Heat and Material Balances for a Rotary Cement Kiln

Experimentally determined material and heat balances for a dry-process rotary Portland cement kiln are reported. The methods of determination are described and the necessary calculations are discussed.

WILLIAM N. LACEY

California Institute of Technology

AND

HUBERT WOODS

Riverside Cement Company,

Pasadena, Calif.

NUMEROUS difficulties are involved in the experimental determination of heat and material balances for continuous furnaces operating at high temperatures and with large rates of production. As a result, most of the quantitative information on such balances found in the literature is based partly upon experimental data and partly upon assumptions or approximations often guided by results obtained from other equipment operating under somewhat similar conditions. In many cases the conditions of operation and methods used in the test are described in such scant detail as to furnish little of value to other engineers.

In the test herein described, experimental data were obtained covering more of the conditions of operation than is usually the case. A detailed description of the methods used and results obtained will be given in order that they may be evaluated critically. The fact that numerous changes in equipment and improvements in methods of operation have been made since the original test (made several years previous to this report) will not detract from the value of these results as a basis of quantitative comparison.

The kiln tested was producing clinker from a dry mix for which the raw materials were limestone and clay. Final grinding of the raw mix was carried out in tube mills. Screen analyses showed 84 per cent passing 200 mesh. The general arrangement of the kiln system and the dimensions of the kiln are shown in Figure 1. The diameters given were measured inside the refractory bricks. The gases passing up the stack were led through an electrical precipitator for recovering the dust. Movement of the gases was produced by natural draft in the stack. The fuel in use was residuum from Dubbs cracking units for petroleum treatment, and contained carbon and solid hydrocarbons in suspension. Its viscosity was very high at room temperature but decreased rapidly as its temperature increased. Special burners were used for this material, since ordinary fuel oil burners with small jets soon became clogged. The burners were of the type utilizing air-atomizing. Neither this primary air nor the secondary air used for combustion was preheated. The kiln was not equipped with a clinker cooler.

Temperature Measurements

Temperatures of fuel entering the burner, kiln feed, and kiln room air were obtained with mercury-in-glass thermometers. The maximum temperature of the clinker in the kiln was measured with an optical pyrometer of the filament comparison type, by sighting through an opening in the kiln hood in such a way that observation through flames was avoided. The temperature of the clinker leaving the kiln was taken by sighting the optical pyrometer on the material just before dropping over the lip of the kiln.

The temperature of the gases just leaving the feed end of the kiln was measured by a recording pyrometer with a chromel-alumel thermocouple in a metal protection tube. The couple and recorder were calibrated before use. A thermocouple measuring the temperature of a gas stream is subject to a correction for radiation losses when the surrounding walls are at a lower temperature. In order to determine this correction, a comparison was made between the temperatures indicated by the regular couple and a thermally shielded couple, past which a rapid stream of the gases was drawn (2).

Since it was not feasible to operate the "high velocity" thermocouple for extended periods, a correction was obtained under usual operating conditions, and this was added to the temperatures obtained by use of the ordinary thermocouple. Under the conditions of this test the correction to be added was 450° F.

In order to determine heat losses from the walls, sets of thermocouples were inserted at intervals along the length of the kiln. Each set consisted of three chromel-alumel couples made from No. 8 wires. The method of placing these couples
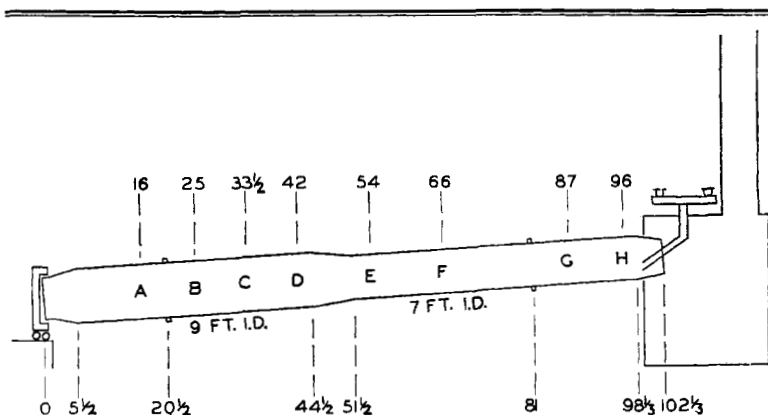

