Radiation From Luminous and Non-Luminous Natural-Gas Flames

By RALPH A. SHERMAN,[1] COLUMBUS, OHIO

From the data presented in the paper, these conclusions in regard to the transfer of heat from luminous and non-luminous gas flames are made: Luminous gas flames are now being obtained principally with slow-moving, stratified streams of air and gas, which, from the viewpoint only of efficient combustion, are much inferior to non-luminous flames. Combustion is extremely rapid in pre-mixed, non-luminous flames, which results in a high-temperature zone near the burners. Although natural-gas flames can be produced that have an emissivity approaching that of a black body and consequently a higher rate of heat transfer than a non-luminous flame, the total radiant-heat transfer from the flame and the wall, in those furnaces having walls hotter than the work being heated, will not be much greater for the same flame temperature than with a non-luminous flame. The advantage of a luminous flame in many heating processes lies not in a higher rate of heat transfer, but in a more uniform transfer over the entire furnace as a result of the slow combustion and slow heat liberation. The presence of free carbon probably has a beneficial effect in the reduction of oxidation and the scaling of steel.

RENEWED interest has recently been evidenced in the combustion and radiation characteristics of gas flames. This has come about from the greater availability of gas for industrial use through the wide spread of natural-gas pipe lines, the desire for increased efficiency in combustion, and the need in certain applications for better control of the oxidizing characteristics of the flame. Gas may be so burned as to produce either luminous or non-luminous flames, and discussion has arisen as to the merits of the two types of flames, particularly in regard to the rate of heat transfer by radiation from the flame to the work in the furnace. Conflicting statements that have appeared in these discussions and in the technical press show that a clear understanding of the differences between the two types of flames is lacking. This paper presents a discussion of the knowledge of the chemistry and physics of combustion and heat transfer of gas flames and some new data on large-scale laboratory combustion experiments in the hope that some of the haze that now surrounds the subject may be dispelled.

[1] Fuel Engineer, Battelle Memorial Institute. Mem. A.S.M.E. R. A. Sherman is a graduate of the University of Iowa. For ten years he was in the fuel section of the U. S. Bureau of Mines at Pittsburgh. Since 1930 he has had charge at Battelle Institute of the research work on the combustion of fuels.

Presented at a meeting, Pittsburgh, Pa., February 17, 1933, of the Pittsburgh Section of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, with the Iron and Steel Institute and the Engineers' Society of Western Pennsylvania.

SOURCES OF FLAME RADIATION

There are two sources of radiation from flames: (1) the non-luminous gases, CO_2 and H_2O, and (2) the luminous carbon particles. The radiation from CO_2 and H_2O does not follow the "fourth-power of the temperature," or Stefan-Boltzmann law that applies to solids; these gases radiate in only certain bands of the spectrum, and although Schack(1)[2] made available formulas for the calculation of their radiation, their use is so complicated that they are best found from curves which have been published in English units by Hottel(2) and recently by Fishenden and Saunders.(3) The data of Schack on the radiation of water vapor have lately been superseded by the work of Schmidt;(4) these data have been presented in English by King.(5)

Luminous radiation—that is, the radiation from solid particles suspended in the flame—follows more nearly the laws of radiation from solids. A flame containing carbon particles is, however, partly transparent, and the radiation depends on the concentration of the particles in the flame. Wohlenberg(6) and Haslam and Hottel(7) have made attempts to derive formulas for the calculation of the radiation from powdered-coal flames, but for gas flames no method is yet available for the calculation, largely because the concentration of particles is unknown.

SOURCE OF LUMINOSITY

The luminosity of gas flames arises from the decomposition, also called pyrolysis or cracking, of the hydrocarbons of the gas. The unsaturated hydrocarbons, as ethylene, C_2H_4, and acetylene, C_2H_2, decompose most readily; saturated hydrocarbons, methane, CH_4, ethane, C_2H_6, propane, C_3H_8, and butane, C_4H_{10}, decompose the more readily the higher their carbon content. Therefore, natural gas which contains 80 to 90 per cent of methane, CH_4, is one of the most difficult of the industrial gases with which to obtain a luminous flame. Complete data on the rate of decomposition of methane at various temperatures are lacking; Trinks(8) has collected data from various original sources in a family of curves showing the rate at different temperatures.

The rates of oxidation of methane and ethane, even if mixed with only a part of the air necessary for complete combustion, are extremely rapid. The rates are so high relative to their rates of decomposition that, to obtain a luminous flame with these gases, it is necessary to heat natural gas to a high temperature before it is mixed with air. The possibility is evident that the cracking might be obtained by passing the gas through heated chambers, possibly with a catalyst, but the liberated carbon tends to deposit on the surfaces and stop the passages.

The method used, therefore, in luminous burners so far developed is to introduce the gas and air into the furnace in separate streams, with care in the design of the furnace to avoid mixing until the desired cracking has taken place. The gas is heated by convection and by radiation from the burning gas at the interface of the air and gas streams. Methane and ethane do absorb radiant heat, but data are lacking to calculate their rates of heat absorption.

Because the air and gas cannot be thoroughly mixed by tur-

[2] Numbers in parentheses apply to references at the end of the paper.

bulence and luminosity obtained, the mixing must occur principally by diffusion, and one manufacturer has applied the name diffusion burner to his luminous-flame burner.

CHARACTERISTICS OF LUMINOUS FLAMES

The ratio of air to gas for the maximum rate of flame propagation of natural gas is almost exactly the ratio for the theoretical air requirements. The perfect mixture of natural gas and air is therefore an explosive mixture, and the rate of burning is so rapid that it is practically a detonation. Because the heat is liberated in a small volume of flame, the heat loss is low, and high temperatures are developed very close to the burner when the gas and air are premixed.

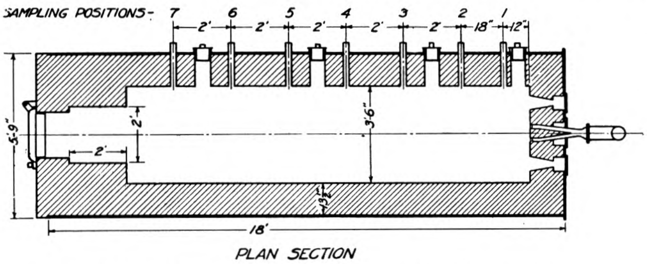

Fig. 1 Plan Section of Experimental Furnace

Where stratification and slow mixing are used to obtain luminosity, the combustion is slow, the heat is released in a large volume of flame from which the heat loss is higher, and the maximum temperature developed may be considerably lower than with a premixed, non-luminous flame.

As previously mentioned, the concentration of carbon particles in a flame may not be readily determined and the radiation cannot be calculated. Nor is it possible to judge accurately the luminosity of a flame by visual observation. Some conception of the degree of blackness of a flame may be obtained by the ability to see the opposite wall or objects in the flame, but accurate information can be obtained only by actual measurement of radiation.

ACKNOWLEDGMENTS

This work has been carried on under the general direction of Clyde E. Williams, assistant director, Battelle Memorial Institute. Lionel F. Fairthorne, assistant fuel engineer, has been engaged in the conduct of all tests. H. W. Russell, physicist of the Institute, has assisted in many phases of the work.

EXPERIMENTAL STUDY

The work reported in this paper includes data on the progress of combustion and on the radiation from the flame when burning natural gas with premixed non-luminous flames and with luminous flames in a large-scale laboratory furnace.

Apparatus and Methods

The Furnace and Burners. Fig. 1 shows a section of the furnace which consists of a horizontal, refractory-lined, steel shell whose seams and joints are welded or cemented to prevent the entrance of air. The inside diameter of the combustion chamber is $3\frac{1}{2}$ ft, and the length from front wall to stack is 14 ft. The drawing shows, at intervals along the furnace, holes through which gas samples are drawn and temperatures are measured. Four 6-in. square ports are provided through which radiation measurements are made.

Fig. 2 shows the details of the burners used in the tests. Fig. 2*A* is the burner for pulverized coal which is being used in an investigation, the results of which have been presented in part;(9) comparative data on the radiation of pulverized-coal flames are included in this paper. Fig. 2*B* shows the premixed non-luminous flame burner, which was made similar to the pulverized-coal burner to obtain comparable flame shape. The inner cone was made larger to reduce the annular section so that the velocity of entrance of the gas-air mixture was above the velocity of flame propagation. The gas entered through 64 $\frac{1}{16}$-in. holes distributed radially in the $1\frac{1}{2}$-in. pipe at the elbow of the burner pipe. The entrance of the gas through the large number of small holes and the passage of the mixture through the venturi throat resulted in good mixing. Fig. 2*C* shows the luminous-flame burner which was purchased from the manufacturer. This type of burner is used with satisfaction in a number of types of industrial furnaces and has been seen by the author in satisfactory operation in "sheet and pair" and annealing furnaces. The solid lines

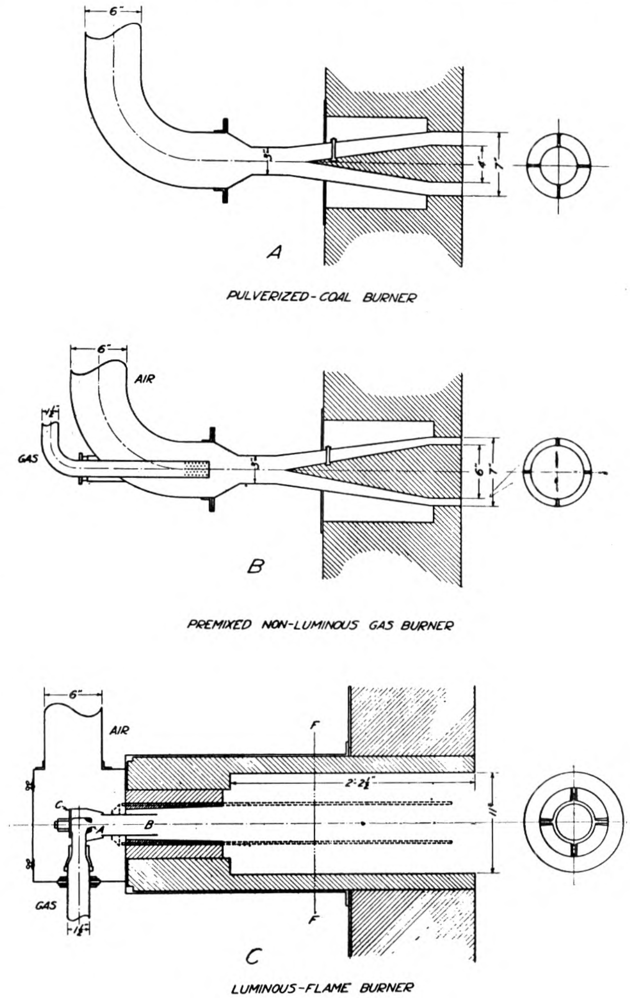

Fig. 2 Styles of Burners

show the burner as furnished; this was installed first with the line *F-F* at the face of the front wall and later with an 18-in. longer tunnel, as shown. The dotted lines show a 4-in. pipe which replaced the original refractory insert in one test.

In this burner the gas enters at *A* through a $\frac{1}{2}$-in. orifice and passes into the refractory insert or 4-in. pipe through the $1\frac{1}{2}$-in. nipple *B*. A shutter *C* is provided which can be opened to permit air to be inspirated with the gas. This was closed during all of these tests. Air can also enter the gas stream between the nipple *B* and the refractory insert. When the 4-in. pipe was used, an adjustable shutter was placed on nipple *B* to vary the amount of air entering with the gas at this point. The air entered the burner box, and the principal part passed around the refractory insert or pipe and mixed with the gas in the tunnel or in the furnace.

Natural Gas. The natural gas used in these tests came from the Columbus mains; it was supplied to the laboratory at a pressure of 10 to 15 lb per sq in. and was reduced by a regulator before the meter used on the tests to 3 to 4 lb per sq in. The gas was measured by a dry displacement meter; the pressure was measured by a mercury column and the temperature by a thermocouple in the gas stream at the meter. All gas volumes were corrected to standard gas conditions, 30 in., 60 F. A thin-plate orifice meter in the gas line allowed easy adjustment of constant flow. The gas furnished during the period of the tests varied rather widely in its composition. Table 1 shows the composition of seven samples of gas.

