over the chimney. In fact, the whole of these contrivances have for their object such an adaptation of the gas to the air, or the air to the gas, as that the flame is just short of smoking. Under these circumstances, the solid particles remain as long as possible in an ignited state, and yet at last they are perfectly consumed.

And now I am anxious to draw your attention to the effect of rarefying the atmosphere, for it has been noticed that the intensity of a flame is much less at high altitudes than at low. This was particularly observed by Dr. Frankland and Professor Tyndall in the autumn of 1859, when they were making experiments on the combustion of candles at the top of Mont Blanc. They noticed that although the candles burnt at the same rate as they did in the valley of Chamounix, yet the flames were blue, and large, and feeble Dr. Frankland was so much struck with the phenomenon that he afterwards made it the subject of careful investigation. He found, indeed, that a gas-flame, like that of a candle, gave less and less light with the rarefaction of the air in which it was burning; and his results show that the loss of light is about 5·1 per cent. for every inch of diminished mercurial pressure, up to a rarefaction of 14 inches. If, for example, the light of a flame be equal to 100 at 30 inches of the barometer, it is but 94·9 at 29 inches, and 89·8 at 28 inches; and so on up to 14 inches, when it is only 18·4 per cent. of the original light. Fortunately, in our photometrical inquiries the loss of light is equally great with the gas and the standard, or the variations of atmospheric pressure from day to day, or even from hour to hour, would show a marked difference in the value of the light. As it is, a variation of 3 inches of the barometer must cause a difference of more than 15 per cent.; and it is not improbable that this may have something to do with visible variations in the light of the public lamps. Certain it is that the same gas in places at different altitudes will have very different values. The gas, for example, which in London has the value of 100, would be but 91 at Munich, and only 61·5 in Mexico. Indeed, the difference would be greater than this, for not only is the light actually less for equal consumptions, but as the volume of the gas expands with the rarefaction and temperature, the real value of the same quantity of gas as measured by the meter in Mexico would be only 46·2. Even in London the difference in the value of the light when the barometer is 31 as compared with what it is at 28 is fully 25 per cent.; and it may well be that this difference is noticeable.

If the rarefaction of the gas and air are carried to a very great extent they cease to burn. The flame of coal gas, as well as that of a candle and of spirit of wine and ether, is extinguished at a rarefaction of about 1-6th of the atmosphere; hydrogen, at 1-7th; sulphur, at 1-15th; and phosphorus, at 1-60th. On the contrary, if the atmospheric pressure is increased, the luminosity of a flame is also increased, and it would seem that up to considerable pressures the rate of increase is in the observed proportion of 5·1 per cent. for every inch of mercurial pressure; and by doubling the atmospheric pressure the light of a gas-flame rises from 100 to 252. So marked is this on the luminosity of flame, that it is not difficult to make a spirit-lamp glow like a candle, or even to make it smoke.

And then there is another circumstance which influences the light of a flame, namely, the temperature at which the combustion is going on. If the temperature is lowered, the light is also proportionally diminished. This is noticed in the flame of a candle which requires snuffing, when the charred wick and the head of sooty carbon radiates the heat and lowers the temperature of the flame. But if by any means the temperature is increased, an opposite effect is produced. I have here a contrivance which was originally designed by Mr. Bowditch, and which has been somewhat modified by Dr. Frankland. It is a common Argand burner and glass, with another glass around it; and it is so arranged that all the air which supplies the burner must pass down between the glasses and be heated before it reaches the flame. The temperature which it thus acquires is from 500° to 600° Fahrenheit, and it passes to the flame as a sort of hot blast. The result of it is that the light for the same volume of gas is increased about 67 per cent., and for equal lights it is found that there is a saving of 46 per cent. of gas.

Illuminating Power with and without the external Glass in Sperm Candles of 120.

Consumption per Hour. Cubic Feet.	Illuminating Power without Glass.	Illuminating Power with Glass.
2·2	..	13·0
2·6	..	15·5
3·3	13·0	21·7
3·7	15·5	—

These are the results with cannel gas, but I do not find there is a like increase of power with common gas.

Lastly, there are cases where the amount of carbon in the vaporous matter is so abundant that contrivances are needed for its oxidation. All these contrivances are plans for diminishing the supply of the combustible and increasing the flow of air. In the paraffin candle the wick is adapted for a small supply of the material; and in the benzole and paraffin lamps there are caps or deflectors, with slits for blowing the air upon the sides of the flame. In the camphine lamp there are additional deflectors in the form of a central button, and a throttled chimney for directing the air upon the inside and outside of the flame; and in the Carcel lamp the oxidation is increased by the length of the chimney. In all cases, however, the points for consideration are—the best means for effecting perfect and prolonged combustion; and having attained this we have to take care that the light is not destroyed by the medium of transmission. Glass is very transparent, but yet it destroys a notable proportion of light, and when the surface is ground the loss of light is often considerable:—

Loss of Light by Glass Globes.

