# Correctly Modeling and Calculating Combustion Efficiencies
# In
# Fired Equipment

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Fired equipment includes furnaces, fired heaters, fired boilers, supplementary fired boilers, and many other types of equipment. But for the purposes of reviewing how the calculations are accomplished and other factors that may affect the results of the modeling, we will use a fired reformer furnace as our example.  All of the methods and issues discussed herein can be applied to any fired equipment.

We will start with the combustion calculation which is necessary to calculate the properties of the flue gas, or the products of combustion as well as heat available from the combustion process.  The chemical reaction formula for combustion is well known, but varies with the composition of the fuel being used, and can be very complicated if the fuel has many components.  As an example, we look at a simple combustion of methane, $CH_4$ in Oxygen, $O_2$.

$$CH_4 + 2O_2 \ \text{---} > CO_2 + 2H_2O$$
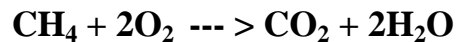
The oxidant in most cases is normally air, but may be other gases such as Gas Turbine Exhaust, or other products of combustion.  If it is air, the wet composition may be similar to the following, in mole %.

| | |
|---|---|
| Nitrogen, N2 | 77.4560 |
| Oxygen, O2 | 20.9108 |
| Carbon Dioxide,CO2 | 0.0299 |
| Water, O2 | 0.3772 |
| Argon, Ar | 0.9364 |

The actual composition of the oxidant will vary depending on the elevation, humidity and temperature at the site you are modeling.  Even though Sulphur Dioxide and Carbon Monoxide are not normally considered to be in atmospheric air, your calculations should allow for these since the equipment may be using products of combustion from another piece of equipment.  Dry air should not be used in combustion calculations because this rarely exists.

For a combustion calculation, you need to know the composition of the fuel and the oxidant.  To perform the combustion calculation you could use a computer software program such as WinBurn, or one of many calculators available on the internet.  However, to make combustion calculations or test equipment for purposes of determining the efficiency of the combustion process, it is better to setup a simple excel work sheet to perform the calculations.

For Liquid Fuels, the Excel sheet may be setup:

| | **Fuel # 1:** | Fuel Oil | **Resulting Composition;** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Component Name | Wt% | Fuel MW | N2 | O2 | CO2 | H2O | Ar | SO2 | CO |
| Sulphur | 0.50 | 32.0640 | 0.000 | -0.998 | 0.000 | 0.000 | 0.000 | 1.998 | 0.000 |
| Hydrogen | 12.80 | 2.0158 | 0.000 | -7.937 | 0.000 | 8.937 | 0.000 | 0.000 | 0.000 |
| Carbon | 86.70 | 12.0112 | 0.000 | -2.664 | 3.664 | 0.000 | 0.000 | 0.000 | 0.000 |
| Nitrogen | 0.00 | 28.0160 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Oxygen | 0.00 | 32.0000 | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Water | 0.00 | 18.016 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 |
| Total | | | 0.0000 | -3.3307 | 3.1768 | 1.1439 | 0.0000 | 0.0100 | 0.0000 |

| | | |
|---|---|---|
| Lower Heating Value, Btu/lb | 18,390 | |
| Fuel Specific heat, Btu/lb-°F | 0.0000 | |
| Atomizing Medium | MECH | MECH (Mechanical), STM (Steam), or AIR |

| | | Air/Steam Pressure, psig | 0.0000 | | |
|---|---|---|---|---|---|

Air/Steam Pressure, psig     0.0000

Injection Rate,
lb/lb     0.0000

| Fuel | Fuel # 1 | Units |
|---|---|---|
| Flow | 1,393.000 | lb/hr |
| Temperature | 60.00 | °F |
| Heat Avail. From Fuel(Datum: 60°F), Btu/hr | 0 | |
| Air/Fuel Ratio, lb/lb @ 0 % Ex. Air | 14.4595 | |
| Excess Air, % | 0.450 | |
| Air Flow, lbs/hr | 20,233 | |
| Fluegas Flow, lbs/hr | 21,626 | |
| Heat Avail. From Combustion of Fuel, Btu/hr | 25,617,270 | |

Notice that with Liquid Fuels, the Lower Heating Value is normally determined by laboratory testing and so it need not be calculated on this sheet, and is an input by user.

For a Gas Fuel, the Excel sheet may be setup:

| Component Name | Component | Mole % | Mol%*MW | Wt% | LHV, Btu/lb | Fuel MW | LHV, Btu/scf | N2 | O2 | CO2 | H2O | Ar | SO2 | CO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gas # 1: | Natural Gas | | | | | | Resulting Composition; | | | | | | |
| Methane | CH4 | 95.6300 | 1,534.0965 | 91.6095 | 21,520 | 16.042 | | 0.000 | -3.990 | 2.743 | 2.246 | 0.000 | 0.000 | 0.000 |
| Ethane | C2H6 | 1.5500 | 46.6054 | 2.7831 | 20,432 | 30.068 | | 0.000 | -3.725 | 2.927 | 1.798 | 0.000 | 0.000 | 0.000 |
| Propane | C3H8 | 0.1900 | 8.3779 | 0.5003 | 19,944 | 44.094 | | 0.000 | -3.629 | 2.994 | 1.634 | 0.000 | 0.000 | 0.000 |
| N-Butane | N-C4H10 | 0.0400 | 2.3248 | 0.1388 | 19,680 | 58.120 | | 0.000 | -3.579 | 3.029 | 1.550 | 0.000 | 0.000 | 0.000 |
| I-Butane | I-C4H10 | 0.0000 | 0.0000 | 0.0000 | 19,629 | 58.120 | | 0.000 | -3.579 | 3.029 | 1.550 | 0.000 | 0.000 | 0.000 |
| N-Pentane | N-C5H12 | 0.0200 | 1.4429 | 0.0862 | 19,517 | 72.146 | | 0.000 | -3.548 | 3.050 | 1.498 | 0.000 | 0.000 | 0.000 |
| I-Pentane | I-C5H12 | 0.0000 | 0.0000 | 0.0000 | 19,478 | 72.146 | | 0.000 | -3.548 | 3.050 | 1.498 | 0.000 | 0.000 | 0.000 |
| Hexane | C6H14 | 0.0000 | 0.0000 | 0.0000 | 19,403 | 86.172 | | 0.000 | -3.528 | 3.064 | 1.463 | 0.000 | 0.000 | 0.000 |
| Carbon Monoxide | CO | 0.0000 | 0.0000 | 0.0000 | 4,347 | 28.010 | | 0.000 | -0.571 | 1.571 | 0.000 | 0.000 | 0.000 | 0.000 |
| Hydrogen | H2 | 0.0000 | 0.0000 | 0.0000 | 51,623 | 2.016 | | 0.000 | -7.937 | 0.000 | 8.937 | 0.000 | 0.000 | 0.000 |
| Nitrogen | N2 | 1.9600 | 54.9114 | 3.2791 | 0 | 28.016 | | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Carbon Dioxide | CO2 | 0.6100 | 26.8461 | 1.6031 | 0 | 44.010 | | 0.000 | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Carbon | C | 0.0000 | 0.0000 | 0.0000 | 14,093 | 12.010 | | 0.000 | -2.664 | 3.664 | 0.000 | 0.000 | 0.000 | 0.000 |
| Sulphur | S | 0.0000 | 0.0000 | 0.0000 | 3,983 | 32.060 | | 0.000 | -0.998 | 0.000 | 0.000 | 0.000 | 1.998 | 0.000 |
| Ethylene | C2H4 | 0.0000 | 0.0000 | 0.0000 | 20,295 | 28.052 | | 0.000 | -3.422 | 3.138 | 1.284 | 0.000 | 0.000 | 0.000 |
| Propylene | C3H6 | 0.0000 | 0.0000 | 0.0000 | 19,691 | 42.078 | | 0.000 | -3.422 | 3.138 | 1.284 | 0.000 | 0.000 | 0.000 |
| N-Butene | N-C4H8 | 0.0000 | 0.0000 | 0.0000 | 19,496 | 56.104 | | 0.000 | -3.422 | 3.138 | 1.284 | 0.000 | 0.000 | 0.000 |
| Benzene | C6H6 | 0.0000 | 0.0000 | 0.0000 | 17,480 | 78.108 | | 0.000 | -3.073 | 3.381 | 0.692 | 0.000 | 0.000 | 0.000 |
| Water | H2O | 0.0000 | 0.0000 | 0.0000 | 0 | 18.016 | | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 |
| Oxygen | O2 | 0.0000 | 0.0000 | 0.0000 | 0 | 32.000 | | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Hydrogen Sulfide | H2S | 0.0000 | 0.0000 | 0.0000 | 6,545 | 34.076 | | 0.000 | -1.409 | 0.000 | 0.529 | 0.000 | 1.880 | 0.000 |
| Argon | Ar | 0.0000 | 0.0000 | 0.0000 | 0 | 39.950 | | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 | 0.000 |
| Ammonia | NH3 | 0.0000 | 0.0000 | 0.0000 | 7,987 | 17.031 | | 0.823 | -1.409 | 0.000 | 1.587 | 0.000 | 0.000 | 0.000 |
| Sulphur Dioxide | SO2 | 0.0000 | 0.0000 | 0.0000 | 0 | 64.060 | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 0.000 |
| | Total | 100.0000 | 1,674.6049 | 100.0000 | 20,427 | 16.746 | 900.89 | 0.0328 | -3.7846 | 2.6326 | 2.1193 | 0.0000 | 0.0000 | 0.0000 |

