Large-scale laboratory experiments on pollutant emissions in heavy oil combustion

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ABSTRACT

Heavy fuel oil combustion tests have been conducted in a semi-industrial experimental furnace. The consequences of some modifications in the oil injection parameters on solid and gaseous pollutant emissions were investigated. The oil spray characteristics proved to have a significant influence on the results. The variations in NOx and solid emissions follow an inverse trend for most of the changes in atomization conditions. It was possible, however to reduce unburnt carbon without increasing NOx levels. The combustion of oil/water emulsions for several water concentrations and oil injection temperatures was also studied. Simultaneous reductions in NOx and particles emissions were achieved with this technique.

Key Words: Heavy oil combustion, Oil/water emulsions.

INTRODUCTION

A traditional concern in heavy oil combustion has been the emission of unburnt particles. This problem increased after the 1973 crisis, that forced refineries to obtain greater quantities of light fractions from the crude, leaving a lower quality residue. As a consequence, combustion systems had to be optimized in order to efficiently burn the heavier and more viscous fuel. The change of atomizers or burner modifications are some of the measures that have been implemented.

Nowadays, another factor that must be taken into account in the design of combustion systems is the formation of nitrogen oxides. Unfortunately, most of the burner modifications that make possible a reduction in particulate emissions lead to an increase in NOx formation. New burners have been developed that meet both requirements by a precise control of the mixing process in the flame, usually through more sophisticated systems of air and fuel injection. Nevertheless, the design of combustion equipment that makes compatible low levels of particulate and NOx emissions is still a developing field.

The present work is part of a research project directed to the reduction of solid emissions in heavy oil-fired boilers (Ballester et al, 1991). The effect of changes in spray characteristics and of the combustion of oil/water emulsions on pollutant emissions have been investigated. The tests were conducted in an experimental furnace working at 0.33 MW (t). This facility is thought to be appropriate for this type of studies, since its size is sufficient to reproduce most of the aspects of a real system, while providing extensive diagnostic capabilities.

EXPERIMENTAL FACILITY

The experiments were conducted in the vertical down-fired furnace represented in Figure 1. The combustion chamber is cylindrical. It has an internal diameter of 0.61 m and a total length of 3.2 m. The furnace consist of ten annular segments that form the cylindrical body, the roof and the flue gas scrubber. Each element is cooled by an independent water jacket with individual temperature and flow rate measurements. The upper half of the inner wall is refractory lined. The temperature profile of the surface is measured by 10 wall thermocouples located in the five upper segments.

The burner is located at the center of the roof of the furnace. Combustion air and fuel are injected as parallel concentric streams. The air duct discharges in a quart built in castable refractory concrete. Flame stability is achieved by the rotating motion transmitted to the air flow by a movable-block variable swirl generator. The heavy oil is injected by a simplex pressure-swirl nozzle, with its front plane located at the throat of the quart.
Combustion air is preheated up to 240 °C by an electric heater. Flow rate is regulated by a closed-loop control that varies the velocity of the forced-draught fan. Flow rate in all the experiments was adjusted so that oxygen concentration in flue gas was 1.2 % (by volume, dry basis).

The oil feeding system allows for a wide regulation interval of mass flow rate (up to 50 kg/h), injection pressure (up to 25 bar) and oil temperature (up to 150 °C). Since the oil spray is greatly influenced by them, the control of these parameters made possible a broad variety of combustion conditions.

Atomization characteristics as a function of injection conditions and nozzle geometry were previously investigated. Isothermal flow tests were conducted at an atomization test rig. Although it was originally designed for large-capacity atomizers (up to 80 bar and 700 kg/h), it was easily adapted to the conditions of this work. A thorough investigation of the effects of oil temperature variations (100 to 135 °C), injection pressure (12 to 20 bar) and internal dimensions of the atomizer on spray characteristics was conducted. Discharge coefficient, spray angle and drop size distributions at several points of the spray were measured. Low speed photography and laser diffractometry techniques were used.

The addition of water to the oil and the subsequent preparation of the emulsion are made on-line. An auxiliary system injects a controlled flow rate of distilled water into the oil, upstream of the pump. Even though the elements of the line (pump, strainers, bends, ...) induce a first dispersion of the water in the oil stream, the quality of the emulsion was guaranteed by a static mixer placed in the high pressure line. Microscope observations of samples of the emulsions demonstrated that water droplets did not exceed 20 µm, most of them being under 5 µm.

The physical and chemical properties of the heavy oil used in the experiments are listed in Table 1.

