Technical Publication

Heat Balance Arithmetic – The Boiler Efficiency Yardstick

by

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HEAT BALANCE ARITHMETIC -
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Direct measurement of fuel input and steam output is one method commonly used to determine boiler efficiency. Given such data, efficiency is directly calculated by dividing the total steam energy output of the boiler by the total fuel energy consumed. It is usually difficult to measure fuel input with a high degree of accuracy. So while this method is an indicator of boiler efficiency for existing boilers, it obviously cannot be applied for purposes of prediction or comparison involving boilers yet to be constructed. For these purposes, heat balance calculation is a practical and flexible method. The heat balance calculation will give us boiler efficiency for any combination of fuel, excess air, and boiler exit temperature we wish to consider.

The first step is to run a chemical analysis of the fuel and determine air and gas weights for one pound of coal. Table 1 gives fuel combustion constants for the more common fuel constituents.

So let us assume an Illinois coal with an ultimate analysis of 12% moisture, 61.8% carbon, 4.3% hydrogen, 7.9% oxygen, 1.2% nitrogen, 3.8% sulfur, and 9% ash. The heating value is given as 11,200 Btu/pound. Table 2 indicates the data avilable from the chemical analysis and the fuel constants. At 50% excess air (12.37% CO_2 by volume) we have

12.8 pounds of air per pound of fuel
13.71 pounds of wet gas per pound of fuel
0.504 pounds of water from fuel moisture and fuel hydrogen
0.164 pounds of water from air
13.042 pounds of dry gas per pound of fuel.

If we have a gas temperature leaving the boiler of 600° F and room temperature or entering air temperature of 80° F, we are ready for the heat balance calculations.

1. The dry flue gas loss is:

$$\frac{\text{(lbs. of gas) (specific heat) (stack temp. - room temp.) } 100}{\text{Btu in fuel}}$$

$$\frac{(13.042)\ (.24)\ (600 - 80)\ 100}{11{,}200} = 14.53\%$$

2. The fuel H_2 and fuel moisture loss is:

$$\frac{\text{(lbs. of water) (vapor enthalpy, stack temp. - liquid enthalpy, room temp) } 100}{\text{Btu in fuel}}$$

$$\frac{(.504)\ (1336 - 48)\ 100}{11{,}200} = 5.80\%$$

3. The air moisture loss is:

$$\frac{\text{(lbs. of air moisture) (specific heat) (stack temp. - room temp.) 100}}{\text{Btu in fuel}}$$

$$\frac{(0.164)\ (.46)\ (600 - 80)\ 100}{11{,}200} \qquad = \qquad 0.35\%$$

4. The carbon loss is:

$$\frac{\text{(\% combustible in ash)}}{\text{(\% incombustible in ash)}}\ \frac{\text{(\% ash in coal) 14,093}}{\text{Btu in fuel}}$$

$$\frac{\text{(assuming 12)}}{88}\ \frac{(9)\ 14{,}093}{11{,}200} \qquad = \qquad 1.54$$

5. Radiation, a function of unit size, assumed = 0.50

6. Miscellaneous losses and margin, assumed, = 1.50

Total losses	24.22
Therefore efficiency is	75.78

We are now in a position to answer all kinds of questions about operation of the unit.

A. Suppose we cut excess air from 50% to 30%

Excess air	50%	30%
Lbs. wet air per lb. of fuel	12.800	11.093
Lbs. gas	13.710	12.003
Lbs. air H_2O	0.164	0.142
Lbs. H_2 and Fuel H_2O	0.504	0.504
Lbs. dry gas	13.042	11.357
Stack temperature	600	600
Stack - room, ΔT	520	520
Fuel water vapor ΔH	1,288	1,288

HEAT BALANCE %

Loss due to dry flue gas	14.53	12.65
Loss due to hydrogen & fuel moisture	5.80	5.80
Loss due to moisture in air	.35	.30
Loss due to radiation	.50	.50
Loss due to unburned combustibles	1.54	1.54

Manufacturer's margin	1.50	1.50
Total losses	24.22	22.29
Efficiencies of complete unit	75.78	77.71

And we have gained almost 2% in efficiency!