FIGURE 1. KILN DIMENSIONS AND THERMOCOUPLE LOCATIONS

is shown in Figure 2. Since the two couples in the refractory brick were at different points in the same heat flow path, they would give a measure of the temperature gradient through the brick, if the distance between the two couples were known. From the temperature gradient and the thermal conductivity coefficient for the brick, the rate of heat loss through that portion of the wall was calculated. The third

couple of each set was welded to the outside of the kiln shell and indicated the temperature of the exterior surface. The longitudinal positions of these thermocouple sets are shown by letters *A* to *H* in Figure 1, the positions being given in feet from the lower end of the kiln. Readings were taken by attaching chromel and alumel leads to the respective wires of the couples. These leads ran to a thermos bottle filled with ice and water mixture, from which copper leads connected to the portable indicating-pyrometer instrument. Attaching the leads to the couple wires was accomplished by means of pinch clips to whose jaws the chromel or

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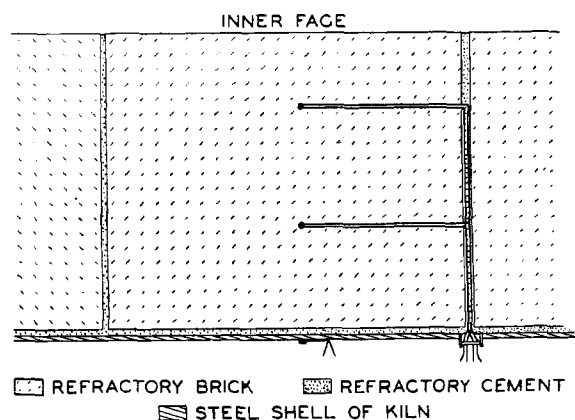☐ REFRACTORY BRICK   ▓ REFRACTORY CEMENT
        ▧ STEEL SHELL OF KILN

FIGURE 2. ARRANGEMENT OF THERMOCOUPLES IN KILN WALLS

alumel lead wires were fastened in such a way that the lead wire was pressed firmly against the thermocouple wire of the same metal. This introduced no disturbing junctions at unknown temperatures. The readings from the three couples of a given set could be made in less than a quarter-revolution of the kiln.

Weighing of Materials

The Dubbs residuum used as fuel was weighed as it was fed to the burners by alternately filling, from the main fuel line, two open steel tanks which were provided with a manometer gage indicating the pressure exerted by the liquid at the bottom of the tank. The weight of liquid in the tank corresponding to a given manometer reading was determined before the test by calibration against actual weighings and construction of a calibration curve. When one of the tanks had been filled with fuel, a weight measurement of its contents was taken. This tank then furnished the supply for the kiln, the fuel passing through a steam-driven pressure pump and a preheater on the way to the burners. When the liquid level had fallen near the bottom, the outlet valve was closed off and the supply was then taken from the other tank, which had been filled and measured in the meantime. After closing off the outlet valve of the first tank, a measurement was taken to determine the weight of the residue, before refilling. The difference between the initial weight and that of the residue gave the weight of fuel fed from the tank. In addition, weight readings were taken at exact one-hour intervals during the period of the test.

The clinker leaving the lower end of the kiln was weighed continuously by collecting it in tared steel cars which were run on a track scale and weighed before dumping into the regular plant clinker conveyor. The weighings were recorded with corresponding times, and a weighing was made exactly at the end of each hour of the test period.

The other stream of solid material leaving the kiln was in the form of dust carried out by the gases from the upper end. A portion of this dust deposited in the stack chamber shown in Figure 1. The rest was carried up the stack and captured by the electrical precipitators above. At regular intervals the dust collecting in the stack chamber was scraped out upon the kiln room floor and weighed. The electrodes of the treater were shaken down once each hour and the total accumulation for the hour was weighed. This treater dust was very fine and thoroughly "aërated" and as a consequence behaved very much like a fluid. This necessitated weighing in a bin mounted on a scale.

A direct measurement of the quantity of gases leaving the upper end of the kiln was found to be impracticable. The high temperature, the turbulence caused by the feed pipe, and the dust burden of the gases made Pitot tube readings taken at the end of the kiln too uncertain. Dilution of the gases with air occurred upon entrance to the stack chamber and rendered subsequent gas measurement useless. It was therefore necessary to calculate the quantity of gases by indirect methods. Knowing the quantity and analysis of the fuel burned, the quantity of clinker produced, the analyses of kiln feed and clinker, and the analysis of the exit gases at the upper end of the kiln, it was possible to calculate the corresponding quantity of the exit gases.

Samples and Analyses

The test run in question continued for a period of 48 hours. During this period both kiln feed and clinker were sampled four times each hour, each group of four being composited to give a representative hourly sample. The treater dust was sampled each hour at the time of weighing, while the stack chamber dust was sampled at the time of each cleaning-out and weighing. All of these samples were subjected to "complete" analyses, such as are ordinarily made in cement mill practice.

