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Computational Fluid Dynamic Modeling and Field Results for Co-Firing Gas over Coal in a Stoker Boiler

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Abstract: The Over Coal Natural Gas (OCNG) system is designed to provide the required combustion of natural gas over the burning coal bed of a stoker fired boiler. The primary goal of the design is to provide as complete a coverage over the coal bed as is possible within the geometric constraints of the furnace configuration. The co-firing of gas fuel over the burning coal bed of a stoker fired boiler has been modeled using Fluent computational fluid dynamic (CFD) program. The model has been verified in the field with actual applications of co-fired gas fuel over the burning coal bed of three stoker boilers. This paper presents computational fluid dynamic modeling of this technology as well as field validation of the results. The OCNG Jet burners have been shown through emissions, capacity, and operational results to be an economical and technically adequate solution to the problems of smoke emissions and the reduction of NOx emissions. This design also provides load response performance improvements to stoker boiler operation.

Keywords: Low NOx Boiler; Over Coal Natural Gas burner; Co-firing Fuel; Low Fuel Cost; Improved Boiler Load; Computational Fluid Dynamics

1. Background

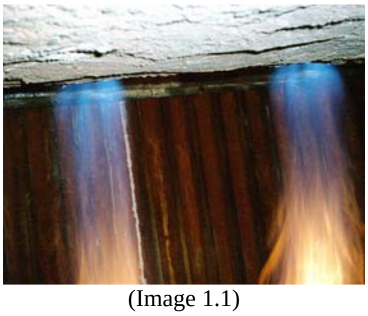
1.1 Boiler Background

Part 1 of this paper refers to in a Keeler "CP" boiler rated at 20,000 lbs/hr of saturated steam at 150 PSIG. This boiler is equipped with a single-retort underfeed ram type stoker. The fresh coal is pushed into the furnace with the ram and forms a pile on the grate. Combustion air is provided by a forced draft fan and is supplied to the furnace from a windbox located under the grate. This windbox is open; it is not divided or sectioned into air zones. The air admission to the furnace is controlled by the openings in the grate tuyeres. These openings control the air fuel ratio of the coal combustion on the grate. Because of this air design the air/fuel of the coal combustion is not uniform from front to back in the furnace. The front of the grate will tend to burn under fuel rich conditions. This is due to the large amount of coal present on the grate relative to the amount of air that is admitted under the coal bed at this location. Most of the visible smoke that is emitted from the furnace is formed in the first two feet of the grate by the fresh coal igniting and devolatilizing in this region of the furnace. The over-coal natural gas (OCNG) burners above this region of the grate are important to controlling the emission of smoke. These burners also provide early ignition of the fresh coal as it enters the furnace. The OCNG burners in this region provide strong radiative heat feedback to the grate. This heat helps to ensure the rapid ignition of the fresh incoming coal. The OCNG burners also provide turbulent mixing of the devolatilized fuel fragments coming from the coal bed with the excess oxygen in the gases above the coal bed. This mixing, at the elevated temperature, ensures the complete combustion of the coal fuel and the elimination of the soot formed by these fuel fragments which cause smoke.

The fixed carbon remaining in the coal particles will continue to burn, primarily by "diffusion mode" combustion, as they are pushed toward the rear and sides of the furnace. When the coal is burned out the remaining ash is dumped from the grate into the ash pit underneath the grate.

1.2 Description of the Over Coal Natural Gas (OCNG) Burner Project

The OCNG system design is to provide the required combustion of natural gas over the burning coal bed of a stoker fired boiler. The primary goal of the design is to provide as complete a coverage over the coal bed as is possible within the geometric constraints of the furnace configuration. In the case of the underfeed fired stokers of the boiler in question, the only available access walls to the furnace are the side walls of the furnace/boiler. The front of the boiler is taken up with the coal feed system and the rear wall is buried inside the boiler passes. The side walls provide good access to the important overbed regions of the furnace. The OCNG burners are high axial component (jet) type burners. These burners provide a very long, collimated flame, shown in images 1.1 and 1.2. These features of the flame shapes are important to the geometry of the furnace. The flames must reach across the width of the furnace to mix and radiate. The OCNG burners are arranged in a staggered pattern over the grate/coal bed. This arrangement provides the greatest coverage with the best mixing and radiation over the center part of the coal bed, where the raw coal is first introduced into the furnace.