| Gas | | Gas # 1 |
|---|---|---|
| Gas Flow, lbs/hr | | 19,313.000 |
| Temperature. °F | | 352.00 |
| Heat Avail. From Gas(Datum: 60°F), Btu/hr | | 3,167,628 |
| Air/Fuel Ratio, lb/lb @ 0 % Ex. Air | | 16.3614 |
| Excess Air, % | | 10.970 |
| Air Flow, lbs/hr | | 350,651 |
| Fluegas Flow, lbs/hr | | 369,964 |
| Heat Avail. From Combustion of Gas, Btu/hr | | 394,504,859 |

In the Excel tables above, we have columns for the resulting composition factor.  In these columns, if the molecule is not changed by the reaction, the factor is simply a 1.0 in the appropriate column.  But for the Methane molecule, since the chemical reaction formula indicates it takes two molecules of $O_2$ for the reaction, then the factor is two molecules of Oxygen/one molecule of $CH_4$ or $2*32/16.042$ and it is negative because it eliminates the $O_2$ molecule.  Likewise factor in the CO2 column for CH4 would be one molecule of $CO_2$/one molecule of $CH_4$ or $44.01/16.042$.  All of the remaining rows and columns are populated in a similar manner.  The table may have as many or as few as the composition for the particular fuel.

The total of each column in the table would be equal to the sum of the weight fraction of the component times the factor. For the heat available from the combustion, we are using the LHV values, which are typical for Fired Heater efficiency calculations, where for boilers the HHV values are typically used.

The Air/Fuel Ratio, lb/lb @ 0% Excess air is the absolute value of the ratio of the O2 Factor/Weight fraction of O2 in the oxidant. So if we use the Wet Air composition from above, we can create a table for the oxidant or combustion air similar to below:

**Combustion Air:**

| Component | Mole % | Wt Frac | Air MW | | |
|---|---|---|---|---|---|
| | | | | Air Temp, °F | 310.380 |
| N2 | 77.7456 | 0.7529 | 28.016 | Air Enth, Btu/lb | 60.698 |
| O2 | 20.9108 | 0.2313 | 32.000 | Air Heat, Btu/hr | 21,283,821 |
| CO2 | 0.0299 | 0.0005 | 44.010 | | |
| H2O | 0.3772 | 0.0023 | 18.016 | | |
| Ar | 0.9364 | 0.0129 | 39.950 | | |
| SO2 | 0.0000 | 0.0000 | 64.060 | | |
| CO | 0.0000 | 0.0000 | 28.010 | | |
| | | | | Air Flow, ACFM | 119,753 |
| Total | 99.9999 | | 28.928 | | |

The weight fractions may be calculated by dividing the product of the component moles times the molecular weight/sum of all the moles multiplied by the molecular weights.

The excess air % is an expression used to describe the additional air above that is required for stoichiometric combustion on a weight basis. Another way to describe this excess air is by wet or dry volume of $O_2$ % in the products of combustion (fluegas). Most handheld measuring devices measure the dry volume %, where many mounted devices measure the wet volume %. To see what a resulting value of $O_2$ is present in the fluegas, we need to create another table similar to below:

**Fluegas:**

| Component | Lbs | Wt Frac | Mole % | | | | |
|---|---|---|---|---|---|---|---|
| N2 | 13.7035 | 0.7154 | 71.0958 | | | | |
| O2 | 0.4152 | 0.0217 | 1.8858 | Dry O2 % | 2.2842 | Wet O2 % | 1.8858 |
| CO2 | 2.6408 | 0.1379 | 8.7218 | | | | |
| H2O | 2.1619 | 0.1129 | 17.4423 | | | | |
| Ar | 0.2348 | 0.0123 | 0.8543 | | | | |

| | | | |
|---|---|---|---|
| SO2 | 0.0000 | 0.0000 | 0.0000 |
| CO | 0.0000 | 0.0000 | 0.0000 |
| Total | 19.1562 | 1.0000 | 100.0000 |
| Flow, lb/hr | | 369,964 | |
| Temp, °F | | 1650 | |
| Enthalpy, Btu/lb | | 460.85 | |

For N2 component burning the gas fuel in above table, Lbs Factor = 0.0328 + 0.7529 * 16.3614*(1 + 10.970/100) =  13.7035, and similar for other components. And then using these factors, the weight fraction and mole % can be calculated.

Of course, you could calculate based on a measured $O_2$ such as when testing a furnace, or if you have your tables set up as above, simply change the excess air until the Measured $O_2$ and calculated $O_2$ are equal.

If you have multiple fuels, just add fuel tables for each fuel; then add resulting composition factors to get the mixed fuel results.

Now that we have reviewed how to do the combustion calculations, we know if we get the fuel compositions and the fuel flow, we can calculate how much heat is released along with the flue gas flow and composition, once we determine the excess air or Oxygen in the fluegas. Traditionally, this is done by taking a sample in the furnace stack.  While this indeed will give you an overall assessment of the furnace operation, it will not help you determine if there are combustion problems, nor will it necessarily tell you what the correct efficiency is for the unit.

Rather than use an example of a simple fired heater, let's take as our example a reformer system that is typical of many in the hydrogen and ammonia plants.  This example will help us see all the pitfalls in performing combustion and efficiency calculations.  A schematic of our example is as shown below.

It is important that all burners be on during a field test for combustion and efficiency.  If burners are turned off, they should be repaired as necessary and re-lit prior to testing.
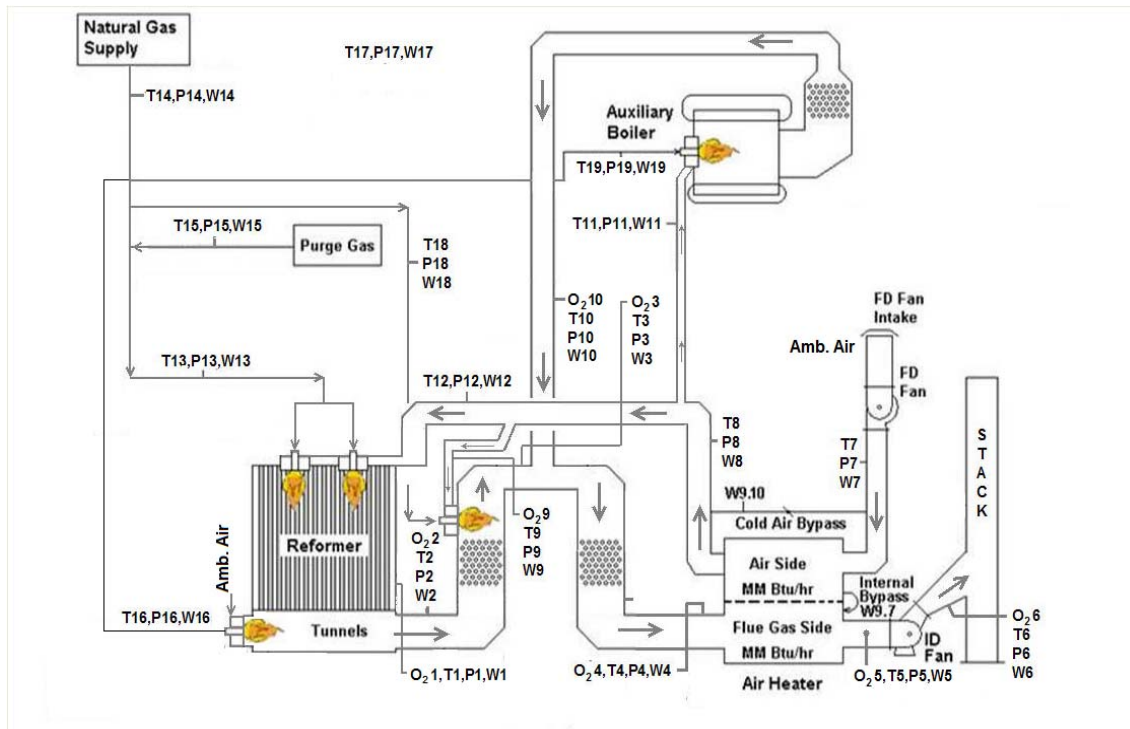


In this example, we have a reformer fired with two fuels, and preheated air in the arch burners.