The fuel was sampled at the beginning and at the end of each 4-hour period, the individual samples being composited to give a 24-hour sample. Upon these samples were made determinations of calorific value by the oxygen bomb calorimeter method, and of carbon, hydrogen, sulfur, nitrogen, oxygen, and ash by the usual methods of organic analysis. Since the analyses and measurement of the fuel were made upon a weight basis, there was no need to determine or use the specific gravity of the fuel.

The kiln gases were sampled by extending a sample tube into the upper end of the kiln itself, aspirating a rapid continuous stream of gas through this tube, and withdrawing slowly a small portion of this stream into a sample container by allowing the mercury originally filling the container to flow out through a capillary tube. The capillary was so adjusted as to require 1 hour for the taking of each sample. Gas samples were analyzed by means of an improved Orsat apparatus, using mercury in the measuring buret. As the result of an extended investigation, it was found to be impracticable to obtain a sample of gas which was representative of the entire stream. This was believed to be due to the high temperature at the upper end of the kiln. It could be observed that, under the conditions obtaining when operation was similar to that prevailing during the test period, the surface particles of the dry kiln feed glowed brightly at the upper end of the kiln, although the average temperature of the charge at this point was comparatively low. As a result of this condition, carbon dioxide was given off from the charge in substantial amount too near the point of sampling to permit thorough mixing of the gases before reaching the end of the kiln. As would be expected from this condition, the percentage of carbon dioxide in the sample varied with

different locations of the sample tube over the cross section of the kiln. However, the ratio of oxygen to nitrogen (inert gases being called nitrogen here) appeared to be comparatively free of such variation for a given condition of kiln operation. This ratio, controlled by firing conditions at the lower end of the kiln and far enough away from the sampling point to insure mixing, would be expected to remain unchanged by subsequent additions of carbon dioxide from the charge. This ratio of oxygen to nitrogen, together with the other measurements and analyses previously mentioned, furnished sufficient information to permit calculation of the average composition of the exit kiln gases and their quantity.

Data Obtained in Test

The results here described are average values for a representative 7-hour period of steady operation under one set of conditions.

The weight of fuel used was 18,445 pounds. Its gross calorific value was 18,450 B. t. u. per pound. Its analysis (by weight) showed 86.2 per cent carbon, 9.1 hydrogen, 1.2 sulfur, 2.1 oxygen, 1.2 nitrogen, and 0.2 per cent ash. After deducting an amount of hydrogen necessary to give water with the oxygen remaining after allowance for enough to form sulfur dioxide, the "net" hydrogen was 9.0 per cent.

The average kiln gas analysis (by volume) for the period was 21.9 per cent carbon dioxide, 1.8 oxygen, 0.1 carbon monoxide, and 76.2 per cent nitrogen (inert). As noted previously, the percentage of carbon dioxide cannot be depended upon accurately.

The measured weights and the percentage analyses of the solid materials entering and leaving the kiln are as follows:

	Kiln Feed	Clinker	Treater Dust	Stack Dust
SiO$_2$	14.7	22.3	11.8	12.0
Al$_2$O$_3$	3.7	6.0	2.7	3.4
Fe$_2$O$_3$	1.4	2.2	1.3	1.2
CaO	43.6	63.8	56.3	55.7
MgO	3.6	5.2	4.1	4.5
SO$_3$	..	..	6.8	5.0
Loss	32.3	0.2	12.4	14.2
Total	99.3	99.7	95.4	96.0
Weight, lb.	..	79,670	4830	820

Special analysis showed that the 32.3 per cent loss on ignition of the kiln feed consisted of 29.1 per cent carbon dioxide and 3.2 per cent water. The moisture removable by drying at 105° C. (221° F.) was 0.2 per cent of the weight of the kiln feed. The low totals of the analyses of treater and stack dusts are largely due to the presence of alkali metals which were not determined.

The average temperatures for the 7-hour test period were as follows: kiln room air, 60° F. (relative humidity, 50 per cent); fuel, 178° F.; kiln feed, 176° F.; kiln charge (maximum), 2650° F.; clinker leaving kiln, 2440° F.; kiln gas at exit, 1950° F. The temperature measurements from the thermocouples in the kiln walls gave the following average values (in ° F.); the letters refer to the positions shown in Figure 1 while the column headings refer to the thermocouples shown in Figure 2:

	Inner	Outer	Shell		Inner	Outer	Shell
A	1400	540	290	E	1460	610	355
B	1780	680	380	F	1370	670	360
C	1850	760	420	G	1060	480	310
D	1700	800	400	H	1140	560	...