Clear glass destroys	12 per cent.
Slightly ground in pattern	24 "
Half ground	35 "
All ground	40 "
Opal glass	60 "

And lastly I have to refer to the methods which are adopted for estimating the value of the light of gas. These are as follows:—

1. By observing the durability of a jet of gas of a given height from an aperture of a given size.
2. By ascertaining the pressure necessary to obtain a flame of a given height from the same jet.
3. By noting the height of the jet when the gas is burning from an aperture of a given size and at a uniform pressure.
4. By ascertaining the quantity of air which is required to destroy the light of a flame burning at a given rate.
5. By comparing the light with a standard flame.

The first method of testing the illuminating power of gas was often used by the late Dr. Fyfe, of Glasgow, and when it was conjoined with another test, namely, the amount of condensation by chlorine, it was much relied on. The jet which he used had a diameter of the 1-33rd of an inch, and the flame was kept at a uniform height of 4 inches. In this way he found that a given volume of gas of different qualities burnt out in different times, thus:—

Durability of a Cubic Foot.

Common Newcastle coal gas . .	50·5 minutes.
Wigan cannel	57·0 "
Lesmahago	65·0 "
Wemyss	75·0 "
Boghead	81·0 "

Secondly, he further ascertained that the pressure necessary to make a gas burn from an aperture of a given size, and with a flame of a given height, was also the exponent ot the quality of the gas; for the better the gas the less the pressure at which it burns, and the less also is the consumption to produce a flame of a given height. For example, with a jet 1-40th of an inch diameter, and a flame 5 inches high, the following were the rates and pressures of different gases:—

Pressure, Inch.	Consump. per Hour, Cub. Ft.	Specific Gravity of Gas.
0·6	0·67	0·841
0·8	0·77	0·729
1·0	0·86	0·552
1·2	0·94	0·595
1·4	1·02	0·551
1·6	1·09	0·515
1·8	1·15	0·486
2·0	1·21	0·461

His deductions from these results were, that the specific gravity of the gas—or, in other words, its quality—was inversely as the square roots of the pressures, and that the volume consumed in a given time was as the square roots of the pressures. He relied so much on this test, that he thought it capable of taking the place of both the meter and photometer.

The third method of ascertaining the value of gas is by observing the height of a flame at a given pressure from a jet with an aperture of a given size. This method has been adopted by Mr. Lowe, and it goes by the name of Lowe's jet. It is, as you perceive, a modification of the preceding, for a poor gas will burn with a shorter flame than a rich gas; and, by using a jet with an aperture 0·04 of an inch in diameter, and a pressure of 0·5, the flame of 14-candle gas will be just 6 inches in height.

The fourth method for determining the quality of gas is by ascertaining the quantity of air necessary to destroy its light. The best instrument for determining it is the apparatus designed by M Erdmann, and which is called a gas-prover. It is a sort of Bunsen burner, with a contrivance for graduating the supply of air. Erdmann recommends the gas to be turned on until there is a flame of a given height, and then the supply of air is admitted until the light is destroyed. This, however, is not the proper way to use the instrument. The gas should first be turned on at a given rate—viz., at the rate of 0·84 of a cubic foot per hour—and then the quantity of air necessary to destroy the light should be read off. In this way reliable results may be obtained, for the richer the gas the more air is required.

I referred in my last lecture to this diagram, which has been prepared from the experiments of Mr. King, of Liverpool:—

Illuminating Power of Gas, as estimated by Erdmann's Gas-Prover, the Gas burning at the Rate of 0·84 Cubic Feet per Hour.

	Description of Gas.			
	Newcastle Coal.	Equal Parts Newcastle and Wigan.	Wigan Coal.	Boghead Coal.
Height of flame (inches)	1·87	2·00	2·75	5·50
Number of index prover	14·72	23·39	32·78	61·14
Relative value of do.	1·00	1·59	2·22	4·15
Coefficient of power	0 70	0·70	0·72	0·70
Illum. power (coefficient = 0·7)	10·30	16·37	22·95	42·80
do. do. by photometer	10·30	16·35	23·58	42·96
Relative values	1·00	1·58	2·29	4·17

Lastly, the common method for ascertaining the illuminating power of gas is by comparing it with a standard flame.