The tunnel burners are fired with one fuel and ambient air.  The superheater burners are fired with one fuel but with preheated air, and the auxiliary boiler is also fired with one fuel and preheated air.

On the day of our test, the ambient temperature was 60 °F with a relative humidity of 40% and the plant is at a 1200 foot elevation.  Using this data with standard air, we calculate the wet air composition to be as follows.

**Air:**

| Component | Mole % | Wt Frac | Air MW |
|---|---|---|---|
| N2 | 77.4714 | 0.7512921 | 28.016 |
| O2 | 20.8371 | 0.2308068 | 32.000 |
| CO2 | 0.0298 | 0.000454 | 44.010 |
| H2O | 0.7286 | 0.0045437 | 18.016 |
| Ar | 0.9331 | 0.0129035 | 39.950 |
| SO2 | 0.0000 | 0 | 64.060 |
| CO | 0.0000 | 0 | 28.010 |
| Total | 100.0000 | | 28.889 |

Our physical examination and walk through of the unit, revealed that the unit has 260 tubes, and the tube seals at the arch consist of a plate with a hole 1/8 " larger than the tube OD, so we must take into account the possible leakage air in this area.   In a plant such as this the FD fan

operation would normally be controlled based on the $O_2$ reading at Point 1, at the tunnel exits. However, it is clear from examination of this design, that the arch burners could be short on air, yet the tunnel exit $O_2$ reading may indicate a sufficient excess air because if there are two independent sets of burners, the sample point must be made at a location between them. So even though the control room indication was that the reformer was operating with a 2.1 % $O_2$ at exit temperature of 1900, sampling at Point 1 in the wall of the radiant section, the results were zero % oxygen and combustibles were present. The ID fan is being operated to maintain a 0.2" W.C. at the reformer arch.

This reformer has two fuels, natural gas plus purge or off gas. And the air is preheated to 532 °F. Therefore we set our Excel worksheet up with a table for two fuels and the resulting combustion calculation would be similar to below.

| Gas/Mixture: | | | Gas # 1 | Units | | Gas # 2 | Units | | Total | Units | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gas Flow | | | 17,350.000 | lb/hr | | 7,150.000 | lb/hr | | 24,500 | lb/hr | | | | | | |
| Temperature | | | 250.00 | °F | | 60.00 | °F | | 197.27 | °F | Adjust until check = Total | | | | | |
| Heat Avail. From Gas(Datum: 60°F), Btu/hr | | | 1,764,599 | | | 0 | | | 1,764,599 | Total | | | | | | |
| Air/Fuel Ratio, lb/lb @ 0 % Ex. Air | | | 16.4143 | | | 7.2955 | | | 1,764,599 | Check | | | | | | |
| Excess Air, % | | | 0.000 | | | 0.000 | | | | | | | | | | |
| Air Flow, lbs/hr | | | 284,789 | | | 52,163 | | | 336,951 | | | | | | | |
| Fluegas Flow, lbs/hr | | | 302,139 | | | 59,313 | | | 361,451 | | | | | | | |
| Heat Avail. From Combustion of Gas, Btu/hr | | | 355,225,311 | | | 72,091,323 | | | 427,316,634 | | | | | | | |
| Gas Flow, SCFH/km3/h | | | 376,333 | 639.393 | | 250,451 | 425.520 | | | | | Vol Fuel Ratio | 60.0 | / | 40.0 | |
| | | Air: | | | | | | | | | | | | | | |
| | | Component | Mole % | Wt Frac | Air MW | Air Temp, °F | 519.495 | | Air/Fuel Ratio, lb/lb @ 0% Ex Air = | | 11.6240 | | Assumed Air Seal Leakage | | | Enth, Btu/lb |
| | | N2 | 77.4714 | 0.7512921 | 28.016 | Air Enth, Btu/lb | 112.704 | | | | | | Percent Leakage, % | 2.71 | | |
| | | O2 | 20.8371 | 0.2308068 | 32.000 | Air Heat, Btu/hr | 37,975,849 | | | | | | Preheated Air Temp, °F | 532.00 | | 115.8414 |
| | | CO2 | 0.0298 | 0.000454 | 44.010 | | | | | | | | Ambient Air temp, °F | 60.00 | | 0.0000 |
| | | H2O | 0.7286 | 0.0045437 | 18.016 | | | | Mix Fuel, SCFH | | 626,784 | | Mixed Air Temp, °F | 519.495 | | 112.7042 |
| | | Ar | 0.9331 | 0.0129035 | 39.950 | | | | | | | | | | | |
| | | SO2 | 0.0000 | 0 | 64.060 | | | | Mix Fuel, Btu/scf | | 681.76 | | | | | |
| | | CO | 0.0000 | 0 | 28.010 | | | | | | | | | | | |
| | | Total | 100.0000 | | 28.889 | Air Flow | 100,753 | | Mix Fuel, Btu/lb | | 17,441 | | Number of Tubes | 260 | | |
| | | Fluegas: | | | | | ACFM | | | | | | Tube Dia, in. | 4.8750 | | |
| | | Component | Lbs | Wt Frac | Mole % | | | | | | | | Hole Dia, in. | 5.0000 | | |
| | | N2 | 10.5141 | 0.7127 | 69.8680 | | | | | | | | Gap Area, ft2 | 1.7504 | | |
| | | O2 | 0.0000 | 0.0000 | 0.0000 | Dry O2 % | 0.0000 | | Target, O2 %= | 2.100 | Balance by adjusting Excess Air | | Arch Pressure, In.H2O | -0.2 | | |
| | | CO2 | 2.0433 | 0.1385 | 8.6437 | | | | | | | | Press Drop, lbs/ft2 | 1.0286 | | |
| | | H2O | 1.9840 | 0.1345 | 20.5020 | | | | | | | | Density, lb/ft3 | 0.075 | | |
| | | Ar | 0.2117 | 0.0143 | 0.9864 | | | | | | | | Air Ingress, lb/hr | 9,125 | | |
| | | SO2 | 0.0000 | 0.0000 | 0.0000 | | | | | | | | | | | |
| | | CO | 0.0000 | 0.0000 | 0.0000 | | | | | | | | | | | |
| | | Total | 14.7531 | 1.0000 | 100.0000 | | | | | | | | | | | |
| | | Flow, lb/hr | | | 361,451 | | | | Total Heat to Reformer, Btu/hr | | 467,057,082 | | | | | |
| | | Temp, °F | | | 1900 | | | | Assumed Heat Loss, Btu/hr | | 9,341,142 | | | | | |
| | | Enthalpy, Btu/lb | | | 551.49 | | | | Heat Loss Out Exit, Btu/hr | | 199,337,645 | | | | | |
| | | | | | | | | | Total Heat Absorbed, Btu/hr | | 258,378,296 | | | | | |

It is important to note that the actual excess air would be negative, since the sampling result indicated no $O_2$ present, and it cannot make a determination on how much additional $O_2$ is required. The second thing to note is that the calculated seal leakage air, where it may be present in the radiant section, it is not entering the fire zone from the correct location, i.e., through the burner tile, so it does not promote good

combustion. Even though our calculator will handle a negative excess air, or incomplete combustion, we set the Excess Air to zero for the arch burners.

