1913

Relation of carbon dioxide in flue gases to the efficiency of a boiler

Richard A. Wagstaff
Philip A. Moore
William Ehlers
James Hopkins

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RELATION OF CARBON DIOXIDE IN FLUE GASES TO THE
EFFICIENCY OF A BOILER.

A
THESIS
submitted to the faculty of the
SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY
OF MISSOURI
in partial fulfillment of the work required
for the
DEGREE OF
BACHELOR OF SCIENCE IN MINE ENGINEERING
James Hopkins
Richard A. Wagstaff.

BACHELOR OF SCIENCE IN CIVIL ENGINEERING
William Ehlers, Jr.

BACHELOR OF SCIENCE IN GENERAL SCIENCE
Philip A. Moore.
Rolla, Mo.
1913.

Approved by

A L McRae
Professor of Physics.

15689
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This thesis was undertaken to demonstrate the practical utility of measuring the efficiency of a Heine Boiler, installed in the Power Plant at the Missouri School of Mines, by the amount of CO₂ in the flue gases.

The tests were made on a new boiler which had recently been installed in the Power Plant. The boiler and setting being new, the tests should show a high percentage of CO₂ in the flue gases and a high evaporative efficiency by the boiler.
The boiler is a Heine Boiler, rated at
130 H. P. at 150 lbs. sq. in. pressure, 1132 sq. ft.
of heating surface. Grate bars 5 ft. 7 ins. wide, 5
ft. 3 ins. long, having a grate area of 30 1/3 sq. ft.
Steam and water drum 43 ins. in diameter, 19 ft. 10 ins.
long. 57 tubes, 3 1/2 in. diameter, 16 ft. long. Latest
model using heavy baffle plates to protect the dry
steam from moisture saturation.

APPARATUS.

THERMOMETERS: standard Fahrenheit thermometer.
MOISTURE CALORIMETER: Ellison Throttling and Evaporat­
ing Calorimeter was connected about one foot above
the boiler on the steam outlet pipe.
STEAM FLOW METER: The steam flow meter used was type
'T S' 2 Portable Steam Flow Meter made by the General
Electric Company.
ORSAT GAS APPARATUS: Orsat gas apparatus was used for
the determination of the CO₂ in the flue gases. Absorbing
solution for CO₂ one part KOH in two parts water.
The coal was weighed in a box and dumped into a pile in front of the boiler. From this pile it was shoveled in to the fire box of boiler.

The coal used was sampled and analysed by the Mine Experiment Station in connection with the school.

ANALYSIS:

B.T.U.DRY = 12410 moisture 9.55% ash 13.35%
ASH

The ash content was determined for one test and this content used in other two tests. By ash content is meant amount of material rejected by the grates of the boiler. The boiler grates were carefully shaken before the run was started and at the end of the run.

The ash was removed from the ash pit and weighed.

\[
\frac{\text{Amt. of Ash}}{\text{Amt. of Coal}} = \% \text{Ash.}
\]

WATER

The water used during these tests was taken from the mains of the School of Mines water supply and run into a calibrated tank. From the tank it was fed to boiler by means of a Worthington Boiler Feed Pump. The method employed to calibrate water tank was to allow water to run into barrel and weigh. The temperature of water as used during tests varied from 62°F to 74°F.
Analysis of Flue Gases.

The flue gases were drawn from the furnace and analyzed by the Orsat apparatus. The sample tube was located in flue just in front of the dampers on the fire side. To prevent that part of the sampling tube, inserted in the flue, from having any action on the flue gases, a hard glass tube was inserted in the iron tube and cemented in place so that all gases passed through the glass tube and were cooled down enough to be brought down from the top of the boiler in an iron pipe. The sample tube extended to the center of the flue so as to secure an average sample of the flue gas.

The gas to be analyzed was drawn from the flue by means of two sampling bottles. By adjusting the flow of water from the bottle into which the sample of gas was being drawn, a sample representing an average for an interval of fifteen minutes was secured.

Combustion of fuel.

