The Next Generation of Oxy-Fuel Boiler Systems

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ABSTRACT:

Research in the area of oxy-fuel combustion which is being pioneered by Jupiter Oxygen Corporation combined with boiler research conducted by the USDOE/Albany Research Center has been applied to designing the next generation of oxy-fuel combustion systems. The new systems will enhance control of boiler systems during turn-down and improve response time while improving boiler efficiency. These next generation boiler systems produce a combustion product that has been shown to be well suited for integrated pollutant removal. These systems have the promise of reducing boiler foot-print and boiler construction costs. The modularity of the system opens the possibility of using this design for replacement of boilers for retrofit on existing systems.

BACKGROUND:

One of the problems in applying oxy-fuel combustion systems to power generation has to do with our engineering view of boilers. We have steadily improved the design of boilers based on the idea that the oxygen supply for our combustion systems would be air. This has constrained us to the standard composition of air which typically consists of approximately 77.3% nitrogen, 20.7% oxygen, 0.9% argon, and 1% water vapor (with smaller portions of CO_2, neon, helium, and other gases). In our standard view of boiler systems we count on a mass of combustion products that contains a large volume of inactive nitrogen. Since this mass must be heated with the combustion products, it drops the flame temperature and increases the volume of combustion products. To optimize the heat transfer surfaces we count on the high volume of diluted combustion products at a flame temperature determined by heating the extra mass. Because of the design constraint we traditionally look at the heat transfer as being balanced between radiant and convective sections. In our investigations of advanced oxy-fuel designs we employed an industry standard power plant modeling software (GateCycle[1]).

There are many areas where oxy-fuel systems have the potential to outperform air-fired boilers. Some of the primary ones are:

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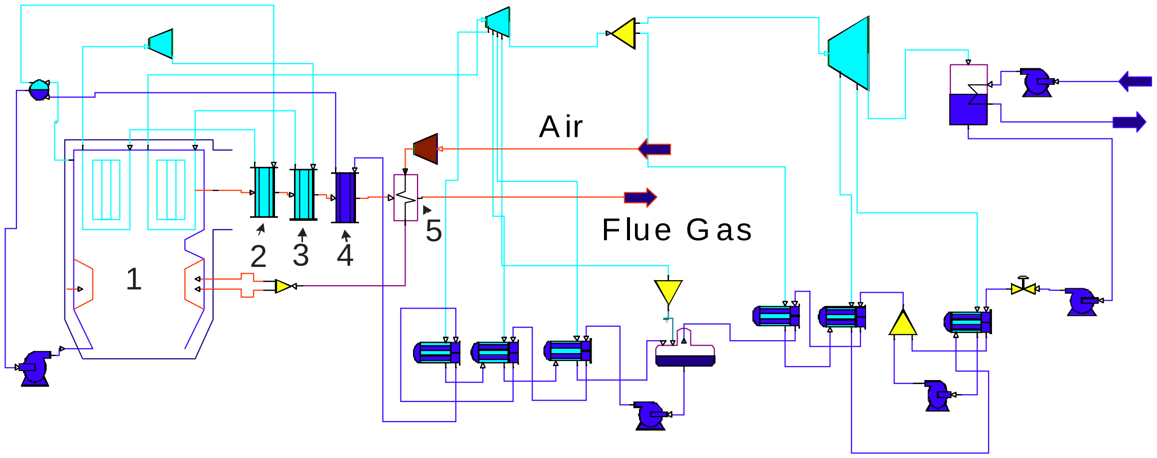
[1] The USDOE does not endorse or recommend any commercial products. Specific product or company names are included to ensure complete disclosure of techniques and partners.

- Increased boiler efficiency
- Reduced combustion product volume/mass
- Increased condensable vapors
- Increased specific concentration of pollutants
- Increased radiant heat transfer
- Multistage for advanced control

An example of a simple computer model of a typical 400 MW power plant is shown in Figure 1. In the standard design (Figure 1), air is used for both primary and secondary air in a single fossil fueled boiler. The path of the air/combustion products is numbered in Figure 1. Air first enters the system through the APH.