<table>
<thead>
<tr>
<th>Ultimate analysis</th>
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<tbody>
<tr>
<td>Carbon</td>
<td>86.45 %</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>11.12 %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.36 %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1.18 %</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Proximate analysis</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Ash</td>
<td>0.04 %</td>
</tr>
<tr>
<td>Asphaltenes</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Conradson</td>
<td>9.24 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gross Calorific Value</th>
<th>42.868 MJ/kg</th>
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<tbody>
<tr>
<td>Density at 20 °C</td>
<td>983 kg/m³</td>
</tr>
<tr>
<td>Viscosity at 50 °C</td>
<td>354.46 cPo</td>
</tr>
</tbody>
</table>

Table 1 - Physical and chemical properties of heavy oil
variables could not be achieved by this method. Atomizers with different internal dimensions were tested in two cases (Runs 1 and 4). The results for spray 4 do not follow the general inverse trend displayed by the rest of the points, and will provide some insight into the individual effect of both parameters.

Solid and NOx emissions are presented in Figure 3 for all the tests. With the exception of Run 4, the results clearly indicate an inverse relationship between both variables. Sprays 5, 6 and 7 are characterized by a high drop size and a narrow spray angle. The consequences to combustion are high particulate loading and relatively low NOx levels. Tests 1, 2 and 3 are at the opposite side. A wide and fine spray leads to high NOx and low unburnt carbon levels.

Case 4 has a mean drop size lower than Runs 5 and 6, but with a similar spray angle. The analysis of the flue gases displays an important decrease in particle loading with respect to Runs 5 and 6, and similar values of NOx emissions. These results suggest that particle emissions are largely determined by the SMD of the spray. On the contrary, the decrease in drop size does not affect NOx emissions. The role of these variables in the processes that take place in the flame are discussed in what follows.

In the first place, a brief description of the characteristics of the flame is given. A general scheme can be seen in Figure 4. This structure has been constructed from extensive measurements of flow field, temperature and species distributions inside the flame (Ballester, 1992).

The combustion air enters the chamber with a swirling motion. As a consequence, an adverse axial pressure gradient appears and a reverse flow zone is created along the axis (the Internal Recirculation Zone, IRZ). The annular jet is surrounded by a toroidal reverse flow region caused by the confinement of the jet (the External Recirculation Zone, ERZ).

The oil is injected at the axis of the furnace as a hollow cone spray. Drop trajectories are influenced by the reverse flow of the IRZ, the magnitude of the deviation depending on the diameter of the drop. Smaller drops are largely affected and they can even be transported backwards. The trajectory of the larger sizes will penetrate more into the IRZ, even crossing it.

The IRZ transports upstream hot combustion products from the flame with a very low oxygen concentration. The high temperature of these gases and the large relative velocity between drops and surrounding gas causes a fast evaporation rate inside the IRZ. Therefore, this region is characterized by a high concentration of fuel vapor and very low oxygen availability.

Intense combustion takes place in the limits of the IRZ. The high shear flow provides a fast mixing between the outer fresh air jet and the fuel rich gases from the IRZ. The maximum flame temperatures are located in this zone, corresponding to the points of near-stoichiometric conditions.

Most of the oil evaporates and then burns in the gaseous phase. But, unlike lighter fuels, heavy oil combustion is characterized by the formation of solid particles. A detailed description of the evaporation history of a heavy oil droplet is given by Lightman and Street (1983). The lighter components of the fuel evaporate at a first stage. The heavier fractions undergo a series of pyrolysis reactions yielding fuel vapor and a carbonaceous solid residue (cenosphere). Several workers (Marrone et al., 1984, Urban et al., 1990) have found that the proportion of fuel that is converted into the solid residue only depends on the original composition of the oil. Therefore, the final mass is a function of the subsequent history of the cenospheres. Particle burnout is affected by particle diameter, temperature and composition of the surrounding gases. These factors will determine the solid emissions obtained for a given oil composition. Since the diameter of a cenosphere is directly proportional to the size of its parent drop, the amount of unburnt carbon must be a strong function of the drop size distribution of the spray, as the present results demonstrate.

Although it is not apparent from the graphs, spray angle is also expected to have some influence on solid emissions. Mixing conditions are strongly affected by the dynamics of the spray, and therefore by its angle of injection. In order to illustrate this point, fuel vapor distribution in the flame under two different conditions are presented in Figures 5 and 6.

The narrower spray flame (Figure 5) display a large fuel rich zone along the furnace axis. The extremely low oxygen concentration in this zone will limit particle burnout. A wider spray angle provides faster mixing. The drops spread radially, even crossing the radial limits of the IRZ and entering the air jet. The higher oxygen availability will promote particle burnout. Therefore, an increase in spray angle should yield a reduction in unburnt carbon at the exit. Results indicate however, that drop size is a more important parameter in relation to solid emission for these conditions.

Figures 5 and 6 are helpful to explain the influence of spray angle on the formation of nitrogen oxides. The characteristics of the narrow spray flame (Figure 5) are similar to a low-NOx burner. The large fuel-rich zone limits the oxidation of fuel nitrogen to NO, favouring the reactions of conversion to molecular nitrogen. Figure 6, however, indicates an extensive region of better mixing where oxygen availability will result in higher fuel-NO formation rates.
The results for Runs 1, 2 and 3 suggest that under these conditions a maximum in NOx formation has been reached and it is not affected by additional spray angle increase.