(Image 1.1)

(Image 1.2)

1.3 The OCNG Burner Heat Input

Our burners themselves are virtually 100% efficient, with burners experiencing near complete combustion resulting in equivalent heat output. The OCNG burners are positioned over the entire grate/coal bed area so that the heat input to the furnace simulates the coal bed firing. It is important that the heat input to the furnace be uniform. The burners are sized at 2.562 mmbtu/hr heat output. This corresponds to 45% of the boiler full load capacity of 20,000 lbs (150 psig steam)/hr. This steam has 1195.6 btu/lb of heat. Dividing by the boiler efficiency of 70% then gives the total required heat input to the furnace of 34,160,000 btu/hr. When this total heat input is divided among six burners and multiplied by 45% the burner size comes out to be 2,562,000 btu/hr. This is the design point for the OCNG burners. It is this value that is the guarantee point for the burners. The OCNG burners may be fired at any load from zero heat input to the maximum rating on each burner. The turn down on each burner allows the OCNG burners to operate at very low firing loads over a wide range of Theoretical Air (T/A = 100 for Stoichiometric Air/Fuel) conditions. The range of operation for the OCNG burners is from T/A = 0.75 to 2.00 at all loads from 100,000 btu/hr to 2.5 mm btu/hr. This feature of the OCNG burners allows them to be used to control the over coal bed Air/Fuel**.**

2. Computational Fluid Dynamics

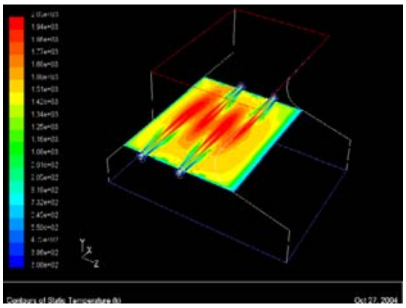
2.1 Computational Fluid Dynamics (CFD) Model Parameters

The modern approach to furnace and boiler modeling is to use CFD calculations on a computer, is explained in Part 2 of this paper. The CFD model parameters were selected based on the experience of using over-fire air in the side walls of coal fired stoker boilers. The four burners are located 18 inches above the active section of the fuel bed and were spaced and staggered to provide coverage of the over bed region. This coverage is important to the reduction of smoke and the improvement of boiler efficiency in stoker fired boilers. The design philosophy is that if the soot that causes smoke can be eliminated before it forms then it won't be an emission problem. To this end we design the co-fire burners at the elevation and spacing to provide the optimum mixing coverage over the coal bed that is available.

The coal bed was modeled at seventy percent of boiler full load at one hundred percent excess air (200%T/A). The gas co-firing was modeled at thirty percent of boiler full load at twenty percent excess air. The resulting flames from the jet burners were shown to be contained nicely within the furnace of the stoker boiler.

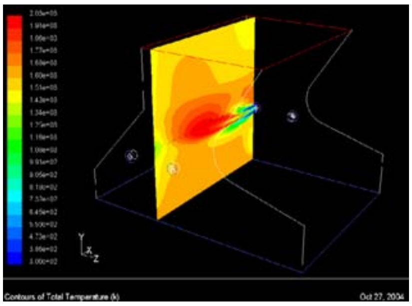
2.2 CFD Model Results

The modeling results are contained in the following images. Figure # 2.1 shows a plan view of the four burners firing all at once over the coal bed. The temperature contours clearly show the combustion air entering the furnace around the co-fired burners as it reacts with the gas fuel and the combustion products from the coal bed. The high temperature regions of the co-fired gas occur over the center of the coal bed in exactly the region where soot is formed. These center sections of the coal bed are the most difficult regions to reach from the front and back walls with conventional over-fire air. The jet burner's plume is seen to reach these regions and mix with and combust the volatile fuel fragments coming from the coal bed. The reactive flame mixture of hot gases is the perfect medium for accomplishing this task.