These analyses were made in a Bureau of Mines type orsat in which the hydrocarbons are determined by slow combustion and can only be calculated as CH_4 and C_2H_6. The gas supplied in Columbus may come from 3400 different wells in 14 producing sands, and a small amount of petroleum-refinery gas is also used. The gas from some of these wells is wet; that is, it contains considerable amounts of the higher hydrocarbons. As these could not be determined on the apparatus available, the analyses are to some extent in error.

TABLE 1 NATURAL GAS COMPOSITION

Test	3	5	8	9	10	12	13
Date	7–14	7–20	9–2	9–15	9–22	10–4	10–12
CH_4	67.4	66.3	60.9	66.2	72.4	76.8	78.7
C_2H_6	17.2	16.8	25.4	21.7	16.1	12.4	9.7
CO_2	1.0	1.2	1.6	1.5	0.8	0.7	0.8
O_2	0.5	0.6	0.5	0.6	0.6	0.6	0.4
N_2	13.9	15.1	11.6	10.0	10.1	9.5	10.4

The variation in the composition is caused by the necessity of mixing of widely different gases and of the introduction of inerts, CO_2 and N_2, to maintain the calorific value as close to 1000 Btu per cu ft as possible.

Air Supply. In all tests all the air was supplied at the burner through the 6-in. duct shown in the burner drawings. The weight of air supplied was determined from the pressure drop across an orifice in this duct.

Heating of Furnace. The furnace was heated by burning gas at the rate and with the air supply desired for about 4 hours to approach equilibrium conditions before taking data. The actual taking of data, which included the collection of two sets of samples of gas at six points in the furnace, the measurement of gas temperatures, and the measurement of the radiation from the flame at four points, required about 3 hours.

Sampling of Gases. Gas samples were withdrawn through water-cooled samplers and collected over mercury. The samples were analyzed in an orsat apparatus using mercury as the displacing fluid.

Samples were taken along the central axis of the furnace only. Although, because of stratification of gases, particularly with the luminous-flame burner, this did not give the average composition in any plane, it was thought that it did give a better record of the progress of combustion than would an average. The stratification in the furnace and the flow of gases were discussed more completely in the report on the pulverized-coal tests.(9)

Measurement of Temperatures. A Pt, Pt-Rh thermocouple supported in a water-cooled tube with $3^1/_2$ in. at the hot junction exposed to the gases was used for most of the temperature measurements. Comparative trials with a suction-type thermocouple showed that when the two couples were so placed as to read the temperatures at the same point simultaneously, the indications checked within 0.1 millivolt, 15 F, which was the limit of graduation on the potentiometer used. The differences should not be great, because the temperature of the walls of the furnace was not greatly different from that of the gas. Such close agreement was not obtained when successive traverses of the furnace were made with the two thermocouples, particularly near the burner, where there was stratification. The lack of agreement was largely caused by the instantaneous variations in the temperatures.

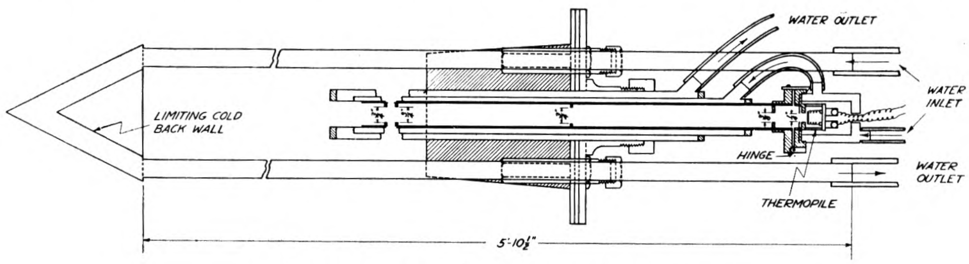

Fig. 3 Apparatus for Measurement of Radiation

Trials were also made in the luminous-flame tests of the two-color pyrometer principle so nicely worked out by Hottel,(10) but, as he predicted in a private communication to the author, the momentary variations in the flame made accurate readings of the temperatures with the optical pyrometer impossible.

It is freely admitted that the temperature measurements were the weakest part of this work, as they generally are of similar investigations. As it was not indicated that any other method would give enough greater accuracy to warrant the difficulties of use, the exposed thermocouple was principally used.

Measurement of Radiation. Fig. 3 shows the arrangement of the apparatus used for the measurement of the radiation from the flame; this was similar to that described by Koessler.(11) It consisted of a Moll thermopile mounted on the end of a water-cooled tube which contained four diaphragms to limit the angle of vision. Around the thermopile was a water jacket through which the water flowed in series with the tube; in this way the cold ends of the thermopile junctions and the surface of the tube that the thermopile "saw" were at the same temperature, and the output was zero independent of changes in room or water temperature.

A water-cooled copper cone served as a limiting cold screen to insure that the radiation falling on the surface of the thermopile was from the flame only. The cone shape was adopted to insure more nearly black conditions by decreasing the possibility of reflection from the surface. This limiting screen was adjustable to obtain any thickness of flame up to the diameter of the furnace.

The entire assembly was mounted in a plate and refractory block and could be changed from one to another of the four ports provided in the furnace.

Another plate and block were provided so that the thermopile and tube could be placed in it to obtain the radiation from the wall and flame or wall alone when the flame was cut off.

The water-jacket assembly for the thermopile was hinged so that it could be swung back from the end of the tube. The tube containing the diaphragms could then be removed and a thermocouple run into the furnace for the measurement of gas temperature.

The output of the thermopile was read on a semi-precision potentiometer with external reflecting galvanometer; this could be read to 1 microvolt.

The thermopile was calibrated with water jacket and water-cooled diaphragm tube as a unit. This eliminated the necessity of making any calculations for the correction for the angle of vision. A graphite cylinder heated in a gas furnace was used as a black-body source; a thermocouple on the inside back wall of the body measured its temperature. A straight-line calibration curve was obtained; the factor was 145 Btu per sq ft per hr per microvolt output.

The thermopile attained full output quickly, but had enough lag so that it ironed out small fluctuations in the flame radiation. Only with violent fluctuations in the flame temperature did the galvanometer swing so rapidly as to make accurate readings difficult.

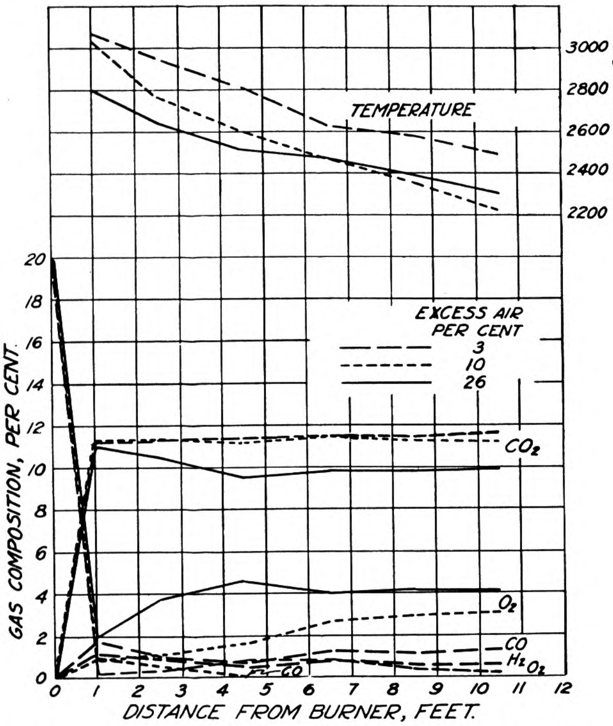

FIG. 4 TEMPERATURE AND COMPOSITION OF GASES, NON-LUMINOUS NATURAL-GAS FLAME

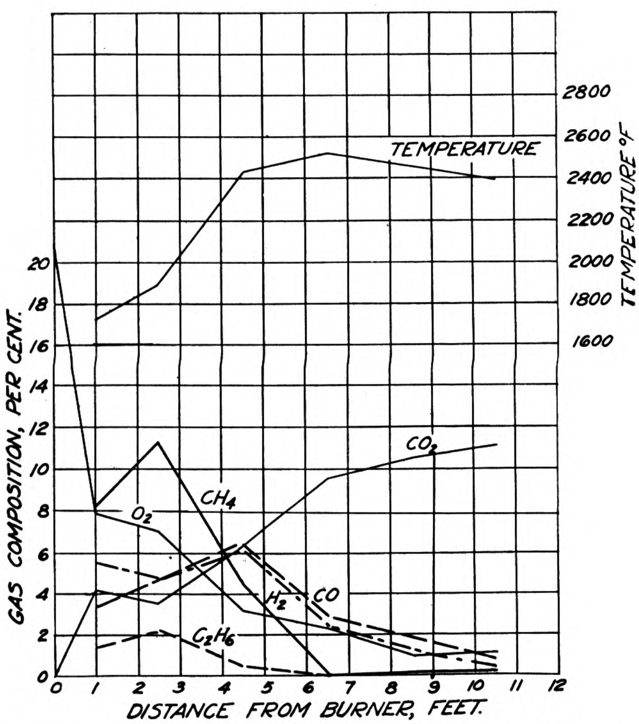

FIG. 5 TEMPERATURE AND COMPOSITION OF GASES, SEMI-LUMINOUS NATURAL-GAS FLAME

(Rate of heat input, 2,800,000 Btu per hr; nominal excess air, 0 per cent.)

DISCUSSION OF RESULTS

Process of Combustion. Fig. 4 shows the change in the temperature and composition of the furnace gas at varying distances from the burner when burning natural gas at a rate of approximately 2800 cu ft per hr with the non-luminous burner with different amounts of excess air. The percentages of excess air given in the figure are the nominal amounts. Because of the

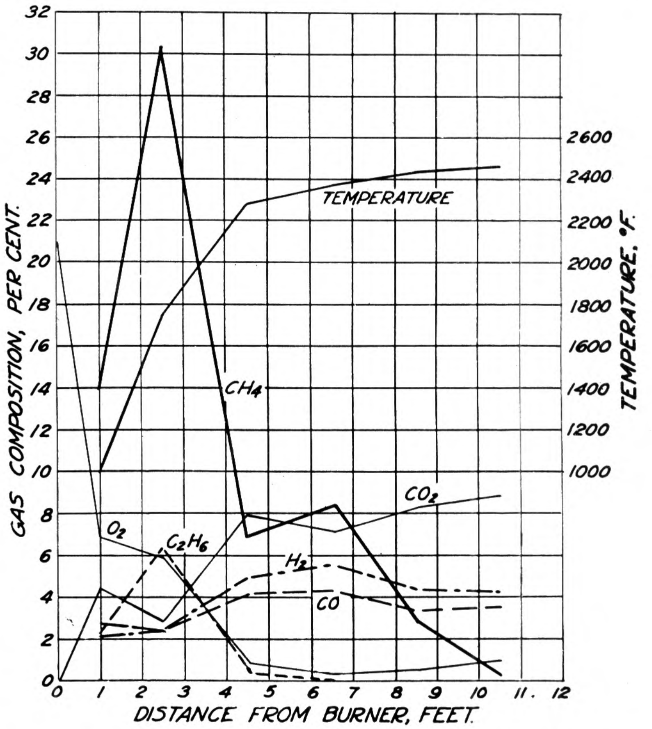

FIG. 6 TEMPERATURE AND COMPOSITION OF GASES, LUMINOUS NATURAL-GAS FLAME

(Rate of heat input, 2,840,000 Btu per hr; nominal excess air, 0 per cent.)

change in the composition of the gas, the actual excess air was somewhat different; for example, in the test marked 0 excess air, there was a deficiency of air, for CO and H_2 were present at the last point of sampling without enough O_2 to burn them.