In this country, the standard was formerly a wax candle burning at the rate of 120 grains per hour, but the variations in the value of the light were so great, that it was abandoned; for, as a wax candle requires snuffing, it was difficult to decide when it was burning in a proper manner. After numerous experiments, extending over a year, I ascertained that, for equal consumptions, the light of wax and sperm was as 14 to 16—in other words, the power of sperm was just one-seventh greater than that of wax.

At present, the standard flame in this country is a sperm candle of six to the pound, burning at the rate of 120 grains per hour. But for some time past this standard has also become uncertain—first, because there has been great irregularity in the construction of the wicks; and, secondly, because the sperm is being adulterated with wax and paraffin, or both. The irregularity of the wick causes a variation in the rate of burning from 116 grains per hour to 140; and the real value of the light in the two cases, when reduced to the standard consumption of 120 grains per hour, is as 96 is to 116. The adulteration of the sperm with wax and paraffin also affects the value of the light, for the former gives 13 per cent. less light than sperm, and the latter gives 23 per cent. more light. These irregularities are becoming so serious, that we must ere long change the standard.

In France, the standard is a Carcel lamp of specified dimensions in every particular, burning refined colza oil at the average rate of 648 grains per hour. With proper precautions this standard appears to be very uniform, care being taken that the consumption of the oil is never less than 617 grains per hour or more than 679.

And now, in concluding this part of the subject, I will direct your attention to the comparative power and value of the most important illuminating agents.

Relative Value of different Illuminating Agents.

Name.	Rate of Consump. per Hour.	Illum. Power. (Sperm 120.)	Quantity = 14 Candles.
Cannel gas	4 feet	18·67	3 feet.
Coal gas	5 „	14·00	5 „
Benzole	301 grs.	4·91	857 grs.
Paraffin oil	265 „	7·11	522 „
Sperm oil	686 „	10·00	960 „
Colza oil	648 „	9·01	1008 „
Paraffin candles	122 „	1·46	1171 „
Sperm „	132 „	1·35	1440 „
Wax „	168 „	1·43	1652 „
Stearic „	140 „	1·13	1732 „
Composite „	144 „	1·08	1858 „
Tallow „	145 „	0·83	2542 „

With regard to the value of other illuminating agents, as the magnesium light, the oxyhydrogen or Drummond light, and the electric light, little can be said, as they vary so much with the consumption of the material.

In the case of the magnesium light, I find that when a wire the 100th of an inch in diameter is doubled and twisted it burns at the rate of 2·4 grains per minute, and gives the light of about 69 standard sperm candles; an ounce of the wire, therefore, is equal in light-giving power to rather more than 3½ lbs. of sperm candles. The power of the Drummond, or oxyhydrogen light, varies with the combustible used. With

Coal gas	and air	it is equal to	19	candles.
„	„ oxygen	„	29	„
Alcohol	„	„	69	„
Ether	„	„	76	„
Hydrogen	„	„	153	„

And the power of the electric light varies from 650 candles to 1444, the average being about 1000.

All these agents are expensive, and they give a light which is characterized by intensity rather than by quantity, but as the light is pure as well as powerful, it is frequently used for signals and for photographic purposes, and also for theatrical illustrations.

I now pass to a very interesting part of our subject, namely, the cause of the marked differences in the colour of the flames of different substances; and in order that you may perceive the reason of this, let me remind you that a pure white light, with all the colours of the spectrum, is never obtained but by the intense ignition of solid or molten matter. This is so with the phosphorus flame, and with the magnesium, the oxyhydrogen, and the electric light. In all these cases there are particles of concrete solid matter in a state of intense ignition, but in the case of coal gas, and in that of other burning hydrocarbons, the light is never pure unless it is intensified by very energetic combustion. The reason of this is that the particles are only heated to the point of yellow whiteness; for Dr. Draper has shown that, according to the temperature, an ignited solid (as a spiral of platinum heated by the galvanic current) passes through all the tints of the spectrum from red to white, according to the intensity of the heat; and these tints and temperatures are somewhat as follows :—

Very dull red	about	970°	Fahrenheit.
Cherry red	"	1500	"
Full red	"	2000	"
Dull red, white, or orange	"	3000	"
Yellow white	"	4000	"
Greenish white . . .	"	5000	"
Bluish white	"	6000	"
Perfect white	"	7000	"

If, therefore, the temperature of combustion is not sufficiently high, the light is never pure. This is especially so with the creamy lagging flame of underburnt gas, and with the smoky flame of hydrocarbons rich in carbon, as benzole, turpentine, and paraffin; but if the combustion of these flames is intensified by a proper supply of air, the temperature of the ignited carbon is increased, and the light becomes purer and purer, so that when it is thrown upon coloured objects it displays the tints in a more or less perfect manner. Such a flame, when examined with the prism, gives a spectrum like that of solar light with all the tints of the rainbow. This is the speciality of pure light from an ignited solid. If, however, the vaporous matter does not contain solid particles in a free or concrete form, the ignition of it produces only certain tints of the spectrum, and hence its variable colours. Examined, therefore, with a prism, we see only those bands of colour which are characteristic of the flame.

