Oxy-Natural Gas Firing of the Jupiter Oxygen Oxy-Fuel Test Facility

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Jupiter Oxygen Corporation, with support from NETL, has constructed a multi-fuel air- or oxygen-fired burner test facility for the testing of burners with capacities of up to approximately 60 mmBtu/hr (known as the Jupiter, Hammond Boiler Test Facility - JHBTF). The system has fired both natural gas and coal during 2008. This report details the information gained during the initial natural gas runs. While the facility is designed for burner testing, it is fully instrumented to obtain information on heat transfer, heat distribution, flame characteristics, ash composition, CO_2 capture, and materials performance. The facility has served as a platform for determining parameters required for boiler scale-up as well as burner design. The boiler is a B&W water tube package boiler designed to produce up to 60,000 lb/hr of 135 psig, 454 °F superheated steam.

The data acquisition system has been designed to determine burner characteristics and also to take advantage of information related to heat transfer distribution in the package boiler. The result of the boiler heat distribution analysis has supported earlier computer models. Comparisons were made between natural gas flames, air-fired flames, oxy-fired flames with and without recirculation where the recirculated flue gas does not mix with the oxygen (resulting in a high flame temperature), and oxy-fired flames with recirculated flue gas that is mixed with the oxygen (the equivalent of all gas flow as primary air). In all, 4 cases were studied, tested, modeled and compared to previous models.

The distribution of heat between the radiant and convective zones is particularly important for retrofits of air-fired boilers; these boilers are designed such that the radiant zone produces saturated steam, whereas the convective zone preheats incoming water, preheats incoming air, and boosts steam to the correct superheated temperature for the installed turbines. When converting to oxy-firing, the rate of heat deposition in the zones and sections of the zones must be carefully matched to the original design to ensure that the flow and temperature of the steam meets the original design conditions[1,2,3]. At the JHBTF, the heat transfer characteristics have been studied in order to understand the potential applications for new boiler designs.

The results from the testing are being used to validate existing models and to understand the relationships of heat transfer within the boiler. Furthermore the results are being used to build new models based in part on test data and additional analytical work. These models will be useful for both retrofit and new boiler designs.

Background:

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Oxy-fuel combustion adds a new engineering dimension for design purposes (comburent composition). In air firing, the comburent composition is determined by the fixed fraction of oxygen in the air and the limits on the approach to reaction stoichiometry. In air-fired systems the flame and heat transfer characteristics are generally controlled through the variation of burner design characteristics including staging. The high nitrogen concentration of air limits the temperature of the flame and bounds the heat transfer characteristics.

In oxy-fired systems the oxygen content of the comburent can be controlled within a broad range. This range of oxygen content allows fine tuning of the flame characteristics for specific applications. An example from a different application is the difference in temperature of an air-acetylene flame compared to an oxy-acetylene flame. In the case of air-acetylene, the flame temperature is on the order of 4,000F (2,500K) while oxy-acetylene flame temperatures are estimated at 6,000F (3,600K). This gives an idea of the range of flame properties that are available once you can vary the oxygen content.

A common misperception about oxy-fuel is that the use of a hot flame (significantly hotter than air firing) will damage any conventional equipment that it might be used in. However, it is heat flux that is important for ensuring that equipment is not damaged. Even in air firing, a misdirected burner can quickly damage boiler tubes. Boiler materials are not made for the flame to contact the heat transfer surfaces. Instead, they are designed to accept a designed heat flux without damage. How that heat flux is delivered is the important concept. The effective temperature of the flame determines the radiative heat transfer from the flame to the boiler wall and as long as the heat flux is kept within design parameters and the flame (or extremely hot gases from the flame) do not come in contact with the walls, the metal will work as designed. A simple thought experiment will demonstrate this concept. As we mentioned above, the temperature of an oxy-acetylene flame is estimated to be approximately 6,000°F. However, if a worker inside a cold boiler is using a welding torch and holds it up in the middle of the boiler the boiler walls, of course, incur no damage. Instead, the amount of heat transferred to the walls is small due to the surface area of the walls compared to the output from the torch. The torch can be scaled up and there will still be no damage to the water walls until the heat flux from the flame exceeds the design heat flux of the water walls. Thus, a hot flame in itself does not damage the boiler. Instead, a higher temperature range becomes a new dimension for the design engineer to work with.