The curves show the great rapidity of the combustion of the gas. At the first point of sampling, 1 ft from the burner, the CO_2 was at or above the maximum reached at the last position of sampling. That the CO_2 was higher at 1 and $2^1/_2$ ft from the burner than later in the curve for 20 per cent excess air shows that even with this burner the mixture was not uniform.

With 10 per cent excess air some CO was found at 1 and $2^1/_2$ ft from the burner, but it was completely burned at $4^1/_2$ ft. With the nominal 0 per cent excess, both CO and H_2 were found at all positions of sampling.

The temperature curves also show the rapidity of combustion.

The temperatures were the highest, 2800 to 3070 F, at 1 ft from the burners, and then decreased regularly through the furnace.

Fig. 5 shows the temperature and composition of the gases in the furnace when burning natural gas in the burner shown in Fig. 2B with the short tunnel. Here the CO_2 content increased slowly, and CO, H_2, and CH_4 were found at all points of sampling; even ethane, C_2H_6, was found up to $4^1/_2$ ft from the burner. The content of H_2 was greatest at $4^1/_2$ ft, at which point the flame first became strongly luminous. The temperature of the gas was lowest near the burner, increased to a maximum at $6^1/_2$ ft, and then decreased. The maximum was 2500 F as compared with 3070 F for similar rate of heat input and excess air with the non-luminous burner.

The temperature and composition of the gases when using the long tunnel on this burner, as it is shown in Fig. 2C, were very similar to those just shown. Some combustion took place within the burner tunnel, so the CO_2 content and temperatures were somewhat higher in the first points of measurement, but the general trend was similar.

Fig. 6 shows the temperature and composition along the path of the gases when using the long pipe insert shown in Fig. 2C, with which mixing of the gas and air occurred only in the furnace. The CO_2 content increased slowly, large amounts of CH_4 and C_2H_6 were found in the early part of the flame, and about 4 per cent each of CO and H_2 remained at $10^1/_2$ ft from the burner. The temperature of the gases increased slowly and did not attain a maximum; heat was still being liberated faster than it was being lost from the flame.

Radiation From Flame. Table 2 shows the results of measurements of the radiation from the non-luminous gas flame which are typical of other results. At each position the radiation was measured at five flame depths. Q_F is the product of the thermopile calibration constant and the output E_F. The temperatures given in the table are averages of six measurements made at different points in the flame. Q_{BF} is the calculated radiation from a black body at the temperature of the flame to a body at absolute zero; the emission of the thermopile at room temperature is so small relative to that of the flame that the thermopile may be considered as at absolute zero. The term p_F is the ratio of the measured radiation to Q_{BF}.

TABLE 2 RESULTS OF RADIATION M SUREMENT

(Non-Luminous Natural Gas Flame. Heat Inp , 2,632,000 Btu/Hr Excess Air, 0 Per Cent.)

Distance from burner, ft	L, depth of flame, in.	E_F, m.v.	Q_F Btu per sq ft per hr	t_F deg F, avg.	Q_{BF} Btu per sq ft per hr	p_F	K
0.5	10	0.056	8,120	2597	150,500	0.054	0.0055
	15	0.084	12,200			0.081	0.0058
	20	0.123	17,850			0.119	0.0065
	30	0.160	23,200			0.154	0.0055
	35	0.176	25,500			0.169	0.0053
3.5	10	0.064	9,280	2645	160,500	0.058	0.0060
	15	0.105	15,200			0.095	0.0067
	20	0.138	20,000			0.125	0.0067
	30	0.195	28,300			0.176	0.0065
	35	0.214	31,000			0.193	0.0053
7.5	10	0.078	11,300	2580	147,500	0.077	0.0081
	15	0.106	15,400			0.105	0.0074
	20	0.130	18,850			0.128	0.0069
	30	0.178	25,800			0.175	0.0062
	35	0.212	30,700			0.208	0.0067
11.5	10	0.060	8,700	2389	114,500	0.076	0.0078
	15	0.078	11,300			0.099	0.0071
	20	0.101	14,650			0.128	0.0069
	30	0.142	20,600			0.180	0.0071
	35	0.165	23,900			0.209	0.0067

The measurements at varying flame thickness were taken in the hope that data would be made available for the calculation of the radiation of a flame of any given thickness. The relation of the emission of a "gray" flame to the thickness is given by:

$$Q = Q_B(1 - e^{-KL}) \qquad [1]$$

or:

$$\frac{Q}{Q_B} = p = 1 - e^{-KL} \qquad [2]$$

where Q_B is the emission of a black body at the temperature of the flame, K is the absorption coefficient, L is the thickness, and p is the emissivity. However, as stated before, non-luminous flames are not "gray," but are strongly selective radiators. Therefore, the emission of a non-luminous flame even in infinite thickness will not have the emission of a black body at the same temperature.

The relation of the emission of a non-luminous flame to thickness is given by

$$Q = Q_M(1 - e^{-KL}) \qquad [3]$$

where Q_M is the emission of the flame at infinite thickness. For any given temperature and concentration of CO_2 and H_2O, Q_M will have a definite relation to Q_B. Hence [3] may be written

$$Q = CQ_B(1 - e^{-KL}) \qquad [4]$$

where $C = Q_M/Q_B$.

Having given the measured radiation at two thicknesses, we have two equations with two unknowns, K and C, but as there may be a zero correction in the distance L, it is better to consider three measurements at three thicknesses. From [3] it develops that

$$\frac{L_2 - L_1}{L_3 - L_2} = \frac{\log \dfrac{Q_M - Q_1}{Q_M - Q_3}}{\log \dfrac{Q_M - Q_2}{Q_M - Q_3}} \qquad [5]$$

If L_1, L_2, and L_3 are so chosen that the ratio on the left-hand side of [5] is 1, then

$$Q_M = \frac{Q_3Q_1 - Q_2^2}{Q_1 + Q_3 - 2Q_2} \qquad [6]$$

Equation [6] has been applied to a number of the measurements on the non-luminous flames, but the agreement was poor and some absurd results were obtained. Possible reasons for this are (1) lack of uniformity of temperature of the gas, (2) lack of uniformity of composition, or (3) inaccuracy of measurements.

The foregoing argument is based on the general assumption that non-luminous flames are truly selective radiators which have no emission except in narrow bands. If this were not true and other gases radiated over the entire spectrum or there were small amounts of carbon in the flame, even so little that it could not be visually detected, then an infinite thickness of the flame would radiate as a black body and K could be calculated from [1]. The last column of Table 2 gives the values of K so calculated for this set of readings. Although the constancy of K is by no means all that could be desired, it may be significant that the constancy is as good as it is.

With flames that should be truly "gray" and where, therefore, K can be validly computed by [1], as pulverized-coal and lumi-

TABLE 3 COMPARISON OF ABSORPTION COEFFICIENTS K, FOR VARIOUS FLAMES

(Heat Input, 2,600,000 to 3,000,000 Btu per Hr. Excess Air, 0 Per Cent Depth of Flame, 35 In.)

Distance from burner, ft	Pulverized Hocking coal		Non-luminous natural gas		Semi-luminous natural gas		Luminous natural gas	
	p_F	K	p_F	K	p_F	K	p_F	K
0.5	0.63	0.0249	0.17	0.0053	0.19	0.0060	0.72	0.0366
3.5	0.47	0.0159	0.19	0.0053	0.21	0.0067	0.44	0.0222
7.5	0.42	0.0136	0.21	0.0067	0.31	0.0106	0.69	0.0344
11.5	0.43	0.0141	0.21	0.0067	0.26	0.0085	0.68	0.0325

nous gas flames, the agreement of the calculated values of K for various flame thicknesses was not so good as for the non-luminous flames. This is explained by the known greater variation in the temperature and composition of the gas and in the concentration of solids across the flame.

Table 3 shows comparative values of p_F and K for pulverized-fuel, non-luminous, semi-luminous, and luminous natural-gas flames. The greater the emissivity, the greater is the value of K. As K is the slope of the curve when the logarithm of the transmissivity, $1 - p_F$, is plotted against depth of flame, the greater is K, the more rapidly does the emission of the flame increase with increase in the depth of the flame.

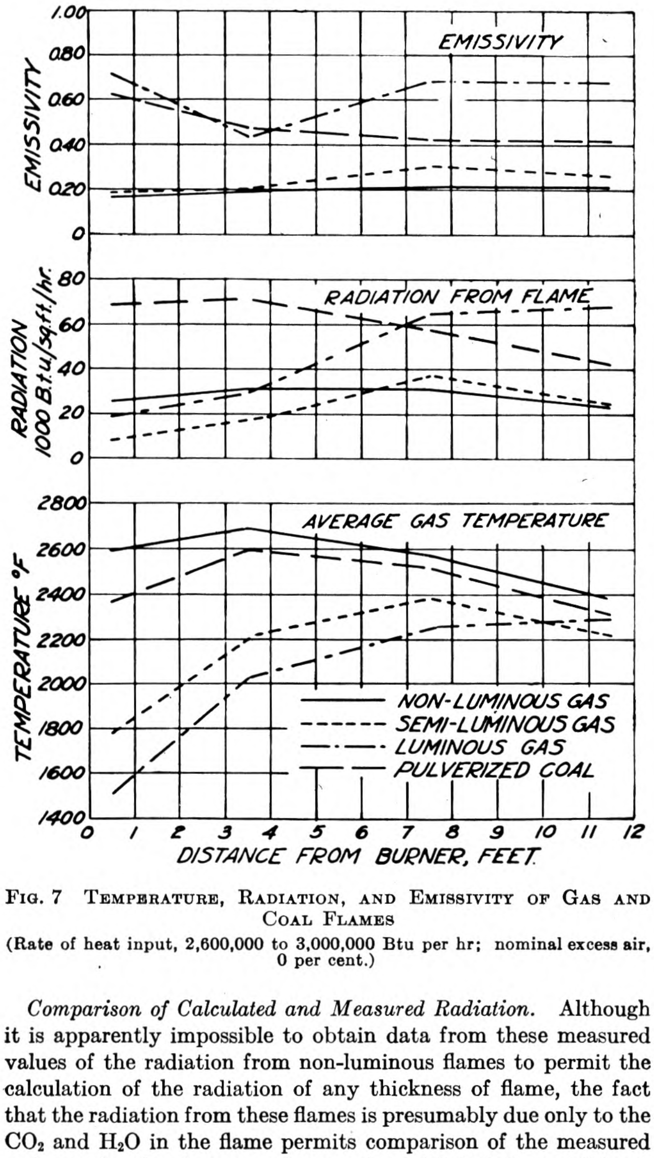

Fig. 7 Temperature, Radiation, and Emissivity of Gas and Coal Flames

(Rate of heat input, 2,600,000 to 3,000,000 Btu per hr; nominal excess air, 0 per cent.)

Comparison of Calculated and Measured Radiation. Although it is apparently impossible to obtain data from these measured values of the radiation from non-luminous flames to permit the calculation of the radiation of any thickness of flame, the fact that the radiation from these flames is presumably due only to the CO_2 and H_2O in the flame permits comparison of the measured and calculated values according to the published data of Schack and Schmidt. Table 4 shows the comparative values for 15 measurements. The first position of measurement, 6 in. from the burner, was not included because of the uncertainty of the composition of the gas and the exact thickness of the flame.

