5-1915

A Theoretical Discussion of the Variation in Temperature of a Gas Flame That Occurs When The Proportion of Air Supplied, and The Temperature of This Air, Varies

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To the Graduate Council:

I am submitting herewith a thesis written by C. L. Henderson entitled "A Theoretical Discussion of the Variation in Temperature of a Gas Flame That Occurs When The Proportion of Air Supplied, and The Temperature of This Air, Varies." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

, Major Professor

We have read this thesis and recommend its acceptance:

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Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

A THEORETICAL DISCUSSION OF THE VARIATION IN TEMPERATURE OF A GAS FLAME THAT OCCURS WHEN THE PROPORTION OF AIR SUPPLIED, AND THE TEMPERATURE OF THIS AIR, VARIES.

By

C. L. Henderson

SUBMITTED AS THESIS FOR THE DEGREE OF ELECTRICAL ENGINEER

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The object of this paper is, to show how the temperature of a gas flame is affected by the amount of air supplied to burn this gas; also, to show how the temperature of the flame is affected by preheating this air supply.

This paper is limited to a theoretical discussion, and the data calculated is based upon a sample of natural gas from the North Osage Field in Oklahoma.

The analysis by volume and by weight, of this sample of gas is shown in the table below. The data and method used to calculate the analysis by weight are also shown.

Percent by volume		Lbs. per Cu. Ft.	Weight of each constituent in a Cu.Ft.of gas	Percent by Weight
CO_2	1.50	0.11634	0.00174510	3.37
O_2	0.28	0.08462	0.00023693	0.45
CH_4	74.64	0.04231	0.03158018	61.06
C_2H_6	13.26	0.07933	0.01051915	20.34
N_2	10.32	0.07404	0.00764092	14.78
	100.00		0.05172228	100.00

It is interesting to note that the specific gravity of this gas is 0.67, and this is an average figure for the specific gravity of the natural gas of the mid-continent Field. (The specific gravity was obtained by dividing the weight of a cubic foot of gas by the weight of the same volume of air, measured under standard conditions.)

This gas contains two combustible gases, namely: C_2H_6 and CH_4; and the calorific value is determined by multiplying the heating value in B.T.U.'s per pound of the two combustible gases contained in the sample by the weight of these gases contained in one pound of the sample.

The results of Favre and Silberman are here used for the calorific value of the combustible gases, as shown below:

CH_4	.0.6106 x 23513=14357
C_2H_6.	0.2034 x 22338= 4534
Total	18900

The above total, 18900, is the gross heating value of the sample in B.T.U.'s per pound. This value when reduced to the B.T.U.'s per cubic foot, becomes 977.

The net calorific value of the gas is obtained by subtracting the latent heat which is contained in the steam that is formed when the combustion of the hydrogen occurs, these values are shown below:

CH_4	0.6106 x 20998= 12821
C_2H_6.	0.2034 x 20326= 4134
Total	16955

The above total, 16955, is the net heating value of the sample in B.T.U.'s per pound. This value when reduced to the B.T.U.'s per cubic foot of gas, becomes 877.

The net calorific value is the quantity generally used in making calculations, because the latent heat is very seldom recovered from the steam in the products of combustion.

When complete combustion of this sample of gas occurs, then the following equations represent the chemical reactions that take place:

$CH_4 + 2\ O_2 = CO_2 + 2\ H_2O.$

$2\ C_2H_6 + 7\ O_2 = 4\ CO_2 + 6\ H_2O.$

From the above equations the amount of oxygen required to burn one pound of CH_4 is calculated as 4 pounds, and the oxygen required per pound of C_2H_2 is 3.73 pounds. The air needed to supply enough oxygen to burn one pound of the gas is calculated as follows:

CH_4	$0.6106 \times 4 =$	2.4424
C_2H_6.	$0.2034 \times 3.73 =$	0.7587
		3.2011
The oxygen already present in the gas should be subtracted		0.0045
		3.1966 lbs. of O_2.

The weight of air which will contain this number of pounds of oxygen is:

$3.1966 \times \frac{77}{23} + 3.1966 = 13.8982$ pounds. For convenience in calculations, 3.90 pounds will be used instead of 13.8982.