The term combustion as used in engineering practice may be defined as the chemical union of the oxygen of the air with the carbon and hydrogen of the flue gases.
and light are evolved and oxides of carbon and hydrogen are the chemical products of the reaction.

The heat of combustion of a fuel is the quantity of heat formed when a unit weight is burned in oxygen. The determination of the heating value of a fuel is usually made in an instrument called a calorimeter. But if the percentage of carbon, hydrogen and oxygen of the fuel be known, a close approximation of the heating value can be attained by calculation.

The heating value of fuels is ordinarily expressed in British Thermo Units per pound of fuel. One B.T.U. is the quantity of heat that is required to heat one pound of water from 62° F. to 63° F.

The following formula is one that is in common use. The values of C, H and O are the relative amounts of carbon, hydrogen and oxygen in one pound of fuel.

\[ \text{B.T.U.} = 14650 \text{ C} + 62100\left(\frac{\text{H}}{8}\right) \]

The following table gives the heating value, in B.T.U.'s per pound, of fuels that are used under boilers to produce steam.

\begin{align*}
\text{C to } \text{CO}_2 &= 14650 \text{ B.T.U.} \\
\text{C to } \text{CO} &= 4400 \text{ B.T.U.} \\
\text{H}_2 \text{ to } \text{H}_2\text{O} &= 62100 \text{ B.T.U.}
\end{align*}
Bituminous Coal, 20000 to 25000 B.T.U.

Wood, ----------- 8500 to 9000 B.T.U.

Fuel Oil, ---- 19000 to 20000 B.T.U.

To burn a fuel a certain amount of oxygen is necessary, the quantity of oxygen required depending upon the amount of carbon and hydrogen that are present. Air, which consists of a mechanical mixture of oxygen and nitrogen, 21 % of oxygen by weight and 79 % of oxygen by volume, furnishes the necessary oxygen for combustion.

One pound of carbon requires \( \frac{32/12}{1} = 2.67 \) lbs. of oxygen, and one pound of hydrogen, \( \frac{2}{1} = 2 \) lbs. of oxygen. The weight of air required to furnish the oxygen for one pound of carbon is \( \frac{3.66}{0.23} = 16.0 \) lbs., and for one pound of hydrogen \( \frac{5}{0.4} = 34.8 \) lbs.

The weight of air required for the complete combustion of a fuel is calculated by means of the following formula:

\[
\text{Weight of air per pound of fuel} = 11.6 + 36.2 \times \frac{0.8}{c} - \frac{0.4}{a} - \frac{0.6}{h}
\]

where \( c, h, a \) are the amounts of \( C, H, A \), and \( c \) in one pound of fuel.

Coal, which forms the greatest proportion of the fuels used for steam generation, consists of carbon and hydrocarbons together with varying amounts of moisture, sulphur and ash forming material. When a sample of any coal is heated to a red heat with cut
access of air the volatile constituents are driven off, fixed carbon and ash remaining. The amount of volatile matter given off when a coal is heated varies with the different types of coal, bituminous coal evolving the largest amount and anthracite the least. Coals may be classified according to the amount of volatile matter which they contain. Bituminous coal 20 to 50 per cent, semi-bituminous coal 12 to 20 per cent, volatile matter, and Anthracite coal less than 12%. The volatile matter, which consists largely of hydrocarbons, breaks up on heating, forming free carbon, which leaves the stack in the form of smoke, unless enough air is present to burn it.

The furnace, under ordinary conditions, requires an excess of from 50% to 100% more air than is necessary for the complete combustion of the carbon and hydrogen. All of this excess air must be heated from the boiler room temperature to that of the flue gases. It is very desirable to limit the amount of excess air to a minimum and still have complete combustion.

The hydrogen content of bituminous coal ranges from 3.5 to 6.5, and as the oxygen contained in the coal is not enough to combine with all of the hydrogen, some oxygen must be furnished from the air.
This leaves about 19.2% available oxygen to combine with the carbon, and if all this oxygen could be used, the resulting flue gases would contain about 19.2% CO₂ which would be the maximum per cent obtainable for this type of coal.