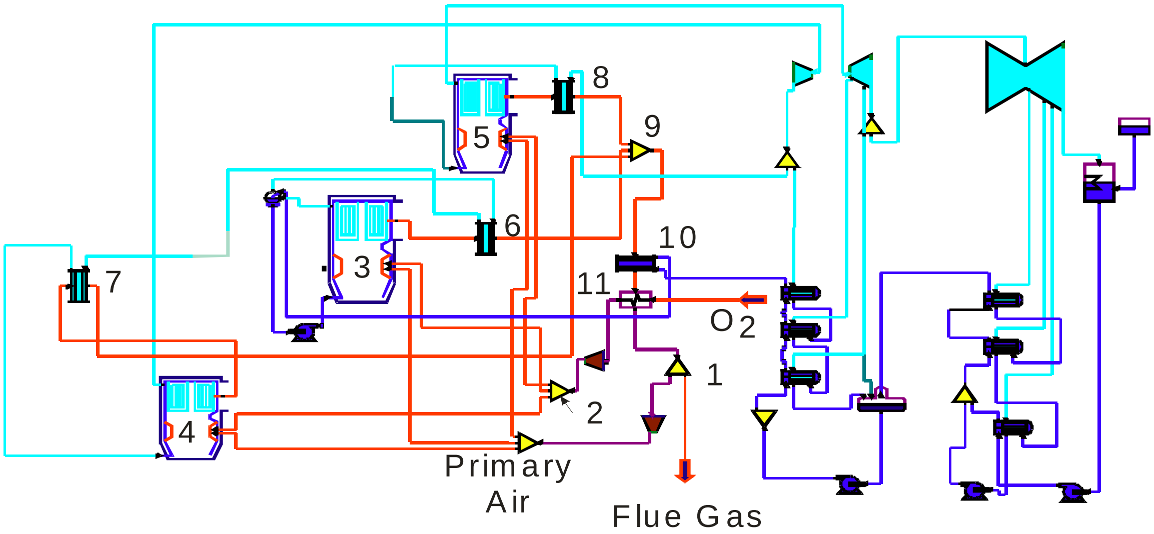
1. Air enters the boiler as both primary and secondary air where it is mixed with fuel and the oxygen in the air supports combustion in the boiler while the hot combustion products transfer energy to the boiler walls and the pendent superheaters primarily through radiant heat transfer. The boiler is a thermally dynamic area with heat serving three basic purposes. First, the heat is used to boil water in the water walls, second it superheats at the secondary (pendent) superheater, and third, it adds superheat at the secondary pendent reheater.
2. The hot combustion products then move through the boiler to the primary superheater where heat is transferred through both radiation and convection.
3. The combustion products then pass through the primary reheater where heat is transferred by a mix of radiant and convective heat transfer.
4. The cooler combustion products are then passed on to the economizer where heat is transferred primarily through convection to the boiler feedwater.
5. Finally, the remaining useful heat from the hot combustion products is exchanged with the incoming air to prevent loss of excessive heat up the exhaust stack and to bring up the temperature of the entering air.

Figure 1: Standard single boiler coal fired power plant



An advanced design multistage oxy-fuel boiler system is shown in Figure 2. In this system there are multiple boiler sections to take advantage of the higher flame temperatures found in an oxy-fuel flame.

Figure 2: Advanced design three combustion section oxy-fuel power plant



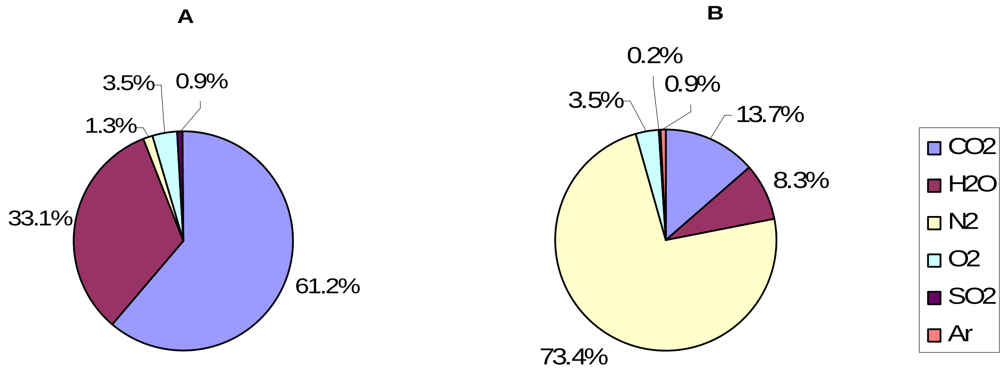
Again, the path of the oxygen/combustion products is numbered in Figure 2 and we can follow that path. In this system, oxygen is shown entering the system through an air preheater (APH).