With the fuel flow reading to the tunnel burners known and the $O_2$ reading at the exit, we can now perform the tunnel burner combustion calculation with the following result. But since we know that the Arch Burners are operating with no excess air, which is not the same as the Tunnel Burners, we have to introduce an overall heat & mass balance sheet to determine the excess air in the Tunnel Burners. This new sheet might look like the following:

| Arch Burner | Fluegas | | Tunnel Burner | Fluegas | | Fluegas Leaving Convection #1 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Wt Frac | | Component | Wt Frac | | Component | Wt Frac | Mole % | Target O2 | 2.1 | Balance by adjusting Tunnel Burners |
| N2 | 0.7127 | | N2 | 0.7362 | | N2 | 0.7158 | 70.5111 | | | |
| O2 | 0.0000 | | O2 | 0.1470 | | O2 | 0.0198 | 1.7045 | Dry % O2 | 2.100 | |
| CO2 | 0.1385 | | CO2 | 0.0560 | | CO2 | 0.1274 | 7.9896 | | | |
| H2O | 0.1345 | | H2O | 0.0481 | | H2O | 0.1229 | 18.8197 | | | |
| Ar | 0.0143 | | Ar | 0.0126 | | Ar | 0.0141 | 0.9752 | | | |
| SO2 | 0.0000 | | SO2 | 0.0000 | | SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | | CO | 0.0000 | | CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | | Total | 1.0000 | | Total | 1.0000 | 100.0000 | | | |
| Enth, Btu,lb | 551.4924 | | Enth, Btu/lb | 507.0196 | | Enth, Btu/lb | 309.7510 | | | | |
| Flow, lb/hr | 361,451 | | Flow, lb/hr | 56,134 | | Flow, lb/hr | 417,585 | | | | |
| Temp, °F | 1,900.000 | | Temp, °F | 1,900.000 | | Temp, °F | 1,155.180 | | Adjust to Point 3 Measured Temperature | | |

So now we can adjust the excess air in the Tunnel Burners until the total leaving the tunnels is equal to the measured $O_2$.

| Gas/Mixture: | | Gas # 1 | Units | | Gas # 2 | Units | | Total | Units |
|---|---|---|---|---|---|---|---|---|---|
| Gas Flow | | 1,170.000 | lb/hr | | 0.000 | lb/hr | | 1,170 | lb/hr |
| Temperature | | 250.00 | °F | | 0.00 | °F | | 352.00 | °F |
| Heat Avail. From Gas(Datum: 60°F), Btu/hr | | 118,996 | | | 0 | | | 118,996 | Total |
| Air/Fuel Ratio, lb/lb @ 0 % Ex. Air | | 16.4143 | | | 0.0000 | | | 118,996 | Check |
| Excess Air, % | | 186.200 | | | 0.000 | | | | |
| Air Flow, lbs/hr | | 54,964 | | | 0 | | | 54,964 | |
| Fluegas Flow, lbs/hr | | 56,134 | | | 0 | | | 56,134 | |
| Heat Avail. From Combustion of Gas, Btu/hr | | 23,954,675 | | | 0 | | | 23,954,675 | |
| Fuel Flow, SCFH | | 25,378 | | | | | | | |

| Air: | | | | | | | | |
|---|---|---|---|---|---|---|---|
| Component | Mole % | Wt Frac | Air MW | Air Temp, °F | 60.00 | | | |
| N2 | 77.4714 | 0.7512921 | 28.016 | Air Enth, Btu/lb | 0.000 | | | |
| O2 | 20.8371 | 0.2308068 | 32.000 | Air Heat, Btu/hr | 0 | | | |
| CO2 | 0.0298 | 0.000454 | 44.010 | | | | | |
| H2O | 0.7286 | 0.0045437 | 18.016 | | | Mix Fuel, SCFH | | 25,378 |
| Ar | 0.9331 | 0.0129035 | 39.950 | | | | | |
| SO2 | 0.0000 | 0 | 64.060 | | | Mix Fuel, Btu/scf | | 943.91 |
| CO | 0.0000 | 0 | 28.010 | | | | | |
| Total | 100.0000 | | 28.889 | Air Flow | 16,435 | Mix Fuel, Btu/lb | | 20,474 |
| Fluegas: | | | | | ACFM | | | |
| Component | Lbs | Wt Frac | Mole % | | | | | |
| N2 | 35.3229 | 0.7362 | 74.8030 | | | | | |
| O2 | 7.0543 | 0.1470 | 13.0789 | Dry O2 % | 14.1536 | | | |
| CO2 | 2.6888 | 0.0560 | 3.6247 | | | | | |
| H2O | 2.3057 | 0.0481 | 7.5932 | | | | | |
| Ar | 0.6062 | 0.0126 | 0.9002 | | | | | |
| SO2 | 0.0000 | 0.0000 | 0.0000 | | | | | |
| CO | 0.0000 | 0.0000 | 0.0000 | | | | | |
| Total | 47.9778 | 1.0000 | 100.0000 | | | | | |
| Flow, lb/hr | | | 56,134 | | | | | |
| Temp, °F | | | 1900 | | | | | |
| Enthalpy, Btu/lb | | | 507.02 | | | | | |

If the only data looked at was the reformer outlet, Point 2, Dry Volume O2 of 2.1 %, then the conclusion would be "Everything is fine", but we now know that the complete combustion is not occurring in the designed flame zone for the Arch Burners, as well as all the combustion air is not entering at the flame zone as it should. This poor combustion will result in poor radiant flux distribution and may shorten the life of tubes and catalyst. Also, operating the Tunnel Burners with 186.2 % Excess Air causes these burners to be operating very inefficiently.

Our next sample point is just downstream of the Superheater Burners, where we have an O2 reading of  2.25 % and a temperature of 1390 °F.  Once again, we cannot directly determine this temperature or the excess air in the combustion without adding to our heat & mass balance sheet.  We adjust the firing conditions on the Superheater Burners until we meet our targets on the Heat balance Sheet.

| Arch Burner  Fluegas | | | Tunnel Burner Fluegas | | | Fluegas Leaving Convection #1 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Wt Frac | | Component | Wt Frac | | Component | Wt Frac | Mole % | Target O2 | 2.1 | | Balance by adjusting Tunnel Burners |
| N2 | 0.7127 | | N2 | 0.7362 | | N2 | 0.7158 | 70.5111 | | | | |
| O2 | 0.0000 | | O2 | 0.1470 | | O2 | 0.0198 | 1.7045 | Dry % O2 | 2.100 | | |
| CO2 | 0.1385 | | CO2 | 0.0560 | | CO2 | 0.1274 | 7.9896 | | | | |
| H2O | 0.1345 | | H2O | 0.0481 | | H2O | 0.1229 | 18.8197 | | | | |
| Ar | 0.0143 | | Ar | 0.0126 | | Ar | 0.0141 | 0.9752 | | | | |
| SO2 | 0.0000 | | SO2 | 0.0000 | | SO2 | 0.0000 | 0.0000 | | | | |
| CO | 0.0000 | | CO | 0.0000 | | CO | 0.0000 | 0.0000 | | | | |
| Total | 1.0000 | | Total | 1.0000 | | Total | 1.0000 | 100.0000 | | | | |
| Enth, Btu,lb | 551.4924 | | Enth, Btu/lb | 507.0196 | | Enth, Btu/lb | 309.7510 | | | | | |
| Flow, lb/hr | 361,451 | | Flow, lb/hr | 56,134 | | Flow, lb/hr | 417,585 | | | | | |
| Temp, °F | 1,900.000 | | Temp, °F | 1,900.000 | | Temp, °F | 1,155.180 | | | Adjust to Point 3 Measured Temperature | | |

| Fluegas Entering Superheat Burners | | | Superheat Burner Fluegas | | | Fluegas Leaving Superheat Burners | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Component | Wt Frac | | Component | Wt Frac | | Component | Wt Frac | Mole % | Target O2 | 2.25 | |
| N2 | 0.7158 | | N2 | 0.7159 | | N2 | 0.7158 | 70.5937 | | | |
| O2 | 0.0198 | | O2 | 0.0338 | | O2 | 0.0212 | 1.8316 | Dry % O2 | 2.250 | Balance by adjusting SH Burners |
| CO2 | 0.1274 | | CO2 | 0.1312 | | CO2 | 0.1278 | 8.0234 | | | |
| H2O | 0.1229 | | H2O | 0.1069 | | H2O | 0.1212 | 18.5883 | | | |
| Ar | 0.0141 | | Ar | 0.0123 | | Ar | 0.0139 | 0.9631 | | | |
| SO2 | 0.0000 | | SO2 | 0.0000 | | SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | | CO | 0.0000 | | CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | | Total | 1.0000 | | Total | 1.0000 | 100.0000 | | | |
| Enth, Btu,lb | 309.7510 | | Enth, Btu/lb | 1003.6264 | | Enth, Btu/lb | 381.4796 | | | | |
| Flow, lb/hr | 417,585 | | Flow, lb/hr | 48,144 | | Flow, lb/hr | 465,730 | | | | |
| Temp, °F | 1,155.180 | | Temp, °F | 3,286.250 | | Temp, °F | 1,390.000 | | | Target Temperature Point 3 = 1390 °F | |