One of the issues facing retrofit applications is the need for balancing the heat transfer in the existing boiler to approximate the heat transfer of the air-fired gases that the boiler was designed for. If this balance is not maintained there can be too much or too little steam generated or the steam can be at the wrong temperature for the turbine. To maintain the steam production conditions close to those of air-firing, the engineers must be able to reliably predict heat transfer for each heat transfer surface in the existing boiler. Present estimation tools used for boiler design are semi-empirical in nature and have problems when the gas composition varies from that of air-fired systems. Radiant heat transfer is modified by higher concentrations of water vapor and CO_2 in oxy-fuel combustion products than are found in air-fuel combustion products, which are diluted by nitrogen. The Hammond Boiler Test Facility has been built to develop a better understanding of oxy-fuel combustion systems, heat transfer from oxy-fuel flames, and to serve to verify computer model predictions.

Figure 1 shows an exploded view of the heat transfer zones in a typical boiler. As indicated by the names of the zones, the main mode of heat transfer in the radiant zone is thermal radiation and the predominant mode of heat transfer in the convective zone is convection. A transition zone exists between the radiant and convective zones where the amount of radiation tapers off and convection takes over. The changes in amount and mode of heat flux are shown in Plot A and Plot B from Figure 1. This paper is not presenting the details of the modes of heat transfer. Instead, it is showing how the change to oxy-fuel combustion affects design choices when trying to build a retrofit for an existing boiler. The reason Figure 1 is important is that it shows that heat transfer surface design and distribution are optimized around the temperature and flow history of an air-fuel flame-type to extract energy through both radiation and convection as the energy output of the flame and combustion gases changes from radiative to convective. If the arrangement of the heat transfer surfaces does not match the arrangement of heat transfer mode in the flame and combustion gases, there will be an imbalance in the boiler (as has been shown by many organizations[2,3] in their analyses of oxy-fuel boiler performance). Prediction and evaluation of heat transfer modes of the designed flame are key to the matching of heat transfer surface to flame/gas output (and vice versa). Available engineering computational tools have been designed based on a century's worth of calculations of commercial air-fired systems.

The additional variable of oxygen content, in current computational tools, moves heat transfer prediction into new areas due to the uncertainty in the new radiative component. Plot A, from Figure 1, shows that the total heat flux changes as the gas moves through an air-fired boiler and Plot B shows that the percentage of heat flux from radiation and convection also changes.

Table 1 shows the approximate calculated distribution of heat in a typical air-fired PC subcritical boiler. The fractions of radiant and convective energy used to change the feedwater to superheated steam are approximately: 0.55 radiant and 0.45 convective respectively[5]. Using **Table 1** and Figure 1, we can see that there are stringent heat transfer requirements when converting an air-fired boiler to oxy-fuel firing. These balances and technologies to meet the needs of the steam system are a reason that boiler and burner test facilities have been constructed. Knowing how systems respond under experimental conditions makes estimates for scale-up more feasible.

Figure 1: A typical boiler layout showing the details of the transition from the radiant zone to the convective zone with the approximate distribution of radiant and convective heat transfer in each region. The

transition starts out nearly all radiative and then shifts to more convective. The figure is based on a figure in "Steam its generation and use"41st Ed, The Babcock and Wilcox Company, pg4-28[4]. In plots A and B the red represents the radiant heat transfer and the blue represents the convective transport. Also in plots A and B the x-axis numbers correspond to the numbered sections of the transition zone.