1. In the advanced combustion system the flue gas stream is shown being split into two parts - (1) is sent through a forced draft fan and being distributed to all three boilers as primary air to mobilize the coal. The second part of the combustion gas stream is rejected as flue gas. It is clear that here, the mass of flue gas products rejected must balance the combined mass of the fuel flow and the oxygen flow to keep the system mass balanced.
2. The oxygen is split into three streams to send secondary air on to all three combustion systems.
3. The first combustion system takes a flow of coal motivated by the primary air stream of combustion products. The secondary air comes from the oxygen supply. This combustion system serves only to boil the water to saturated steam in a set of water walls transferring most of the energy released in the hot flame as radiative energy to the water.
4. The second combustion system serves only to superheat the steam generated in the first combustion system.
5. The third combustion system serves only to add superheat to the reheat stream coming from the high pressure turbine.
6. The first combustion system does not transfer all of the energy in the flame to the water walls. Excess energy in the combustion products from the boiler is transferred into the steam leaving the boiler as it would in a primary superheater.

7. In like manner, excess energy from the second combustion system is used to preheat the steam prior to entering the second combustion system.
8. The excess energy from the third combustion system is transferred into the reheat steam in the equivalent of a primary superheater prior to its entrance to the third combustion system.
9. The combustion products are combined.
10. The combustion products then go through an economizer adding energy to the feedwater prior to the entry into the water walls.
11. The combustion products finally go through a counterflow heat exchanger and transfer energy to the incoming oxygen.

One remarkable comparison between standard air fired systems and oxygen fired systems is the compositions of the two flue gas streams. When treating standard combustion products to remove pollutants and CO_2, we must treat the entire stream of gases including a substantial portion of N_2. In an oxy-fuel combustion system there is little N_2 in the combustion gases which greatly reduces the mass of combustion products which must be treated as well as greatly changing the composition. To see a comparison of the compositions of the flue gases look at Figure 3. Figure 3 shows the two cases we examined in Figure 1 and Figure 2. In the first case (A) the system is using oxy-fuel combustion as in Figure 2. It is clear that the major constituent of the flue gas is CO_2 (approximately 61%) followed by water vapor (approximately 33%). For the second case (B) as illustrated in Figure 1 the system is using air for the oxygen supply and the major constituent of the flue gas is nitrogen (approximately 73%) followed by CO_2 at approximately 14%. The reason this composition difference is so important is that the water vapor can be easily removed from the gas stream through condensation leaving a greatly reduced mass in the case A. Furthermore, if we want to remove CO_2 from the flue gas it is a much larger component in case A than in case B (making it easier to remove because the concentration is higher).

Figure 3: Combustion product composition for oxy-fuel boiler system (A) and an air fired combustion boiler (B)



In the cases we have investigated using computer modeling, the mass flow through a 400 MW standard flue gas exhaust system using air as the combustion supporting gas (as shown in Figure 1) is approximately 3,780,000 lb/hr. The flow of exhaust gas out of a comparable 400 MW oxy-fuel system, as shown in Figure 2, is only about 913,000 lb/hr.

That means that the mass ratio of the two flue gas streams is approximately 4 to 1. The treatment facilities in an advanced oxy-fuel boiler will have to handle approximately 1/4 the mass with the attendant decrease in costs.

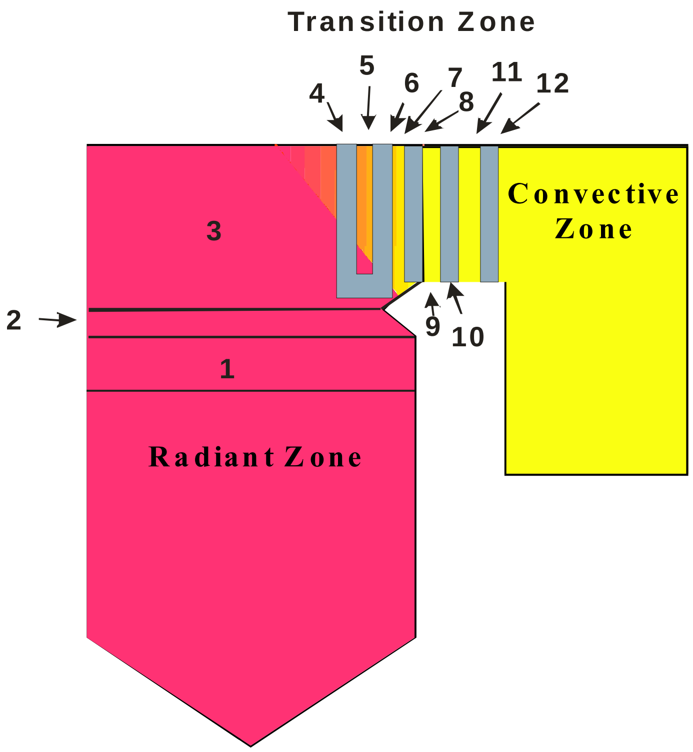
Combining the new flue gas compositions with the greatly reduced mass flow shows that oxy-fuel systems have potential advantages in post combustion treatment to remove pollutants and CO_2.