The products of combustion obtained when a pound of this gas is burned with the exact amount of air needed, i.e. 13.9 pounds may be calculated as shown in the table below:

Analysis of gas by weight		CO_2 per lb. of		H_2O per lb. of		N_2
		Constituent	Mixture	Constituent	Mixture	
CO_2	3.37		0.0337			
CH_4	61.06	2.75	1.6791	2.25	1.3739	
C_2H_6	20.34	2.93	0.5960	1.80	0.3661	10.7016 N_2 in a[illegible]
N_2	14.78					0.1478 " " g[illegible]
			2.3088		1.7400	10.8494

For convenience in calculations, the following values will be used:

CO_2	2.31
H_2O	1.74
N_2	10.85
Total	14.90 lbs.

The analyses of the products on combustion by volume, when the exact amount of air needed is supplied, and when there is an excess of 10%, are shown by the tables following:

	Lbs.	Cu. Ft. per lb.		Percent by volume.	Percent by volume neglecting water vapor
CO_2	2.31	x 8.681	= 20.053	9.8	12.0
H_2O	1.74	x 21.057	= 36.639	18.0	
N_2	10.85	x 13.506	= 146.540	72.2	88.0
	14.90		203.232	100.0	100.0

When there is 10% excess of air by weight, then the products of combustion will be as follows:

	Lbs.	Cu. Ft. per lb.		Percent by volume	Percent by volume neglecting water vapor
CO_2	2.31	x 8.681	= 20.053	9.0	10.8
H_2O	1.74	x 21.057	= 36.639	16.5	
N_2	11.92	x 13.506	= 160.991	72.8	87.2
O_2	0.32	x 11.818	= 3.782	1.7	2.0
			221.465	100.0	100.0

HEAT OF FORMATION OF COMBUSTIBLE GASES.

The heat of formation of a combustible gas may be defined as the difference between the thermal value of that gas and the thermal value of its constituent elements. This quantity for any gas is the same whether the gas is broken up into its constituent elements, or whether it is formed from its constituent elements.

The heat of formation for the Parafine Series of Hydrocarbons is a minus quantity, i.e., a certain amount of heat must be supplied to perform this internal work; and for the Olefine Series it is a positive quantity, i.e., a certain amount of heat is liberated during the change.

The following calculations show how the heat of formation for this sample of gas was obtained:

The following constants are taken from the results of Favre and Silbermann. Thermal value in B.T.U's per lb., considering the water of combustion as a liquid:

C	14544
H	62032
CH_4	23513
C_2H_6 . . .	22338

Now, a pound of CH_4 contains twelve parts of C and four parts of H; so that, theoretically, its calorific value should be

$$3/4 \times 14544 + 1/4 \times 62032 = 26414 \text{ B.T.U's}$$

This difference between 26414 and 23513, which is 2901 B.T.U's, is the heat formation for CH_4.

By applying this same process to obtain the heat of formation of C_2H_6 there is obtained

$$(\frac{4}{5} \times 14544 + \frac{1}{5} \times 62032) - 22338 = 1703 \text{ B.T.U's}$$

Now, the heat of formation of the sample of gas under consideration is obtained by multiplying the percentage, by weight, of CH_4 and C_2H_6 in the gas by their heats of formation, as follows:

CH_4 .6106 x 2901 = 1771
C_2H_6 .2034 x 1703 = 346
2117 B.T.U's

When a pound of this gas is burned, this figure must be substracted from the total heat value of the gas, because this quantity is used as internal work, and is not available for heating the products of combustion.

FLAME TEMPERATURE.

Flame temperature is here taken to mean the temperature to which the prodcuts of combustion, formed by the chemical union of oxygen and the gas, will be raised by the heat that is liberated during this reaction. Now, the thermal capacity of the products of combustion can be calculated from the thermal capacity table given on page 530, Kent. A curve can then be drawn showing the relation between the heat liberated and the temperature to which the products of combustion will be raised. Then, if the heat content of the mixture is known, by referring to the curve, the flame temperature can be ascertained.