By chance, two of the measured values agreed exactly with those calculated, and only one measured value was less than the calculated. The other 11 measured values were higher than those calculated by 2 to 21 per cent; the findings of other investigators have been similar. If Schack's values for the radiation of

TABLE 4 COMPARISON OF CALCULATED AND MEASURED RADIATION FROM NON-LUMINOUS NATURAL-GAS FLAMES

Test	Heat input, million Btu per hr	Excess air, per cent	Distance from burner, ft	Radiation, 1000 Btu per sq ft per hr Calc.	Measd.	Diff.	Per cent
1	2.71	20	3.5	23.9	23.9	0.0	0.0
			7.5	22.5	23.8	+1.3	+ 5.8
			11.5	20.05	21.0	+0.95	+ 4.7
2	2.67	14	3.5	22.5	24.7	+2.2	+ 9.8
			7.5	21.0	24.1	+3.1	+14.7
			11.5	19.0	19.4	+0.4	+ 2.1
3	2.63	4.5	3.5	22.6	23.9	+1.3	+ 5.8
			7.5	25.4	30.7	+5.3	+20.9
			11.5	27.7	31.0	+3.3	+11.9
4	2.77	10	3.5	30.2	30.7	+0.5	+ 1.8
			7.5	28.3	29.0	+0.7	+ 2.5
			11.5	23.1	22.3	—0.8	— 3.7
5	2.17	12	3.5	22.0	25.4	+3.4	+15.5
			7.5	19.9	23.2	+3.3	+16.6
			11.5	17.8	17.8	0.0	0.0

H_2O had been used, the discrepancies would have been greater; this shows that Schack's values for CO_2 radiation need careful experimental checking, and it is understood that this is being done.

The maximum deviation of the measured from the calculated radiation was 21 per cent and the average was 7 per cent. For this type of measurement this is considered excellent agreement and indicates that for non-luminous flames the radiation may be calculated with a probable error of not more than 10 or 15 per cent.

Comparison of Radiation From Various Flames. Fig. 7 shows graphically the temperature, radiation, and emissivity at varying distances from the burner with non-luminous, semi-luminous, and luminous natural-gas flames and pulverized Hocking coal at similar rates of heat input and excess air. The temperatures shown are the average of a number of readings across the flame, and are therefore lower than those taken on the axis of the furnace, as shown in the preceding figures.

The highest temperatures occurred with the non-luminous gas flame; the temperature curve of the pulverized-coal flame was lower, but similar in shape to that of the non-luminous gas flame. The temperature of the semi-luminous flame reached a maximum at 7.5 ft from the burner, and then decreased below that of the fully luminous flame, which increased at each point of measurement.

The highest radiation from the flame was found when burning pulverized coal; it was practically the same at the first two points of measurement, and then decreased as the solid carbon was burned from the flame.

The radiation from the non-luminous gas flame was practically constant over the length of the furnace. The decrease in the temperature was compensated by the increase in the actual thickness of the flame. The radiation from the flame called semi-luminous was greater than that from the non-luminous flame at only one point, although the flame was so luminous that one could not see the opposite wall, whereas the non-luminous flame was perfectly transparent.

The radiation from the luminous flame increased along the length of the furnace until at 11.5 ft from the burner it was practically as great as that from the pulverized-coal flame near the burner.

The emissivity (the ratio of the radiation from the flame to that of a black body at the same temperature) of the non-luminous flame was the lowest of those of the four flames; it was practically uniform at 0.17 to 0.21. The emissivity of the semi-luminous flame was not much higher, but that of the luminous flame was higher even than that of the pulverized-coal flame, except at the second position; this low value may have been a chance occurrence in this test. The emissivity attained, 0.70, shows that with a not much greater depth this flame would radiate practically as a black body.

PRACTICAL CONCLUSIONS

Burner Design

The purpose of this investigation was not to study burners, but the principles of combustion and radiation; therefore the study of the luminous-flame burner was not carried to any degree to develop a better burner. From the data presented on the progress of combustion, it is quite obvious that from this viewpoint either the semi-luminous or fully luminous burner was much inferior to the non-luminous burner. The ultimate capacity of the non-luminous burner with complete combustion of the gases had apparently not been approached, if at least 10 per cent excess air were supplied. With the luminous-flame burner the heat input would have had to have been decreased considerably to have attained complete combustion in the furnace.

On the assumption that the rate of combustion depends on the rate of diffusion between air and gas layers, Burke and Schumann(12) developed a theory for the prediction of flame length, and report excellent agreement with measured values.

It is apparent, therefore, that the non-luminous burner could have been much improved in regard to completeness of combustion with the proper changes in thickness of air and gas layer and with regard to the possibility of mixing. It is possible, although not probable, that this could be accomplished without decrease in the emissivity of the flame. The low temperature in the early part of the flame probably could be increased, and it and the radiation made more nearly uniform throughout the length of the furnace. Few data on the actual performance of commercial luminous-flame burners have been published; it would be desirable to have such data.

Net Rate of Heat Transfer

The data presented have shown that the radiation and emissivity of the fully luminous flame were much higher than those of the semi-luminous and non-luminous flames. If, however, the test furnace had been an industrial furnace which heated plates or bars of steel, or had been a glass furnace, the steel or glass would not have been shielded from the opposite wall by a water-cooled plate as was the thermopile with which these measurements were made. In addition to receiving heat from the gases, the work would have received heat from the refractory walls as well, which are heated nearly to the temperature of the gases and which have a high emissivity.

The heat which passes through the gases from the roof or walls to the work depends on the transmissivity of the gases to radiant heat; the transmissivity is equal to 1 minus the absorptivity, which is equal to the emissivity. Therefore the total net heat received by radiation by the work whose temperature is T_W and emissivity 1 from the flame whose temperature is T_F and emissivity is p_F and a parallel roof whose temperature is T_R and emissivity 1 may be calculated as follows, assuming for simplicity both the work and the roof as infinite parallel planes:

$$Q = \sigma p_F(T_F^4 - T_W^4) + \sigma(T_R^4 - T_W^4)(1 - p_F)$$

where σ is the constant of radiation. The first term represents the transfer from the flame to the work and the second the transfer from the roof to the work.

From this equation it can be seen that, although the rate of heat transfer from the flame to the work increases as the emissivity of the flame increases, the rate of heat transfer from the wall to the work decreases. Therefore, the total net rate of transfer from the flame and wall will not be greatly increased with an increase in emissivity of the flame, even if the temperature of the flame does not change. Table 5 gives some numerical calculations that may make this point clearer. Flame emissivities of 0.2 to 0.8 with a constant flame temperature of 3000 F have been assumed. The temperature of the surface of the work has been assumed as 2000 F, and the temperature of the roof has been assumed to increase from 2600 to 2900 F as the emissivity of the flame is increased; the exact temperature increase assumed may not be valid, but the order of increase is correct.

TABLE 5 CALCULATED NET TRANSFER OF HEAT BY RADIATION WITH INCREASE IN EMISSIVITY OF FLAME

p_F	T_F, °F	T_W, °F	T_R, °F	$\sigma p_F (T_F^4 - T_W^4)$	$\sigma(1 - p_F)(T_R^4 - T_W^4)$	Q
0.2	3000	2000	2600	36,600	70,400	107,000
0.4	3000	2000	2700	73,200	65,400	138,600
0.6	3000	2000	2800	109,800	52,600	162,400
0.8	3000	2000	2900	146,400	31,300	177,700

The values show that as the emissivity is doubled, the net transfer is increased by only about 30 per cent, and when the emissivity is made four times as great, the radiation is increased by only about 70 per cent.

The calculations assume that the temperature of the flame remains constant as the emissivity is increased, but it has been shown that, other things being equal, the temperature will normally decrease; therefore the increase in the rate of heat transfer by radiation will be lower than that calculated.

Measurements were made of the radiation from the flame, flame and wall, and the wall only at 7.5 ft from the burner on similar tests, with luminous and non-luminous flames. The radiation from the flame was measured as usual; then the water-cooled background was removed and the radiation of the wall and flame was measured. The gas and air were then shut off, and readings of the radiation and temperature of the wall were taken at intervals of 1 min to extrapolate back to time of shut-off, as the temperature of the wall decreased rapidly at first. Table 6 presents the results.

TABLE 6 MEASURED AND CALCULATED RADIATION FROM WALL AND FLAME

	Non-luminous	Luminous
Measured radiation, Btu per sq ft per hr:		
Flame	27,700	64,600
Wall	103,800	88,450
Flame and wall	120,500	104,000
Emissivity of flame	0.19	0.69

Calculated radiation:

Flame and wall = $27{,}700 + 103{,}800\,(1 - 0.19) = 106{,}300$

$64{,}600 + 88{,}450\,(1 - 0.69) = 92{,}020$

Difference of calculated and measured =

$$\frac{(120{,}500 - 106{,}300)\,100}{120{,}500} = 12 \text{ per cent}$$

$$\frac{(104{,}000 - 92{,}000)\,100}{104{,}000} = 11 \text{ per cent}$$

At this position in this furnace, therefore, work on the hearth would have received heat by radiation at a greater rate when burning the gas with a non-luminous than with a luminous flame.

The transfer of heat by convection has been neglected in this consideration, but it is obvious that, because of the higher temperature of the gas, the higher velocity, and the possibility of impingement of a non-luminous flame directly on the work, or both, whereas the non-luminous flame must flow with less turbulence, the rate of heat transfer by convection should be higher with non-luminous than with luminous flame.

The problem of radiant-heat transfer in actual furnaces is somewhat more complex than the illustration, because the factors of the relative areas of the work and the walls, their angular relation, and their emissivities enter. However, it can safely be stated that in furnaces where the roof and walls are at a higher temperature than the work to be heated, the possibility of increasing the rate of heat transfer by increasing the luminosity of the flame is limited.

This important factor, the effect of the emissivity of the flame on the radiation from an opposite wall, is one apparently generally overlooked. It has, however, been very well covered by

Schack.(13) He believes that in furnaces, such as open-hearth steel furnaces, where the roof temperature is kept only about 50 F above the slag temperature, an increase in the emissivity of the flame may increase the rate of heat transfer by radiation. In furnaces, such as boiler furnaces, with water-cooled walls where no high-temperature solid radiating surfaces are found, the overall transfer of heat by radiation can be increased directly as the emissivity of the flame is increased.

Effect of Distance on Radiation Exchange

The observation has been made that engineers frequently misapply the "inverse square of the distance" law which they loosely quote as saying that the radiation received per unit area of a surface varies inversely as the square of the distance from the source. They then conclude that this means that, if the flame can be placed near the work, the rate of heat transfer by radiation will be much greater than if it is farther away or is being received from the roof.

This law applies strictly, however, only to radiation from a point source. The actual effect of the distance between planes has been presented by Hottel.(14) He expresses the heat exchange as

$$Q = A \cdot F_A \cdot F_E \cdot \sigma(T_1^4 - T_2^4)$$

where A is the area, F_A is the angle factor including the effect of distance, and F_E is the emissivity factor. He presents a curve in which F_A for squares or disks connected by non-conducting but re-radiating walls is plotted against the ratio of the side or diameter to the distance between the planes. For values of the ratio above 1, the change in F_A is not rapid—not nearly so rapid as the inverse square law would show. For example, the following points have been taken from his curve:

Ratio	4	2	1
F_A	0.78	0.63	0.50
Ratio to 0.78	1	0.81	0.64
Ratio by inverse square law	1	0.25	0.06

The wide departure of the true relation from the inverse square law is obvious.

ADVANTAGES OF LUMINOUS FLAMES

If luminous flames do not transfer heat at a greater rate than non-luminous flames, wherein do their advantages lie, or are they merely imaginary? The term "soaking heat" is a common one among practical furnace men, and there is some evidence of their belief that the heat of a luminous flame is more penetrating than that of a non-luminous flame.

The difference may probably best be explained by a practical example. A continuous furnace for heating steel for forging in which the steel moved countercurrent to the gas was operated with a non-luminous gas flame and with a highly luminous oil flame. With the oil flame the steel was withdrawn at just the right temperature for forging and was heated entirely through to a practically uniform temperature. With the non-luminous gas flame, although the steel was almost dripping when withdrawn, it did not forge well because only the surface was heated.

The difficulty here was not a difference in the overall transfer of the two flames, but the difference in the distribution of the transfer over the length of the furnace. At any point in the oil flame the rate of transfer was not so great as the maximum from the gas flame, but it was more uniform over the entire length of the flame. The heat was not transferred at a greater rate than it could penetrate the steel; therefore, as commonly expressed, it "soaked in"—that is, the temperature increased substantially uniformly through the piece. In the gas flame the rate of heat transfer was low until the zone of combustion was reached; here the sum of the rates of heat transfer by radiation from the flame and walls and of the convection from the high-temperature gases was greater than the possible rate of heat penetration into the steel, and the outer surface was raised to the melting point while the inside was yet at too low a temperature for forging.