B. Suppose we have a cold day and entering air temp. is 40° F.

Excess air	50%	50%
Lbs. wet air	12.800	12.800
Lbs. gas	13.710	13.710
Lbs. air H_2O	0.164	0.164
Lbs. H_2 and Fuel H_2O	0.504	0.504
Lbs. dry gas	13.042	13.042
Air temperature	80	40
Stack temperature	600	600
Stack - room, ΔT	520	560
Fuel water vapor, ΔH	1,288	1,328

HEAT BALANCE %

Loss due to dry flue gas	14.53	15.65
Loss due to hydrogen & fuel moisture	5.80	5.98
Loss due to moisture in air	.35	.38
Loss due to radiation	.50	.50
Loss due to unburned combustibles	1.54	1.54
Manufacturer's margin	1.50	1.50
Total losses	24.22	25.55
Efficiencies of complete unit	75.78	74.45

And we have lost 1-1/3% in efficiency!

C. Suppose we have very wet coal to contend with.

Fuel moisture	12%	20%
Btu/lb.	11,200	10,182
Excess air	50%	50%
Lbs. wet air	12.800	11.636
Lbs. gas	13.710	12.554

Lbs. air H_2O	.164	.149
Lbs. H_2 and Fuel H_2O	.504	.549
Lbs. dry gas	13.042	11.856
Stack temperature	600	600
Stack - room, ΔT	520	520
Fuel water vapor ΔH	1,288	1,288

HEAT BALANCE %

Loss due to dry flue gas	14.53	14.53
Loss due to hydrogen & fuel moisture	5.80	6.94
Loss due to moisture in air	.35	.35
Loss due to radiation	.50	.50
Loss due to unburned combustibles	1.54	1.54
Manufacturer's margin	1.50	1.50
Total losses	24.22	25.36
Efficiencies of complete unit	75.78	74.64

And we have lost more than a percent in efficiency!

D. Suppose the weighted average combustible in the total ash goes from 12% to 24%

Carbon loss is $\frac{24}{76} \times 9 \times \frac{14{,}093}{11{,}200} = 3.58$ and we have lost 2% in efficiency!

E. Suppose we add heat recovery equipment and cut the stack temperature from 600° F to 350° F, both with and without excess air reduction from 50% to 30%.

Stack temperature	600	350	350
Flue gas - air ΔT	520	270	270
Fuel water ΔH	1,288	1,171	1,171
Excess air	50	50	30
Lbs. wet air	12.800	12.800	11.093
Lbs. gas	13.710	13.710	12.003
Lbs. air H_2O	0.164	0.164	0.142
Lbs. H_2 and Fuel H_2O	0.504	0.504	0.504
Lbs. dry gas	13.042	13.042	11.357

HEAT BALANCE %

Loss due to dry flue gas	14.53	7.55	6.57
Loss due to hydrogen & fuel moisture	5.80	5.27	5.27
Loss due to moisture in air	.35	.18	.16
Loss due to radiation	.50	.50	.50
Loss due to unburned combustibles	1.54	1.54	1.54
Manufacturer's margin	1.50	1.50	1.50
Total losses	24.22	16.54	15.54
Efficiencies of complete unit	75.78	83.46	84.46

So the 250 degree drop in exit temperature yields 7.68% efficiency gain with an extra percent if we also drop the excess air. Perhaps we should point out that moving the efficiency up from 75.78 to 84.46, 8.68 percent efficiency gain is more than an 8.68% fuel reduction. The new fuel requirement would be 75.78/84.46ths and this is a fuel saving of 10.3%.

F. And finally suppose we substitute a sub-bituminous 30% moisture, 5% ash, 49% carbon, 11.6% oxygen, 0.4% sulfur, 0.6% nitrogen, 3.4% hydrogen, 8,100 Btu/lb. coal for the 11,200 Btu Illinois Coal. If we use the 30% excess air and 350° F, alternate 375, gas stack temperature, the heat balance is as follows. (See Table 3 for fuel calculation)

Fuel	Illinois	Sub-bituminous	
Btu/lb.	11,200	8,100	8,100
Excess air	30	30	30
Lbs. wet air	11.093	8.339	8.339
Lbs. gas	12.003	9.289	9.289
Lbs. air H_2O	0.142	0.107	0.107
Lbs. H_2 and Fuel H_2O	0.504	0.604	0.604
Lbs. dry gas	11.357	8.578	8.578
Stack temperature	350	350	375
Gas out - air in ΔT	270	270	295
Fuel water ΔH	1,171	1,171	1,182

HEAT BALANCE %

Loss due to dry flue gas	6.57	6.86	7.50
Loss due to hydrogen & fuel moisture	5.27	8.73	8.81
Loss due to moisture in air	0.16	0.16	0.18
Loss due to radiation	0.50	0.50	0.50
Loss due to unburned combustibles	1.54*	1.19*	1.19
Manufacturer's margin	1.50	1.50	1.50
Total losses	15.54	18.94	19.68
Efficiencies of complete unit	84.46	81.06	80.32

*12% carbon in ash

Efficiency drops 3.4% with the sub-bituminous coal assuming we could maintain 350 stack temperature, and drops 4.14% if extra gas flow raises the stack temperature 25 degrees.