Seven curves are drawn, (Plate 1.) Curve "O" shows the thermal capacity of the products of combustion at different temperatures when there is the theoretical amount of air required for perfect combustion present in the mixture.

Curve "A" shows the conditions when the over-ventilation is 10% of air
Curve "B" " " " " " " " " 25% " "
Curve "C" " " " " " " " " 50% " "
Curve "D" " " " " " " " " 100% " "
Curve "X" when there is only 90% of the air required.
Curve "Y" when there is 75% of the air required.

The data for each curve are worked out in the following pages, each step in the process being explained. Actual use of these curves to obtain values for the temperature of the flame is explained in the last few pages of this paper.

THERMAL CAPACITY AND SPECIFIC HEAT TABLES.

The following table of thermal capacities in calories per kilogram was taken from Kent's Mechanical Engineer's Pocket Book; the values in B.T.U's per pound, were calculated from this data. The specific heat table was also calculated from the same source.

THERMAL CAPACITIES

Temp. °F	Temp. °C	Calories per kilogram CO_2	CO N_2	H_2O	Air	B.T.U. per pound CO_2	CO N_2	H_2O	Air
1832	1000	277	277	609	256	498	475	1097	461
2192	1200	354	325	770	315	637	585	1386	567
2552	1400	435	383	943	372	784	690	1695	670
2912	1600	523	445	1130	423	942	802	2038	761
3272	1800	618	508	1330	493	1112	915	2395	887
3632	2000	728	575	1542	558	1310	1035	2780	1005

SPECIFIC HEAT IN B.T.U.S PER POUND

Temp. °C	°F	CO_2	CO N_2	H_2O	O_2	Air
200	392	.216	.250	.500	.236	.247
400	752	.228	.250	.508	.220	.244
600	1112	.251	.247	.543	.223	.249
800	1472	.260	.259	.575	.226	.251
1000	1832	.277	.264	.609	.232	.256
1200	2192	.295	.271	.642	.237	.263
1400	2552	.311	.276	.675	.239	.267
1600	2912	.327	.278	.708	.245	.270
1800	3272	.343	.282	.738	.247	.274
2000	3632	.364	.288	.773	.251	.280

Thermal capacity of products of combustion when 100% of the air required is supplied:

Constituent	Lbs. in products of combustion from 1 lb. gas.	Temp. °F. 2552°	2912°	3272°	3632°
CO_2	2.31	1811	2178	2572	3280
N_2	10.85	7480	8700	9940	11350
H_2O	1.74	2950	3542	4170	4840
	Totals	12241	14420	16682	19470

The above totals are the data for Curve O.

Thermal capacity of products of combustion when there is 10% excess of air, which means an excess of 1.39 lbs. air per pound of gas:

	Temp. °F 2552°	2912°	3272°	3632°
CO_2, H_2O and N_2	12241	14420	16682	19470
1.39 lbs. air	932	1058	1232	1398
Totals	13173	15478	17914	20868

The above totals are the data for Curve A.

Thermal capacity of products of combustion when there is an excess of air of 25%, or 3.475 lbs:

	Temp. °F 2552°	2912°	3272°	3632°
CO_2, H_2O, N_2	12241	14420	16682	19470
3.475 lbs. air	2325	2642	3080	3495
Totals	14566	17062	19762	22965

The above totals are the data for Curve B.

Thermal capacity of products of combustion when 150% of the air required is supplied:

	Pounds	Temp. °F. 1832°	2192°	2552°	2912°	3272°
CO_2	2.31	1150	1470	1811	2178	2572
N_2	10.85	5160	6350	7480	8700	9940
H_2O	1.74	1910	2410	2950	3542	4170
Totals		8220	10230	12241	14420	16682
Air excess	6.695	3080	3800	4480	5100	5940
Totals		11300	14030	16721	19520	22622

The above totals are the data for Curve C.

The thermal capacity when the air excess is 100% is as follows:

	1832°	2192°	2552°	3272°
CO_2, N_2, H_2O	8220	10330	12241	14420
air in excess 13.9 lbs.	6180	7600	9320	11580
Totals	14400	17830	21561	26000

The above are the data for Curve D.