The proper heating of the steel might have been obtained with a non-luminous flame, if the heat input had been distributed among a number of burners along the furnace to maintain a uniform and not too high a rate of heat transfer.

CHEMICAL EFFECTS OF LUMINOSITY

As this paper is principally concerned with radiant-heat transfer, the problem of the chemical effect of the flames will only be briefly mentioned. This is of particular importance in the heating of steel which will oxidize and scale not only in atmospheres containing oxygen, but also in those containing no oxygen but CO_2 and H_2O. It is therefore necessary to maintain a reducing

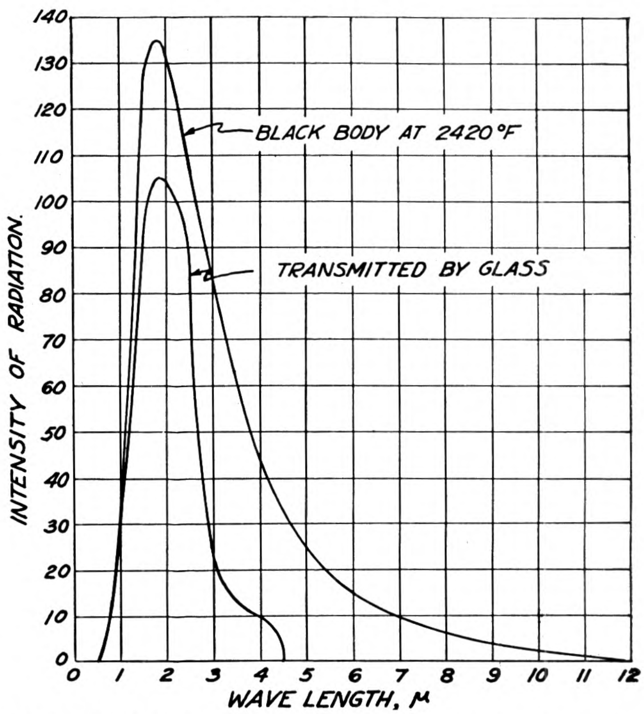

Fig. 8 Comparison of Radiation of Black Body and Transmission of Glass, 2.11 Mm Thick, at 2420 F

atmosphere, a certain percentage of CO, to avoid the scaling of steel when burning gas with a non-luminous flame. This will usually result in an appreciable loss of heat in unburned gases.

In a luminous flame CO, H_2, and perhaps methane will be present, but free oxygen also remains. However, there is free carbon present, and as this will deposit on the work, it probably reduces the oxidation of the steel. In some luminous-flame burners a raw-gas blanket is introduced over the work being heated. This will result in an increased consumption of gas, but this may be more than offset by the better quality of the product.

HEAT TRANSFER IN GLASS TANKS

In the melting and refining of glass it is highly desirable that the glass be heated as uniformly as possible from top to bottom of the tank. Convection from the gases can heat the top of the glass only, and this heat can be transferred to the bottom only by conduction and by convection currents set up in the glass. The conductivity of glass is comparatively low, and until the glass is at high temperature, convection will be low because of its high viscosity; therefore, the rate of heating of the bottom may be low.

As glass is transparent to visible radiation, it is frequently assumed that it is transparent to the invisible thermal radiation also. Data are lacking on the transmission of glasses at high temperatures, but the transmission of a number of glasses at room temperature has been measured; these measurements show that even in thin layers practically all glasses are opaque to wave lengths beyond 3 to 4μ.

Fig. 8 shows in the upper curve the intensity of black radiation at different wave lengths at 2420 F, and the lower curve shows the intensity of radiation transmitted by a piece of window glass 2.11 mm in thickness, assuming that the transmission of the glass at 2420 F is the same as at room temperatures at which the transmission was measured by Coblentz.(15) The area under the curves is the total radiation over the entire band. Measurements of these areas by a planimeter show that the glass would transmit about 48 per cent of the energy entering it. As molten glass may not have the same transmission as cold glass and as the depth of glass baths is much greater than that of the example, the actual transmission would probably be much different from this value.

The relation of the absorption of radiant heat to the thickness is, as for gases, expressed by

$$Q = Q_0(1 - e^{-KL})$$

where Q is the amount absorbed and Q_o the amount entering the thickness L. A consideration of this expression brings out an interesting fact. If the absorption coefficient K were 0 (that is, if the glass were perfectly transparent), then $Q = 0$, and with any depth of glass no radiant heat would be absorbed. All the radiant heat would pass to the bottom of the tank and would be transferred to the glass by conduction. On the other hand, if $K = \infty$, the glass is perfectly opaque; then any thickness would absorb all the heat, and none would reach the bottom of the bath. It is clear, therefore, that for a maximum absorption of radiant heat in a layer at same depth in a bath, there is a definite intermediate value for the absorption coefficient.

A complete understanding of the problem of heat transfer to molten glass cannot be had until data are obtained on its absorption of radiant heat. It is considered possible that the advantages reported in the current literature for the use of luminous flames lie not in an increased rate of heat transfer, but in a more uniform rate of heat transfer over the area of the bath. This would avoid the formation of localized areas of high-temperature and thinly fluid glass and other localized areas of low-temperature and viscous glass.

SUMMARY

From the data and analytical considerations presented, the following conclusions in regard to the transfer of heat from luminous and non-luminous gas flames can be made:

1 Luminous gas flames are now being obtained principally with slow-moving, stratified streams of air and gas, which, from the viewpoint only of efficient combustion, are much inferior to non-luminous flames.

2 Combustion is extremely rapid in premixed, non-luminous flames which results in a high-temperature zone near the burners, whereas combustion is spread out over a larger area in luminous flames which results in a lower maximum temperature. With proper burner design a more uniform temperature over the length of the furnace could probably be obtained with a luminous flame.

3 Although natural-gas flames can be produced that have an emissivity approaching that of a black body and consequently a higher rate of heat transfer than a non-luminous flame, the total radiant-heat transfer from the flame and the wall, in those furnaces having walls hotter than the work being heated, will not be much greater for the same flame temperature than with a non-luminous flame. As the temperature and convection transfer are generally lower, the total rate of heat transfer will normally be lower with a luminous than with a non-luminous flame.

4 The advantage of a luminous flame in many heating processes lies not in a higher rate of heat transfer, but in a more uniform transfer over the entire furnace as a result of the slow combustion and slow heat liberation.

5 The presence of free carbon probably has a beneficial effect in the reduction of oxidation and the scaling of steel.

6 A complete analysis of the transfer of heat to molten glass is not possible because of lack of data on its absorption of radiant heat, but the conclusion is reached that any advantage of a luminous flame in glass melting lies in a more uniform distribution of heat transfer rather than an increased rate of transfer.

REFERENCES

1 Schack, A., *Zeit. für Tech. Physik*, vol. 5 (1924), p. 266.

2 Hottel, H. C., *Ind. & Eng. Chem.*, vol. 19 (1927), p. 888.

3 Fishenden, M., and Saunders, O. A., "The Calculation of Heat Transmission," H. M. Stationery Office, 1931.

4 Schmidt, E., *Forschungsarbeiten auf dem Gebiete des Ingenieurwesens*, vol. 3 (1932), p. 57.

5 King, W. J., *Mechanical Engineering*, vol. 54 (1932), p. 495.

6 Wohlenberg, W. J., and Morrow, D. G., Trans. A.S.M.E., vol. 47 (1925), p. 127. Wohlenberg, W. J., and Lindseth, E. L., Trans. A.S.M.E., vol. 48 (1926), p. 849. Wohlenberg, W. J., and Anthony, R. L., Trans. A.S.M.E., vol. 51 (1929), no. FSP-51-36.

7 Haslam, R. T., and Hottel, H. C., Trans. A.S.M.E., vol. 50 (1928), paper no. FSP-50-3.

8 Trinks, W., *Heat Treating & Forging*, vol. 18 (1932), p. 319.

9 Sherman, R. A., Proceedings of the Third International Conference on Bituminous Coal (1931), vol. 2, pp. 510–551.

10 Hottel, H. C., and Broughton, F. P., Anal. Ed., *Ind. and Eng. Chem.*, vol. 4 (1932), p. 166.

11 Koessler, P., *Archiv. für Wärmewirtschaft*, vol. 11 (1930), p. 229.

12 Burke, S. P., and Schumann, T. E. W., *Ind. & Eng. Chem.*, vol. 20 (1928), p. 998.

13 Schack, A., *Der Industrielle Wärmeübergang*, Verlag Stahleisen (1929), p. 303.

14 Hottel, H. C., *Mechanical Engineering*, vol. 52 (1930), pp. 699–704.

15 Coblentz, W. W., Emerson, W. B., and Long, M. B., Bulletin of the Bureau of Standards, vol. 14 (1918–19), p. 670.

Discussion

H. V. Flagg.[3] The paper shows evidence of careful planning, deep study, and patient experimental work. The contribution should be very helpful and valuable, and it is hoped that it may be followed up by further experimentation. The writer's observations and plant work do not lead to complete agreement with the conclusions reached in the paper, but it is believed that the differences can be accounted for by what are believed to be errors in the basic assumptions.

The writer would like to consider the subject as a comparison of the relative merits of luminous and non-luminous flames for metallurgical heating rather than as a discussion of the two types of flame from natural gas alone. Luminous flame can be developed from any of the commercial fuels in common use, so that the differences become merely those of degree, either in heat-transfer rates or in flue-gas compositions which affect the chemistry in the furnace. The assumption throughout the work that the net transfer of heat in a furnace is the sum of the heat transfer from the flame and that from the furnace wall, or at least the method of arriving at the same, is open to question. This is

[3] Combustion Engineer, The American Rolling Mill Co., Middletown, Ohio.

certainly not right in the case of a sharp-working open-hearth furnace where, as is often the case, the furnace is so organized that the roof temperature is actually lower than the bath temperature. In such a furnace the heat transfer from the flame certainly plays the predominant part. The convection transfer is undoubtedly important, but cannot be the predominant influence, as is evidenced by repeated failure of tests to run an open-hearth furnace with a premixed natural-gas flame, which is practically non-luminous, and with a heat transfer that is predominantly convective. In a metallurgical heating furnace, it is necessary to secure the maximum heat transfer with the least possible difference between the temperature of the flame and the temperature desired in the work in order to obtain uniform heating.

This result can be obtained with non-luminous flame by making the heating time sufficiently long, but in many cases this requires a furnace size and space that is prohibitive. The use of a luminous flame in such furnaces makes it possible either to obtain better heating for given production or greater production for the same standard of heating, because of a higher heat transfer from the flame and the decidedly lessened influence of the transfer from the walls. The development of the luminous-flame burner has resulted from the need to secure from natural gas a flame with this resultant higher heat transfer which is so easily secured from producer gas or fuel oil. The old-time heater who burned natural gas prior to the time of the development of the premix burner knew how to get the luminous flame, but his control of furnace atmosphere and of fuel economy left much to be desired, since one vital element, that of combustion-air supply, was never completely under his control. The new luminous-flame burner is designed to produce the luminous flame from natural gas with all three essential factors—fuel input, air supply, and furnace pressure—under exact control. Evidently, the heat transfer in a furnace under luminous-flame conditions is very largely from the flame, the wall transfer being of minor importance. In this type of combustion, the most important function of the wall is to screen off heat losses so that flame temperature can be maintained. The old sheet heater maintains a heavy flame in his furnace, not only to establish the maximum possible heat transfer from the flame, but also to hold the wall temperature down so as to prevent radiation from the wall surfaces which might cause local overheating.

