Robertson and Treischel.

A Study Of The Efficiency Of A Producer-Gas Fired Continuous Kiln.
A STUDY OF THE EFFICIENCY OF A PRODUCER-GAS FIRED CONTINUOUS KILN

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Hugh Schuyler Robertson and Chester Charles Troischel

ENTITLED A STUDY OF THE EFFICIENCY OF A PRODUCER-GAS

FIRED CONTINUOUS KILN.

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science

in Ceramic Engineering and Ceramics.

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HEAD OF DEPARTMENT OF Ceramic Engineering.
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A STUDY OF THE EFFICIENCY OF A PRODUCER-GAS-FIRED CONTINUOUS KILN.

At no place in the available ceramic literature does there appear a complete heat balance of a continuous kiln. The value of studying the heat distribution in boiler plants, gas producers, periodic kilns, and other heat-using devices has been recognized for a number of years and many such studies have been made. Due to the lack of data in regard to the consumption of fuel in a continuous kiln and because of the claims made by those who own or have such kilns for sale it was thought desirable to make a study of the heat distribution in a typical kiln which was in successful operation.

THE KILN: Of the several different types of continuous kilns which were available a producer-gas-fired kiln was chosen because it represented the true continuous type in that it followed the regenerative principle of heating the air used in combustion. In construction, this kiln was of the chamber type, having fourteen chambers arranged in one continuous row. Each chamber received its fire from one side only, working on the down draft principle — the flames coming up over a bag wall spreading over the chamber and passing out thru the floor. The half of the floor nearest the bag-wall was closed while the half furtherest away from the bag-wall was open thus providing for a good distribution of heat over the entire chamber. A return-flue used

for carrying the hot combustion gases from the fourteenth chamber to the first chamber extended the full length of the kiln beneath the floor. The waste gases and water-smoking gases were led from each chamber by an auxiliary flue which was connected to a main watersmoking flue and a main waste-gas flue by bell dampers. These main flues were placed underneath the ground outside of and parallel to the kiln and each one was provided with a fan for creating draft.

The watersmoking was accomplished by drawing the air from the cooling chambers behind the fire thru a sheet-steel flue supported about ten feet above the top of the kiln. (This flue is a short-circuiting flue and it must be borne in mind that in speaking of the watersmoking flue the main flue drawing the gases from the chambers which are watersmoking and which lies beneath the ground outside the kiln is the one designated)

The producer gas was supplied thru a large main flue beneath the ground extending the full length and parallel to the kiln on the opposite side from the main watersmoking and main waste-gas flues. Distributing flues, one for each chamber, rose perpendicularly to the top of the kiln at which point they led off at right angles into horizontal flues which extended across the kiln parallel to the axis of the chambers. These horizontal flues were integral with the kiln and were built into the brickwork between the chambers. The gas was delivered to the combustion chamber at the foot of the bag-walls by small ducts.

The producers were in two batteries of four each, being of the simple or carbon monoxide type; ¹

very desirable for a brick-yard due to their simplicity and ease of operation. They were rectangular in section with a single hopper at the top for feeding the coal and with two holes in each side thru which a poker could be thrust for stirring up the fuel bed. The producers were not sealed, the coals resting upon horizontal grates at the bottom. They were fired every fifteen minutes and the grates cleaned once every eight hours.

Both the kiln and producers were designed by Mr. E. B. Rodgers of the Alton Brick Company, Alton, Illinois, where they have been in successful operation for three years.

APPARATUS USED.

2. Thermocouples.
   a. One noble metal and two base-metal.
4. Pitot tube. 1
5. Large gas pressure tank for Junker Calorimeter.
7. Thermometers. (6)
10. Rubber tubing, stoppers, etc.
11. Chemicals.

1. A pitot tube capable of withstanding high temperatures would offer a means of direct measurement of the velocity of the gases and an indirect measurement of the volume of the same. Such a piece of apparatus would be extremely valuable in such a work as this.
4.

THE HEAT BALANCE.