DETAILED DESIGN:

We have made a number of advances that can be applied to a next generation of oxy-fuel combustion systems that will take advantage of the fact that we can change the oxygen content as well as modify the other gases in the system. If we move to oxy-fuel systems and recognize that we can control the amount of inert gas in the system we have new engineering flexibilities that allow us to improve our systems. If we do not recognize the techniques we can apply we are constrained to produce less-than-optimal combustion systems.

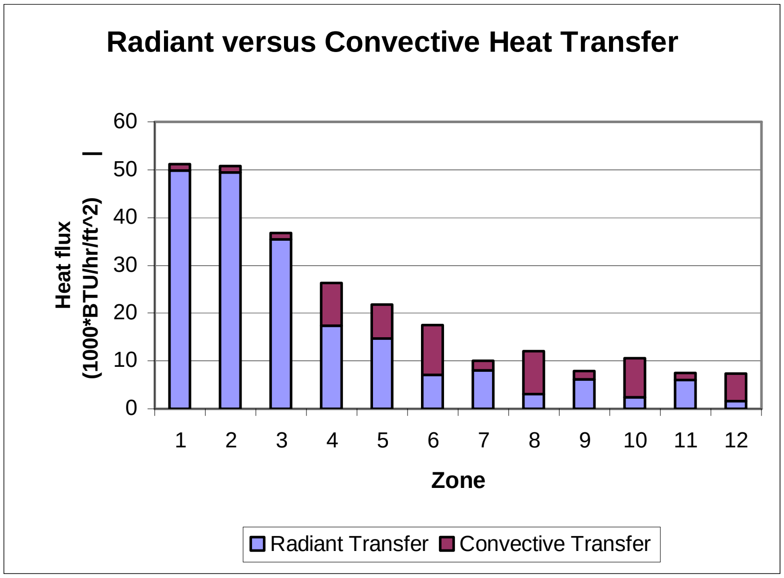
In order to better understand the situation, we have to look carefully at the way a standard boiler is built. Figure 4 illustrates the distribution of heat transfer mechanisms in a standard fossil fuel boiler[steam1]. The amount of heat transferred by radiative means starts high as the flame temperature is high and then drops as the combustion products give up heat to the walls.

Figure 4: Traditional boiler radiant versus convective heat transfer from hot combustion gases by zone (steam1)



The proportion of radiative to convective transfer can be clearly seen in Figure 5 which shows the distribution of heat flux in each zone of a standard fossil fired power plant.