And the resulting combustion calculation for the Superheater Burners is as follows:

| Gas/Mixture: | | | Gas # 1 | Units | | Gas # 2 | Units | | Total | Units | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gas Flow | | | 2,360.000 | lb/hr | | 0.000 | lb/hr | | 2,360 | lb/hr | |
| Temperature | | | 250.00 | °F | | 0.00 | °F | | 250.00 | °F | Adjust until check = Total |
| Heat Avail. From Gas(Datum: 60°F), Btu/hr | | | 240,026 | | | 0 | | | 240,026 | Total | |
| Air/Fuel Ratio, lb/lb @ 0 % Ex. Air | | | 16.4143 | | | 0.0000 | | | 240,026 | Check | |
| Excess Air, % | | | 18.190 | | | 0.000 | | | | | |
| Air Flow, lbs/hr | | | 45,784 | | | 0 | | | 45,784 | | |
| Fluegas Flow, lbs/hr | | | 48,144 | | | 0 | | | 48,144 | | |
| Heat Avail. From Combustion of Gas, Btu/hr | | | 48,318,832 | | | 0 | | | 48,318,832 | | |
| Fuel Flow, SCFH | | | 51,190 | | | | | | | | |
| | Air: | | | | | | | | | | |
| | Component | Mole % | Wt Frac | Air MW | Air Temp, °F | 532.00 | | | | | |
| | N2 | 77.4714 | 0.7512921 | 28.016 | Air Enth, Btu/lb | 115.841 | | | | | |
| | O2 | 20.8371 | 0.2308068 | 32.000 | Air Heat, Btu/hr | 5,303,711 | | | | | |
| | CO2 | 0.0298 | 0.000454 | 44.010 | | | | | | | |
| | H2O | 0.7286 | 0.0045437 | 18.016 | | | | Mix Fuel, SCFH | | 51,190 | |
| | Ar | 0.9331 | 0.0129035 | 39.950 | | | | | | | |
| | SO2 | 0.0000 | 0 | 64.060 | | | | Mix Fuel, Btu/scf | | 943.91 | |
| | CO | 0.0000 | 0 | 28.010 | | | | | | | |
| | Total | 100.0000 | | 28.889 | Air Flow | 13,690 | | Mix Fuel, Btu/lb | | 20,474 | |
| | Fluegas: | | | | | ACFM | | | | | |
| | Component | Lbs | Wt Frac | Mole % | | | | | | | |
| | N2 | 14.6040 | 0.7159 | 71.3181 | | | | | | | |
| | O2 | 0.6891 | 0.0338 | 2.9464 | Dry O2 % | 3.5311 | | | | | |
| | CO2 | 2.6762 | 0.1312 | 8.3197 | | | | | | | |
| | H2O | 2.1804 | 0.1069 | 16.5585 | | | | | | | |
| | Ar | 0.2503 | 0.0123 | 0.8573 | | | | | | | |
| | SO2 | 0.0000 | 0.0000 | 0.0000 | | | | | | | |
| | CO | 0.0000 | 0.0000 | 0.0000 | | | | | | | |
| | Total | 20.4001 | 1.0000 | 100.0000 | | | | | | | |
| | Flow, lb/hr | | | 48,144 | | | | | | | |
| | Temp, °F | | | 1390 | | | | | | | |
| | Enthalpy, Btu/lb | | | 377.04 | | | | | | | |

Efficient operation of these burners would be with 10% excess air, but they are operating with 18.2 % excess air.

Point 10 of our field measurements is the fluegas returning from the Auxiliary boiler, which has a Dry Volume % $O_2$ of 3.5 and a temperature of 676.7 °F.

This is a straight forward combustion calculation as shown below.

| Gas/Mixture: | | Gas # 1 | Units | | Gas # 2 | Units | | Total | Units | |
|---|---|---|---|---|---|---|---|---|---|---|
| Gas Flow | | 6,800.000 | lb/hr | | 0.000 | lb/hr | | 6,800 | lb/hr | |
| Temperature | | 250.00 | °F | | 0.00 | °F | | 250.00 | °F | Adjust until check = Total |
| Heat Avail. From Gas(Datum: 60°F), Btu/hr | | 691,601 | | | 0 | | | 691,601 | Total | |
| Air/Fuel Ratio, lb/lb @ 0 % Ex. Air | | 16.4143 | | | 0.0000 | | | 691,601 | Check | |
| Excess Air, % | | 18.000 | | | 0.000 | | | | | |
| Air Flow, lbs/hr | | 131,709 | | | 0 | | | 131,709 | | |
| Fluegas Flow, lbs/hr | | 138,509 | | | 0 | | | 138,509 | | |
| Heat Avail. From Combustion of Gas, Btu/hr | | 139,223,753 | | | 0 | | | 139,223,753 | | |
| Fuel Flow, SCFH | | 147,496 | | | | | | | | |

**Air:**

| Component | Mole % | Wt Frac | Air MW | Air Temp, °F | 532.00 | | |
|---|---|---|---|---|---|---|---|
| N2 | 77.4714 | 0.7512921 | 28.016 | Air Enth, Btu/lb | 115.841 | | |
| O2 | 20.8371 | 0.2308068 | 32.000 | Air Heat, Btu/hr | 15,257,311 | | |
| CO2 | 0.0298 | 0.000454 | 44.010 | | | | |
| H2O | 0.7286 | 0.0045437 | 18.016 | | | Mix Fuel, SCFH | 147,496 |
| Ar | 0.9331 | 0.0129035 | 39.950 | | | | |
| SO2 | 0.0000 | 0 | 64.060 | | | Mix Fuel, Btu/scf | 943.91 |
| CO | 0.0000 | 0 | 28.010 | | | | |
| Total | 100.0000 | | 28.889 | Air Flow | 39,383 | Mix Fuel, Btu/lb | 20,474 |
| | | | | | ACFM | | |

**Fluegas:**

| Component | Lbs | Wt Frac | Mole % | | | | |
|---|---|---|---|---|---|---|---|
| N2 | 14.5805 | 0.7158 | 71.3090 | | | | |
| O2 | 0.6819 | 0.0335 | 2.9199 | Dry O2 % | 3.5003 | Target O2 % | 3.5 | Balance by adjusting Excess Air |
| CO2 | 2.6762 | 0.1314 | 8.3320 | | | | |
| H2O | 2.1803 | 0.1070 | 16.5819 | | | | |
| Ar | 0.2499 | 0.0123 | 0.8572 | | | | |
| SO2 | 0.0000 | 0.0000 | 0.0000 | | | | |
| CO | 0.0000 | 0.0000 | 0.0000 | | | | |
| Total | 20.3689 | 1.0000 | 100.0000 | | | | |
| Flow, lb/hr | | | 138,509 | | Total Heat to Aux Boiler, Btu/hr | 154,481,064 |
| Temp, °F | | | 676.7 | | Assumed Heat Loss, Btu/hr | 3,089,621 |
| Enthalpy, Btu/lb | | | 166.83 | | Heat Loss Out Exit, Btu/hr | 23,106,907 |
| | | | | | Total Heat Absorbed, Btu/hr | 128,284,536 |

The efficiency of the Auxiliary Boiler is 128284536/154481064 *100 = 83.0 % and could be improved by adjusting burners to a lower excess air.

Now we add to our heat and mass balance to determine the fluegas after the mixture.