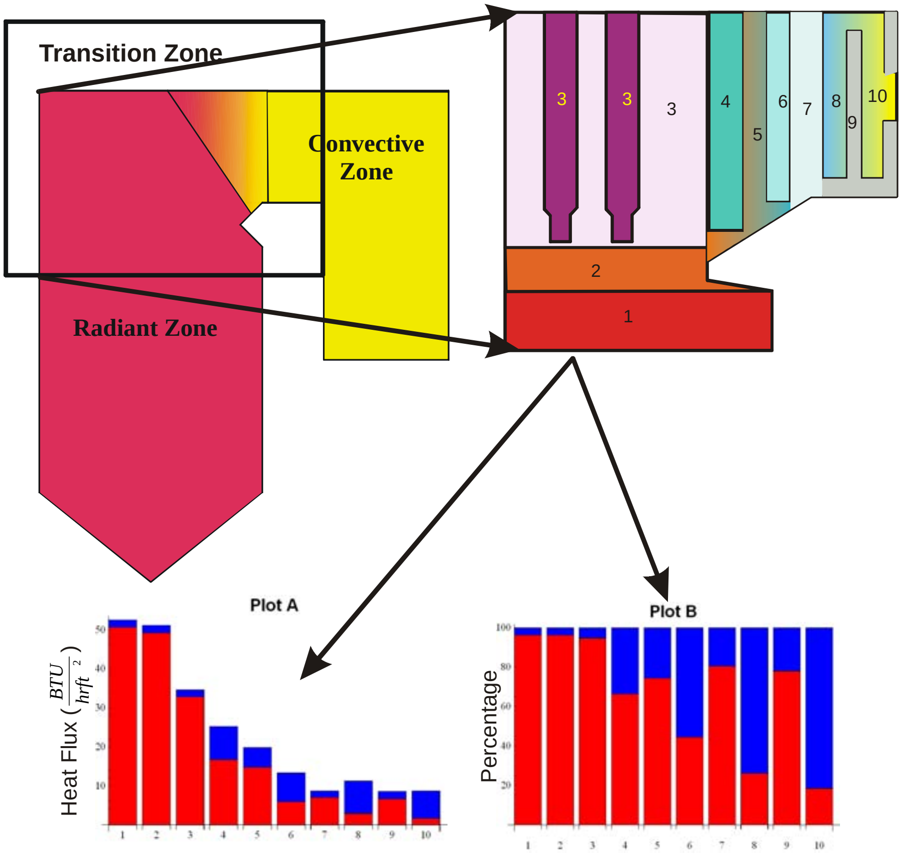


Table 1:[5] Distribution of heat in a typical sub-critical PC boiler. Taken from Power Plant Heat Balance in NETL Modeling OSAP document: "Cost and Performance Baseline for Fossil Energy Plants" Volume 1: Bituminous Coal and Natural Gas to Electricity Final Report (Original Issue Date, May 2007) Revision 1, August 2007. Baseline example air firing PC sub-critical Case 9.

	BTU/hr	Fraction of total BTUs
Water boiling	1,503,000,000	0.46
Steam superheating	1,042,000,000	0.32
Steam reheat	496,700,000	0.15
Economizing	229,300,000	0.07

The Jupiter HBTF covers the entire range of oxygen content from oxygen with high levels of recirculated combustion products for reproducing air-fired heat transfer parameters to oxygen with low recycle rates, for producing high temperature flames (5,000+ °F, known as "untempered" flames). The properties of flames and combustion products at low recycle rates (high oxygen content) are of interest because low recycle rates have the possibility of reducing both capital and operating costs in retrofits and green-field plants.

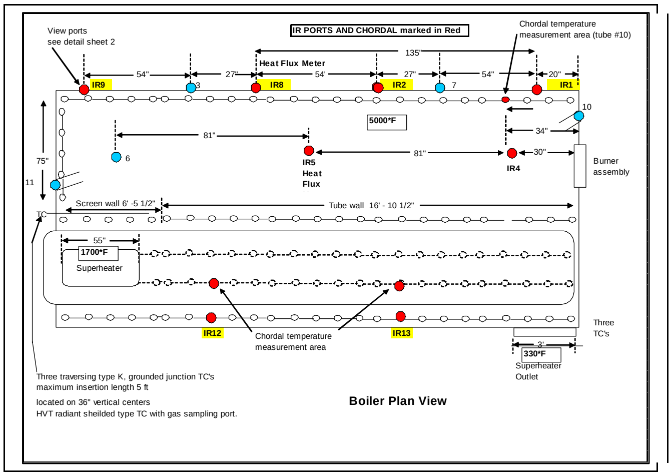
Investigating untempered flames moves design away from the assumed requirement for flame dilution, which has grown from constraining oxy-firing to match heat transfer surfaces in an air-fired boiler. If, instead, the designer can start with a fresh look at an unconstrained approach, there is a possibility of reducing costs and improving performance beyond the traditional approach.

Initial testing of both tempered and untempered natural gas (NG) burners has taken place at the Jupiter HBTF. This paper reports, predominantly, on the oxy-NG testing. Initial shake down with tempered oxy-coal combustion has also taken place and preliminary optical results are reported.