Thermal capacity of products of combustion when the air supply is 10% less than that which is theoretically needed. The combustion takes place according to the following equations:

$$CH_4 + 1.8\ O_2 = 2\ H_2O + 0.6\ CO_2 + 0.4\ CO$$
$$2\ C_2H_6 + 6.3\ O_2 = 6\ H_2O + 2.6\ CO_2 + 1.4\ CO$$

The products of combustion are shown by the following table:

Analysis of mixture.		CO_2 per lb. of Constit.	Mixture	CO per lb. of Constit.	Mixture	N_2O per lb. of Constit.	Mixture	N_2
CO_2	3.37		0.0337					
CH_4		1.65	1.0075	0.70	0.4274	2.25	1.374	
C_2H_6	20.34	1.91	0.3885	0.65	0.1320	1.80	0.366	
N	14.78							0.1478
N in air	9.63							9.6315
			1.4297		0.5594		1.740	9.7793

Thermal capacity of products of combustion:

	lbs.	2552°	2912°	3272°	3620°
CO_2	1.43	1120	1348	1590	1872
CO	0.56				
N_2	9.78	7150	8300	9480	10720
H_2O	1.74	2950	3542	4170	4840
Totals		11220	13190	15240	17432

The above totals are the data for Curve X.

When the air supply is only 75% of that needed, then the combustion takes place according to the following equations:

$$CH_4 + 1.5\ O_2 = 2\ H_2O + CO$$
$$2\ C_2H_6 + 5.25O_2 = 6\ H_2O + 4CO + 0.25\ CO_2$$

The products of combustion are as follows:

Analysis of mixture		CO_2 per lb. of Constit.	Mixture	CO per lb. of Constit.	Mixture	N_2O per lb. of Constit.	Mixture	N_2
CO_2	3.37		0.337					
CH_4	61.06			2.25	1.374	1.75	1.07	
C_2H_5	20.34	.367	0.0746	1.8	0.366	1.87	0.38	
N_2	14.78							0.148
N_2 in air								8.037
			0.108		1.740		1.45	8.185

Thermal capacity of products of combustion:

	Lbs.	Temp. °F. 1832°	2192°	2552°	2912°	3272°
CO_2	0.11	55	70	86	104	122
H_2O	1.74	1910	2410	2950	3542	4160
CO + N	9.63	4580	5650	6650	7730	8800
Totals		6545	8130	9686	11376	13082

The totals are the data for Curve Y.

Example Showing Use of Curves.

The net calorific power of the gas in B.T.U.'s per pound, was calculated to be 16955; also the heat of formation was calculated to be 2117 B.T.U.'s per pound of gas. The net heat available to increase the temperature of the products of combustion is equal to 16955-2117 = 14838 B.T.U.'s. By reference to curve O, plate I, the temperature corresponding to this value is 2980°, and this is the theoretical flame where there is supplied the exact amount of air required.

In the same manner the following values are taken from Curves A, B, C and D, and represent the flame temperatures under the conditions for which the curves are drawn, and when there is no preheating of the air supply:

Curve O 2980°
" A 2810°
" B 2592°
" C 2305°
" D 1880°

Now, for Curve X, where the air supply is 90% of that needed, the heat available is 14838, minus the heat value of the 0.559 lbs. of CO which pass out unburned, and this is 0.559 x 4400 = 2460 B.T.U.'s, so that the net heat available is 12378, and this corresponds to a flame temperature of 2765°.

For Curve Y, there are 1.45 lbs. of CO unburned, so that the net heat available is 14838, minus 4400 x 1.45 = 8458 B.T.U.'s and this corresponds to a flame temperature of 2270°.

The above values for Curves X and Y should be slightly higher because the correction for the heat of formation should be made; but this is so small as to be negligible.

The above points on the Curves O, A, B, C, D, X and Y, which show the flame temperatures when there is no preheating of the air supply, are connected by the curve M.M.M. This curve is very interesting, in that it shows the effect of over-and under-ventilation upon the flame temperature.