I will show you this by moistening little balls of coke with the chlorides of the following metals, and then introducing them into the colourless flame of a Bunsen burner, or, better still, into that of Griffin's blast jet ; and you note how different are the tints, and how they fail to illuminate certain colours of these dyed ribbons.

Chloride of sodium	gives	a rich yellow flame,
Chloride of copper	"	a deep blue-green flame,
Chloride of strontium	"	a rich scarlet flame,
Chloride of barium	"	a pale pea-green flame,
Chloride of lithuim	"	a bright crimson flame,
and a salt of thallium	"	a beautiful grass-green flame.

The chlorides are used because they are the most volatile, and they exist in the flame in a vaporous condition. These tints are so characteristic of the several metals, that they afford the most delicate means of discovering their presence ; but the great fact which modern investigations have brought out is the circumstance that the spectrum of these flames consists of certain well-defined and constantly placed bands of colour. This diagram will show you the spectra of the metals which I have been using; and so true and constant are the positions and tints of these bands, and so delicate are the manifestations of them, that they become the means of discovering the merest traces of the several metals. But I must not pursue this further, except by showing you the differences in the tints of this spectrum and ribbons when examined with the pure white light of burning magnesium.

And now I will briefly describe the contrivances which are used for increasing, or rather I should say for fully developing, the temperature of burning gas. I have shown you that the light of a flame depends on the presence of ignited carbon; if, therefore, by any contrivance we can at once burn this carbon, and not permit it to stand as it were idle in an ignited condition, the temperature must be considerably increased. This is the principle concerned in all the contrivances for developing the heat of gas.

One of the simplest means of accomplishing this is to mix a sufficient quantity of air with the gas before it reaches the place of combustion; and this is easily done by putting a cap of wire gauze upon the chimney of an Argand burner, and setting fire to the gas above it. The effect of this arrangement is that as the gas passes from the burner to the top of the chimney, it draws in a quantity of atmospheric air, which freely mixes with it and burns the solid particles. The same is the case with the burner of Bunsen, which I have already described; and you will note how strongly it ignites this platinum crucible. The same arrangement is adopted by Mr. Griffin in his reverberatory furnace, which is a Bunsen's burner enclosed in a clay chamber. I have here another contrivance of the same nature called an *atmopyre*, which is used by Professor Hofmann in his furnace for effecting organic analysis. It is a hollow cylinder of baked pipe-clay pierced with a large number of small holes. When it is placed on a small fishtail burner, the gas, in issuing from the holes, draws in a sufficient quantity of atmospheric air to make it burn at all the apertures with a clear blue light; and thus the temperature is so much increased that the entire body of the numerous cylinders composing the furnace becomes almost white hot.

But we shall find that a still higher temperature is obtained by blowing air into a large volume of flame. This is the plan adopted by Mr. Herapath in this blow-pipe jet. Observe how intensely it ignites a mass of platinum wire; and by putting together a number of these jets, as Mr. Griffin has done, in this arrangement, which he calls a blast-furnace, you will perceive what a high temperature is obtained; and by surrounding the blast with a case of baked clay, so that the heat may be concentrated, the temperature is sufficiently high to melt all the common metals. As much as a quarter of a hundredweight of cast-iron can be melted at a time in one of these furnaces; and 3 or 4 lbs. of cast-iron or copper can be thus melted in fifteen minutes. Even the very refractory metals, as nickel and cobalt, can be thus fused.

And if instead of atmospheric air a jet of oxygen is used, as I will now show you, the temperature is still higher. This is the principle of Deville's furnace, which is a jet of oxygen blowing into a large flame of coal gas, and directed down upon the refractory substance; the whole apparatus being enclosed in a chamber of non-conductors. With this furnace large masses of platinum are easily melted, the platinum being placed upon a hollow bed of lime. I have seen a mass of platinum, weighing about 350 lbs., which had been melted in this manner; and I was informed by Messrs. Johnson and Matthey, the platinum assayers of Hatton Garden, that the mass required six hours for its fusion. During that time about 360 cubic feet of coal gas and the like quantity of oxygen were used; in fact, Deville found in his experiments at the *Ecole Normale*, that it required a little more than a cubic foot of gas and a cubic foot of oxygen to melt a pound of platinum. The temperature of the flame must be enormous; calculated from the thermotic powers of gas with air and oxygen, it may be said that it is equal to about 5228° of Fahr. when air is used, and 14,320° with oxygen.