The Jupiter Hammond Test Equipment:

The JHBTF consists of a well-instrumented commercial B&W package boiler with modifications to investigate the use of oxy-fuel burners in a typical boiler environment. Figure 2 shows the boiler layout with the radiant zone at the top of the figure and the convective zone at the bottom of the figure. View ports are represented in the figure as are chordal thermocouples.

Figure 2: Plan view Layout of Jupiter Hammond BTF.



This test facility is a fourth generation oxy-fuel test facility for Jupiter Oxygen. The facility has a cryogenic air separation unit (ASU) and uses an oxygen stream from the ASU to run the test burners.

Jupiter performed 4 sets of natural gas (NG) screening tests at the 15 MWth test facility to collect data under each of 4 conditions. One set of coal shake-down tests was made for burner adjustment. Test types are listed as:

1. Oxy-NG firing with high flame temperature using only oxygen and natural gas at the burner

2. Oxy-NG firing with high flame temperature using only oxygen and natural gas at the burner while recycling flue gas and not cooling the flame by keeping the recycled flue gas away from the burner.
3. Air-NG firing using a Gordon Piatt 42 mmbtu / hr. burner operating at manufacturer specifications for excess air.
4. Oxy-NG firing using the Gordon Piatt burner operating with the recycled flue gas and oxygen mixed entirely through the burner thus cooling the flame with recycled flue gas
5. Oxy-coal firing with recycle to move the coal and also outside of the flame.

Natural Gas Test Results:

The goal of the natural gas testing was to verify the predicted flame properties and performance of the different burner configurations. The resulting effective temperatures of the four firing modes are shown in Table 2. The temperature of a flame is a difficult parameter to measure since flames are heterogeneous and are not at strict local thermal equilibrium. Oxy-fuel flames are also hotter than can be easily directly measured without damaging the measurement equipment. In this set of experiments two optical methods were applied and then compared with the calculated adiabatic flame temperatures. The first method was an inverse calculation (project team member Purdue University) of the temperature using mid-IR data to look at the intensity of specific mid-IR emission bands. The second method was a direct measurement of the Wien black body peak applied by the technical staff from NETL. The Wien approach used the temperature of the soot produced in the flame to serve as a proxy for the actual flame temperature by measuring the black body peak of soot emissions. Limits on the wavelength of the peak due to equipment wavelength cut-off prevented the application of the Wien method for temperatures below approximately 4,400°F and so prevented the measurement by that method of the temperature of the air firing or the low-temperature oxy-fuel firing with mixed recycle. The inverse method relied on band emission intensities from the CO_2 and H_2O in the combustion products. The inverse method was suitable for measurements across the temperature range. Both approaches measure the emissions from a virtual columnar section that passes through the flame and includes all of the material in the path of the column. These temperature determination techniques are biased to emphasize the hottest emitter along the column (since $\boldsymbol{Emissions} \propto \boldsymbol{T^4}$), whose contribution overwhelms that from the lower temperature components. However, there is no indication of the location of the hot spots along the column using these methods, only the effective temperature of the respective emitters.

From the measured data shown in Table 2, it is clear that there are two methods for producing a high temperature oxy-NG flame: (1) limiting recycle and (2) introducing the recycle in such a way that it does not interact with the core of the flame until combustion is nearly complete.

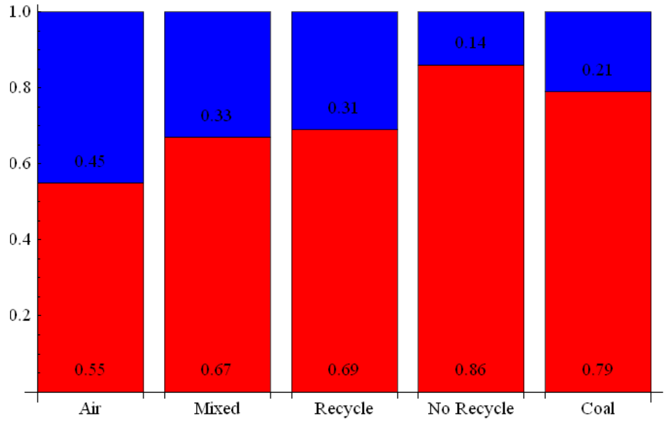
Table 2: Effective oxy-natural gas flame temperatures. Test types correspond to list above.