The Curve M on Plate 2 shows the effect of over-ventilation and under-ventilation on the flame temperature. This curve is worked out on a percentage basis, so that the importance of having the proper quantity of air supplied, may be seen at a glance.

The above process may be applied to the ordinary commercial combustible gases. It is interesting to note that the above calculations more closely approach the actual values, as found in practice, than do the results of other methods that do not take into account all the factors that have been considered in this paper.

EFFECT OF PREHEATING AIR.

When the air for combustion is preheated, then sensible heat is added to the mixture, and this sensible heat must be added to the amount of heat already available in the gas in order to get the figure for the total heat available. Then, by referring to the curve which corresponds to the condition of over-ventilation and under-ventilation, the flame temperature is obtained.

If the air supply is 100% of that required, Curve O, and if the air is preheated 500°, then the heat added is 13.9 x 500 x 0.246 = 1710 B.T.U.'s, 0.246 being the specific heat of air at 500°. The total heat, then, is 14838 plus 1710 equals 16548 B.T.U.'s, and this corresponds to a temperature of 3260°.

By the same process the following data are calculated for the various conditions as represented by Curves O_1, A_1, B_1, C_1, D_1, X_1 and Y_1.

Preheat	x	Specific Heat	x	Lbs. air	=	Sensible heat added by preheating air	Heat liberated by combustion		Total heat in products of combustion	Corresponding temperature
				Curve O.						
500		0.246		13.9		1710	14838	=	16548	3260
800		0.247		13.9		2747	14838	=	17585	3390
1200		0.250		13.9		4170	14838	=	19008	3575
				Curve A.						
500		0.246		15.29		1881	14838	=	16719	3100
800		0.247		15.29		3022	14838	=	17860	3265
1200		0.250		15.29		4587	14838	=	19425	3455
				Curve B.						
500		0.246		17.37		2137	14838	=	16975	2895
800		0.247		17.37		3434	14838	=	18272	3070
1200		0.250		17.37		5211	14838	=	20049	3300
				Curve C.						
500		0.246		20.85		2564	14838	=	17402	2640
800		0.247		20.85		4120	14838	=	18958	2835
1200		0.250		20.85		6255	14838	=	21093	3095
				Curve D.						
500		0.246		27.8		3419	14838	=	18257	2235
800		0.247		27.8		5493	14838	=	20331	2435
1200		0.250		27.8		8340	14838	=	23178	2685
				Curve X.						
500		0.246		12.51		1539	12378	=	13917	3040
800		0.247		12.51		2472	12378	=	14850	3205
1200		0.250		12.51		3753	12378	=	16131	3420
				Curve Y.						
500		0.246		10.42		1281	8458	=	9739	2565
800		0.247		10.42		2059	8458	=	10517	2730
1200		0.250		10.42		3126	8458	=	11584	2950

The above data are shown graphically by Curves O_1, A_1, B_1, C_1, D_1, X_1, and Y_1 on Plate #1.

It is interesting to note that the flame temperature is increased approximately two per cent for each one hundred degrees of preheat of the air supply.