In making a heat balance on a producer-gas-fired continuous kiln the following factors must be determined:-

A. Heat introduced as fuel.
B. Heat lost by unburned carbon in ashes.
C. Heat lost in the producer.
D. Heat used in the burning of the ware.
E. Heat lost in the combustion gases.
F. Heat lost in watersmoking gases.
G. Heat taken up by the kiln and lost by radiation.

In order to obtain the data for the above factors the following observations, analyses, etc., were made:-

1. Tons of coal used.
   A. Calculated from firing sheets kept by producer fireman

2. Heating value of coal.
   A. Determined on one average sample in Oxygen bomb calorimeter.

3. Analysis of Coal.
   A. Proximate analysis.
   B. Ultimate analysis.

   A. Determination of carbon and ash.

5. Analysis of Producer Gas.
   A. Absorption and combustion method with portable Burrell apparatus.

6. Analysis of Flue Gas.
   A. Absorption method in portable Burrell apparatus.
   A. Determined with base-metal thermocouple.

8. Maximum burning temperature.
   A. Determined with a platinum-platinum rhodium thermocouple.

   A. Wet and dry bulb thermometers.

10. Atmospheric temperature.


12. Tons of clay burned.
   A. Obtained from data kept in the office of the company.

   A. Junker's calorimeter.

1. TONS OF COAL USED.

The weight of coal required to charge the hopper of the producer to each of three different depths was determined and subsequent charges were noted as 1/4, 1/2, and full hoppers. In each case the depth of charge was determined by measurement and recorded on a firing sheet. This process was continued for a complete cycle of the kiln which covered a period of four hundred and seventy-eight hours. Knowing the weight of coal corresponding to each of the three depths, the total amount of coal used during the period was calculated.

This method must necessarily depend upon the intelligence of the fireman and the interest which they take in the work.
Small errors will be of a compensating nature, so that large errors need only be guarded against.

2 And 3. HEATING VALUE AND ANALYSIS OF COAL.

An average sample of the coal was taken over a period of seventy two hours. Each time the fireman fired his producer he threw a small quantity of coal on a pile. At the end of the period this pile was quartered\(^1\) to a small pile and gathered in a sampling can. This sample was analyzed by the Department of Applied Chemistry of the University of Illinois under the direction of Mr. J. M. Lindgren.

4. ANALYSIS OF PRODUCER ASHES.

Each time the fireman cleaned the grates he threw a small quantity of ashes onto a pile. This pile was quartered\(^1\) down and the sample gathered in a sampling can. This sample was also analyzed by the Department of Applied Chemistry, U of I.

5 And 6. ANALYSIS OF PRODUCER GAS AND ANALYSIS OF FLUE GAS.

These analyses were made with a Burrell apparatus\(^2\) of the portable type equipped with pipettes for the determination of $\text{CO}_2$, $\text{CO}$, $\text{O}_2$ and unsaturated hydrocarbons by absorption and $\text{H}_2$ and $\text{CH}_4$ by combustion.

7. TEMPERATURES OF GASES IN PRODUCER GAS, AND WASTE-GAS TUNNELS.

A base-metal thermocouple was inserted into the flue thru

---

an opening in the top and readings taken in millivolts with a portable Leeds and Northrup potentiometer equipped with compensation coils for temperature correction of the cold junction of the thermocouple. The thermocouples were calibrated¹ and the millivolt readings were transferred to temperature readings by interpolation from the calibration curves.

8. MAXIMUM BURNING TEMPERATURE.

A platinum-platinum rhodium thermocouple was inserted thru the crown into the chamber on high fire. Readings were taken with a potentiometer in millivolt readings and afterwards converted to temperature by interpolation from a calibration curve.

9. HUMIDITY OF THE AIR.

The relative humidity was calculated from the wet and dry bulb thermometer readings and humidity tables.²

11. HUMIDITY OF WASTE GASES.

Due to the inaccessibility of the top of the Waste gas sack, and the large volume of sulfur gases coming from the stack this determination was neglected.