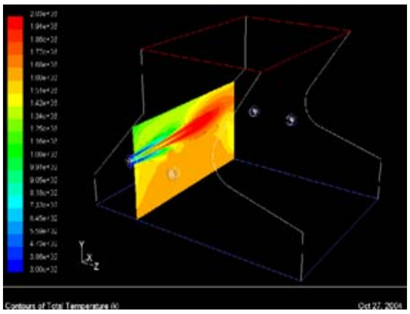
(Figure # 2.1)

Figure # 2.2 contains the flame from the second opposite side wall burner firing into the open furnace. The burner produces a uniform high temperature profile in the vertical dimension above the coal bed. The light red and tan zones above the burner at the firing wall confirm that these regions are also heated and mixed to provide the required co-firing even at the wall.



(Figure # 2.2)

Figure # 2.3 contains the model results of a jet burner firing under a small ignition arch in the front of the furnace. It is seen that the arch guides the flame in a longer more collimated fashion than the other flames shown. This is important in that the jet burner has been shown to be a good enhancer of ignition arch performance in stoker firing. This is especially important for wet coals and other hard to ignite fuels. The jet burner's basic performance is not altered by the presence of an arch or a wall in the furnace.



(Figure #2.3)

2.3 Conclusions from the CFD Modeling

The use of CFD reacting flow modeling has been used to place the co-firing burners over the burning coal bed of the furnace of a stoker fired boiler. The model has been validated by field application of the burner installation using the same parameters of the model. The results are excellent in all respects. Emissions of CO, NOx, smoke, particulate and SOx have all been dramatically reduced with the use of 30% co-firing over the coal bed.

The boiler's operational load was increased to thirty percent above nameplate. The response time to load spikes was dramatically increased with the use of co-fired gas.

Boiler load turn down was increased by an order of magnitude.

The co-firing burners are a cost effective way to improve the emissions and operation of coal fired stoker boilers.

3. OCNG Implementation

3.1 Implementation of OCNG Firing

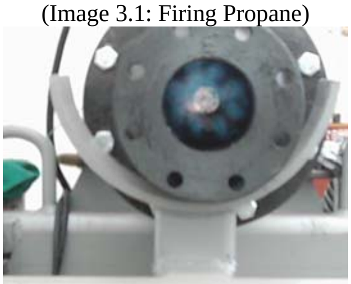
Part 3 of this paper outlines the Mechanical, Electrical, and Control elements of the burner installation at SSGC.

The burner is mounted to the sidewall of the furnace at the location specified by the manufacturer. A nine inch (9") diameter hole is bored through the refractory wall of the furnace and the skin of the furnace. Any boiler tubes that are in front of the burner entrance are to be bent away from the burner opening. Typically this is only one boiler tube for each burner. The discharge end of the air sleeve and flange are welded into the furnace wall onto the skin of the furnace. The refractory is patched around the discharge tip and the reducer. The air sleeve reducer tip should be brought to the centerline of the diameter of the boiler tubes in the wall. This avoids any flame impingement on the tubes. On the outside the flange bolts are ready to accept the body of the burner when it is ready to install. The body of the OCNG is bolted to the flange on the reducer discharge tip and supported externally by a support strut or a hanger. The burner weighs about 300 lbs. The gas piping may now be plumbed to the burner. The wiring for the motor can be made at this point. The control BMS package may now be installed and wired to the burner's igniter and flame scanner and the valve train.

The burner may now be test fired into the furnace. Continuous controlled firing must have the CCS installed and tested.