## Arch Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7127 |
| O2 | 0.0000 |
| CO2 | 0.1385 |
| H2O | 0.1345 |
| Ar | 0.0143 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 551.4924 |
| Flow, lb/hr | 361,451 |
| Temp, °F | 1,900.000 |

## Tunnel Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7362 |
| O2 | 0.1470 |
| CO2 | 0.0560 |
| H2O | 0.0481 |
| Ar | 0.0126 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 507.0196 |
| Flow, lb/hr | 56,134 |
| Temp, °F | 1,900.000 |

## Fluegas Leaving Convection #1

| Component | Wt Frac | Mole % | Target O2 | 2.1 | Balance by adjusting Tunnel Burners |
|---|---|---|---|---|---|
| N2 | 0.7158 | 70.5111 | | | |
| O2 | 0.0198 | 1.7045 | Dry % O2 | 2.100 | |
| CO2 | 0.1274 | 7.9896 | | | |
| H2O | 0.1229 | 18.8197 | | | |
| Ar | 0.0141 | 0.9752 | | | |
| SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | 100.0000 | | | |
| Enth, Btu/lb | 309.7510 | | | | |
| Flow, lb/hr | 417,585 | | | | |
| Temp, °F | 1,155.180 | | Adjust to Point 3 Measured Temperature | | |

## Fluegas Entering Superheat Burners

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0198 |
| CO2 | 0.1274 |
| H2O | 0.1229 |
| Ar | 0.0141 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 309.7510 |
| Flow, lb/hr | 417,585 |
| Temp, °F | 1,155.180 |

## Superheat Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7159 |
| O2 | 0.0338 |
| CO2 | 0.1312 |
| H2O | 0.1069 |
| Ar | 0.0123 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 1003.6264 |
| Flow, lb/hr | 48,144 |
| Temp, °F | 3,286.250 |

## Fluegas Leaving Superheat Burners

| Component | Wt Frac | Mole % | Target O2 | 2.25 | |
|---|---|---|---|---|---|
| N2 | 0.7158 | 70.5937 | | | |
| O2 | 0.0212 | 1.8316 | Dry % O2 | 2.250 | Balance by adjusting SH Burners |
| CO2 | 0.1278 | 8.0234 | | | |
| H2O | 0.1212 | 18.5883 | | | |
| Ar | 0.0139 | 0.9631 | | | |
| SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | 100.0000 | | | |
| Enth, Btu/lb | 381.4796 | | | | |
| Flow, lb/hr | 465,730 | | | | |
| Temp, °F | 1,390.000 | | Target Temperature Point 3 = 1390 °F | | |

## Fluegas Leaving Superheat Burners

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0212 |
| CO2 | 0.1278 |
| H2O | 0.1212 |
| Ar | 0.0139 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 381.4796 |
| Flow, lb/hr | 465,730 |
| Temp, °F | 1,390.000 |

## Auxiliary Boiler Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0335 |
| CO2 | 0.1314 |
| H2O | 0.1070 |
| Ar | 0.0123 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 166.8265 |
| Flow, lb/hr | 138,509 |
| Temp, °F | 676.700 |

## Fluegas Entering Convection 2

| Component | Wt Frac | Mole % | | |
|---|---|---|---|---|
| N2 | 0.7158 | 70.7564 | | |
| O2 | 0.0240 | 2.0791 | Dry % O2 | 2.540 |
| CO2 | 0.1286 | 8.0936 | | |
| H2O | 0.1180 | 18.1319 | | |
| Ar | 0.0135 | 0.9390 | | |
| SO2 | 0.0000 | 0.0000 | | |
| CO | 0.0000 | 0.0000 | | |
| Total | 1.0000 | 100.0000 | | |
| Enth, Btu/lb | 332.2750 | | | |
| Flow, lb/hr | 604,238 | | | |
| Temp, °F | 1,233.415 | | | |

Our next sample point is Point 4 entering the Air Preheater, which has an O2 reading of 2.8 % and a temperature of 643 °F.  Examination of our heat and mass balance indicates that this $O_2$ reading should have been 2.540 %, which tells us that there has been ingress of tramp air between Point 3 and Point 4.  Physical examination of the unit reveals that there are no port seals on the interconnecting pipes, and a tissue test shows that air is entering the convection at these locations.  We can expand our heat and mass balance to determine the amount of the air leakage.

## Arch Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7127 |
| O2 | 0.0000 |
| CO2 | 0.1385 |
| H2O | 0.1345 |
| Ar | 0.0143 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 551.4924 |
| Flow, lb/hr | 361,451 |
| Temp, °F | 1,900.000 |

## Tunnel Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7362 |
| O2 | 0.1470 |
| CO2 | 0.0560 |
| H2O | 0.0481 |
| Ar | 0.0126 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 507.0196 |
| Flow, lb/hr | 56,134 |
| Temp, °F | 1,900.000 |

## Fluegas Leaving Convection #1

| Component | Wt Frac | Mole % | Target O2 | 2.1 | Balance by adjusting Tunnel Burners |
|---|---|---|---|---|---|
| N2 | 0.7158 | 70.5111 | | | |
| O2 | 0.0198 | 1.7045 | Dry % O2 | 2.100 | |
| CO2 | 0.1274 | 7.9896 | | | |
| H2O | 0.1229 | 18.8197 | | | |
| Ar | 0.0141 | 0.9752 | | | |
| SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | 100.0000 | | | |
| Enth, Btu/lb | 309.7510 | | | | |
| Flow, lb/hr | 417,585 | | | | |
| Temp, °F | 1,155.180 | | Adjust to Point 3 Measured Temperature | | |

## Fluegas Entering Superheat Burners

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0198 |
| CO2 | 0.1274 |
| H2O | 0.1229 |
| Ar | 0.0141 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 309.7510 |
| Flow, lb/hr | 417,585 |
| Temp, °F | 1,155.180 |

## Superheat Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7159 |
| O2 | 0.0338 |
| CO2 | 0.1312 |
| H2O | 0.1069 |
| Ar | 0.0123 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 1003.6264 |
| Flow, lb/hr | 48,144 |
| Temp, °F | 3,286.250 |

## Fluegas Leaving Superheat Burners

| Component | Wt Frac | Mole % | Target O2 | 2.25 | |
|---|---|---|---|---|---|
| N2 | 0.7158 | 70.5937 | | | |
| O2 | 0.0212 | 1.8316 | Dry % O2 | 2.250 | Balance by adjusting SH Burners |
| CO2 | 0.1278 | 8.0234 | | | |
| H2O | 0.1212 | 18.5883 | | | |
| Ar | 0.0139 | 0.9631 | | | |
| SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | 100.0000 | | | |
| Enth, Btu/lb | 381.4796 | | | | |
| Flow, lb/hr | 465,730 | | | | |
| Temp, °F | 1,390.000 | | Target Temperature Point 3 = 1390 °F | | |

## Fluegas Leaving Superheat Burners

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0212 |
| CO2 | 0.1278 |
| H2O | 0.1212 |
| Ar | 0.0139 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 381.4796 |
| Flow, lb/hr | 465,730 |
| Temp, °F | 1,390.000 |

## Auxiliary Boiler Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0335 |
| CO2 | 0.1314 |
| H2O | 0.1070 |
| Ar | 0.0123 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 166.8265 |
| Flow, lb/hr | 138,509 |
| Temp, °F | 676.700 |

## Fluegas Entering Convection 2

| Component | Wt Frac | Mole % | | |
|---|---|---|---|---|
| N2 | 0.7158 | 70.7564 | | |
| O2 | 0.0240 | 2.0791 | Dry % O2 | 2.540 |
| CO2 | 0.1286 | 8.0936 | | |
| H2O | 0.1180 | 18.1319 | | |
| Ar | 0.0135 | 0.9390 | | |
| SO2 | 0.0000 | 0.0000 | | |
| CO | 0.0000 | 0.0000 | | |
| Total | 1.0000 | 100.0000 | | |
| Enth, Btu/lb | 332.2750 | | | |
| Flow, lb/hr | 604,238 | | | |
| Temp, °F | 1,233.415 | | | |

## Fluegas Entering Convection 2

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0240 |
| CO2 | 0.1286 |
| H2O | 0.1180 |

## Convection # 2 Air Leakage

| Component | Wt Frac |
|---|---|
| N2 | 0.7513 |
| O2 | 0.2308 |
| CO2 | 0.0005 |
| H2O | 0.0045 |

## Fluegas Leaving Convection # 2

| Component | Wt Frac | Mole % | Target | 2.8 | |
|---|---|---|---|---|---|
| N2 | 0.7163 | 70.8348 | | | |
| O2 | 0.0265 | 2.2982 | Dry % O2 | 2.800 | |
| CO2 | 0.1271 | 7.9994 | | | |
| H2O | 0.1166 | 17.9287 | | | |

This is not a great amount of leakage, but does have an associated cost in loss of energy, and the repair will have a relatively short payout.

The Air Preheater on this sample analysis is a regenerative, rotary type, which when in new condition with new seals has an inherent air bypass (leakage) from the high pressure, Forced Draft (FD), side to the low pressure, Induced Draft (ID), side, therefore we expect to see a leakage bypass of over 10 % by volume.  The actual bypass leakage is easy to calculate using our heat and mass balance sheet, with the $O_2$ reading known to be 2.8 % at the inlet and 5.76 % at outlet. We also measure a fluegas exit stack temperature of 252 °F.