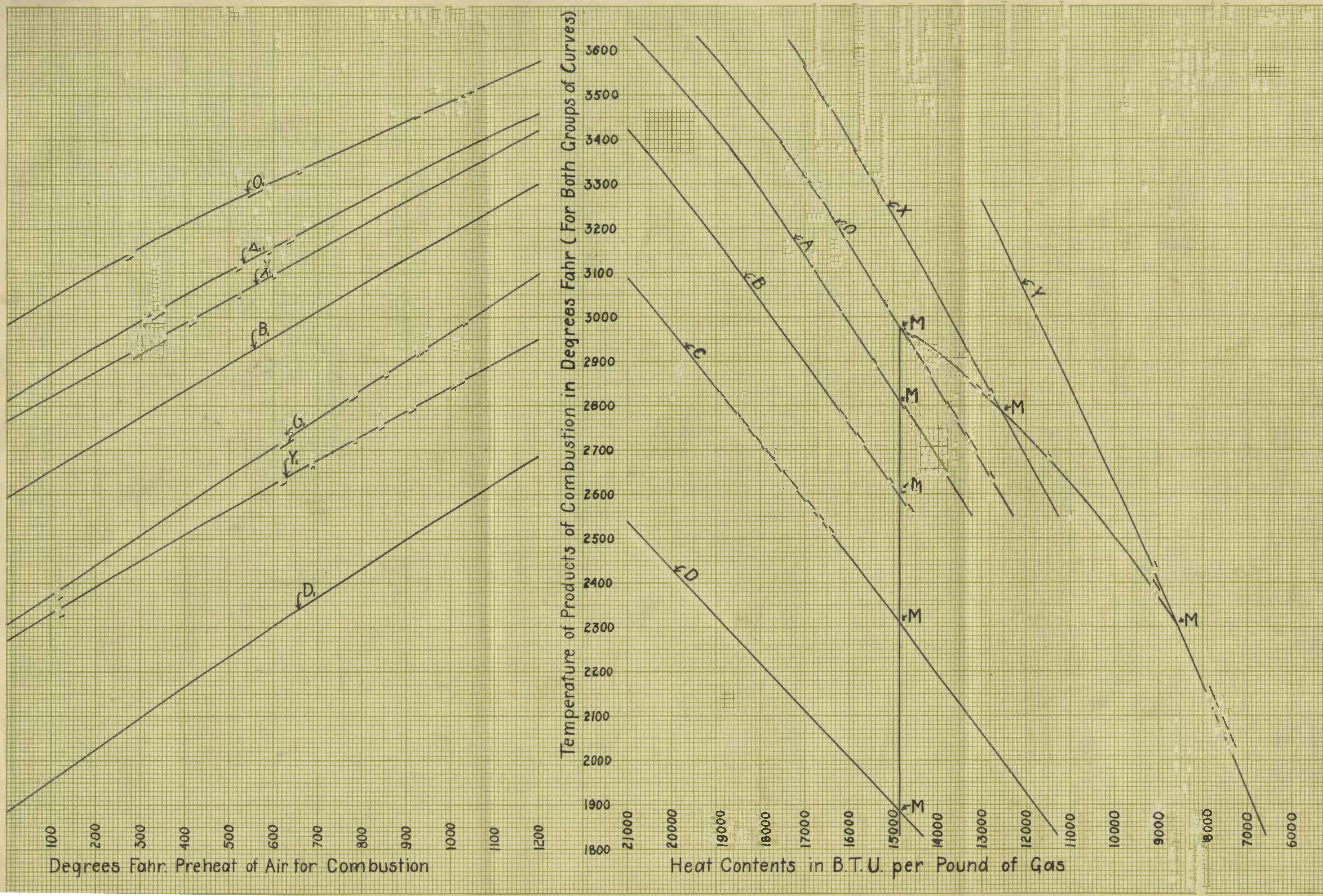
Curves O, A, B, C and D on Plate 2 are drawn to show the relation between the sensible heat carried away from a gas furnace by the escaping flue gases and the total heat liberated by combustion.

An example showing the advantage to be gained by preheating the air for combustion, by utilizing the heat in the escaping flue gases, is here given:

Assume that a temperature of 1500° is to be maintained in a furnace, and that the flue gases leave the furnace at a temperature of 1800°, which temperature is 20% higher than the operating temperature, and this is a very conservative assumption. The efficiency of this operation, when the flame temperature is 2980°, is 46%, neglecting radiation and other losses. Now, if an air preheater were used so that the air for combustion is pre-heated 1200°, then the flame temperature becomes 3575°, and the efficiency under these assumed conditions becomes 58%, which is an increase in efficiency of 12%; but this 12% means a saving in gas consumption of 26%.