Jupiter Oxy-NG			Oxy-fuel
High-Temp	High-Temp		Low-Temp

	Test Type 1	Test Type 2	Test Type 3	Test Type 4
Flame Temperature (°F)	no recycle	with recycle	Air firing	Mixed gas
Purdue Calculation Inversely Estimated	5,435	5,300	3,758	3,851
NETL - Wien's displacement peak for particles	4,924	4,930	NA	NA
Adiabadic Flame Temperature by HYSIS	5,173	5,159	3,444	4,131

The two high-temp methods produce comparable flame temperatures as indicated by both temperature determination methods and as reflected by a HYSIS model. The method for the production of a lower temperature oxygen flame (Low-Temp in Table 2) mixed the comburent with the natural gas. The recycled gas has high CO_2 and H_2O contents, which interact with infrared radiation; the high-temperature flame with recycle test was done to determine the role of this optically interactive recycle gas in distributing heat in a manner different from the untempered high temperature oxy-NG flame.

Figure 3: Normalized relative heat transferred in the radiant zone versus the convective zone for the experimental package boiler (based on gas temperature changes between zones). Red is the radiative zone heat transfer and blue represents the convective zone heat transfer.



As can be seen in Figure 3, the relative distribution of heat in the boiler changes with the type of firing, the air-fired distribution in the JHBTF was identical to that determined by modeling as shown in Table 1. The other distributions reflect the increase in temperature of the flame, with the exception of the recycle high-temperature flame which showed a heat distribution closer to the fully mixed than to the "no-recycle" case. Due to recycle fan flow limitations (originally sized for coal motive only) full recycle was unable to be performed. This in an interesting observation that indicates the optically interactive combustion products are picking up heat and then moving it to the convection pass without allowing the radiant energy to be fully deposited in the boiler walls. The reason that is important is that the oxy-NG firing produces radiant energy mostly in the non-radiant bands where CO_2 and H_2O will most strongly absorb. The emission, absorption, and scattering of infrared energy are important mechanisms contributing to radiant transport from flame to heat transfer surface. Oxy-fuel combustion greatly increases the fraction of optically interactive gases due to the absence of nitrogen (nitrogen, oxygen, and argon do not interact with light in the infrared range). Figure 4 shows the general bands of emission from H_2O and CO_2. While it appears that the two overlap strongly in this infrared range, that is not exactly the case.

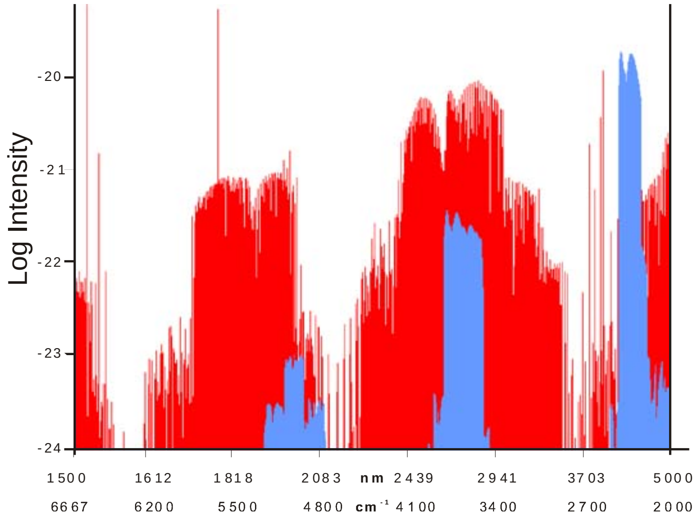


Figure 4: Emission lines for CO_2 and H_2O over the mid-IR range. Red is H_2O and blue is CO_2. Plotted using JavaHawks[6] with the HITRAN emission line database.

The figure shows what appear to be bands. However, if we were to stretch the x-axis, we would see that the bands are actually lines and that only a select number actually overlap. Moreover, there are issues of broadening of the lines; this causes them to spread out and some to overlap. This makes generalizations of radiant heat transfer through these gases difficult to calculate. As the temperature goes up, the certainty of predicted heat transfer through these gases goes down, demonstrating the need for experimental work to produce reliable predictive models.