12. TONS OF CLAY BURNED.

The number of bricks or blocks set in each chamber was obtained from records in the company office. Ten blocks and ten bricks were weighed, to determine the average weight of each burned block or brick. From these weights and the number of

¹. The flue gas thermocouple was calibrated by Mr. F.J. Hoehn, a contemporary student in ceramics.
blocks or bricks set in the kiln the tonnage of the kiln for the entire cycle was calculated.

13. HEATING VALUE WITH JUNKER'S CALORIMETER.

This method is a direct method for obtaining the heating value of a gas. A known volume of gas is burned and allowed to heat a known weight of water, the temperature rise in the water being observed. From this data the heating value is calculated:

Due to the fact that conditions were not favorable for the accurate working of the calorimeter, -- there being drafts blowing over the work-table, and a variable gas supply -- these results were used only as a check, the calculated heat value being used throughout the work.

--- METHOD OF CALCULATION ---

The method of calculation employed followed the general method set down by Bleininger, Gelstharp, and Kratz. In specific cases the method was altered to suit the conditions of the data used.

The items to be calculated in the determination of the factors necessary for a complete heat balance are: ---

A. Heat Introduced as Fuel.

1. Number of pounds of coal fired per ton of burned clay.

---

2. Number of B.t.u. in coal used per ton of burned clay.

B. Heat lost in unburned carbon in ashes.

C. Heat lost in Gasification.
   1. Cubic feet of gas per pound of dry coal.
   2. Heating value of gas per cubic foot.
   4. Total heat in gas per pound of dry coal.

D. Heat used in burning the ware.
   1. Heat used in driving off hygroscopic water.
   2. Heat used in dehydrating the clay.
   3. Heat used in heating up clay substance.

E. Heat lost in the combustion gases.
   1. Cubic feet of flue gas per cu. ft. of produce gas.
   2. Cubic feet of flue gas per pound of dry coal.

F. Heat lost in watersmoking gases.
   1. Cubic feet of gases per pound of dry coal.
   2. Sensible heat of gases per pound of dry coal.

G. Heat absorbed by kiln and lost by radiation.

A. HEAT INTRODUCED AS FUEL:

This was calculated on the basis of pounds of coal per ton of ware burned. The total weight of coal used was divided by the total tonnage of the kiln. This gave the pounds of coal used per ton of ware. Multiplying this result by the heating value of the coal per pound as fired gave the heat introduced.
B. HEAT LOST IN UNBURNED CARBON IN ASHES.

The percentage of unburned carbon in the ashes was obtained from the analysis of the ashes. Since the earthy matter in the ashes corresponds to the "ash" of the coal, the unburned carbon in the ashes per pound of coal, is readily obtained. The total ashes per lb. of coal equals 100% divided by the percentage of ash in the ashes and multiplied by the percentage of ash in the coal. This multiplied by the percentage of carbon in the ashes gives the percentage of unburned carbon in the ashes in terms of one pound of coal. Multiplying this result by the heat value of carbon per pound gives the heat lost.

C. HEAT LOST IN GASIFICATION.

Since the basis of the efficiency calculations is one pound of dry coal the volume of producer gas per pound of dry coal must be first obtained. The weight of carbon combined in CO₂, CO, and CH₄ per cubic foot of producer-gas is calculated from the per cent composition. The weight of carbon burned on the grate per pound of coal is the difference between the percent of carbon in the coal and the percent of unburned carbon in the ashes in terms of one pound of coal. This difference divided by the weight of carbon per cubic foot of gas gives the volume of gas per pound of dry coal.

The heating value of the gas per cubic foot is calculated from the percent composition and heating value of the combustible constituents. In obtaining the total heat of the gas per cubic foot it is necessary to add to the heating value, the sensible heat at the temperature at which the gas enters the kiln. This
is obtained from the percent composition, the specific heat of the constituents, and the temperature. Multiplying the total heat per cubic foot by the cubic feet per pound of coal gives the heating value of the gas per pound of coal. This value subtracted from the heating value of one pound of coal gives the heat lost by gasification.