The following photographs (images 3.1 to 3.2) show the OCNG Jet burner in operation on test stands at the manufacturing facility in Carrollton, OH. The photographs show the burner being fired on propane and synthetic gas from tires. Each burner is test fired on the fuel to be used before shipment to the customer.

(Image 3.1: Firing Propane)



(Image 3.2: Firing Synthetic Gas)

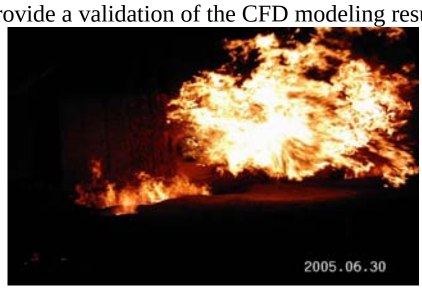
3.2 Technical Basis for the Use of OCNG Jet Burners

The OCNG Jet burners have been shown to be an economical and technically adequate solution to the problems of smoke emissions and the reduction of NOx emissions. The OCNG Jet burners also provide load response performance improvements to stoker boiler operation. The co-fired gas can pick up the load increases much more quickly than the coal fuel can respond. While the gas is providing the rapid load demand the coal can follow and eventually take over for the gas. This limited use of gas is economical and can save the cost of installing a gas fired package boiler to do the same function. The co-fired OCNG jet burners provide this load following capability in the same boiler. The OCNG jet burners can also be used for smokeless cold light off and start-up. The operation is much the same as in the load following scenario. The boiler furnace is fired on gas to heat it up and start producing steam. The coal is introduced into the preheated furnace and is ignited with the OCNG jet burners firing over the front section on the coal bed. Load is gradually changed over to coal and the gas is taken out of the furnace in part or completely. If rapid load swings are anticipated where the load increase is to be followed by a rapid load decrease, then the coal firing would not be increased to follow the gas firing up on the initial load increase, but would rather continue at the base load firing rate and allow the gas to cover the increased load demand. When the load drops, the gas fuel will take the drop back to the base loaded coal firing rate. This type of operating scenario is very beneficial to the emissions performance of the coal bed since it is not upset by the rapid load swings.

4. Field Validation of the Model Results

4.1 Image Validation

Part 4 will discuss field results from SSGC. The following images (images 4.1 to 4.3) show three forty thousand pounds of steam per hour stoker coal fired boilers that were retro-fitted with four side wall co-fired gas burners. These boilers provide a validation of the CFD modeling results.



(Image 4.1:Full load flame co-firing with coal)

(Image 4.2: Two burners on each side of the boiler (4 total)

(Image 4.3: Back elevation view of LPJB-20)

4.2 Data Validation

The following table (Table 4.1) contains the measured values of NOx and O2 at SSGC. The full load values on coal have been taken from the FGR measurements for Stoker Boilers. The other values have been determined by the slope of the respective dNOx/dO2 line. The values at low O2 may be lower than actual since no "prompt" NOx has been taken into account. However, the NOx reductions are impressive with the COG over coal co-firing. The projected NOx emission values at reasonable O2's are in the 50 to 60ppm range. The reductions in CO emissions from 2500 ppm on coal only to 43 ppm when co-firing are even more impressive. This reduction represents a fuel savings of 3.7%.

Table 4.1

COG/COAL NOx EMISSIONS AT SSGC

Mt/h(steam) Coal	COG	O2 ppm	NOx ppm @3%O2 dry	dNOx/ dO2	meas/ calc.	Reduction	item #
6	16	12.6	218	17.3	meas.	60% from coal only #7	1
6	16	5	87	17.3	calc.		2
0	22	12.6	196	15.6	calc.		3
0	22	5	78	15.6	calc.	88% from high air coal only	4
6	0	14.6	411	28.2	meas.	#6	5
22	0	14.6	628	43.0	NOx Plot		6
22	0	12.6	542	43.0	NOx Plot		7