## Arch Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7127 |
| O2 | 0.0000 |
| CO2 | 0.1385 |
| H2O | 0.1345 |
| Ar | 0.0143 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 551.4924 |
| Flow, lb/hr | 361,451 |
| Temp, °F | 1,900.000 |

## Tunnel Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7362 |
| O2 | 0.1470 |
| CO2 | 0.0560 |
| H2O | 0.0481 |
| Ar | 0.0126 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 507.0196 |
| Flow, lb/hr | 56,134 |
| Temp, °F | 1,900.000 |

## Fluegas Leaving Convection #1

| Component | Wt Frac | Mole % | Target O2 | 2.1 | Balance by adjusting Tunnel Burners |
|---|---|---|---|---|---|
| N2 | 0.7158 | 70.5111 | | | |
| O2 | 0.0198 | 1.7045 | Dry % O2 | 2.100 | |
| CO2 | 0.1274 | 7.9896 | | | |
| H2O | 0.1229 | 18.8197 | | | |
| Ar | 0.0141 | 0.9752 | | | |
| SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | 100.0000 | | | |
| Enth, Btu,lb | 309.7510 | | | | |
| Flow, lb/hr | 417,585 | | | | |
| Temp, °F | 1,155.180 | | Adjust to Point 3 Measured Temperature | | |

## Fluegas Entering Superheat Burners

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0198 |
| CO2 | 0.1274 |
| H2O | 0.1229 |
| Ar | 0.0141 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 309.7510 |
| Flow, lb/hr | 417,585 |
| Temp, °F | 1,155.180 |

## Superheat Burner Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7159 |
| O2 | 0.0338 |
| CO2 | 0.1312 |
| H2O | 0.1069 |
| Ar | 0.0123 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 1003.6264 |
| Flow, lb/hr | 48,144 |
| Temp, °F | 3,286.250 |

## Fluegas Leaving Superheat Burners

| Component | Wt Frac | Mole % | Target O2 | 2.25 | |
|---|---|---|---|---|---|
| N2 | 0.7158 | 70.5937 | | | |
| O2 | 0.0212 | 1.8316 | Dry % O2 | 2.250 | Balance by adjusting SH Burners |
| CO2 | 0.1278 | 8.0234 | | | |
| H2O | 0.1212 | 18.5883 | | | |
| Ar | 0.0139 | 0.9631 | | | |
| SO2 | 0.0000 | 0.0000 | | | |
| CO | 0.0000 | 0.0000 | | | |
| Total | 1.0000 | 100.0000 | | | |
| Enth, Btu,lb | 381.4796 | | | | |
| Flow, lb/hr | 465,730 | | | | |
| Temp, °F | 1,390.000 | | Target Temperature Point 3 = 1390 °F | | |

## Fluegas Leaving Superheat Burners

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0212 |
| CO2 | 0.1278 |
| H2O | 0.1212 |
| Ar | 0.0139 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu,lb | 381.4796 |
| Flow, lb/hr | 465,730 |
| Temp, °F | 1,390.000 |

## Auxiliary Boiler Fluegas

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0335 |
| CO2 | 0.1314 |
| H2O | 0.1070 |
| Ar | 0.0123 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |
| Enth, Btu/lb | 166.8265 |
| Flow, lb/hr | 138,509 |
| Temp, °F | 676.700 |

## Fluegas Entering Convection 2

| Component | Wt Frac | Mole % | | |
|---|---|---|---|---|
| N2 | 0.7158 | 70.7564 | | |
| O2 | 0.0240 | 2.0791 | Dry % O2 | 2.540 |
| CO2 | 0.1286 | 8.0936 | | |
| H2O | 0.1180 | 18.1319 | | |
| Ar | 0.0135 | 0.9390 | | |
| SO2 | 0.0000 | 0.0000 | | |
| CO | 0.0000 | 0.0000 | | |
| Total | 1.0000 | 100.0000 | | |
| Enth, Btu,lb | 332.2750 | | | |
| Flow, lb/hr | 604,238 | | | |
| Temp, °F | 1,233.415 | | | |

## Fluegas Entering Convection 2

| Component | Wt Frac |
|---|---|
| N2 | 0.7158 |
| O2 | 0.0240 |
| CO2 | 0.1286 |
| H2O | 0.1180 |
| Ar | 0.0135 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |

## Convection # 2 Air Leakage

| Component | Wt Frac |
|---|---|
| N2 | 0.7513 |
| O2 | 0.2308 |
| CO2 | 0.0005 |
| H2O | 0.0045 |
| Ar | 0.0129 |
| SO2 | 0.0000 |
| CO | 0.0000 |
| Total | 1.0000 |

## Fluegas Leaving Convection # 2

| Component | Wt Frac | Mole % | Target | 2.8 |
|---|---|---|---|---|
| N2 | 0.7163 | 70.8348 | | |
| O2 | 0.0265 | 2.2982 | Dry % O2 | 2.800 |
| CO2 | 0.1271 | 7.9994 | | |
| H2O | 0.1166 | 17.9287 | | |
| Ar | 0.0135 | 0.9389 | | |
| SO2 | 0.0000 | 0.0000 | | |
| CO | 0.0000 | 0.0000 | | |
| Total | 1.0000 | 100.0000 | | |

We can see from the heat and mass balance that the bypass air leakage is 19.92 %, or twice what it should be. We can also see that our air preheater balance is a little off, by 2.31 % which is not unusual since heat loss to the atmosphere has not been taken into account.

To recap the findings from this sample furnace test to demonstrate combustion, efficiency calculations, and heat and mass balance techniques, the following is a brief list of problems uncovered:

1) **The lack of reformer tube seals is allowing tramp air to enter radiant section**
2) **The primary arch burners are not receiving sufficient air for complete combustion**
3) **The tunnel burners are being operated with excessive excess air**
4) **The superheater burners are being operated with excessive excess air**
5) **The auxiliary boiler burners are being operated with excessive excess air**
6) **The second convection section has no port seals and this allows ingress of tramp air**
7) **There is excessive air bypass in the air preheater**
8) **The ID fan is being overloaded due to excessive excess air in the Tunnel, SH, and Aux. Boiler, tramp air ingress, and air bypass in air preheater**
9) **The FD fan is being overloaded due to excessive bypass air in the air preheater**

With all the combustion and mass and heat balance calculations complete, we can now look at our results. We can use the methods described in API 560 to calculate the efficiencies.

Fuel Efficiency = Heat Absorbed/Total Heat From Fuel * 100

Net Thermal Efficiency = ((Heat From Fuel + Air Heat + Fuel Heat)-(Set. Loss + Stack Loss)) / (Heat From Fuel + Air Heat + Fuel Heat)

| Total Heat Absorbed, MM Btu/hr (Assumes 2% Setting Losses) | | | Total Heat From Fuel, MM Btu/hr | | | Air Heat MM Btu/hr | Fuel Heat MM Btu/hr |
|---|---|---|---|---|---|---|---|
| Reformer | 258.378 | | Arch Burners | | 427.317 | 37.976 | 1.765 |
| Convection #1 | 80.761 | | Tunnel Burners | | 23.955 | 0.000 | 0.119 |
| Auxiliary Boiler | 128.285 | | Superheater Burners | | 48.319 | 5.304 | 0.240 |
| Convection #2 | 102.895 | | Auxiliary Boiler Burmers | | 139.224 | 15.257 | 0.692 |
| Total | 570.320 | | Total | | 638.814 | 58.537 | 2.815 |
| Fuel Efficiency, % | | 89.278 | | | | | |
| Net Thermal Efficiency, % | | 84.517 | | | | | |
| | | | (Using 900 Btu/lb of Steam) | | | | |
| | | | FD Fan (0.02 lb stm/lb air) | | 11.105 | | |
| | | | ID Fan (0.03 lb stm/lb air) | | 19.283 | | |
| | | | Total | | 30.388 | | |

We should note here that these efficiency calculations do not take utilities or fan power into account. The amount of energy used to drive the fans is estimated roughly above.

This overall efficiency doesn't tell us about the poor combustion in the primary reformer and doesn't account for the loss of tube or catalyst life.