D. HEAT USED IN BURNING THE WARE.

In this calculation it is assumed that the clay contains 2% hygroscopic water and three percent of chemical water. The total heat absorbed then is the heat used in driving off and turning into steam the hygroscopic and chemical water plus the heat used in burning the clay substance. The latter is obtained by multiplying the weight of clay by the specific heat of clay and multiplying this result by the temperature rise.

E. HEAT LOST IN COMBUSTION GASES.

The volume of flue gas per cubic foot of producer gas is obtained by dividing the weight of carbon in the producer gas per cubic foot by the weight of carbon in the flue gas per cubic foot. This result multiplied by the cubic feet of producer gas per pound of dry coal gives the volume of flue gas per pound of dry coal. From the per cent composition of the flue gas, the specific heats of the constituents at the flue gas temperature, the temperature of the flue gas, and the volume of flue gas per pound of coal, the heat lost in the combustion gases is readily calculated.
F. HEAT LOST IN WATERSMOKING GASES.

Due to the fact that the water-smoking gases left the flue at approximately atmospheric temperature this loss was negligible and was not taken into account.

G. HEAT ABSORBED BY KILN AND LOST BY RADIATION.

As the factors which enter into this calculation are so variable and the data so difficult to obtain it is determined by the difference between 100% and the summation of the calculated factors in the heat distribution. It is plainly evident that radiation will be small in this type of kiln due to the great thickness of the walls, the small area subjected to high temperatures at any one time, and the high velocity with which the gases are moving thru the kiln.
DATA

Coal used, as obtained from data sheets and recorded by producer firemen.  524728 lbs.

B.T.U. value of coal per pound by combustion in oxygen bomb calorimeter and furnished by the University of Illinois, Department of Applied Chemistry.  (dry basis 12630
(as received 11175

Tonnage of burned clay in the 14 Chambers 1743 Tons
Coal used per ton of burned clay 301 Lbs.
Coal used per 1000 blocks 1400 Lbs.
Coal used per 1000 builders 834 Lbs.
Average weight of blocks 9.3 Lbs.
Average weight of builders 5.7 Lbs.
Average temperature of producer-gas flue 708 °F
Average temperature of waste gas flue 406 °F
Average temperature of Water smoking flue 80 °F
Average temperature of atmospheric air 70 °F
Maximum temperature of burning clay 1120 °C

Analysis of Coal:

<table>
<thead>
<tr>
<th>Ultimate.</th>
<th>Proximate.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry.</td>
</tr>
<tr>
<td>C - 69.90</td>
<td></td>
</tr>
<tr>
<td>H₂ - 4.95</td>
<td>Fixed Carbon 41.30</td>
</tr>
<tr>
<td>O₂ - 10.29</td>
<td>Volatile Matter 44.48</td>
</tr>
<tr>
<td>N₂ - 0.62</td>
<td>Moisture 0.00</td>
</tr>
<tr>
<td>S - 4.71</td>
<td>Ash 9.52</td>
</tr>
<tr>
<td>Ash - 9.52</td>
<td>Sulphur 4.71</td>
</tr>
</tbody>
</table>
14.

ANALYSIS OF ASHES.

C = 22.34
Ash = 77.76

Average Gas Analysis, samples taken over a period of 72 hours.

<table>
<thead>
<tr>
<th>Producer Gas</th>
<th>Flue Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ = 4.3</td>
<td>CO₂ = 3.5</td>
</tr>
<tr>
<td>CO = 24.4</td>
<td>O₂ = 17.1</td>
</tr>
<tr>
<td>CH₄ = 1.5</td>
<td>N₂ = 79.5</td>
</tr>
<tr>
<td>H₂ = 7.4</td>
<td></td>
</tr>
<tr>
<td>O₂ = .6</td>
<td></td>
</tr>
<tr>
<td>N₂ = 62.1</td>
<td></td>
</tr>
</tbody>
</table>

CALCULATIONS.