Material Balance Calculations

The weight of kiln feed, which was not measured, was calculated on the basis of a balance of total lime entering and leaving the kiln during the test period. The lime entering the kiln feed was set equal to the total lime in the clinker,

the stack dust, and the treater dust. From the lime in the feed and the analysis of the latter, its total weight was calculated. The value obtained was 123,600 pounds. A similar balance using silica instead of calcium oxide gave 124,600 pounds, and a third balance using all nonvolatile constituents together gave 124,700 pounds. The average of these three was 124,300 pounds which was taken as the weight of kiln feed.

TABLE I. HEAT BALANCE

Heat Supplied	B. t. u.	Per cent
Heat of combustion of fuel	340,300,000	98.9
Sensible heat of fuel	870,000	0.3
Sensible heat of kiln feed	2,880,000	0.8
Total	344,100,000	
Heat Used and Lost		
Heat used in reactions	64,600,000	18.8
Sensible heat of clinker	46,850,000	13.6
Sensible heat of kiln gases	166,500,000	48.4
Potential heat of combustion of CO	1,160,000	0.3
Latent heat of water from combustion	15,700,000	4.6
Heat lost through walls	28,650,000	8.3
Heat not accounted for	20,640,000	6.0
Total	344,100,000	

In order to calculate the correct gas analysis, it was assumed that the relative proportions of oxygen, carbon monoxide, and nitrogen found were correct. Taking the composition of air, for the purposes of calculation, as 20.9 per cent oxygen and 79.1 per cent nitrogen by volume, and comparing this to the oxygen and nitrogen ratio in the kiln gases, it is seen that 0.0894 of the oxygen of the entering air was unused in combustion and 0.9106 was used. The fuel contained 1325 pound-atoms of carbon, and if burned completely would consume 1325 pound-moles of oxygen and produce 1325 pound-moles of carbon dioxide. While the 1325 pound-moles of oxygen were used to oxidize the carbon of the fuel, there would be required 412 pound-moles of oxygen to oxidize the corresponding "net" hydrogen, making a total of 1737 pound-moles of oxygen used from the air, if one neglects the small amount of oxygen thus allocated but unused by the 0.1 per cent carbon monoxide found in the kiln gas analysis. By using the ratio of carbon monoxide to unused oxygen in the flue gas analysis as correct, it was calculated that this carbon dioxide amounted to 9.5 pound-moles and this would lower the total oxygen used by approximately 5 pound-moles, leaving 1732 pound-moles. As found above, this used oxygen corresponds to only 0.9106 of the total entering, which would then be 1902 pound-moles. With this oxygen there came from the air 7199 pound-moles of nitrogen. By adding the carbon dioxide contributed to the gases by the kiln feed, 821 pound-moles, to that produced by combustion (after deduction for 10 pound-moles of carbon monoxide), the total present in the kiln gases was found to be 2136 pound-moles. The total quantity of dry kiln gases would then be 2136 + (0.0894) (1902) + 10 + 7199 = 9515 pound-moles, and their corrected analysis would be 22.4 per cent carbon dioxide, 1.8 oxygen, 0.1 carbon monoxide, and 75.7 per cent nitrogen.

The water vapor carried by the kiln gases came from the air, from the kiln feed, and from combustion of the fuel. That from the air was calculated from the amount of dry air admitted, previously found, and the relative humidity value found in the kiln room air, giving 82 pound-moles. The water vapor from the kiln feed was 223 pound-moles and that resulting from combustion of the fuel was 824 pound-moles. Adding these three quantities, the total water vapor in the kiln gases was found to be 1129 pound-moles.

Converting the number of pound-moles of each constituent in the kiln gases to pounds and adding the values so obtained

indicated 301,400 pounds of dry kiln gases and 20,320 pounds of water vapor, or a total weight of moist kiln gases of 321,700 pounds. The weight of incoming moist air, similarly calculated, was 264,000 pounds.

We are now in a position to strike a material balance. The following table shows such a balance between ingoing and outgoing streams of materials:

———Ingoing Materials———			———Outgoing Materials———		
	Pounds	Per cent		Pounds	Per cent
Fuel	18,445	4.5	Clinker	79,670	19.6
Kiln feed	124,300	30.6	Treater dust	4,830	1.2
Moist air	264,000	64.9	Stack dust	820	0.2
			Moist kiln gases	321,700	79.0
Total	406,700		Total	407,000	

It is interesting to note the large percentage of the ingoing materials contributed by air entering the lower end of the kiln and the even larger percentage which the kiln gases represent in the outgoing materials. The discrepancy of 300 pounds (< 0.1 per cent) between ingoing and outgoing totals is fortuitously much smaller than the probable error.