The temperature of different combustibles is shown on the diagram on the following page, and you will notice that the highest temperature produced by the various constituents of coal gas is that of acetylene, or the vapour of benzole when burned in oxygen, the heat of which exceeds 17,000° Fahr.; the lowest temperature of all the constituents is about 12,700° Fahr., the temperature of burning carbonic oxide.

On the same diagram I have tabulated the thermotic power of a great number of substances. It is expressed in the number of pounds of water raise 1° Fahr. by a pound of the substance, and when the body is capable of being converted into gas or vapour, I have also expressed it in the

Table of the Combustion Temperature and Explosive Power of Gases.

	Per lb. Substance.			Pounds Water Heated 1° Fahr.			Temperature of Combustion.				Explosive Power.		Mechanical Power per lb.
							Open Flame.		Closed Vessel.				
	Ox. Used.	CO_2 Produced.	Air Vitiated.	Per lb. Substance.	Per Cubic Foot Substance.	Per lb. Ox. Used.	With Ox.	With Air.	With Ox.	With Air.	With Ox.	With Air.	Tons Raised 1 Foot High.
	Cub.Ft.	Cub.Ft.	Cub Ft.	Lbs.	Lbs.	Lbs.	Deg.	Deg.	Deg.	Deg.	At.	At.	Tons.
Hydrogen	93·4	0·0	467	62030	329	7754	14510	5744	19035	7852	25·6	12·5	21390
Marsh gas	47·2	23·6	826	23513	996	5878	14130	4762	18351	6680	37·0	14·0	8108
Olefiant gas	40·5	27·0	878	21344	1585	6225	16535	5217	21344	7200	42·9	15·1	7360
Propylene	40·5	27·0	878	21327	2376	6220	16522	5239	21327	7177	67·3	22·5	7360
Butylene	40·5	27·0	878	21327	3168	6220	16522	5232	21327	7177	85·8	30·2	7360
Acetylene	36·3	29·1	909	18197	1251	5914	17146	5142	22006	7009	37 9	17·6	6275
Benzole	36·3	29·1	909	18197	3860	5915	17146	5142	22006	7009	113·7	52·8	6275
Carbonic oxide	6·7	13·5	371	4325	320	7569	12719	5358	16173	7225	21·8	11·7	1490
Bisulphide carbon	14·9	5·0	689	6120	1239	4845	15280	4314	20031	5917	30·2	11·6	2110
Sulphuretted hydrogen	16·7	0·0	630	7444	671	5271	13688	4388	17542	6026	28·3	12·7	2567
Cyanogen	14·5	14·5	435	6712	925	5142	13488	5028	17645	6167	35·6	17·8	2314
Common coal gas	37·5	17·6	618	21060	650	6816	14320	5228	18101	7001	29·2	14·6	7262
Cannel gas	31·0	22·0	698	20140	760	6503	14826	5121	19046	7186	38·8	18·0	6945
Wood spirit	25·3	11·8	422	9547	819	6363	11435	4641	14902	6347	40·3	15·3	3290
Alcohol	24·6	16·4	533	12929	1597	6195	13305	4831	17223	6629	46·4	16·1	4455
Ether	30·9	20·4	664	16249	3217	6158	14874	5150	19225	6953	58·6	19·0	5603
Camphine	38·9	27·8	880	19573	7134	5942	16271	5026	20953	6922	47·6	16·0	6750
Spermaceti	37·0	25·2	815	17589	...	6088	14599	4413	...	...	..	...	6065
Wax	37·7	25·6	829	15809	...	4995	12921	4122	...	...	...	...	5451
Stearic acid	34·6	24·0	783	17050	...	6061	15885	4818	...	...	...	...	5880
Stearin	34·4	14·2	527	18001	...	6143	15815	5095	...	...	...	...	6207
Paraffin	40·5	27·0	878	21327	...	6220	16522	5239	...	...	...	...	7354
Paraffin oil	40·5	27·0	878	21327	...	6220	16522	5239	...	...	...	...	7354
Rape oil	38·7	24·3	801	17752	...	6123	15830	5087	...	...	...	...	6121
Sperm oil	38·7	24·3	801	17230	...	6088	15363	4937	...	...	...	...	5941
Carbon	31·0	31·5	943	14544	...	5447	18329	3026	...	...	...	...	5015

cubic foot at common temperatures and pressures. Hydrogen, you perceive, is the most powerful thermotic agent, and carbonic oxide is the weakest; a pound of the first of these gases will raise 62,030 lbs. of water 1°, whereas a pound of the latter will only heat about 4325 lbs. of water to that extent. Examined by the cubic foot, and considering that for every pound of water raised 1°, about 48 cubic feet of air are raised to the same extent, we may say the chief constituents of coal gas have this thermotic power:—

Pounds of Water and Cubic Feet of Air raised 1° Fahr. by a Cubic Foot of the Gas Burning in Air.