Calculation of Producer efficiency:

For each cubic meter of CO₂, CO and CH₄, \( \frac{12}{22.4} \) kilograms of carbon are required.

\[
\begin{align*}
\frac{.043 \times 12}{22.4} &= .023 \text{ Kg. of C in CO₂ per M}^3 \text{ of gas.} \\
\frac{.244 \times 12}{22.4} &= .131 \text{ Kg of C in CO per M}^3 \text{ of gas.} \\
\frac{.015 \times 12}{22.4} &= .008 \text{ Kg of C in CH₄ per M}^3 \text{ of gas.} \\
\frac{.162 \times 2.2}{35.25} &= .0101 \text{ Lbs. of coal per Cu. Ft of gas.} \\
\end{align*}
\]

Carbon per lb. of coal from analysis = .6990 lbs.
15.

Unburned C in Ashes per Lb. of Dry Coal. =
\[
\frac{100}{77.76} \times 0.952 \times 0.2224 = 0.0273 \text{ Lbs.}
\]

Volume of producer gas per Lb. of dry coal. =
\[
\frac{6690 - 0.0273}{0.0101} = 66.5 \text{ cu. Ft.}
\]

Heating value of gas,
\[
\begin{align*}
0.244 \times 341.3 &= 83.3 \text{ B.T.U. in CO per Cu ft. of gas}, \\
0.074 \times 291.0 &= 21.5 \text{ B.T.U. in H}_2 \text{ per cu ft of gas}, \\
0.015 \times 955.0 &= 14.3 \text{ B.T.U. in CH}_4 \text{ per Cu ft of gas}, \\
\end{align*}
\]

\[
119.1 \text{ B.T.U. per Cu Ft. of Gas.}
\]

Sensible heat in Gas:-
\[
\begin{align*}
0.043 \times 0.0257 \times 708 &= 0.82 \text{ B.T.U. in CO}_2, \\
0.96 \times 0.0177 \times 708 &= 12.00 \text{ B.T.U. in CO, CO}_2, \text{CH}_4, \text{H}_2 \text{ and N}_2 \\
12.82 \text{ B.T.U. per cu. Ft. of gas.}
\end{align*}
\]

Total heat in producer gas per pound of coal.
\[
12.82 \times 66.5 = 852. \text{ B.T.U. sensible heat.}
\]
\[
119.1 \times 66.5 = 7920. \text{ B.T.U., at atmospheric conditions.}
\]
\[
8772. \text{ B.T.U., total heating value of gas.}
\]
\[
\frac{8772}{12630} \times 100 = 69.4 \text{ per cent = efficiency of the producers.}
\]

Percent Heat lost by unburned carbon in the ashes =
\[
\frac{0.0273 \times 14600 \times 100}{12630} = 3.15 \text{ per cent.}
\]

Percent Heat lost by gasification in the Producers =
\[
100 - (69.4 + 3.15) = 27.45 \text{ percent.}
\]
THERMAL EFFICIENCY OF THE KILN

Maximum temperature of burning = 1120° C.
Average Atmospheric temperature = 200° C.
Temperature rise of clay in chambers = 1100° C.

Heat of dehydration of Clay = 200 gm. cal. per gm of water.
Latent heat of hygroscopic water = 476 gm cal. per gm of water.
Hygroscopic water leaves at 200° C.
Dehydration temperature of clay = 650° C.
Clay is assumed to contain 2\% hygroscopic water and 3\% chemical water.

The specific heat of clay = 0.200.

Distribution of the heat in clay.

Hygroscopic water

\[0.02 \times 180 \times 1 = 3.6 \text{ Kg. cals.}\]
\[0.02 \times 476 = 9.5 \text{ Kg. cals.}\]

Chemical water

\[0.03 \times 0.02 \times 650 = 3.9 \text{ Kg cals.}\]
\[0.03 \times 200 = 6.0 \text{ Kg cals.}\]

Clay

\[0.97 \times 200 \times 1100 = 236.4 \text{ Kg. cals.}\]

Total heat required for 1 Kg of clay = 236.4 Kg. Cals.
236.4 Kg. Cals. = 425 B.T.U. per pound of clay.
1 ton of clay requires 2000 X 425 = 850,000 B.T.U.