Spectral measurements were taken of the emissions from the UV-VIS-NIR (200 nm to 1,100 nm) and the Mid-IR (1,500 nm to 4,800 nm) ranges using two different instruments. The UV-VIS-NIR signal was predominantly black body radiation from the soot formed during combustion. The Mid-IR was clearly dominated by the emissions from the CO_2 and H_2O. However, emission from the flame is only part of the picture. The other part of the picture is the amount of heat that is transferred from the flame and combustion products to the boiler wall and into the water/steam. There were two approaches used to measure the heat transfer.

The first method for measuring heat transfer into the water being boiled in the radiant zone was to use chordal thermocouples. These are thermocouples embedded in the walls of the boiler tubes at different depths. Knowing the physical properties of the boiler tube (thermal conductivity) the depth of the thermocouples in the boiler tube wall and the temperature difference between them, you can directly calculate the heat flux through the boiler tube. This translates directly to the heat flux from the flame/combustion products to the boiling water. This does not discriminate between radiant and convective transfer but it does a very good job of looking at total heat transfer from the flame to the water. A second method for determining heat distribution in the sections of the boiler is to measure the drop in temperature of the gas as it passes through the boiler. Knowing the combustion product composition and temperature, it is straightforward to calculate enthalpy at various points in the boiler and, therefore, the amount of heat that has been deposited up until each of those points. To make these measurements, there is a set of suction pyrometers at the exit from the radiant zone (screen wall) and another set at the exit from the boiler. Knowing the chemical energy input from the fuel, the temperature and mass of the recycle, and the temperature of the combustion products at the suction pyrometers, the energy left in each section can be calculated (as it was for Figure 3 above). Figure 5 shows the measured results of heat transfer through the boiler tube walls for all four oxy-NG modes. The colors of the points represent the particular pair of chordal thermocouples used for the measurement. The X-axis represents the individual tests and the Y-axis shows heat transfer in BTU/(ft^2 hr). It is interesting to see that even with high indicated flame temperatures the radiant heat transfer to the walls seems effectively mitigated by the recycled gas. We expect even more interaction between the flame and the combustion products when coal is used as reported in the next section.

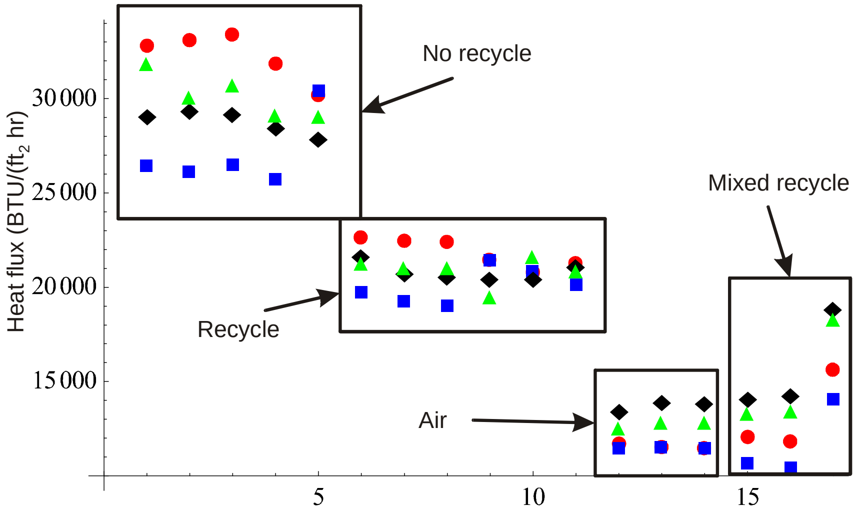


Figure 5: Heat transfer through the boiler tube walls using chordal thermocouples for estimation. Test sequence number is given along the X-axis. Colors indicate specific chordal thermocouple pairs.

As can be seen by combining Figure 5 and Table 2, the heat transfer is markedly higher in the untempered high-temperature flame formed when no recycle is used in the burner. This makes it clear that the simple radiant heat transfer ratio due to peak flame temperature is not the whole story for heat transfer from these flames to the boiler walls when the gases involved are strong interactors with the IR radiation from the flame. More detailed flame profile measurements are planned to determine if the temperatures seen are from a smaller segment of the high-temperature recycle flame than from the non-recycle flame (as would be expected with a shroud of recycled flue gas). Heat transfer for the case where recycle is employed, but unmixed with the flame (high temperature with recycle) is reduced but remains significantly greater than either air firing or mixed recycle (cooler flame). This shows experimental evidence that the heat transfer flux can be moderated by recycle, even in the case of a high-temperature core flame.