Cubic Foot of		Lbs. Water raised 1° Fahr.	Cub. Ft. Air raised 1° Fahr.
Hydrogen . . .	heats	329 . .	15,837
Marsh gas . . .	„	996 . .	47,946
Olefiant gas . .	„	1585 . .	76,299
Propylene . . .	„	2376 . .	114,378
Butylene . . .	„	3168 . .	152,502
Acetylene . . .	„	1251 . .	60,220
Benzole vapour .	„	3860 . .	185,814
Carbonic oxide gas	„	320 . .	15,403
Common coal gas .	„	650 . .	31,290
Cannel coal gas .	„	760 . .	36,585

From this we can determine the practical thermotic power of any of these agents. A cubic foot of common gas will heat 65 gallons of water 1°, or 6·5 gallons 10°, or 3·25 gallons 20°; so that a bath containing 250 gallons of water would require about 77 cubic feet of common gas, or 66 of cannel, to raise its temperature from 55° to 75°. In practice, however, this is rarely attained, because of the faulty construction of the heating apparatus. I find, indeed, that a bath in my own house, made by Phillips, of Skinner Street, takes nearly twice this proportion of gas to heat it, and being in a closed room the atmosphere is almost poisoned before the bath is ready; and the circulation of the hot water is so imperfect, that the top layer becomes boiling hot before the bottom of the water is warm. This is a subject which requires attention, for it is open to much improvement.

Again, with regard to the boiling power of gas, although in good practice a cubic foot of gas should boil off about 4712 grains of water, or about 22 times its own weight, yet this is not often attained, for in an open vessel we rarely evaporate more than 2866 grains of water, or about 13 times its weight.

But the heat of the burning gas is more surely applied to the warming of rooms; for, as you will see by the table, a cubic foot of common gas will heat an apartment containing 3129 cubic feet of air 10°, and the same quantity of cannel gas will heat 3658 cubic feet to the same extent. Other illuminating agents will, however, light for light, heat the atmosphere, and vitiate it to a larger extent. This is seen in the table which I brought under your notice at the last lecture.

Heating and Vitiating Effects of Different Illuminating Agents, when Burning so as to give the Light of 12 Sperm Candles.

	Lbs. Water raised 1° Fahr.	Oxygen consumed, Cub. Ft.	Carb. Acid produced, Cub. Ft.	Air vitiated, Cub. Ft.
Cannel gas . . .	1950	3·30	2·01	50·2
Common gas . .	2786	5·45	3·21	80·2
Sperm oil . . .	2335	4·75	3·33	83·3
Benzole	2326	4·46	3·54	88·5
Paraffin	3619	6·81	4·50	112·5
Camphine . . .	3251	6·65	4·77	119·2
Sperm candles . .	3517	7·57	5·77	131·7
Wax „ . .	3831	8·41	5·90	149·5
Stearic „ . .	3747	8·82	6·25	156·2
Tallow „ . .	5054	12·00	8·73	218·3

The vitiating effect is calculated on the actual loss of oxygen, and on the power which 4 per cent. of carbonic acid has on the vital qualities of the atmosphere; and, although the results indicate that there should be less discomfort in a room lighted with coal gas than with any other illuminating agent, yet common experience is altogether in the opposite direction. The explanation of this is to be found not only in the fact that gas is used more lavishly than other agents, but also that in burning it produces a larger proportion of aqueous vapour, which becoming diffused into the surrounding atmosphere occasions great discomfort. Professor Tyndall has shown that the molecules of aqueous vapour are endowed with a remarkable power of absorbing the radiant heat of burning gas, and by thus becoming warm they create a sense of oppression; and again, when the warm atmosphere of a room is overcharged with moisture, it checks the action of vaporous or insensible perspiration, and this also causes distress. In all cases, therefore, where gas is largely used in rooms, provision should be made for the quick removal of the products of combustion.