It is therefore better to have a flue gas with 10% CO₂ and no CO, than with 14% CO₂ and 2% CO. The loss due to presence of CO in the flue gases can be calculated by the following formula.

\[
\text{B.T.U. loss} = \frac{\% \text{ CO}}{\% \text{ CO}_2 + \% \text{ CO}} \times \% \text{ CO} \times 10150
\]

With western coals 13% CO₂ is about the maximum obtainable without the formation of excessive amounts of CO.

In many plants, due to careless handling and leaky boiler settings, the CO₂ content of the flue gases may be as low as 3% to 5%. This low amount of CO₂ indicates a great excess air and a large heat loss which should not occur. The excess air supplied and the heat loss is calculated from the CO₂ present in the flue gases.

Taking 19.2% CO₂ as the maximum and 10% CO₂ as the content of the flue gases, 19.2/10 = 1.92 times as much air as required, is furnished to the furnace. By calculation, the fuel requires 12 lbs. of
air per pound of fuel, then 12 x 1.92 = 23 pounds of air supplied to the furnace, which represents about 24 lbs. products combustion. Excess air = 11 pounds.

Taking .24 as the specific heat of the flue gas and 400° as the difference in temperature of the flue gas and the boiler room, the loss in B.T.U. is 11 x .24 x 400° = 1056 B.T.U. loss per pound of fuel. This is with a high per cent of CO₂. A low per cent of CO₂ represents a much greater loss.

Moisture in coal forms another loss which is not ordinarily considered. As the amount of water formed by the combustion of the hydrogen of the fuel can not be changed for a given fuel it will not be considered. Only the moisture present as free water. The total loss of heat due to this free moisture is the sum of the following.

d.Q. = MSdt + WL + WS, dt

\[
\frac{X}{100} \times 1(212 - 55) + \frac{X}{100} \times 970 + \frac{X}{100} \times .46(Ts - 212)
\]

dQ = Total heat in B.T.U. lost, due to moisture in coal.
X = Percent moisture in coal.
S = Specific heat of water.
L = Latent heat of evaporation.
S₂ = Specific heat of super heated steam.
dt = Temperature difference.
Ts = Temperature of Flue Gases.
From the discussion it can readily be seen that up to 13\%, the CO\(_2\) content of the flue gases should be a direct and easy way to measure the efficiency of a boiler, provided no CO is present in the flue gases, and the boiler is in good condition.
### TEST I.

<table>
<thead>
<tr>
<th>Time</th>
<th>gage</th>
<th>Moisture</th>
<th>Steam Temp.</th>
<th>After M.S.T.</th>
<th>CO₂</th>
<th>Br.Rd.</th>
<th>S.F.M.</th>
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</thead>
<tbody>
<tr>
<td>3:00</td>
<td>75</td>
<td>2.3</td>
<td>215</td>
<td>156</td>
<td>29.15</td>
<td>910</td>
<td></td>
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<td>218</td>
<td>151</td>
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<td>247</td>
<td>151</td>
<td>8.4</td>
<td>&quot;</td>
<td>714</td>
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<td>&quot;</td>
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<tr>
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<td>&quot;</td>
<td>820</td>
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<td>103</td>
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<td>&quot;</td>
<td>570</td>
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<td>60</td>
<td>2.2</td>
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<tr>
<td>4:50</td>
<td>60</td>
<td>2.5</td>
<td>230</td>
<td>156</td>
<td>10.4</td>
<td>&quot;</td>
<td>545</td>
</tr>
</tbody>
</table>

---

**TEST I.**

Duration of test, 5:00 - 5:10 5/4-13.