The author's reservation as to the use of the "inverse square of the distance" law is open to question. It is commonly accepted that the heat transfer to an open-hearth bath is predominantly radiation from the flame. Furthermore, it is axiomatic that the flame must "wipe the bath." A non-luminous flame will melt down a charge very rapidly, but as soon as the bath is under cover "it goes dead," which indicates that convection transfer is not the controlling factor. When a luminous flame "wipes the bath," the distance between the source of radiation and the work approaches zero, so that the distance factor is practically eliminated. It is probable that this law has much more importance in the range of very small distance than it has in the range considered in this paper, so that the importance of the effect of distance on radiation may be much greater than the author believes. The example of the forging furnace using non-luminous flame and the one using the luminous flame for the same work and the comparison of results obtained is a familiar one, but the author's solution is not borne out in practise. The writer has in mind two continuous annealing furnaces similar in size and construction. One of these is fired with a large number of natural-gas premix burners over its entire length and the other with fuel oil over its entire length. The output from the luminous-flame furnace is distinctly larger than that from the non-luminous furnace. One could cite other instances equally as convincing which indicate that the solution offered of merely adding more burners would not have remedied the situation.

The question of efficiency of combustion is referred to in connection with improvements in burner design. In metallurgical heating, the aim is to secure maximum production and greatest yield at least overall cost. Fuel practise under these conditions may appear wasteful from the standpoint of efficiency of fuel utilization, but the waste may be justified from the results secured. In most steel-mill heating operations, luminous-flame combustion helps to meet these conditions, so that any experimental work which has as its aim the improvement of flame heat transfer is bound to have value.

F. B. Jones.[4] The writer agrees that this subject in the past has been shrouded with some mystery and that many conflicting statements have appeared in the technical press as well as in discussions on this subject. There seems to be a great need for determining fundamental data regarding the subject of combustion.

The author states that the purpose of this investigation was to study the principles of combustion and radiation. It is regretted that he found it necessary to limit the investigation to this phase of the subject, as a much more valuable contribution could have been made had he been able to study not only different types of flames as produced by different types of burners, but also the effect of the furnace chamber on the various types of flames.

It seems that the two phases of this subject are very closely interrelated, and it would be most difficult to arrive at conclusions on the luminous and diffusion types of combustion if the data were limited only to one type of flame and one type of furnace chamber. With this thought in mind, the writer would seriously question whether sufficient data were available from this investigation to justify the author's conclusions 3 and 4.

The author uses the terms "luminous" and "diffusion" flames interchangeably. To the writer's mind there is a distinct difference. He can find no evidence in the author's data to show whether the flame that he produced with his burner and furnace was a luminous or a true diffusion flame. Taking into consideration the design of the burner that the author terms a "luminous" burner, and also the fact that the experimental furnace was a cylinder $3^1/_2$ ft in diameter and about 14 ft long, the writer does not believe it is possible to produce a true diffusion flame with such a burner and with such a furnace chamber. Therefore, the flame the author used was a luminous flame of the delayed combustion and incomplete mixing type.

If we are to assume that true diffusion combustion is obtainable only when we have parallel streams of gas flowing in a suitable furnace chamber that permits parallel or streamline flow without turbulence, it would seem to be most difficult to produce a true diffusion flame with the furnace set-up used in this investigation.

A cylindrical type of furnace of a rather restricted diameter and length as used in this investigation, having a gas capacity of 2800 cu ft per hr, would tend to break up and distort parallel lines of flow if they were once set up by a suitable burner. In fact, the combustion of the gases that the author shows with his luminous flame indicates incomplete and delayed combustion even at the point of discharge of the furnace gases.

Fig. 6 shows that, even at a point 10 ft from the burner, about 4 per cent of CO and hydrogen existed in flame products; also, that the percentage of CO_2 was about 9 per cent, which is below that secured with his non-luminous natural-gas flame of 11.5 per cent at the same point in the furnace. The oxygen content at the same point in the furnace was about 1 per cent.

A rectangular type of furnace, much longer, would be more

[4] Equitable Gas Company, Pittsburgh, Pa.

adaptable for studying various types of flames, because there would be less tendency to set up turbulence in the flame, and there would be ample length for the full development of the flame length. Of course, the cylindrical type of furnace would be satisfactory for studying a non-luminous flame.

It seems that this whole question of energy radiation from the combustion in various types of flames is still one on which much experimental and fundamental data are lacking. We are told by physicists that heat radiation is a phenomena involving energy waves in the ether, very similar to sound waves in the air. We are also told by men who have made studies of various wave lengths in the air that we have a wide variety of wave lengths possible in the ether. At one extreme we have very short cosmic rays, gradually getting longer through the X-rays, ultra-violet, visible rays, solar, heat, short radio, and finally the regular radio rays. It seems that we need data as to when and how the radiation waves from a flame are produced. Is the radiation produced at the moment of chemical union of the various contents of the gases such as carbon and hydrogen with oxygen, or are they produced continuously after combustion has taken place and after the resulting flue gases consisting of carbon monoxide and carbon dioxide and water vapor have been heated to a very high temperature? Possibly the total radiation is a combined effect of radiation sent out from the molecules of gas, both during the process of combustion and after they have been chemically united.

The writer's conception of the true diffusion flame is a flame in which microscopic or even ultra-microscopic particles of carbon are produced from the carbonaceous gases in the fuel and hang in suspension in the flame and set up energy radiations from the carbon particles as a result of the carbon particles being heated to a high temperature by the release of heat energy as a part of the fuel has been united with oxygen. He is of the opinion that the total radiation from the true diffusion flame is a result of the heat waves produced from the incandescent carbon particles, plus the heat waves sent out at the moment the chemical union of oxygen with either carbon or hydrogen is effected, plus the heat waves sent out from the resulting flue products which are still at a high temperature. If we could determine, for example, the total amount of energy that might be radiated from any flame from the instantaneous production of heat radiation due to the chemical union of oxygen and fuel—if it is true that such union produces heat radiation—and then determine the amount of energy that will be radiated from the resulting hot flue gases at various temperatures, then we would be in a position to predict the value of a true diffusion flame as a means of increasing the heat radiated to the work in the furnace.

If we had such data we would also be able to evaluate the efficiency or effectiveness of various diffusion burners in terms of the amount of energy they would release in radiant form from the incandescent carbon particles that they produce in the flame. Until we have such data we will continue to remain, so far as this question of applying luminous and diffusion combustion to industrial heating operations is concerned, in a process of engineering guessing as to the value of one type of flame or burner over another.

F. M. Washburn.[5] A large number of those who have not made a study of heat transmission as a rule have in their minds several misconceptions; chief among these are the thought that no heat transfer by radiation takes place from a non-luminous flame, the thought that the heat transfer by radiation from a flame is directly proportional to the luminosity or brightness of the flame, and the thought that the "inverse square of the distance" law applies to radiant-heat transfer in a furnace. The author shows clearly that all of these conceptions are indeed more or less erroneous.

[5] Chief Chemist, International Harvester Co., Wisconsin Steel Works.

Schack, of course, developed some time ago the formulas for radiation from the CO_2 and H_2O vapor present in a non-luminous flame, but the magnitude of the quantities of heat transferred by such radiation is not generally realized by operators of industrial furnaces. The excellent agreement between the experimental data obtained by the author and the results calculated by means of the published formulas should serve to bring home the importance of the consideration of radiation from a non-luminous flame. It is only natural, since a strictly non-luminous flame is invisible, to consider that no great amount of radiation is taking place from it, but when it is remembered that by far the greater part of the radiation which transmits heat from a flame is outside of the visible spectrum and that at the highest temperatures met with in industrial furnaces the visible radiation is only a fraction of the total radiation, it is seen that it is possible for a flame to be practically invisible—that is, devoid of luminosity—and still radiate a considerable amount of heat. In a non-luminous flame the radiation comes principally from CO_2 and H_2O, which substances emit radiation in bands entirely outside of the visible spectrum, or in other words, such radiation is invisible.

Table 5 and the statement by the author that as the emissivity of a flame is doubled the net heat transfer is increased by only 30 per cent shows that the thought that the heat transfer by radiation is directly proportional to the luminosity of the flame is incorrect. However, from a standpoint of practical operation, an increase in the luminosity of a flame does mean an increase in heat transfer by radiation, and although the increase in heat transfer may not be directly proportional, nevertheless a considerable gain in heat transfer may be made by this means.

The application of the "inverse square of the distance" law for radiation, which holds for a point source only, where no reflecting walls are present, to the conditions existing in a furnace, is shown to be erroneous by the author. However, although this "inverse square of the distance" law cannot be applied in the case of a furnace, where radiation emanates from walls, roof, and flame, from a practical standpoint, when using a luminous flame, there is a distinct gain in heat transfer obtainable by keeping the flame close to the work.

In this case, while the gain in heat transfer would, as shown by the author, not be nearly as great as would be shown by application of the "inverse square of the distance" principle, when using a luminous flame, it is highly desirable, if not essential, to keep the flame close to the work. Another point which is not generally well understood, and which is clarified by the author, is the effect of a luminous flame in screening or shutting off the radiation from the walls and roof of a furnace. It is rather startling to find that as much or in some locations even more heat is transferred from a non-luminous flame as from a luminous flame, when the sum of radiation from flame and from roof and walls is considered. Since, as pointed out by the author, a non-luminous flame is certainly more efficient for the transfer of heat by convection, the total amount of heat transferred by a non-luminous flame would be considerably greater than by a luminous flame. However, although this greater transfer of heat, due to the sum of radiation and convection, may take place from a non-luminous flame in some parts of the furnace, it is still possible that when the greater area covered by the luminous flame with its nearly uniform heat transfer is considered, the total heat transferred to the work in the furnace may be greater when a luminous flame is used. There are, in addition, other factors which greatly influence the heat transfer. For example, a non-luminous, sharp, high-velocity flame is more efficient in melting down the charge in an open-hearth furnace, where heat transfer by convection can take place readily due to the penetration of the interstices of the charge by the hot gases, as well as taking advantage of radiation from flame and from roof and walls. However, after such a charge is melted down, and a liquid bath is formed, practical experience shows that heat transfer is facilitated by the use of a slow moving, highly luminous flame.

This latter effect is particularly well shown in the case of an open-hearth heat where the slag has risen up in a foam. Under these conditions, it is very difficult and frequently impossible to transfer enough heat to the bath with a non-luminous or weakly luminous flame, to flatten down the foam and to cause the reactions in the bath to proceed. If the flame is made highly luminous, enough heat can be transferred to the bath to reduce the foam and proceed with the heat with much less delay than in the former case.

Chief among the advantages of a luminous flame, the author lists "soaking heat." The explanation of "soaking heat" as applied to a continuous steel heating furnace is undoubtedly correct, and explains clearly the advantage of a luminous flame in this application. There is, however, another distinct advantage obtained by the use of a luminous flame, particularly in open-hearth furnaces, where the refractories are required to withstand an extremely high temperature, and that is that a luminous flame transfers a much greater portion of its heat by direct radiation to the work than a non-luminous flame, and makes this transfer with a lower flame temperature. When a non-luminous flame is used, a much greater portion of the heat transferred must take place by radiation from the walls and roof than when a luminous flame is used. Such a large transfer of heat by the walls and roof necessarily means heating these parts of the furnace to a higher temperature than when more heat is transferred direct from the flame. Having the refractories at a higher temperature necessarily means shorter life and a higher refractory cost. From a practical standpoint, this factor in favor of the luminous flame cannot be neglected.

C. George Segeler.[6] Not only Mr. Sherman but also other workers in the field of luminous or diffusion combustion have assumed that the air and gas layers introduced into a furnace absorb considerable heat prior to combustion at the interfaces. This point is open to some question, because the absorption of any considerable amount of heat, such as raising the absolute temperature of the gas from an incoming 520 F to, let us say, double that amount, or 1040 F, will be accompanied by an expansion in volume to double the initial volume. The same is true, of course, of the air volume, and under such conditions there would be expected a high degree of turbulence and an immediate destruction of anything remotely resembling air and gas layers. It seems to the writer that rather the contrary should be true; that in order to preserve luminous-flame conditions in the way they can be observed in diffusion-combustion operations, it is essential that a relatively small amount of heat be absorbed by the layers of air and gas. Consequently, combustion speed remains rather slow. Reference to Fig. 30 in the new American Gas Association book, "Combustion," would show that raising the temperature of natural gas to, say, 500 F would approximately triple its flame speed. Thus, from the admission end to the discharge end of a luminous-flame furnace one would expect combustion to be progressing at respectively increasingly rapid rates. Observation on these points, although superficial as yet, does not seem to indicate that any such procedure is taking place.