When the heat of gas is required for warming a room, its radiant power should be increased by allowing it to ignite some solid substance, for the radiant heat of a non-luminous flame is very insignificant. I have here a Bunsen's burner, which gives with this gas the highest temperature of combustion, but the amount of heat which radiates from it is very small—smaller indeed than is the case when the gas is burnt in the ordinary way, when every atom of ignited carbon becomes a centre of radiation. The proportions of radiant heat from the same flame under different circumstances is very variable. From Bunsen's burner it is only 12, from the same gas burnt as a luminous flame it is 30, and with a spiral of platinum in it it is 85. The introduction of solid matter into a non-luminous flame of high temperature changes its character altogether, and from the heat of convexion it becomes heat of radiation. No doubt the quality of the vibrations is greatly changed, and they pass from the large and comparatively slow undulations of obscure heat to the small and quick vibrations of light; and the more this is effected, the greater and greater becomes the intensity of the radiant heat. Professor Tyndall found that the following were the quantities of radiant heat from a platinum spiral, at different degrees of luminosity:—

			Degrees of Heat radiated.
Platinum spiral	Feebly red	. . . . .	19
do.	do. Dull red	. . . . .	25
do.	do. Full red	. . . . .	62
do.	do. Orange red	. . . . .	88
do.	do. Yellow red	. . . . .	158
do.	do. Yellow white	. . . .	200
do.	do. Blue white	. . . .	276
do.	do. Intense white	. . . .	440

So that, when we wish to economize the radiant heat of burning gas, it is best to use it with some solid body, as fragments of pumice or pieces of asbestos.

The last point to which I would refer is the available or convertible motive power of burning gas.

The calculations of Dr. Mayer, of Heilbronn, and the experimental inquiries of Mr. Joule, of Manchester, show that the mechanical power of heat is 772 lbs., raised a foot high for the heat necessary to raise the temperature of a pound of water 1° Fahr. A cubic foot of hydrogen in burning has therefore the mechanical power of (329 × 772 =) 253,988 lbs.; and the same quantity of common gas has the power of (650 × 772 =) 501,800 lbs.; while the power of a cubic foot of cannel gas is (760 × 772 =) 586,720 lbs., raised a foot high. But, if the same quantity of these gases is exploded with air or oxygen in a closed chamber, the mechanical power is somewhat different. I have here tabulated the expansive force of such a mode of combustion, and I may say that the calculations are deduced from the temperatures of combustion and from the volumes of the products—allowance having been made for the specific heats of the several products. It would seem, therefore, that the explosive powers of the several constituents of coal gas, when mixed with their proper proportions of air or oxygen, are as follows:—

Explosive Power of Mixed Gases.

	Mixed with Air. (Ats.)	Mixed with Ox. (Ats.)
Hydrogen	12·5	25·6
Marsh gas	14·0	37·0
Olefant gas	15·1	42·9
Propylene gas	22·5	67·3
Butylene gas	30·2	85·8
Carbonic oxide	11·7	21·8
Common gas	14·6	29·2
Cannel gas	18·0	38·8

These are the theoretical pressures exerted upon the sides of the containing vessel when these several gases are exploded with their proper proportions of air or oxygen; but as the explosion is never instantaneous, but proceeds from particle to particle, and therefore occupies time, and as the walls of the vessel always cool the products of the exploded gas to a great degree, this theoretical value is never obtained in practice, the highest pressure in the exploding chamber of a gas-engine being only 75 lbs. on the square inch, or five atmospheres. The power of this has been determined experimentally by Mr. Evans, who informs me that with a cubic foot of a mixture of nine air and one gas he has propelled a wooden shot (three inches by four) 50 yards; and he ascertained that the same effect was produced with an ounce of gunpowder. The motive power, therefore, of the exploding mixed gas is considerable.

In the gas-engines of Lenoir it has been found that the best proportions of air and gas are eight volumes of air to one of common gas; theoretically the best proportion for London (13-candle) gas is 5·6 volumes of air to one gas. A larger portion of air is required for cannel gas, as 11 to one; but in practice it is found that cannel gas does not produce so good an effect as common gas. The time of the explosion is about the 27th part of a second, and the temperature of it is about 2474° Fahr. instead of from 5228° to 7000°—the calculated temperatures for open and closed chambers.