Heat Balance Calculations

For the purposes of heat balance calculations an arbitrary datum temperature of 60° F. has been chosen. This was the temperature of the air in the kiln room, and for this reason the incoming air stream carried with it no sensible heat when considered from this datum. The sources of heat supplied to the kiln were the heat produced by combustion of the fuel, the sensible heat of the preheated fuel, and the sensible heat of the kiln feed. The heat of combustion of the fuel was obtained from the fuel weight and its gross calorific value, being equal to 340,300,000 B. t. u. The sensible heat of the fuel was obtained from its weight, the difference between its temperature and datum temperature, and its specific heat which was taken as 0.40, the calculation giving 870,000 B. t. u. Consultation of International Critical Tables indicated the most probable value of the specific heat of the kiln feed between 60° and 176° F. to be 0.20 B. t. u. per pound per ° F. Using this value, the sensible heat carried in by the kiln feed was found to be 2,880,000 B. t. u. Thus, the total heat input was 344,100,000 B. t. u. for the 7-hour period under consideration.

During the calcining and clinkering processes taking place in the kiln there are several reactions involving heat effects. Dehydration of clay is an endothermic process. For clays cited by International Critical Tables of similar moisture content to that used in the kiln feed under consideration, the heat requirement for dehydration is 4000 B. t. u. per pound of water removed. This value corresponds closely with that chosen by Pike (4). Using this figure with the known water content of the kiln feed, the heat absorption for clay dehydration was 15,910,000 B. t. u.

Heat is absorbed in decomposing calcium carbonate and magnesium carbonate, to form calcium oxide and magnesium oxide. In the present case it was not known how much of the carbon dioxide of the kiln feed was combined with calcium oxide and how much with magnesium oxide. It was therefore assumed that the number of moles of calcium carbonate and of magnesium carbonate were proportional to the moles of calcium oxide and magnesium oxide given in the kiln feed analysis. On the basis of this assumption and the known amount of carbon dioxide present, there were found to be 85 pound-moles of magnesium carbonate and 737 pound-moles of calcium carbonate. Using 50,000 B. t. u. per pound-mole as the heat of decomposition of magnesium carbonate and 76,500 B. t. u. per pound-mole for that of calcium carbonate, the heat required for decomposition of the carbonates was 60,640,000 B. t. u.

During the recombination of the oxides constituting the kiln charge to form the various cement compounds, an exothermic reaction occurs. This heat evolution amounts to approximately 150 B. t. u. per pound of clinker produced (4), or a total of 11,950,000 B. t. u. The net heat absorption for carrying on the various reactions in the kiln was 15,910,000 + 60,640,000 − 11,950,000 = 64,600,000 B. t. u.

The hot clinker falling from the lower end of the kiln and the gas stream leaving the upper end of the kiln carry out heat, owing to their high temperatures. Harrison (1) gives sensible heat curves for Portland cement clinker at various temperatures. From these data (the observed temperature and the weight of outgoing clinker) the sensible heat carried out in this material was 46,850,000 B. t. u. Using molal heat capacity equations (3) corresponding to the different constituents of the kiln gases, their molal composition as previously calculated, the total quantity, and the exit temperature, the sensible heat of these moist exit gases was calculated to be 166,500,000 B. t. u. The carbon monoxide in the kiln gases represents a loss of potential heat of combustion which was calculated, from the quantity of this constituent present and a pound-molal heat of combustion of 122,400 B. t. u. (5), to be 1,160,000 B. t. u. Since the gross heating value of the fuel was used, the outgoing kiln gases also carry out a quantity of latent heat corresponding to that obtainable by condensing at 60° F. the water formed by the combustion process. This latent heat quantity was 15,700,000 B. t. u.

The remaining way in which heat could leave the kiln was by conduction through the walls. The amount of heat thus lost during the test period was estimated by determining the rate of heat loss at the thermocouple stations A to H (Figure 1), using the temperature difference between the outer and inner couples in the refractory bricks, the distance between the junctions, and the thermal conductivity of the refractory materials, plotting from them a rate distribution curve for the length of the kiln to obtain a mean value and multiplying this value by the mean of the interior and exterior refractory surface areas and by the time. This calculation resulted in a value for the total loss of heat through the kiln walls of 28,650,000 B. t. u. The various amounts of heat entering and leaving the kiln are summarized in the heat balance presented in Table I. The large amount of heat lost in the high-temperature exit gases from this short kiln indicates the desirability of waste heat boilers for power development if such operating conditions as were followed during the test period were to be continued.

Acknowledgment

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