4.3 Accomplished Goals at SSGC:

- The boilers could be run at 25 mt/hr steam load on 100% Coke Oven Gas fuel (COG).
- The NOx emission in co-firing mode was reduced 60%.
- The Carbon Monoxide (CO) emissions in co-firing mode were cut from 2500 ppm to 43 ppm.
- Particulate emissions and smoke are eliminated.
- Boiler load response was improved to seconds from many minutes.
- All of the powerhouse steam demand can now be carried by one boiler.
- Fuel cost is dramatically reduced.
- The automatic computer control system worked perfectly.
- Operational technicians learned the system and quickly became fond of it.
- The LPJB-20 system is a very forgiving burner; it lights quickly and easily even without air flow in the air sleeve see burner.
- Burner turn down in excess of 100:1 is available.

5. Co-Firing at Rockview State Correctional Institution (RVSCI)

5.1 The High Pressure Jet Burner (HPJB) Design

Part 5 of this paper will describe field testing at RVSCI. The HPJB-10, co-firing burner is shown in Image 5.1. This patented jet burner develops an axial flame that penetrates into the furnace and can reach the opposite wall of the furnace to provide over bed coverage to control smoke and opacity as well as NOx formation. The long collimated flame is a naturally low NOx producer when firing natural gas alone; but in conjunction with a co-firing fuel such as coal on a grate the HPJB flame becomes the staging component. The HPJB can operate at a very wide range of loads, A/F, and has extreme turndown range capability. Field experience has shown turndown ratios of 500:1. This capability allows one to accurately control the stoichiometry above the coal bed for a wide range of coal bed firing A/F ratios. This control allows precise control of opacity caused by soot formation as well as NOx emissions. The design of the discharge end of the burner is unique in that it incorporates an eductor section at the entrance of the 8" X 4" concentric reducer. The gas discharge tip provides the motive power for the eductor and the reducer provides the vena contracta. The flame holder provides positive flame anchoring at any load and A/F. The flame is incredibly stable and cannot be "blown out" by any air or fuel flow.

The HPJB provides the standard package of accessories such as:

1. Spark Ignition
2. UV Flame Scanner
3. Optional Dual Ignition with Hot Surface Igniter
4. Ports for visual observation of the flame and burner internals
5. Integrated FD Fan, Inlet Damper, and motor with VFD
6. Flame Safety Burner Management System

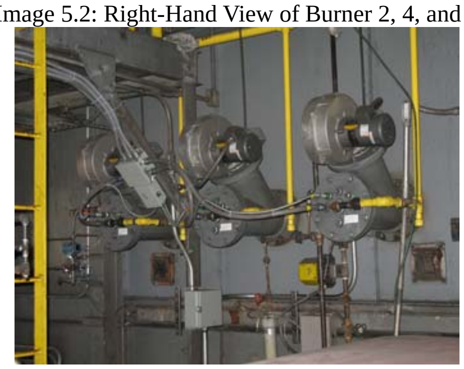
This burner designs comes in size ranges up to 250 mmbtu/hr and can be equipped to burn any gaseous fuel, any liquid fuels, and finely divided solid fuels. The burners can be equipped with a range of high swirl tip designs to produce the desired flame shape for the furnace it will be used in.

(Image 5.1: HPJB Jet Burners Crossing over the center of boiler with no flame impingement)

5.2 Arrangement of the Burners

The co-firing natural gas High Pressure Jet Burners were installed as shown in Image 5.2 and 5.3, on the number 3, Keeler boiler at RVSCI. The #3 boiler is a 20,000 pph steam (550 bhp) underfeed fed stoker boiler, generating 150 psig saturated steam for heating and institutional use. The boiler can fire low volatility and high volatility bituminous coal. The furnace is nominally 8' X 8' square and 10' tall to the top of the bridge wall into the steam generating tube bank. Forced draft air is fed to the underside of the grate and enters the furnace through openings in the cast iron grate sections. The coal is pushed into the furnace with a single ram, underfeed retort stoker. The coal builds up in the tuyeres and burns as the air mixes with it on the grate. Ash remaining after the combustion falls to each side of the grate and is removed periodically by dumping the manual ash gates on each side of the grate.