The machines which are used for practically employing this power are all modifications of the original engine of Lenoir. They consist of a cylinder with a double-action piston, receiving the mixed gas alternately on either side of the piston. The arrangement is such that in the movement of the piston the air and gas, in proper proportions (eight to one), are drawn into the cylinder by a suitable side valve, and when the piston has made half a stroke it shuts off the valve; at that moment the mixed gas is fired in the cylinder by means of an electric spark from a Ruhmkorffs coil passing between the points of two wires in the cylinder. One of these wires is insulated by traversing a rod of porcelain fixed in the cylinder, and, being in connexion with a make-and-break contrivance, called a distributor, attached to the fly-wheel of the engine, it receives the charge of electricity, and so fires the mixed gas at the right moment. The expansion caused by the explosion and heat of combustion drives the piston through the rest of the stroke, and it generally ends with a good deal of unutilized pressure. In one case I find that the indicator recorded an initial pressure of 75 lbs. on the inch at the moment of explosion, and a final pressure of 25 lbs. The loss of power in this case must have been considerable, for not only is there the loss of the difference (12·5 lbs.) between the calculated pressure 37·5 lbs. (75÷2), and the real (25), but there is also the total loss of the unavailable final pressure. A part of this loss is no doubt due to leakage, and to the cooling effect of the walls of the cylinder, for the temperature has been observed to fall from 2474° Fahr. at the moment of explosion to 1438° at the end of the stroke—the calculated temperature being 2156°; indeed the management of the temperature is one of the difficulties of the engine, for the cylinder has to be cooled by a stream of water. Improvements will no doubt be made in the construction of the engines, and especially in the utilization of the residual power, and this must be done by shutting off the valve and firing the gas earlier in the stroke. This has already been done to some extent in America with engines of half-horse power, as with cylinders of 4⅝ inch diameter by 8¾ inch stroke; and this with 185 revolutions or 370 explosions in a minute raises 16,280 lbs.

one foot high in a minute. In France and in this country much larger engines are made, as from 1 to 3 horse power.

The quantity of gas used in the working of the engine is rather variable. In the American engine, already alluded to, it took 105 cubic feet of gas an hour to work an engine of half-horse power, and a one-horse engine in London takes about 185 cubic feet of London gas—say it is 200 cubic feet—per horse power. This is 1,980,000 lbs. a foot high; whereas the theoretical power of 200 feet is more than 100 millions of pounds.

The advantages of the engine are very great, for it takes up but little room, it is very clean, it works with great regularity, it requires little or no attention, and it costs nothing for fuel when it is not at work.

One thing I ought to mention in speaking of the explosive power of mixed gas, and that is the effect of using mixtures in improper proportions. Sir Humphrey Davy found, in his experiments with marsh gas, that there was but one proportion of air and gas which gave the maximum effect, and that was a mixture of 1 of gas and 7·5 of air (theoretically it should be 1 to 9·5). When the proportions are reduced in either direction the mixture becomes less and less explosive, until with 1 gas and 15 air, or with equal volumes of gas and air, the mixture ceases to explode.

In the case of coal gas, although the theoretical proportions for London gas are 1 of common gas* to 5·6 of air, and 1 of cannel gas to 7·4 of air, yet the best results are obtained with 1 of the former to 8 of air, and 1 of the latter to 11. On either side of this proportion the mixture rapidly becomes less and less explosive.

The effect of mixing other gases with explosive mixtures has been well studied by Davy and others: taking, for example, an explosive mixture of 2 volumes of hydrogen and 1 of oxygen, it is found that 1 of nitrogen to 6 of the gas, or 1 of carbonic acid to 7 of it, will stop its explosion.

Lastly, the temperature at which these gases are fixed is a matter of considerable importance. Davy found that he could not set fire to marsh gas (the firedamp), or to an explosive mixture of it with air, by using the strongest heat of glowing charcoal. He even blew a mixture of the gas upon glowing charcoal until he got it at a maximum heat without firing it; nor can it be fired by the sparks from flint and steel. Not so, however, with hydrogen, or olefiant gas or carbonic oxide, all of which are fired by the sparks and by glowing charcoal—perhaps the igniting temperature is about 3900° Fahr.; and the vapour of bisulphide of carbon is fired at as low a temperature as 300° Fahr. These facts are deserving of attention, for they show that gas leaking from the mains may be fired by a spark from a pick, or from the chipping of a hole in the pipe in laying a service.

And now, gentleman, we have gone over the question of the phenomena of gaseous combustion, and of the manner in which gas is to be most profitably and most economically used for illuminating purposes. We have also examined the thermotic powers of coal gas, and I hope if I have the opportunity of meeting you again, I shall be able to bring under your notice one other question of interest to gas engineers, and that is the profitable utilization of the waste products of gas-works.

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* *Average Composition of London Gas by Volume.*

	Common Gas.	Cannel Gas.
Hydrogen	46·0	27·7
Light carburetted hydrogen	39·5	50·0
Olefiant, &c.	3·8	13·0
Carbonic oxide	7·5	6·8
Carbonic acid	0·7	0·1
Aqueous vapour	2·0	2·0
Nitrogen	0·5	0·4
	100·0	100·0

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