Coal shake-down:

Testing with coal has just begun. Based on initial optical measurements comparing natural gas operation with coal shake-down (Figure 6 and Figure 7) the coal particles emit a considerable amount of gray body radiation in addition to the band emission of CO_2 and H_2O. In Figure 6 the curve shows the typical band emissions from water vapor and CO_2 in an oxy-NG flame. In Figure 7, the characteristic bands have been displaced upward by a curve (shown in orange) that is produced by the gray body radiation from the coal and ash particles.

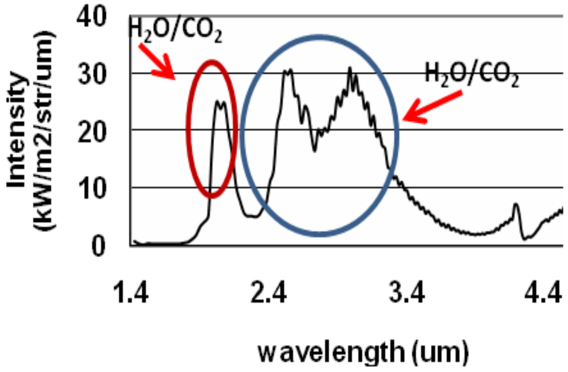


Figure 6: Oxy-natural gas flame

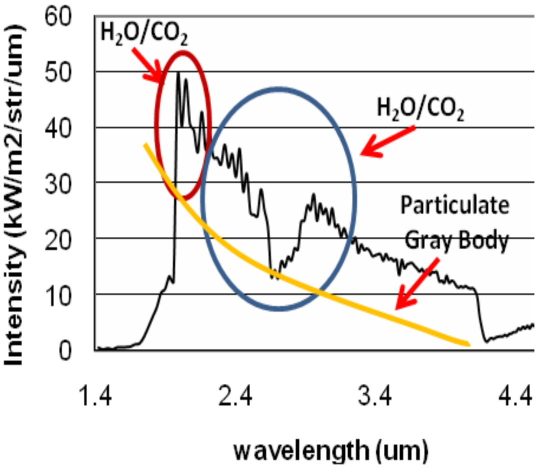


Figure 7: Measured oxy-coal thermal radiation

The gray body contribution will be dependent on the type of fuel used. A high ash coal will have more of a contribution from gray body emissions but will also have more ash in the non-luminous section of the radiant zone to absorb energy from the flame. However, gray body emissions at wavelengths below the strongly absorbing bands for water vapor and CO_2 will not be absorbed by the gaseous components. This means that the calculation of meaningful engineering approximations of radiative heat transfer in the radiant zone is a difficult problem. Existing radiant transfer models are tuned for air, based on a century worth of experience building boilers. When we change the parameters by adjusting the comburent oxygen content we move out of the reliable range of commercially available models. If we want also to raise the flame temperature by limiting dilution of the oxygen the current industry models become even less reliable. To try to make better models, NETL is planning to use the data from the JHBTF and other NETL-supported efforts to verify and improve their oxy-fuel models. To be reliable, models must take into consideration the interaction of particles and the IR interacting gases (CO_2 and H_2O). To give an idea of how the flame emissions change with temperature we can examine the data we have so far and draw some order-of-magnitude conclusions. If we expect an air-fired PC burner to produce an effective temperature of approximately 2000K and if we expect a high temperature oxy-coal burner to produce an effective temperature of approximately 3000K, we can determine the ratio of power output from two black bodies at those respective temperatures by looking at the ratio of the temperatures taken to the fourth power.