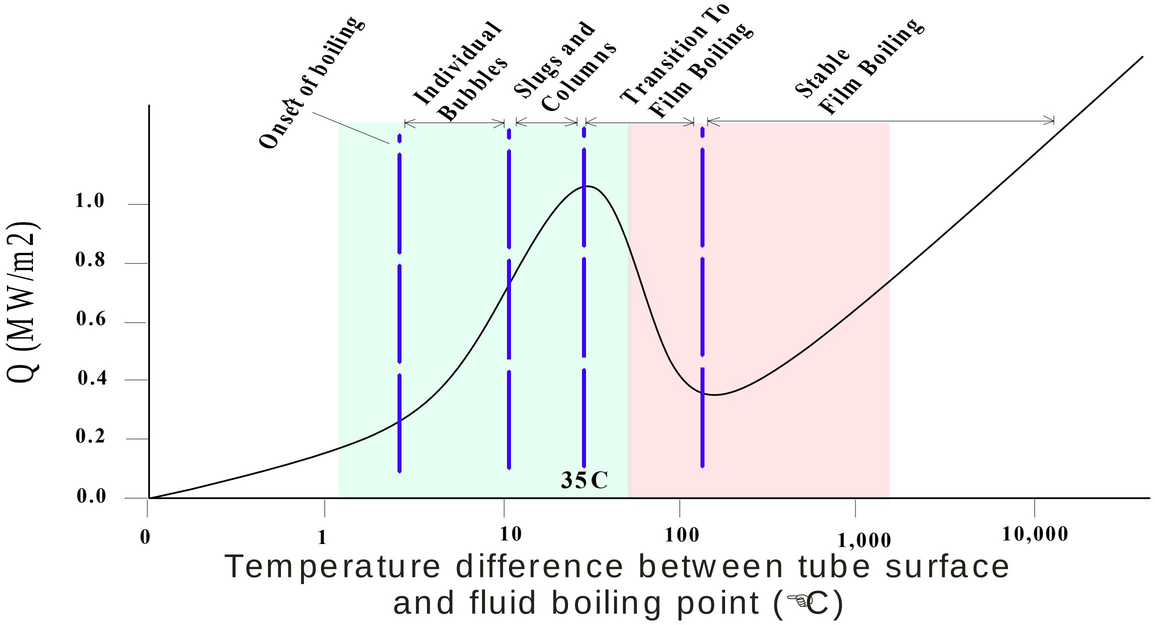
Figure 5: Typical ratio of radiant to convective heat transfer from combustion gases by zone (steam1) (note that 1,000 BTU/(hr-ft2) ≈ 3.1546 kW/m^2)



From the distribution of energy transfer mechanisms shown in Figure 4 and Figure 5 it can be seen why the boiler system is built the way it is. In a conventional boiler, as shown in Figure 1, the "adiabatic flame temperature" (which is a calculated temperature the flame would be at if there were no heat lost from the flame) is in the range of 3,500°F. In an oxy-fuel boiler, as shown in Figure 2, the adiabatic flame temperature is approximately 6,400°F since there is no extra nitrogen in the flame to be heated. In radiant transfer, the amount of heat transferred between the source and the sink is proportional to the difference between the fourth power of each absolute temperature (absolute zero on the Fahrenheit scale is approximately -459.7°F). The result is that in the conventional system there is a significant requirement to remove much of the heat energy through convection to the incoming water and lower superheat steam.

The higher flame temperatures give us an opportunity to use the principles of heat transfer to our advantage. We are still restricted though to heat transfer ranges in which the tubes carrying the working fluid are not damaged. In order to ensure that the metal in the tubes is not damaged we must operate in a heat transfer range where sufficient heat can be transferred from the metal surface facing the flame to the water to keep the temperature difference between the metal surface and the water in a safe range. Figure 6 shows that there are different types of boiling that take place when a surface is in contact with water. In this case the type of heat transfer is "free convection" in which the fluid is allowed to flow by density difference and is not forced across the hot surface. The high point in the curve of heat flux occurs at a temperature difference between the surface and the water of about 35°C. After this temperature difference is exceeded the heat transferred to the working fluid is not sufficient to cool the tube and the temperature difference between the fluid and the tube surface rises steeply. Since boiler tubes are working at a temperature close to their failure point, a sudden increase in temperature of the tube surface will cause the tube to fail. For this reason it is important to recognize that the high heat transfer rates of the hot oxy-fuel flame can overheat a tube if the maximum heat flux is exceeded.

Figure 6: Boiling regimes for water with a submerged heat source (Kreith1)