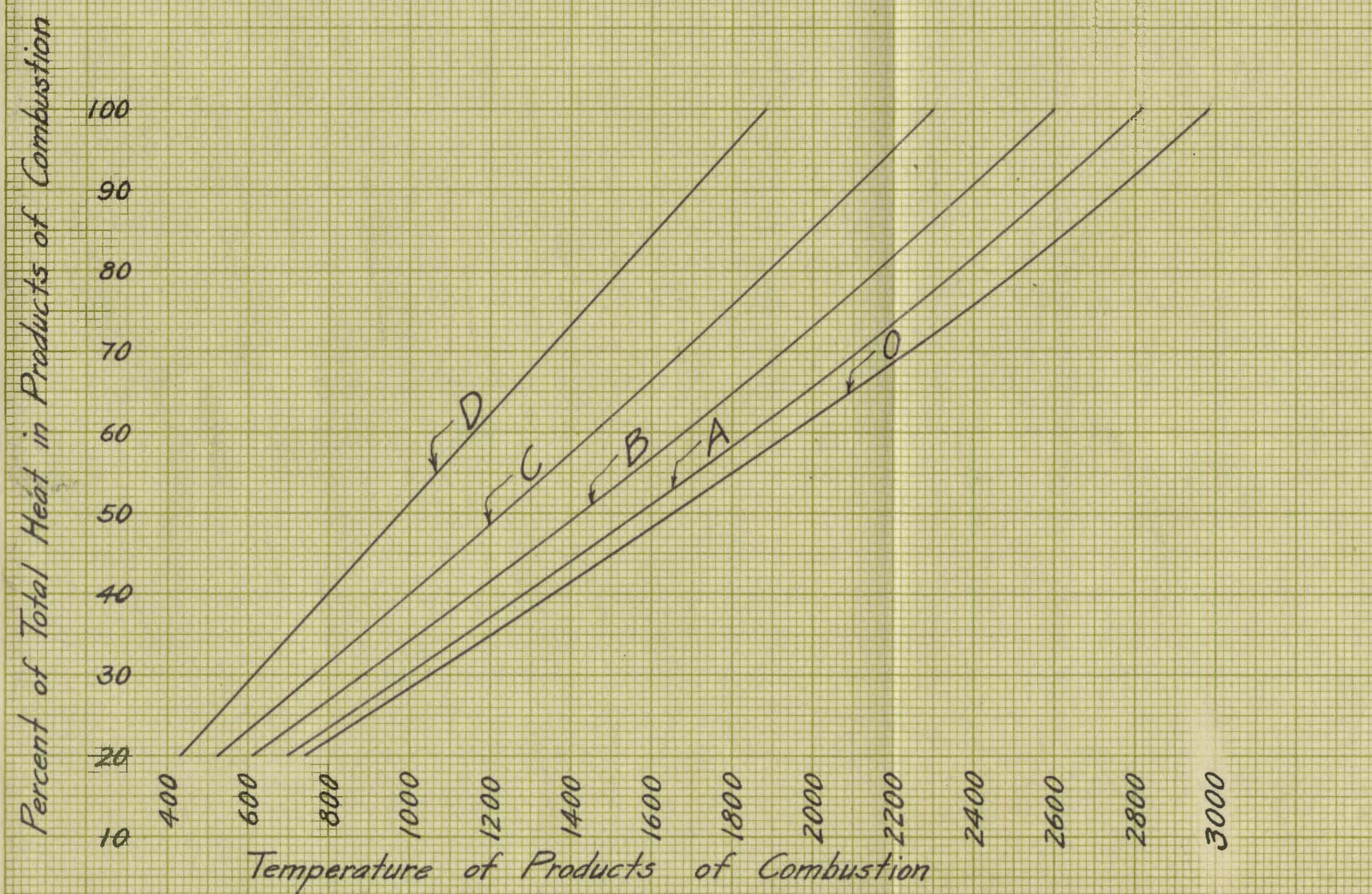
All of the above could be accomplished and still allow the flue gases to leave the air preheater at a temperature close to that which is obtained in modern boiler plants.

