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Low Emission BITUMEN Combustor for Steam Generation

Bitumen is a heavy hydrocarbon based fuel with a good heating value, no doubt it can potentially be burned to generate steam. The real challenge is to do it while minimizing the pollutants emissions and maximizing boiler reliability as well as durability.

Bitumen is a residue obtained from the Tar Sands oil extraction process. It contains very high levels of fuel bound nitrogen, typically 0.5%. Uncontrolled, this nitrogen has the potential to emit 600 ppm of NOx. After adding up the contribution of the thermal NOx, which is typically about 100 ppm, the total NOx emission level of Bitumen is obviously not acceptable when compared to that of Natural Gas (30 to 100 ppm total). With a NOx emission target of less than 120 ppm, the conventional approach of sticking a burner in a boiler furnace to burn Bitumen is without doubt a technically obsolete approach.

Bitumen also contains a fair amount of ash and a very high sulfur content that makes it flue gas extremely corrosive when cold.

The above preliminary considerations dictate that not a burner alone but rather a special type of integral combustor with multiple combustion zone will be necessary to reach the desired performance.

It is well known fact that thermal NOx are massively formed in areas where flame temperatures exceed 2800°F. Since boiler furnaces are designed to operate at average outlet temperatures ranging from 1800 to 2400°F, NOx formation is simply the result of poor temperature uniformity within the furnace and more particularly within the flame zone. In the same way, unburned hydrocarbons and carbon monoxide result from cold spots where the temperature falls below 1400 °F. If a uniformly mixed combustion zone with a temperature of 2200°F plus or minus 200 °F throughout the furnace could be obtained, it would generate virtually no thermal NOx and no CO. This is essentially the basic concept of advanced combustion techniques for NOx and CO control.

Unfortunately, most available burners today are still being designed almost independently from the furnace. The reason is that boiler manufacturers are segregated from burner manufacturers.

By adequately designing a burner to be compatible with a given furnace aerodynamics, it is possible to optimize the mixing rates not only between the air and the fuel, but also with the products of combustion inside the furnace. By doing so, temperature peaks are reduced and cold spots minimized, thus reducing both NOx and CO emissions. When it comes to special fuels like BITUMEN, the necessity to integrate the furnace design with the burner aerodynamics becomes paramount, to the point that there is no longer a burner here and a furnace there, but rather an integrated combustor working as one unit.

Boiler owners and operators have long observed that combustion chamber or furnace geometry and construction greatly affect burner performances. It has been proven many times that the same burner installed in different boilers will not produce the same results. The universal burner that fits all is a technical utopia that has long plagued the boiler industry.

Facing the challenge of generating steam efficiently with ultra-low emissions, new engineering practices using a more advanced technical toolbox are required. Burner design can no longer be made independently from the furnace in which it is to be installed; it must integrate the furnace effects and provide means of adapting combustion aerodynamics to match the furnace. This trend will lead to a total integration of the boiler, burner and controls into a compact low cost, energy efficient and low emission steam generating system.

It is very likely that the boiler industry will be following a technological path similar to that of the gas turbine industry. In gas turbine engines, the constraints of volumetric heat generation are significantly higher than in current boilers. Yet, the high level of temperature uniformity obtained by fast and efficient mixing allows for extremely low NOx emissions even without FGR. The achievements of the aircraft and gas turbine industries are largely due to the use of advanced test facilities and computer simulations, something that only very recently reached the boiler industry.

A burner is a mixer

Whether it is a pre-mix or a nozzle-mix diffusion type flame, the very first function of a burner is to insure that the fuel is evenly mixed with air so that it burns completely within a confined combustion chamber volume. The lower the excess air required for complete combustion in a given volume, the more efficient the burner. The efficiency of a burner can in fact be defined as an inverse function of the amount of excess air required to achieve complete combustion in a given flame volume.
For a nozzle-mix burner, the mixing power required to obtain the desired mixing rate is the sum of the combustion airflow pressure drop and the fuel flow pressure drop. On the air side, the burner dissipates some fan horsepower to affect mixing. On the fuel side, gas pressure or atomizer pressure multiplied by volumetric flow through the injectors provides another source of mixing power. These air and fuel pressure drops at a given volumetric flow rate provide the potential mixing power for a burner to accomplish its task of mixing the two streams. The volumetric heat generation of the flame of any burner is a function of this quantity: the larger it is, the better the mixing and the smaller is the resulting flame.