Since radiation is not a one-sided phenomenon, but in practise must represent the net result between the heat radiated from the hottest point and that re-radiated and reflected from other points, it is possible that other factors influencing the heat transfer of a furnace also affect the net radiation from a flame. It has roughly been established that there is a relation between heat transfer, at any given temperature, and the pressure loss over a given length of heat travel. To be sure, such a relationship is only a rough measure, but it is of importance in this connection that the results obtained by the author strictly apply only to the furnace conditions which were set up by the physical limitations of the furnace in use. The relation of flue area to total heat input affected the heat transfer over the entire furnace. It affected in part the emissivity of the walls, although to only a small extent, as near as is known from the limited data of brick emissivities at high temperatures. This point is raised in connection with the attempt to draw practical conclusions from the material at hand. It is the thought of this writer that insufficient information is available from the tests performed to draw any definite conclusions on the rates of heat transfer which can be accomplished by various types of flame.

Recent investigation[7] of forging practise comparing both diffusion flame and non-luminous types of heating indicates that the diffusion flame does permit higher rates of heating in general. At the same time this paper discusses the limitations of heating rates determined by the thickness of the stock, the physical nature of the steel, and other considerations, which of course should not be looked upon as limiting the theoretical nature of the flames. However, the fact remains that faster work has been reported regularly from the diffusion-flame operations, which is contrary to the conclusions drawn by the author. It is quite possible that this difference has been due in part to the difficult question of furnace layout and design, which in turn affects the rate of heat transfer. Mr. Sherman calls attention to some of these points in the discussion which he makes of the transmissivity and the absorptivity of flames in relation to the roof and walls. It is possible that further efforts along this line will bring to light why certain diffusion-flame operations were capable of being carried on more rapidly than with non-luminous flames.

These considerations might suggest reconsideration of the summary statements made by the author. For example, statement 1 has already been discussed.

In statement 2, the author indicates that the luminous flame would give a more uniform temperature. This statement is only partly true, as it overlooks the present practical methods for obtaining uniformity by using a multiplicity of burners properly located.

Statement 3 is subject to question based on the data collected and reported in the A.G.A. Industrial Service Letter on "Forging." The conclusions drawn therein are somewhat contrary to the theoretical considerations made by the author. It is quite possible, however, that additional data will eventually correlate these apparent discrepancies.

W. J. King.[8] This paper represents a valuable contribution to the data of combustion and radiation in gases. The practical significance of the results is enhanced by the large scale of the tests, the amount of data obtained, and the excellent experimental technique. With regard to the latter, there is just one question which occurs to the writer: Referring to Fig. 3, is it not possible that the water-cooled tube containing the thermopile at its right end may have become filled with gases, including about 11 per cent CO_2, which would absorb part of the radiation from the flame? Perhaps a very slow stream of dry air or nitrogen might have been passed into the tube to clear out these gases.

An examination of the data of Table 2 suggests that the

[6] Engineer of Utilization, American Gas Association.

[7] As published in the A.G.A. Industrial Service Letter No. 11 on "Forging."

[8] Engineering General Department, General Electric Co., Schenectady, N. Y.

failure of Equation [6] and the significance of the constancy of K may be explained by the fact that the depth of the flame was not extended far enough to get beyond the almost linear increase of p_F with L. In other words, up to a depth of L = 35 in. the curve of p_F against L had not begun to bend over and approach the limiting value, i.e., the value of C in Equation [4]. On the flat portion of the curve beyond this bend, any variation of K would be revealed more plainly and the value of Q_M in Equation [6] could be calculated more accurately.

Perhaps a system of mirrors could be used with this apparatus to secure the effect of greater flame depth, by reflecting the heat rays back and forth across the flame several times, as was done by E. Schmidt in his measurements of the emissivity of water vapor.

No mention is made in the paper of the possible effect of radiation due to chemical reactions in the combustion process. This would not appear in the non-luminous flame, since combustion was complete within a very short distance from the burner, but if this effect has any significance in this type of combustion, it might have been revealed if more complete data were given for the luminous flames.

The conclusions drawn in the paper should not be applied too generally in practise, and the data should be used advisedly. For example, it is stated that, "In furnaces, such as boiler furnaces, with water-cooled walls where no high-temperature solid radiating surfaces are found, the overall transfer of heat by radiation can be increased directly as the emissivity of the flame is increased." This is true, as the author points out elsewhere, only when the temperature is maintained constant. In small boilers particularly, the flame temperature will decrease rapidly as the luminosity and emissivity are increased, and if the surrounding water-backed surfaces are not protected by refractory material, the temperature may be too low to support proper combustion. In such cases a non-luminous flame will give higher temperatures, better combustion, and higher rates of heat liberation in a given combustion space with smaller amounts of refractory.

And in connection with Fig. 7 it should be observed that the curves of gas temperature and radiation versus distance from the burner will be quite different when a charge of cold metal is being heated in the furnace. Due to the transfer of heat from the flame to the work, all of the curves would be rotated clockwise, so that the luminous flame would probably show the most uniform temperature and radiation.

It is to be hoped that the author will continue his investigations in this field. Similar data on combustion and radiation in oil flames would be welcomed by designers of combustion equipment.

J. D. Keller.[9] In the mass of glittering generalities talked and extravagant claims made with regard to luminous-flame burners, it is refreshing to listen to a paper dealing with actual facts. On a few small points, errors may be pointed out, with the understanding that they are not emphasized as detracting from the value of the paper. Thus, exception may be taken to the statement that, of the industrial gases, natural gas is the most difficult to crack. Coke-oven gas is much more difficult to crack than natural gas, while blue water gas cannot be cracked. The statement that mixing must be by diffusion is too broad—mixing can be effected *after* cracking by means of turbulence. Similarly, the conclusion that luminous flames transmit no more heat than non-luminous flames must be limited to present commercial burners which are "cracking" but not "mixing." With "cracking and mixing" burners much higher heat-transmission rates are attainable than with non-luminous flames.

[9] Engineer with Prof. W. Trinks, Carnegie Institute of Technology, Pittsburgh, Pa.

It is possible that there are three sources of radiation from flames, instead of two as stated in the paper. Besides the radiation from solid particles and the continuing radiation from the non-luminous gaseous products of combustion after they have reached equilibrium, there may be additional radiation resulting from the act of combustion or chemical combination. The experiments of David on combustion in gas-engine cylinders seem to point to something of this sort. This possibility has already been alluded to by Mr. Jones in his discussion. It is to be noted, however, that the author measured *total* radiation from all sources; hence if radiation due to chemical action is present, its effect is included in the values found by the author.

It may be pointed out that there is one special case where a luminous flame is of outstanding advantage—namely, in heating large ingots for forging where the furnace interior is cooled down before a cold ingot is charged, and walls and ingot heat up together. In that case, the compensating radiation from the walls, as in Table 5 of the paper, is not present, and the heat transmission (for a given flame temperature) is almost directly proportional to the emissivity of the flame.

All of the author's tests were made with cold air. Much better results are obtainable if the air can be highly preheated (to 1800 F or over). As far as concerns luminosity of the flame, it is useless to preheat the air a small amount, such as 400 to 800 F, because this decreases the luminosity below that obtained with cold air. The same applies to preheating the gas, because methane does not dissociate appreciably below 1400 F, and must be heated to 1800 or 2000 F for really rapid cracking.

Exception must be taken to conclusion 6, that the advantage of the luminous flame in glass tanks lies in a more uniform distribution of heat transfer. The advantages which would accrue from deeper penetration of heat into the glass bath are almost self-evident. The reasons why the luminous flame should cause radiant heat to penetrate more deeply are by no means clear, but that it does so has been shown beyond doubt by tests made by the writer and by independent tests made by others. In fact, when standing underneath the tank and looking upward through the joints of the bottom blocks, one can easily observe that the glass at the bottom of a tank working with a luminous flame is decidedly hotter than in one with non-luminous flame.

The fact that the author tested only one type of luminous-flame burner may lead to claims that better results would have been obtained with other commercial luminous-flame burners. While tests of other burners would be very desirable, it seems improbable that such claims would be substantiated, since there is no essential difference in principle between the various luminous-flame burners now on the market. Since the present uncertain state of the art—illustrated by the rapidity with which some makers shift from one design to another, changing almost overnight—indicates that the ideal luminous-flame burner has not yet been attained, it may not be amiss to state the requirements which such a burner should fulfil:

1 It should produce a flame of high emissivity *and* high temperature. This requirement apparently would necessitate cracking first and, later, turbulent mixing. The latter is necessary not only for attaining high temperature, but also for avoiding too great an incomplete-combustion loss.

2 The gas and air should leave the burner with sufficient velocity to give direction to the flame.

3 The emissivity or luminosity should be regulable. Present luminous-flame burners often cause trouble when starting up from cold, because combustion with a luminous flame is then very slow indeed; the furnace smokes excessively and heats slowly. If the flame could be made non-luminous when starting up, and changed to luminous when the furnace comes up to temperature, operation would be much more satisfactory.

4 The luminosity should not change greatly with the degree of turndown; it should be nearly the same when gas is burned at one-third the rated capacity as when it is burned at full capacity.

5 The action of the burner should not interfere with the maintenance of a neutral or reducing gas blanket over the hearth.

6 The burner should be simple, not too bulky, and so designed as to avoid burning-off of metal parts, binding of sliding or turning parts, or clogging by carbon deposits.

7 Cracking gas should be kept out of contact with brickwork.

Additional requirements would no doubt have to be taken into account for special applications of the burner.

In the discussion, the penetration of radiant heat into the interior of steel pieces was mentioned as a possibility. The calculations of Dr. Northrup have shown, however, that heat radiation consisting of the usual wave lengths can penetrate into steel, as radiation, only to a depth of the order of 1/20,000 millimeter. Beyond this, heat penetration can, so far as at present known, take place only by conduction.

P. Nicholls.[10] The paper will be very helpful to combustion engineers and operators in that it crystallizes one's ideas on the relative action of different types of gas flames. Although what the tests show and the author's deductions are in accordance with the general ideas one has had and which follow from first principles, yet this confirmation and illustration of their relative numerical values will enable operators to plan changes with more assurance.

Knowing the difficulties in obtaining true temperatures and radiation measurements, one would expect that much more work will be needed before assured values for the constants of the theoretical equations can be determined exactly, and it is rather remarkable that the agreements were as close as those cited in the paper. The definition of flame depth at a given location must have been somewhat arbitrary; the uncertainty of the outer edge of the flame and the effect of the depth of the cooling cone could be quite a large percentage of the nominal value. One would expect that a much larger flame would be needed and that allowance would have to be made for the variation of the temperature through the flame.

The paper makes no attempt to evaluate the effect of the loss of heat to the walls or to give the magnitude of this heat transfer, nor is there any assurance that it was similar in the various tests. When one compares the temperature curves of Fig. 7, it does not look logical that the curves for the semi-luminous and the luminous flames do not show more tendency to cross that of the non-luminous; one would expect that the loss of heat from the luminous flame previous to the 11-ft position would have been considerably greater than that from the other flames, and that in consequence its temperature would have been below those of the other two.

It is to be presumed that the gas-air ratio was the same for all the tests shown in Fig. 7. There is some omission in stating these ratios for all the tests, and there is uncertainty as to their values for Figs. 5 and 6.

There is need for a better understanding of the relative advantage of the type of flame as well as for the methods by which a desired type of flame may be obtained and controlled. As the author points out, all the advantages do not accrue to one type, and therefore a clear understanding of the principles involved is necessary in the interpretation of results obtained when experimenting with a given installation. The Bureau of Mines had planned to make such studies of the application of gas to brick kilns, in the investigations which it was conducting at Roseville, Ohio, in cooperation with the Ohio State University. A special experimental kiln was built, and studies of the effect of burner placement and of the flame control were two of the main features to be investigated, but this work was stopped because of the lack of the relatively small additional funds required.