The enthalpy calculations used herein are based on our internal calculators, but if you don't have any of the equations, you can use curve fits of the curves in API 560, Figure G6 and G7, reproduced below.
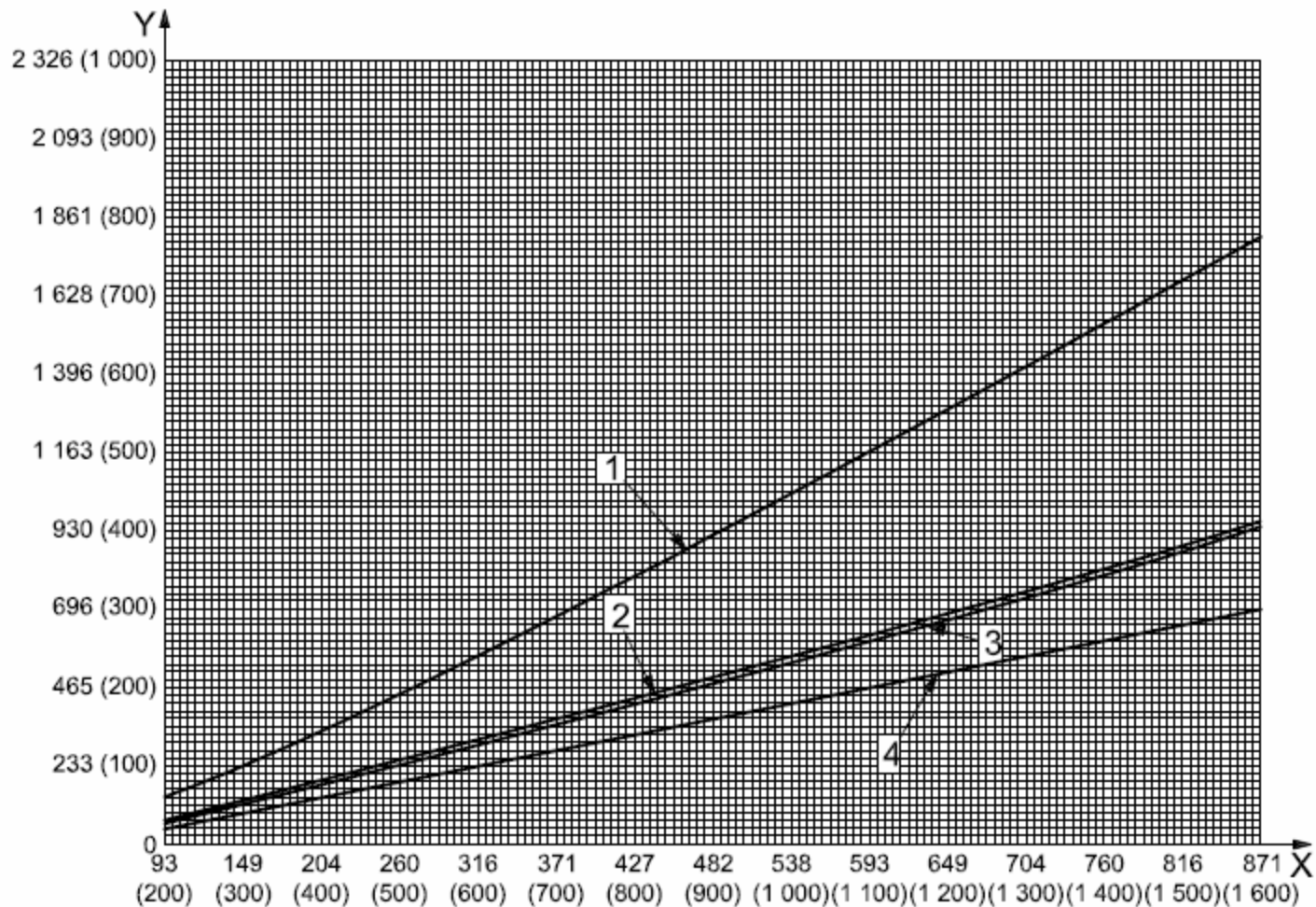
**Key**

X : temperature, expressed in degrees Celsius (degrees Fahrenheit)
Y : enthalpy above 15 °C, kJ/kg (60 °F)
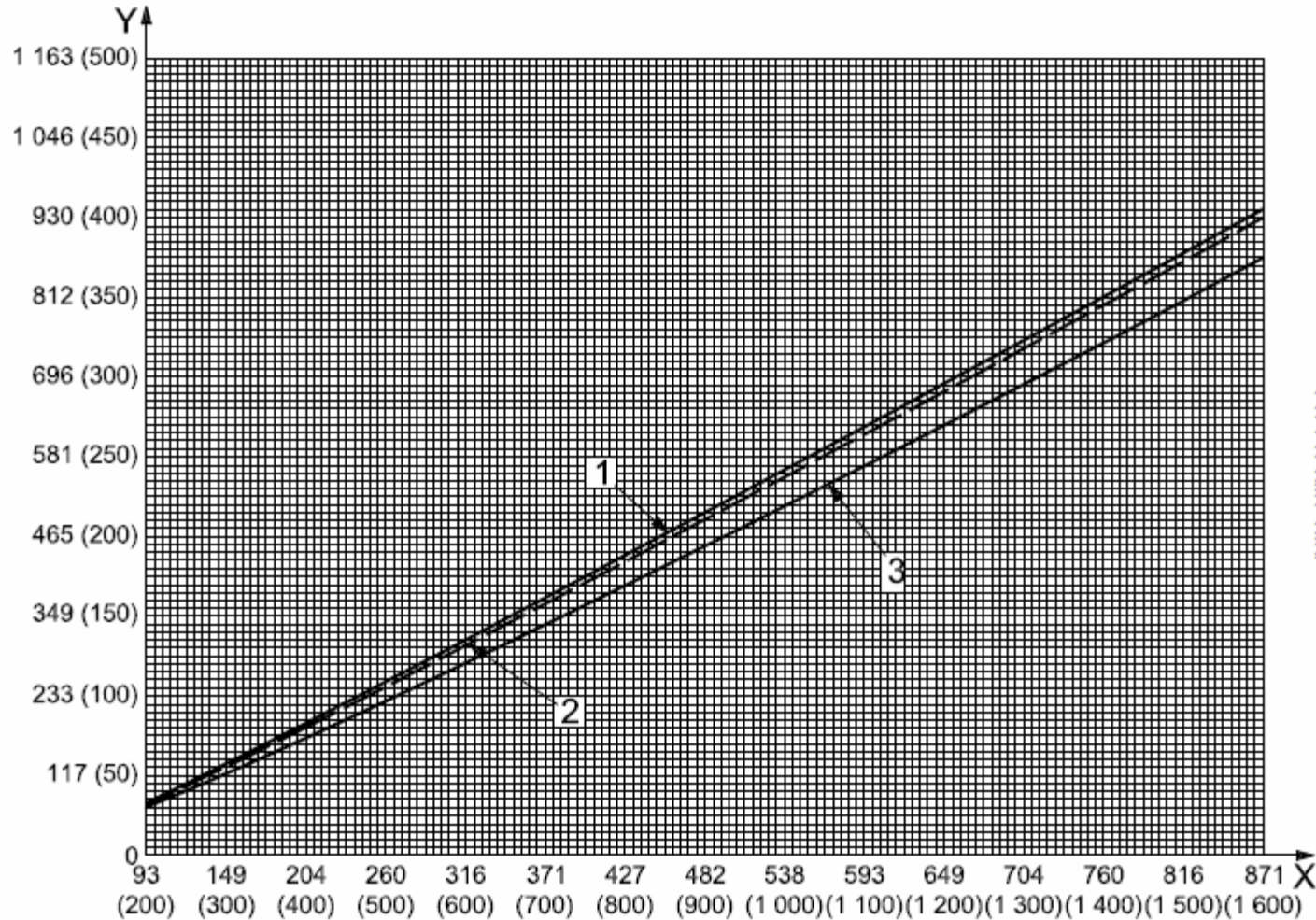
1 : water vapour
2 : carbon monoxide
3 : carbon dioxide
4 : sulfur dioxide

NOTE    Figure G.6 is taken from Reference [37], pp. 14-23.

**Figure G.6 — Enthalpy of $H_2O$, CO, $CO_2$ and $SO_2$**

**Key**

X    temperature, expressed in degrees Celsius (degrees Fahrenheit)

Y    enthalpy above 15 °C, kJ/kg (60 °F)

1    nitrogen

2    air

3    oxygen

NOTE    Figure G.7 is taken from Reference [37], pp. 14-23.

**Figure G.7 — Enthalpy of air, $O_2$ and $N_2$**

If possible, it is also desirable to calculate the heat absorbed in the fired equipment to compare against the combustion calculations to assure an accurate heat balance has been achieved.