The heat balance method of efficiency calculation is a very useful tool to estimate boiler performance for alternate fuels, alternate modes of operation, and alternate heat-recovery equipment possibilities. We should apply this yardstick whenever possible.

TABLE .

FUEL COMBUSTION CONSTANTS

RILEY STOKER CORPORATION

CONSTITUENT	(1) CHEMICAL FORMULA	(2) MOLECULAR WEIGHT	(3) LBS PER CU. FT.	(4) BTU PER CU.FT.(GROSS)	(5) BTU PER LB. (GROSS)	(6) LBS. C/LB. CONSTITUENT	(7) LBS. H_2/LB. CONSTITUENT	(8) LBS/LB OF COMBUSTIBLE: AIR REQ'D FOR COMBUSTION	(9) LBS/LB OF COMBUSTIBLE: FLUE PRODUCTS CO_2	(10) LBS/LB OF COMBUSTIBLE: FLUE PRODUCTS H_2O	(11) LBS/LB OF COMBUSTIBLE: FLUE PRODUCTS N_2
METHANE	CH_4	16.043	.04249	1015.3	23896	0.7487	0.2513	17.265	2.744	2.246	13.275
ETHANE	C_2H_6	30.070	.07965	1774.8	22282	0.7988	0.2012	16.119	2.927	1.798	12.394
PROPANE	C_3H_8	44.097	.11680	2513.9	21523	0.8171	0.1829	15.703	2.994	1.634	12.074
n - BUTANE	C_4H_{10}	58.124	.15396	3301.1	21441	0.8266	0.1734	15.487	3.029	1.550	11.908
ISO - BUTANE	C_4H_{10}	58.124	.15396	3272.7	21257	0.8266	0.1734	15.487	3.029	1.550	11.908
N - PENTANE	C_5H_{12}	72.151	.19111	4215.5	22058	0.8323	0.1677	15.353	3.050	1.498	11.805
ISO PENTANE	C_5H_{12}	72.151	.19111	4023.2	21052	0.8323	0.1677	15.353	3.050	1.498	11.805
NEO PENTANE	C_5H_{12}	72.151	.19111	4007.6	20970	0.8323	0.1677	15.353	3.050	1.498	11.805
N - HEXANE	C_6H_{14}	86.178	.22827	4780.0	20940	0.8362	0.1638	15.266	3.064	1.464	11.738
HEPTANE	C_7H_{16}	99.197	.26275	5429.5	20664	0.8390	0.1610	15.201	3.074	1.438	11.688
ETHYLENE	C_2H_4	28.054	.07431	1608.6	21647	0.8563	0.1437	14.807	3.138	1.285	11.385
PROPYLENE	C_3H_6	42.081	.11146	2392.4	21464	0.8563	0.1437	14.807	3.138	1.285	11.385
N - BUTENE	C_4H_8	56.108	.14862	3203.1	21552	0.8563	0.1437	14.807	3.138	1.285	11.385
ISO - BUTENE	C_4H_8	56.108	.14862	3193.0	21484	0.8563	0.1437	14.807	3.138	1.285	11.385
N - PENTENE	C_5H_{10}	70.135	.18577	4012.6	21600	0.8563	0.1437	14.807	3.138	1.285	11.385
BENZENE	C_6H_6	78.114	.20691	3945.4	19068	0.9226	0.0774	13.297	3.381	0.692	10.224
TOLUENE	C_7H_8	92.141	.24406	4768.2	19537	0.9125	0.0875	13.527	3.344	0.782	10.401
XYLENE	C_8H_{10}	106.168	.28122	5244.8	18650	0.9051	0.0949	13.695	3.317	0.849	10.530
ACETYLENE	C_2H_2	26.038	.06897	1472.1	21344	0.9226	0.0774	13.297	3.381	0.692	10.224
NAPHTHALENE	$C_{10}H_8$	128.174	.33951	5872.8	17298	0.9371	0.0629	12.964	3.434	0.562	9.968
METHYL ALCOHOL	CH_3OH	32.043	.08488	870.8	10259	0.3870	0.0974	6.482	1.374	1.125	4.984
ETHYL ALCOHOL	C_2H_5OH	46.070	.12203	1606.0	13161	0.5214	0.1313	9.018	1.922	1.170	6.934
AMMONIA	NH_3	17.032	.04511	436.1	9668		0.1775	6.097		1.587	5.511
HYDROGEN SULFIDE	H_2S	34.082	.09028	641.0	7100		0.0591	6.097	*1.880	0.529	4.688
SULFUR DIOXIDE	SO_2	64.066	.16970								
CARBON MONOXIDE	CO	28.011	.07420	320.8	4323	0.4288		2.471	1.571		1.900
CARBON DIOXIDE	CO_2	44.011	.11658			0.2729			1.000		
WATER VAPOR	H_2O	18.016	.04772							1.000	
NITROGEN	N_2	28.016	.07421								1.000
HYDROGEN	H_2	2.016	.00534	325.7	60991		1.0000	34.344		8.937	26.407
OXYGEN	O_2	32.000	.08476					-4.310			-3.310
SULFUR	S	32.066			3983			4.285	*1.998		3.287
CARBON	C	12.011			14093	1.0000		11.527	3.664		8.863
AIR		28.9	.07655								