- **Average gage reading**: 33.5
- **Average moisture**: 2.38%
- **Average barometer**: 29.6
- **Average feed water temperature**: 64.7°C
- **Average flue gas temperature**: 485°C
- **Average CO₂ % in flue gas**: 9.3%
- **Average steam flow meter reading**: 754

**Amount of coal used**: 1440
**Amount of ashes left**: 215
**Amount of water used**: 7611
**Pounds of steam indicated by the steam flow meter**: 6774.
Barometer 29.2 - 0.491 = 14.34 Atmospheric pressure.
Gage pressure 35.3 + 14.34 = 97.64
Total heat = 878 + 264.1 = 1142.6
Total water divided by total coal used
\[
\frac{7611 \text{ water}}{1302.6} = 5.61 \text{ pounds of water per pound of coal.}
\]
Total B.T.U. used = 1142.6 \times 5.61 = 6409.425
\[
\frac{6409.425}{12410} = 51.74 \% \text{ efficiency.}
\]

\[
100 - 13.35 = 86.65 \% \text{ of coal combustible.}
\]
\[
\frac{12410}{.8665} = 14322 \text{ B.T.U.}
\]
\[
\frac{215}{1440} = 14.92 \% \text{ Ash.}
\]
\[
100 - 14.92 = 85.08 \text{ Amount of available coal.}
\]
\[
\frac{5.61}{.8508} = 6.6 \text{ Pounds of water per pound of Coal.}
\]
\[
6.6 \times 1142.6 = 7541.16 \text{ B.T.U.}
\]
\[
\frac{7541.16}{14322} = 52.6 \% \text{ Efficiency of Boiler.}
\]
### TEST II

<table>
<thead>
<tr>
<th>Time Gage Moist.</th>
<th>Dry Temp</th>
<th>Steam Temp</th>
<th>Baromtemp</th>
<th>Feed Water</th>
<th>Flue CO₂ %</th>
<th>C.F.H.</th>
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</thead>
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<td>64</td>
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<td>9:00) 30°F</td>
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<td>530</td>
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<tr>
<td>9:15) 105°F</td>
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<td>156</td>
<td>64</td>
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<td>530</td>
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<tr>
<td>9:30) 75°F</td>
<td>214</td>
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<td>75</td>
<td>64</td>
<td>6.3</td>
<td>530</td>
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<tr>
<td>9:45) 85°F</td>
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<tr>
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<td>530</td>
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</tbody>
</table>

5/9/15 A.M.

---

**TEST II.**

Duration of Test 9:00 A.M. – 12:00 A.M.

- Average Cage Reading: 36.9
- Average Moisture: 3.76
- Average Air: 23.3
- Average Feed Water Temperature: 70°F
- Average Gas: 412°F
- Average CO₂ % in Gas: 8.9%
- Average Steam Flow Meter Reading: 592

- Amount of Coal used: 1600#
- Amount of Ashes left: 87#
- Amount of Water used: 9098#

Pounds of steam for test indicated by Steam Flow Meter: 3700#
Barometer = 29.3 = 14.43 in. sq. at.
Gage Pressure = 36.8 + 14.3 = 101.1 one sq. in.
Total Heat = 255.1 + 354.6 = 1109.7 B.T.U.
Total Water divided by total coal used
9098 water = 6.26 water per pound of coal.
14472 Coal
Total amount of B.T.U. used
1109.7 x 6.26 = 6968.9
6968.9 = 56.1%, Efficiency of boiler and grate.
14410

100 - 13.33 = 86.65% coal combustible.
14410 = 14322 B.T.U.
316 = 14.92
14472
6.26 = 7.36
8308
7.36 x 1109.7 = 8160 B.T.U.
3160 = 57.2%, Efficiency of Boiler.
14322
### TEST III.