Structure of the flame: reaction zone

As a second function, a burner must be able to ignite and generate a stable flame that, most importantly, fits the furnace geometry. Flame stabilization is generally performed without much difficulty by a bluff effect and/or a critical swirl effect. Flame shape can be described by its length-to-maximum diameter ratio and is determined by the aerodynamics of the air and fuel injection pattern. The swirl, defined as the ratio of tangential momentum to axial momentum fluxes, added to the injected fluid streams, is the key controlling parameter for flame shaping. To achieve good practical results, it is imperative that the burner-generated flame is compatible with furnace geometrical constraints. This is most critical in water-cooled furnaces such as boilers and especially in packaged boilers. If flame impingement occurs on cold surfaces, carbon monoxide and other by-products of incomplete combustion will be produced at the point of impingement and, in large proportions, produce severe furnace vibrations upon violent re-ignition of these by-products.

Controlling emissions of pollutants: NO_X, CO and Particulates

Since the mixing rate and its specific distribution determines the temperature and chemical species concentrations within a given furnace, the configuration of the burners in relation with the geometry and flow pattern in the combustion chamber exert a significant influence on NO_X, CO and Particulate formation. The emission of pollutants is intimately linked with furnace configuration and distribution of heat dissipation. It is obvious that reducing pollutants successfully in a given furnace requires that the burner configuration be sufficiently adaptable to properly match the furnace flow and temperature characteristics.

To achieve Ultra-Low NOx emissions, the burner mixing power must not only provide enough mixing between air and fuel to obtain complete combustion within the furnace volume, but it must also provide enough mixing power per unit furnace volume to evenly mix the inert combustion products within that particular furnace.

NOx formation is triggered in areas where local furnace temperatures exceed 2800^{o}F and CO formation results mainly from low temperature zones well below 1400^{o}F. Since most boiler furnaces are designed to operate at average outlet temperatures ranging from 1800°F to 2400°F, NOx and CO formation is simply the result of poor temperature uniformity within the furnace, particularly within the flame zone.

A perfectly mixed combustion zone would result in negligible NOx formation that could theoretically be close to zero even without the use of flue gas recirculation.
However, such perfect mixing would require a level of mixing power per unit furnace volume that would be prohibitive for commercial boiler applications. Even an imperfectly mixed furnace with temperatures within 1300°F to 2900°F would still result in very low emissions for both CO and NOx.

The use of FGR as an additional inert mass released into the combustion zone is a good way to reduce the peak temperature of the flame. The major drawback of FGR is that it also reduces the temperature of colder zones in the furnace and increases CO emissions.

Fuel bound nitrogen is another path for the formation of NOx. Unlike thermal NOx, it is not temperature dependent. Its formation occurs in the early steps of the fuel oxidation process where nitrogen compounds are released. To limit the conversion of this nitrogen to NOx, the only known way is to reduce the availability of oxygen. This then requires a multi-step combustion process beginning with a fuel rich zone. For such a process to be successful, very good mixing and atomization quality are required to avoid the generation of large unburned carbon particles.

Integrated boiler-burner design using CFD

With advanced design tools such as CFD, an integrated boiler-burner manufacturer can build a unit capable of burning a fuel like BITUMEN or its MSAR™ emulsion with very low emissions. This can be done with a system of burners and combustion chambers that displays unrivaled mixing homogeneity compared to what was accomplished in the past by the segregated old school of boilers and burner manufacturers.

As a consequence of better homogeneity, there is virtually no unburned fuel and very little of its precursor: carbon monoxide. CO emissions between 0 and 10 ppm across the range were easily demonstrated with this design strategy.
Another point worth mentioning is that flame volume becomes much smaller when homogeneous mixing is achieved. Thus, combustion chamber can be made much smaller than before. Because of this, the next generation of ultra low emission boilers will exhibit a much smaller footprint. The newly created available space will allow for the use of advanced heat reclaim system to reach efficiencies between 90 and 95%. This new boiler concept actually exists. It is a firetube boiler currently being field tested at several locations in North America. It is called the SUPERBOILER, built by Cleaver-Brooks under the sponsorship of DOE.
Our engineered boiler-burner group Nebraska-Natcom is also manufacturing since 2003 an integrated watertube superboiler. It applies the same design principles that are exposed in this short paper. It results in a unit with a smaller footprint, lower emissions and better efficiency than any other previous steam generator design.