Heat introduced as coal per ton of clay =

\[301 \times 11175 = 3,363,675 \text{ B.T.U.}\]

Efficiency of Kiln in terms of coal used at the producers =

\[850,000 = 25.3 \text{ per cent.}\]
\[3,363,675\]

PERCENTAGE OF HEAT USED IN BURNING WARE = 25.3 percent.

HEAT LOST IN WASTE GAS FLUE:

\[ 0.244 \times 1 = 0.244 \text{ cu. ft. of } CO_2 \text{ from } CO \text{ per cu. ft. of gas.} \]
\[ 0.015 \times 1 = 0.015 \text{ cu. ft. of } CO_2 \text{ from } CH_4 \text{ per cu. ft. of gas.} \]
\[ 0.043 \times 1 = 0.043 \text{ cu. ft. of } CO_2 \text{ from } CO_2 \text{ per cu. ft. of gas.} \]

\[ 0.302 \text{ cu. ft. of } CO_2 \text{ in combustion gas from 1 cu. ft. of producer gas.} \]
\[ 0.035 \text{ cu. ft. of } CO_2 \text{ actually in combustion gas from analysis.} \]

\[ 8.63 = \frac{0.302}{0.035} \text{ cu. ft. of combustion gas from 1 cu. ft. of producer gas.} \]

\[ 8.63 \times 0.035 \times 66.5 = 20.1 \text{ cu ft. } CO_2 \text{ per lb. of coal.} \]
\[ 8.63 \times 0.171 \times 66.5 = 98.2 \text{ cu ft. } O_2 \text{ per lb of coal.} \]
\[ 8.63 \times 0.795 \times 66.5 = 456.0 \text{ cu ft. } N_2 \text{ per lb. of coal.} \]
\[ 0.074 \times 0.5 \times 66.5 = 2.5 \text{ cu. ft of water per lb. of coal from } H_2 \]
\[ 0.015 \times 2 \times 66.5 = 2.0 \text{ cu ft of water per lb. of coal from } CH_4 \]

\[ 3000 \times 0.03 = 60 \text{ lb. of water per ton of clay.} \]

\[ \frac{60}{301} = 0.20 \text{ lb of water per lb. of coal from the clay.} \]

\[ 0.20 \times 22.4 \times 1.31 \times 27 = 8.8 \text{ cu ft of water per lb of coal from the clay.} \]

\[ 13.3 \text{ cu ft. of water in gas per lb of coal.} \]
\[ 20.1 \times 0.0246 \times 406 = 201. \text{ B. T.U. in } CO_2 \text{ per lb of coal.} \]
\[ 554.2 \times 0.0175 \times 406 = 3940 \text{ B.T.U. in } O_2 \text{ and } N_2 \text{ per lb of coal.} \]
\[ 13.3 \times 0.023 \times 406 = 119 \text{ B.T.U. in } H_2O \text{ per lb of coal.} \]

Total heat lost in -

flue gas = 4260 B.T.U. per lb of coal.
Heat absorbed by Kiln and lost by Radiation

\[
100 - \left(3.15 + 27.45 + 25.3 + 33.6\right) = 10.5 \text{ percent.}
\]

**SUMMARY.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat lost by carbon in the ashes</td>
<td>3.15%</td>
</tr>
<tr>
<td>Heat lost by gasification in the Producer</td>
<td>27.45%</td>
</tr>
<tr>
<td>Heat used in burning the ware</td>
<td>25.3%</td>
</tr>
<tr>
<td>Heat lost by waste gas</td>
<td>33.8%</td>
</tr>
<tr>
<td>Heat lost by radiation and conduction.</td>
<td>10.5%</td>
</tr>
<tr>
<td></td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Due to the fact that the chambers in this kiln are in one straight row, the coal consumption in the last chamber is twice as large as in the chamber nearest the producers and it can readily be seen that this is not as efficient a type of continuous kiln as the one in which the chambers are arranged in two parallel batteries.

Due to the low radiation loss and increased efficiency in other respects as compared with the periodic kiln, it can readily be seen that this kiln from the standpoint of economy in burning is a step in the right direction for the Ceramic industry and the conservation of the nation's coal supply.