F. B. McKune.[11] It is very evident from the paper that facts are now being obtained on these two flames, the luminous and the non-luminous. The writer does not wish to enter into any discussion on the merits and demerits of the non-luminous flame. So far as combustion is concerned, there is no stratified combustion so rapid and efficient as where you get turbulence. You will understand, of course, that these lighter gases lend themselves to turbulence more readily than the highly luminous flame.

We have been using for the last year straight by-product gas, and there are no reasons why we should not continue to do so. When our blast furnaces are in operation, we also mix blast-furnace gas with by-product gas and get good results.

One very important point in the use of the non-luminous flame is the balanced condition of the furnace. We balance our furnaces in such a manner that the flame will start out the holes in the doors, but return and go back through the furnace. If we did not do this, we would find cold spots in different parts of the furnace. Another advantage this has is that it does not matter what velocity you have coming out of the burner or the port; the flame immediately starts to slow up and distribute itself equally through the furnace. This balanced condition of the furnace is so important that the successful burning of the by-product gas depends on it.

The writer can very easily see that one could rash up a piece of steel much faster with a non-luminous than with a luminous flame. He believes from experience that, if you put two pieces of steel in different furnaces and use the two different flames and watch, if you did not rash up the non-luminous flame too fast, your heat transfer would be much faster than with the luminous flame. If you properly balanced your furnace, you would have an equal distribution of the heat from both flames.

At present we are running our soaking pits with straight by-product gas, with no complaints that this gas is inferior to any other gas.

Three fundamentals about which we are very careful are the velocity of gas, the direction of the gas, and the balanced condition of the furnace. Any success that we have had is entirely due to following the foregoing procedure rigidly.

The combustion is so complete in our furnaces that we have no record of any CO in the outgoing end of the furnaces.

W. J. Wohlenberg.[12] The paper merits a thorough study and contains information that should be of considerable value to the industry. It presents in a simple and clear-cut way the relations which are involved in radiation from gas flames. It shows also how the radiation characteristics of these flames compare with the radiation from a dust cloud in which the dust is pulverized coal. There is, no doubt, information in this paper which may be used to advantage by engineers engaged in the design of pulverized-coal furnaces for boilers as well as that which is contained relative to the operation of industrial furnaces in which gas may be used as a fuel.

From the engineer's point of view, the formulas set up to express the characteristics of the radiation are perhaps fundamental. From the point of view of the more exact scientist, they are of course empirical. The writer is referring in particular to the equations in which the specific radiation characteristics of

[10] Supervising Fuel Engineer, U. S. Bureau of Mines, Pittsburgh Experiment Station, Pittsburgh, Pa.

[11] Steel Company of Canada, Hamilton, Ontario.

[12] Professor of Mechanical Engineering, Sheffield Scientific School, Yale University, New Haven, Conn. Mem. A.S.M.E.

the flame are really included in the factor K, which appears in the product KL as an exponent of e in Equations [1] to [4]. As these formulas are set up, K is really a function of the composition of the gases, of the concentration of the various constituents, and in the case of a dust cloud also of the concentration and mean size of the dust particles. For a given composition of the mixture, K may also vary with the temperature, because for a given temperature it will depend on the wave-length bands in which the radiation occurs. As the temperature of a gas of given composition is changed, the number and position of the bands in which an appreciable amount of radiation occurs may change. It is therefore not surprising that K varies by the amounts shown in Table 3 when the radiation is measured from different parts of the furnace for the same flame. Obviously, most of the factors which have been mentioned as influencing the specific radiation characteristics, and therefore K, may vary from station to station in the flame. Therefore it is something of a relief to find out that the factor K does not vary with position in the flame more than is indicated by the values shown for it in Table 3.

This information, although perhaps not obtained in an experiment conducted with the preciseness which would be characteristic of work done in a physical laboratory, nevertheless, because the data are taken on a mixture of gases rather than on the separate constituents, furnishes bench marks of a sort for comparison with a more fundamental type of information on radiation taken for the separate constituents each by itself, and which data are available from such work as Schmidt on the radiation from water vapor and the more recent data which have been furnished by Schack and also by Hottel and Guerri. The latter appeared in the recent book on heat transfer published under the auspices of the Heat Transfer Committee of the National Research Council. In this book appears also some information based on theoretical considerations of the radiation from luminous flames. It will be very interesting to see how Sherman's data on such flames check with this when the latter is applied to flames of the character on which Sherman has carried on his work. It still remains to be seen whether, by means of such information as is contained in Sherman's tables, simple expressions can be developed to represent the variations of K which would yield results, when applied to furnace conditions, close enough to the actual conditions so that the results could be applied practically.

From a practical point of view, some of the curves showing variations of temperature along the flame axis for the different types of fuel are particularly important. It appears to the writer as though the different distribution of energy which is indicated for the different types of fuel must be of considerable practical significance to the operator of industrial furnaces. It is also of considerable importance to the operator of boiler furnaces in that by means of such information, if this could be extended to the boiler furnace, might be found the zones of high and low heat absorption, and this might lead to information on how water-cooled surfaces should be distributed for best results.

Author's Closure

The complete and frank discussion that has resulted from the presentation of the paper is greatly appreciated. The interest shown proves that the work was timely.

Mr. Nicholls has called attention to the omission of the values for the air ratios on Fig. 7. These were stated in Table 3, but will be put on the published figures to avoid any confusion. He has also questioned the heat loss from the walls and raised the point as to whether they were the same for all tests. The resistance of the walls was the same for all tests, and the temperature attained by the walls was governed only by the rate of heat transfer from the flames. This was considered the only fair way to conduct the tests.

Mr. Nicholls questions why the temperature of the luminous flame was not much lower than that of the other flames. It was lower than that of the non-luminous flame at all points, but it was lower at the first two points, not because of its high emissivity (the absolute radiation was actually somewhat below that of the non-luminous flame), but because of the low rate of heat liberation.

Professor Wohlenberg has properly pointed out that this work is of the engineering type, and the accuracy can not be expected to be equal to that of physical laboratory work. He also has emphasized the many variable factors that enter into the absorption coefficient K, which explain its lack of constancy.

Mr. King has asked about the possibility of CO_2 and H_2O filling the diaphragm tube and absorbing radiation from the flame. This possibility was foreseen, as trouble was had from this source in the calibration of the unit. As the furnace was at all times under a pressure less than atmospheric, however, and as the joints of the thermopile case were not hermetically sealed, enough air flowed in to keep the tube free of absorbing gases. This was proved by taking a reading, opening the case to allow air to flow in freely, and closing the case; the second reading checked the first.

Mr. King and others have brought out the point that, if a furnace is cooled down by a cold charge, the rate of heat transfer will increase directly as emissivity. That is quite true, and review of the text will show that the author limited his conclusions as to the total radiant-heat transfer to furnaces with walls hotter than the work.

Mr. Flagg discusses this subject in the light of much experience with high-temperature heating problems and with all kinds of fuel. He points out the truth that efficiency is secondary to quality in most heating processes. He has questioned whether the inverse-square law may not hold more closely for small distances between planes. He will find, however, on consulting Hottel's curves, to which reference was made by the author, that the smaller the distance between the planes, the wider the departure from the inverse-square law.

Mr. Flagg speaks of the repeated failure of tests to run an open-hearth steel furnace with non-luminous flames. However, an outstanding example of success with this type of operation is that of Mr. McKune, of the Steel Company of Canada, whose remarks speak for themselves. Although it may be more difficult to operate an open-hearth furnace with a non-luminous flame, it is not impossible.

Mr. Flagg, Mr. Segeler, and others have insisted that the output of a furnace is frequently increased by the use of a luminous flame. They do not insist, however, that the output per unit of heat input is increased. The author admits that the output of product per square foot of hearth may well be increased with a luminous flame, but not because of a higher over-all rate of heat transfer. On the contrary, the output may be low with a non-luminous flame because of an excessive rate of heat transfer near the burners which would damage the product. To avoid such damage, the heat input must be reduced and the rate of transfer at distances from the burner is made very low. With the proper luminous flame the heat transfer may be made more uniform over the hearth area and the rate of transfer so adjusted as to raise the temperature substantially uniformly through the work. The increased efficiency in the use of the hearth area will obviously increase the hourly output of the furnace and may even increase the thermal efficiency.

Mr. Keller has properly corrected the author in the inexact statement that natural gas is the most difficult of the industrial gases to crack. He has also pointed out that luminous flames can be produced with mixing rather than with complete reliance on diffusion.

The statements in the paper in regard to the application to glass tanks were primarily speculation, put in to promote discussion. There seems to be no reason in the light of our present theoretical knowledge why luminous flames should heat the bottom of a glass tank more readily than non-luminous flames. If, however, practise shows that luminous flames are more effective, then some parts of our present theories must be incorrect; they certainly are far from complete.

The author has no fault to find with Mr. Keller's statements of the requirements of luminous-flame burners.

Mr. Segeler questions whether the gases absorb heat before combustion at the interface, because he feels that this would promote turbulence. The gas must absorb heat before mixing with air or there will be no cracking. At any rate, in the combustion at the interface the gases absorb the liberated heat and increase in volume, so that a certain amount of turbulence is undoubtedly the result.

In discussion of the effect of temperature on the rate of combustion, Mr. Segeler refers to Fig. 30 of the American Gas Association book, "Combustion," where the relation between the maximum velocity of flame propagation V to the absolute temperature T is expressed as $V = BT^2$, where B is a constant. That refers, however, to premixed gases; when, and if, combustion occurs only when the gases diffuse together, the rate is governed by the rate of diffusion, which is slow relative to the rate of combustion. Taylor, in his "Treatise on Physical Chemistry," states that the diffusion coefficient for gases is proportional approximately to $T^{3/2}$. Burke and Schumann made some rough experiments on the effect of temperature on the length of "diffusion" flames, but arrived at no definite conclusion.

Mr. Segeler believes there is some doubt as to the application of the author's results because of the type of furnace. He states that there is a relation between pressure drop and heat transfer, which is true for convection, and that therefore the ratio of the flue area to the heat input affected the heat transfer. The connection between the pressure drop or flue area to the radiant-heat transfer would need further amplification by the discusser for a conception of its significance by the author.

Mr. Jones has questioned the relation of the furnace shape to the possible turbulence of the flame and has suggested a rectangular furnace. The author feels that the furnace was the proper shape to conform to the round burner.

Mr. Jones states that there is a distinct difference between luminous and diffusion flames, but in his extended discussion of diffusion, delayed combustion, and various types of energy waves he fails to make the distinction clear.

The inference is made that a luminous flame radiates only in the narrow visible band, below 0.7μ, as shown in Fig. 8, whereas a diffusion flame radiates over the entire band. This is obviously untrue. There can be no visible radiation without simultaneous infra-red radiation; cold light has not yet been discovered.

Actually what the author believes Mr. Jones meant to convey was (1) that luminous flames do not necessarily have high emissivities and (2) that diffusion flames and only diffusion flames have high emissivities. The first statement is entirely correct, as has been proved by the experimental data of this paper. The second statement, however, is incorrect. As Mr. Keller pointed out in his discussion, flames of high emissivity can be obtained with mixing, and such flames are highly desirable, as they can be given direction in the furnace. All flames, including those used in the present experiments, in which the gas and air are introduced in separate streams without later provision in the furnace for turbulence, must depend to a certain extent on diffusion for combustion. Diffusion is only the mechanism of mixing of gas and air and is a form of slow mixing and delayed combustion; it has nothing to do with radiant-heat transfer. A diffusion flame may be strongly luminous or semi-luminous; it may have a high or a low radiation and emissivity.

The merits of luminous flames are clearly enough defined and are great enough for certain applications to stand on the determined facts without an attempt to attribute to them properties they do not possess or to interject fine distinctions in terminology that are not supported by the facts. It is the earnest hope of the author that the statement of facts in this paper and the discussion will result in clarification of the subject.