* SO_2

CO_2 - 8.58 CU. FT./LB
O_2 - 11.80 CU.FT./LB
N_2 - 13.48 CU.FT./LB.

AIR - 20.9% O_2 + 79.1% N_2 by VOL.
23.13% O_2 + 76.87% N_2 by WT.

ALL GAS VOLUMES CORRECTED TO 60 F AND 30 IN. HG.

TABLE 2

ILLINOIS COAL FUEL - 11,200 BTU

FUEL		POUNDS PER POUND OF FUEL							
Formula	Weight	DRY AIR REQUIRED		FLUE PRODUCTS					
				CO_2		H_2O		N_2	
H_2O	.120		0		0	1.000	.120		0
C	.618	11.527	7.124	3.664	2.265		0	8.863	5.477
H_2	.043	34.344	1.477		0	8.937	.384	26.407	1.136
O_2	.079	- 4.310	- .340		0		0	- 3.310	- .261
N_2	.012		0		0		0	1.000	.012
S	.038	4.285	.163	1.998	.076		0	3.287	.125
Ash	.090		0		0		0		0
Totals	1.000		8.424		2.341		0.504		6.489

CO_2	2.341
H_2O	0.504
N_2	6.489
Ash	0.090
	9.424
Air	8.424
Fuel	1.000
	9.424

Excess Air	0	10	20	30	40	50	60	24.1
Dry air - lbs.	0	0.842	1.685	2.527	3.370	4.212	5.054	2.029
CO_2 - lbs.	2.341	2.341	2.341	2.341	2.341	2.341	2.341	2.341
N_2 - lbs.	6.489	6.489	6.489	6.489	6.489	6.489	6.489	6.489
Dry flue gas	8.830	9.672	10.515	11.357	12.200	13.042	13.884	10.859
Fuel H_2O	.504	.504	.504	.504	.504	.504	.504	.504
Air H_2O	.110	.120	.131	.142	.153	.164	.175	.136
Wet flue gas	9.444	10.297	11.150	12.003	12.857	13.710	14.563	11.499
Wet air	8.534	9.387	10.240	11.093	11.947	12.800	13.653	10.589
Air volume	0	11.0	22.0	33.0	44.0	55.0	66.0	26.5
CO_2 volume	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1
N_2 volume	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4
Dry gas volume	107.5	118.5	129.5	140.5	151.5	162.5	173.5	134.0
% CO_2	18.70	16.96	15.52	14.31	13.27	12.37	11.58	15.00

Dry Air - 13.06 cu. ft. per lb.
CO_2 - 8.58 cu. ft. per lb.
N_2 - 13.48 cu. ft. per lb.

TABLE 3

SUB-BITUMINOUS COAL FUEL - 8,100 BTU

FUEL		POUNDS PER POUND OF COMBUSTIBLES							
Formula	Weight	DRY AIR REQUIRED		FLUE PRODUCTS					
				CO_2		H_2O		N_2	
H_2O	.300		0		0	1.000	.300		0
C	.490	11.527	5.648	3.664	1.795		0	8.863	4.343
H_2	.034	34.344	1.168		0	8.937	.304	26.407	.898
O_2	.116	- 4.310	- .501		0		0	- 3.310	- .385
N_2	.006		0		0		0	1.000	.006
S	.004	4.285	.017	1.998	.008		0	3.287	.013
Ash	.050		0		0		0		0
Totals	1.000		6.332		1.803		.604		4.875