<table>
<thead>
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<td>164</td>
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<td>73</td>
<td>440</td>
<td>6.0</td>
</tr>
<tr>
<td>5:00</td>
<td>68</td>
<td>3.1</td>
<td>225</td>
<td>161</td>
<td>29.4</td>
<td>73</td>
<td>440</td>
<td>5.8</td>
</tr>
</tbody>
</table>

**Average:**

<table>
<thead>
<tr>
<th>Average</th>
<th>Cage reading</th>
<th>33.22 F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Moisture</td>
<td>2.74 F</td>
</tr>
<tr>
<td>Average</td>
<td>Barometer</td>
<td>29.4&quot;</td>
</tr>
<tr>
<td>Average</td>
<td>Feed Water Temperature</td>
<td>73.0° F</td>
</tr>
<tr>
<td>Average</td>
<td>Flue Gas</td>
<td>482° F</td>
</tr>
<tr>
<td>Average</td>
<td>CO₂ in Flue Gas</td>
<td>7.7 F</td>
</tr>
<tr>
<td>Average</td>
<td>Steam Flow - meter Reading</td>
<td>630</td>
</tr>
<tr>
<td>Amount of Coal used</td>
<td>2400 lb</td>
<td></td>
</tr>
<tr>
<td>Amount of Ashes left</td>
<td>324 lb</td>
<td></td>
</tr>
<tr>
<td>Amount of Water used</td>
<td>13618 lb</td>
<td></td>
</tr>
<tr>
<td>Ends of Steam indicated by Steam Flow Meter</td>
<td>10032.75</td>
<td></td>
</tr>
</tbody>
</table>
Barometer = 29.4" = 14.43 pounds, one sq. in.

Gage Pressure = 33.22" = 97.65 pounds, one sq. in/ abs.

Total Heat $\frac{1255.5 \times 689.3 \times 97.26}{1120.4}$ B. T. U.

Total water divided by total coal used

$\frac{13618}{2170}$ water = 6.27$\frac{\text{lb}}{\text{lb}}$ water per pound of coal.

Total amount of B.T.U. used,

$1120.43 \times 0.72 = 7935.036$

$\frac{7935.036}{12.410} = 56.6 \%$, Efficiency of Boiler and Grate.

$100 - 13.35 = 86.65 \%$ of coal combustible.

$\frac{12.410}{0.8665} = 14322$ B.T.U.

$\frac{324}{2170.8} = 14.92 \%$ Ash

$100 - 14.92 = 85.08 \%$ Amount of available Coal.

$\frac{6.27}{0.3508} = 7.36$

$7.36 \times 1120.43 = 8246.568$ B.T.U.

$\frac{8246.568}{14322} = 57.57 \%$, Efficiency of Boiler.
CONCLUSIONS AND REMARKS.

It was desired to alter the conditions under which these tests were made so that a test could be obtained with a maximum CO₂ value and another with low values. Owing to the fact that the boiler under test was the only one in operation at the time, such results could not be secured. This boiler had to furnish all the steam required for running the school plant and a fairly heavy fire had to be maintained at all times. On test number three the ash pit doors were opened wide to secure an excess of air if possible and so lower the CO₂ value. With the load placed upon the boiler at the time, however, and the thick fire which was maintained, maximum CO₂ values were obtained at times. Cutting down the available draft by partly closing the damper did not seem to change the operation of the boiler.

The low results indicated by the Steam Flow Meter were due to one or more of the following causes: The Steam Flow Meter did not give large enough readings in the regular five inch pipe which connected the boiler to the steam header. A 2 1/2 inch pipe, 34 inches long, was substituted for the five inch pipe. With the increased velocity, due to the smaller pipe,
sufficiently large readings were obtained. Owing to the location of the Steam Flow Meter, near elbows, its calibration may not have been correct.

The readings which were taken every fifteen minutes may have been mostly minimum values instead of the average for the period.

The maximum efficiency of a boiler is obtained when operated with the least possible excess of air above that required for the complete combustion of the fuel, and at its rated capacity. A clean heavy fire free from air holes will give the highest CO₂ results. Care should be taken, however, that CO is not formed in objectionable quantities.

The results obtained by the use of a recording CO₂ meter and a heavy fire are not positive evidence that the boiler is working at maximum efficiency, because of the possible formation of CO.

An indicating Steam Flow Meter for each boiler would quickly determine if each boiler in a plant is doing its share of the work. All Steam Flow Meters should be calibrated, after being placed in position, by an accurate measure of the water feed to the boiler.
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