(Image 5.2: Right-Hand View of Burner 2, 4, and 6)



(Image 5.3: Left-Hand View of Burner 1, 3, and 5)

5.3 The HPJB Location in the Furnace

The six co-fire natural gas burners were installed on 18" centers in a staggered pattern three on each side of the furnace. The burners were positioned 24" above the top of the highest point of the grate. This arrangement was found by the modeling presented in the preceding section to be the optimum arrangement for over-bed coverage and mixing of the gases coming from the coal bed. The burners were limited to 3 million btu/hr heat input by the regulator pressure on the fuel line. The burner in the configuration shown can develop over 10 mmbtu/hr by increasing the gas pressure behind the discharge tip.

(Image 5.4: Jet Burners Crossing over the center of boiler with no flame impingement)

6. Results from RVSCI Co-Firing OCNG

6.1 Opacity

Part 6 of this paper describes field results from Rockview State Correctional Institute, a plant whose primary problems were NOx emissions and opacity.

Opacity was on of the primary problems at RVSCI. The furnace smoked during:

1) Start-Up
2) Load Changes
3) With fine coal feed
4) When pulling ash
5) At high load
6) When coal is wet

The co-firing HPJB at RVSCI provide seamless and smokeless firing from start-up to full load operation and handle any load spikes without smoking.

A cold boiler is started by initiating the burner firing sequence in the control system. The burners come on at low fire and heat up the furnace and boiler to the point of steam generation. When steam is being generated the coal fuel is fed into the furnace and is ignited by the gas flames (as shown in image 6.1. The load is picked up by the coal as the gas fuel is reduced. When steady state load is achieved the gas fuel may be reduced to zero with only the air from the co-firing burners remaining on. This air flow acts like over-fire air to maintain minimum opacity. On low volatility coals only air is required to maintain minimum opacity. On high volatility coals some minimum amount (10%) of natural gas will have to be fired to maintain minimum opacity.

Load spikes are initially carried by the gas fuel with coal filling in behind. If the load spikes are of short duration no coal would be filled in behind the gas.

Definitive tests were run to demonstrate the ability of the co-firing to virtually eliminate the smoke from the furnace. A banked furnace was started up with high volatile coal. The opacity was read at in excess of 50%. When 14% natural gas was fired in the co-firing burners the opacity dropped to less than 10%. This test was a clear demonstration of the ability of the co-firing burner system to control the furnace opacity.

(Image 6.1: Coal Being Ignited by the Gas Burners)

6.2 NOx

The other primary problem at RVSCI was NOx emission. "Prompt NOx" is caused by the increase in the volumetric heat release rate at low excess air. It is explained by the work at Rockview in the description of the NOx as both excess oxygen dependent as well as volumetric heat release rate dependent (adiabatic flame temperature).

The NOx relation is expressed as (50 ppm NOX, dry corr. to and @ 3% O2)/(mmbtu/cf x hr). The well defined "flame basket" of the Maloney Flame Blanket design allows easy circulation of the volumetric heat release rate in the furnace.

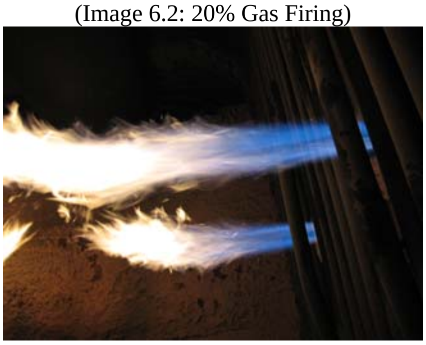
NOx emissions were measured from natural gas only firing without the use of coal co-firing. At a load of 8,600 pph steam which corresponds to 16,000,000 btu/hr heat input from the six gas burners, the NOx emission was 41 ppm at 9.6 % excess oxygen, dry. When corrected to 3% excess oxygen this is 64.8 ppm. The dNOx/dO2 = 6.747. So at 3% excess oxygen the NOx would be *20.2 ppm.* This is a very low NOx value for a burner without any NOx reduction techniques implemented except for its basic design which produces a very long axial, collimated flame. Single digit NOx values are expected with the use of Flue Gas Recirculation (FGR) into the combustion air.