$$\textit{Power Ratio} = \frac{3000^4}{2000^4} \approx 5.0$$

That indicates that each particle will yield about 5 times as much power at the higher temperature. However, we are not sure if the emissivity (grayness) of the particle will change at high temperature, how the particle sizes (agglomeration or evaporation) will change, or how non-luminous emissions from the gases will change (readily available data bases for most gas emissions do not go, without extraploation, to 3000K i.e. HITRAN and HITEMP). One interesting issue is the interaction of CO_2 and H_2O with the gray body emissions. To see this interaction, we can examine the fraction of emissions that occurs below a given threshold. For instance, if we consider a reasonable cutoff for significant absorption by H_2O and CO_2 to be approximately 1,700 nm based on Figure 4, we can calculate that a uniform gray body at 2000K will emit approximately 36% of its total hemispherical power below the cutoff while the same body at 3000K will emit approximately 65% of its power below the same cutoff (1,700 nm) due to the change in wavelength for the maximum emissive power from 1489 nm for 2000K to 965 nm for 3000K. This shift in the gray body peak moves the predominant power emission to shorter wavelengths and reduces the effect of the absorbing gases (Figure 8). However, it does not address the interaction of the shorter wavelength radiation with particles when burning coal.

Initial results of oxy-coal shake-down measurements (as shown in Figure 8) indicate that coal particle interaction will be an important contributor to heat transefer estimations. All of those particulars are wrapped up in the total emissions from the flame that are absorbed into the steam. The JHBTF gives us a good platform for learning more about the radiant transport from the flame to the boiler walls. At this time, the optical measurement system is being upgraded by the addition of a monochromator that will be able to cover the spectrum from 400 nm to 5000 nm with resolution as fine as 0.5 nm (depending on scanning rate). Details of the emission bands for high temperatures will be useful in expanding the capability of existing simulations. However, the interaction of particles is expected to be an active participant in the broad band emissions (as seen in Figure 7). The particles will also interact with the active bands for CO_2 and H_2O.

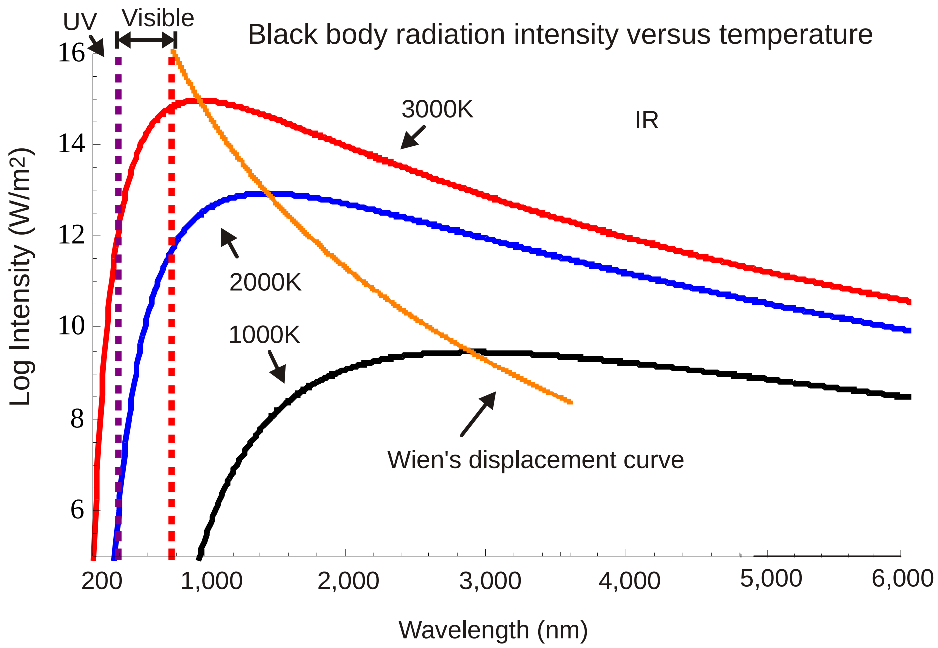


Figure 8: Relationship between black body radiation curves at different temperatures.

Conclusions:

The JHBTF has had multiple campaigns over the past 18 months. Burner stability, heat transfer, and operation with an integrated pollutant removal system (IPR™) have been examined to better predict conditions that will be found in the first full-scale oxy-fuel boiler systems. During the testing with oxy-natural gas and subsequent shake-down using oxy-coal, there have been no indications that an oxy-fuel flame (high-temperature or low-temperature) will produce any unique problems that cannot be engineered to retrofit an existing boiler or to repower a boiler that has passed its useful life span. Although the first full-scale oxy-fuel boilers will not be optimized, they can and should be built. The authors of this paper are convinced that an integrated development program to design, test components, and construct an oxy-fuel boiler for a utility could be implemented at the present time.

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