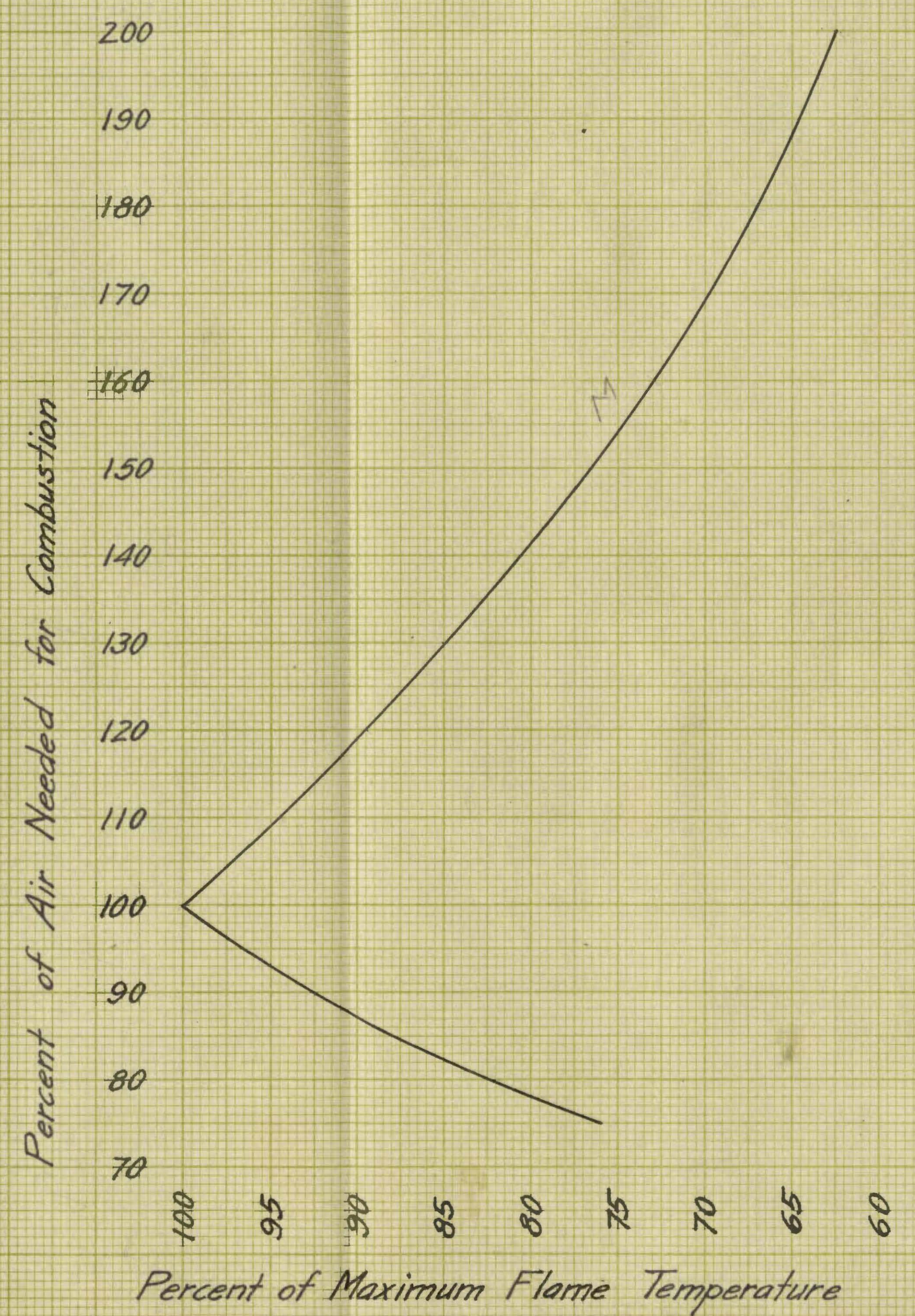
PLATE No. 1



Temperature of Products of Combustion in Degrees Fahr (For Both Groups of Curves)
3600
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
100
200
300
400
500
600
700
800
900
1000
1100
1200
Degrees Fahr. Preheat of Air for Combustion
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
Heat Contents in B.T.U. per Pound of Gas
O.
A.
X.
B.
G.
Y.
D.
X
G
A
B
C
D
Y
M

PLATE No. 2


Percent of Total Heat in Products of Combustion
100
90
80
70
60
50
40
30
20
10
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Temperature of Products of Combustion
D
C
B
A
O


Percent of Air Needed for Combustion
200
190
180
170
160
150
140
130
120
110
100
90
80
70
100
95
90
85
80
75
70
65
60
Percent of Maximum Flame Temperature
M