The volumetric heat release rate can be calculated since the flame basket is well characterized. The furnace dimensions are 8' X 8' and the flame basket is one foot thick. This gives a volume of 64 cf. When the heat release rate is divided by the volume one gets the volumetric heat release rate for the firing system. This value at the above condition is 250,000 btu/hr-cf. When the NOx value is divided by the volumetric heat release rate a value of (80 ppm NOx corrected to and at 3% excess O2/mmbtu/hr.cf) of 20 ppm is obtained. When the heat input is known and the excess oxygen is known; the NOx value can be calculated from this relation.

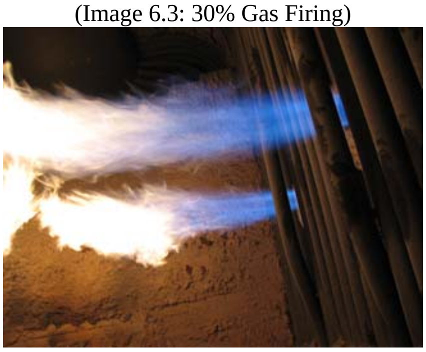
6.3 Photographs of the Natural Gas Flames at RVSCI

Images 6.2 to 6.6 show the natural gas flames from all six burners firing into the cold furnace, without coal. The flame pattern is the same as that shown from the CFD modeling in the section above. The flames do not interfere with each other but provide a "flame blanket" over the grate and the coal bed. The probability that a soot particle will penetrate this "flame blanket" and escape the furnace becomes exceedingly low. It is this coverage that ensures the quality of the process, virtually eliminating smoke from the boiler. The flames hardly interact with each other but provide a "flame blanket" over the grate and the coal bed. It is very unlikely that a soot particle will penetrate this "flame blanket" to escape the furnace. It is this coverage that provides the quality of the process to virtually eliminate smoke from the boiler.

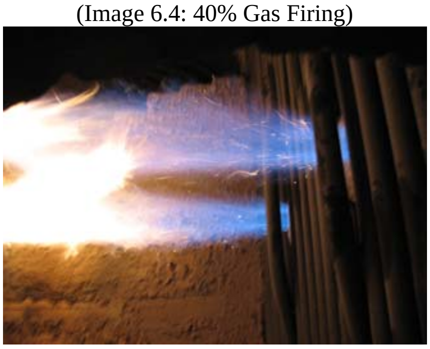
(Image 6.2: 20% Gas Firing)



(Image 6.3: 30% Gas Firing)



(Image 6.4: 40% Gas Firing)



(Image 6.5: 80% Gas Firing)

(Image 6.6: 100% Gas Firing)

The HPJB's Flame Blanket coverage is so effective that natural gas does not have to be used all of the time. This saves money on expensive natural gas.

Other gaseous fuels may be used for the process, such as Coke Oven Gas Fuel. Waste oils and other waste liquids may also be used in the “Maloney Flame Blanket” process.

6.4 Conclusion from RVSCI

The co-fired Maloney Flame Blanket jet burner when properly applied to coal fired stoker furnaces is an effective method to control opacity from the boiler. The burner may be either fired with a gas fuel or used as air only overfire air to achieve compliance opacity at all operating and upset conditions.

The air through the grate acts as “staged” air for the co-fired burners when the co-fired burner is operating at T/A approximately equal to 100. This staging effect results in very low, single digit NOx emission rates, when the volumetric heat release rate of the gas only firing is 0.2 mmbtu/hr. or less.