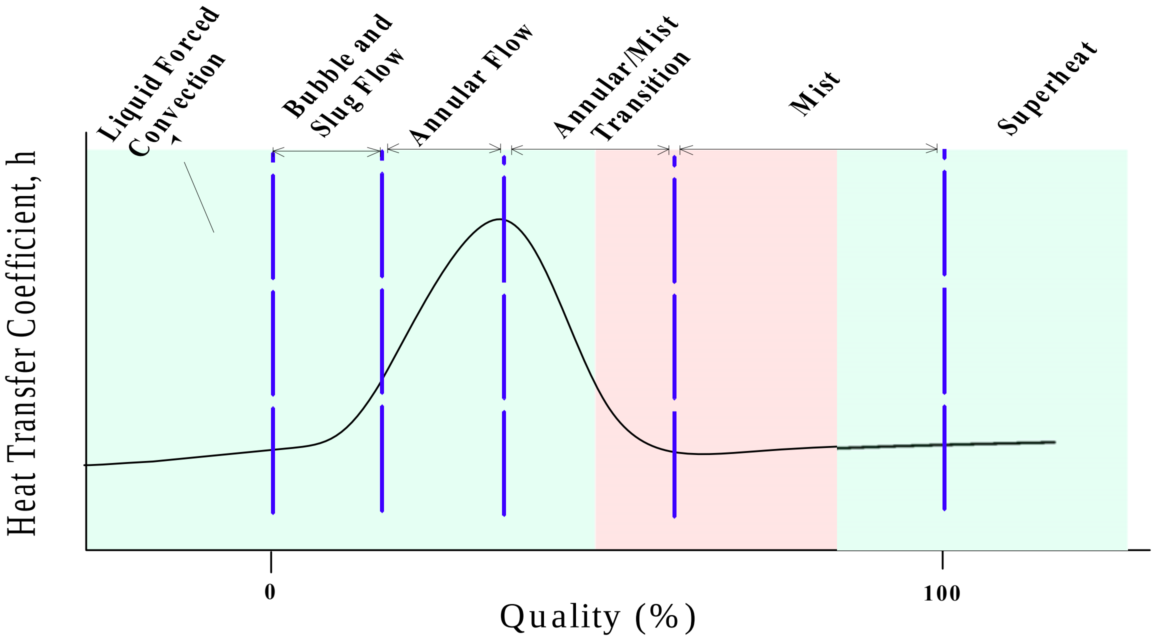


In the case of forced convection (where the fluid is forced to flow across a surface) the amount of heat transferred into the fluid is controlled by the convection coefficient and the temperature difference between the fluid and the combustion products. It is easy to put more energy into the tube than the internal forced convection can carry away – rapidly leading to tube failure. For that reason it is important to limit the amount of heat being transferred to the exterior of the tube to the amount that can be carried away by the working fluid. Figure 7 shows the characteristics of forced convection for two phase flow that are similar to those found in free convection with a distinct maximum heat transfer coefficient. In the case of forced convection the X-axis is shown representing the quality (ratio of steam to total of steam and water flowing through the tube). The difficulty is that it is necessary to balance the flow of heat into the fluid through the convective heat transfer boundary layer. These concepts are found in most heat transfer text books as well as power industry standards such as Steam – chapter 5.

While there are restrictions on the amount of heat that can flow through the boiler tubes, the fact that we can change the temperature of the flame by recirculating flue gas gives us substantial latitude in design. By modifying the combustion system geometry we can provide heat directly to the region where it is needed. In a standard boiler the system is driven by the need to boil water into steam. The other sections of the boiler are cleverly designed to allow convection to provide approximately enough energy to superheat both the main steam and reheat. This is a delicate balancing act that sometimes requires cooling of the steam (atemperation or desuperheat) to keep the steam temperature safe for the turbines. In like manner, sometimes it is difficult to have enough superheat if the system is turned down to produce less power. All of these adjustments to the system cost thermal efficiency in the power conversion cycle.

In the advanced design power plant the heat energy is added to each of the regions of the boiler (water wall, superheater, and reheater) as it is needed without the need to balance flows of combustion products. The result is a combustion system that is simple to operate and control.

Figure 7: Boiling regimes for forced convection (Kreith2)



CONCLUSION:

When oxy-fuel combustion systems are applied to traditional boiler configurations, they are designed in such a way as to make accommodations for the engineering constraints that exist due to the nature of the gas composition of air. Boiler designs in which relatively pure oxygen is used as the combustion agent allow us to consider unique optimization techniques for the heat transfer surfaces that take full advantage of the radiative nature of the flame, while balancing the convective sections proportionately. These new advanced boiler systems themselves mimic, to some extent, an air-fired boiler in that the steps taken to transfer the energy in the fuel to the liquid medium is duplicated by replacing what would have been the convective portions of a traditional boiler with modular components that are designed to accept a higher percentage of radiation rather than convection. The advantages of such systems include, but are not limited to, overall increased boiler efficiency, a reduction of post combustion products in both volume and mass, and an increase in concentration of all pollutants. As a consequence, the system lends itself very well to advanced multistage control methods for the economical capture of flue gas. Most importantly however, this can be done with technology that exists today in a cost competitive manner.

REFERENCE:

Steam1: Steam its generation and use, 40th edition pg 4-23.

Kreith1: Kreith, Frank and Bohn, Mark S., Principles of Heat Transfer 5th ed, West Publishing Company, 1993, pg 647.

Kreith2: ibid, pg 668.