SMD variations are thought to have some influence on mixing characteristics and, therefore, on NOx levels. The reverse flow along the axis reduces the axial penetration of the drops. Therefore, a finer spray should also display similar characteristics to those of a wider injection angle. However, this cannot be observed in the present measurements where NOx is not affected if only mean drop size changes.

COMBUSTION OF OIL/WATER EMULSIONS

The combustion of oil/water emulsions is characterized by the occurrence of a secondary atomization caused by the so-called ‘micro-explosions’. Water droplets contained in an oil drop evaporate disruptively when entering high temperature regions. As a consequence, the real mean drop size is smaller than the one of the initially formed spray. Experimental evidence of the shattering of isolated drops by this phenomenon can be found in the works of Dryer (1977), Jacques et al (1977) and Marrone et al (1983). Recently, Mattiello et al (1992) also found some evidence of the occurrence of micro-explosions in a large heavy oil flame.

The high viscosity of heavy oil makes generally difficult to finely atomize it. Therefore, the utilization of oil/water emulsions may be adequate to improve the combustion of such fuels. The reduction in particulate emissions achieved by the addition of water has been demonstrated by Jacques et al (1977), Sjögren (1977) and Cunningham et al (1983a, 1983b). Even though some other possible explanations have been pointed, micro-explosions are considered to be the main responsible phenomenon (Cunningham et al 1983a, Marrone et al, 1983, Dodge and Moses, 1983).

The consequences of adding water to a heavy fuel oil are analyzed in what follows. Several water proportions were tested (4, 7 and 10 % by weight) at three different oil injection temperatures (100, 120 and 145 °C). The values of particle and NOx emissions obtained with the neat and emulsified fuels are represented in Figures 7 and 8.

For the pressure-swirl atomizers used in this work, an increase in oil temperature causes a reduction in drop size and an increase of spray angle. As discussed in the previous section, the consequences are a decrease of particle emissions. The same evolution is also apparent from Figure 7 for all the water concentrations tested.

The addition of water causes an important decrease of unburnt carbon emissions. The magnitude of the reduction shows a strong dependence with water content up to 7%. However, the benefit of increasing water concentration is much less important between 7 and 10 %, in agreement with the experiments of Cunningham et al (1983a), who suggest that a further increase in water content would not provide significant improvements in solid emissions.

Flue gas analysis did not reveal any noticeable variation in CO and gaseous unburnt hydrocarbons. On the contrary, NOx concentration was significantly affected by water addition (Figure 8).

Combustion of oil water emulsions provide a reduction of NOx close to 25 % for a 10 % water content and oil temperatures of 120 and 145°C. The variation is negligible when oil is injected at 100 °C. An emulsion with 4 % water gives an important reduction in NOx at 120 °C. However, at 145 °C the emission of NOx is similar to that of the neat fuel.

Temperature measurements inside the flame showed a reduction in maximum temperatures of around 60 °C when a 7 % water is added to the oil. The effect of this decrease in temperature on thermal-NO formation is believed to be the cause of the observed reduction in NO emissions.

Water addition can also have an effect on the chemical reactions taking place. Dryer (1977) reports a reduction of 22 % in oxygen atom concentration when 10 % water vapor is added to the combustion air. This effect could have a significant influence in the oil flame in those points where the water of the emulsion provides a significant increase with respect to the existing water vapor concentration. This condition can only occur in the highly fuel-rich zone. In-flame measurements reveal that NOx concentrations in the IRZ are very similar for neat and emulsion flames (Ballester, 1992). The differences are located in the outer regions where the thermal route is the dominant one. Therefore, NOX reduction is attributed to the lower thermal-NO formation due to the decrease in flame temperature.

The addition of water has two opposite effects on NOx formation. The improved combustion would increase NOx. On the other hand, the presence of water lowers thermal-NO formation. These two effects seem to balance when the fuel is injected at 100 °C. At higher temperatures the decrease in thermal-NO formation is dominant, resulting in reduced emissions.

Previous work of Cunningham et al (1983a) reported a decrease in NOx emissions up to 10 %. The results of the present experiments indicate a reduction between 15 and 25 %. Tests conducted in a 500 MW utility boiler showed a reduction of about 30 % with a 10 % water content (Casanova, 1992).
In summary, the combustion of oil/water emulsions provides a reduction procedure for particulate emissions without the penalty of higher NOx levels. On the contrary, a significant reduction in this pollutant is also obtained. This technique seems specially adequate to burn high viscosity fuels which pose serious problems to the achievement of a good atomization quality. Low particle emissions can be maintained without rising excess air levels, and therefore, without deleterious effects on NOx and SOx formation, or heat losses in flue gases.

Combustion modifications for low NOx emissions in heavy oil systems face the problem of maintaining acceptable levels of unburnt carbon. The use of oil/water emulsions can help to attain a high particle burnout under the difficult conditions of controlled mixing of the new systems.

CONCLUSIONS

The combustion of heavy oil under different conditions has been studied in a large-scale experimental furnace. Interest was focused on the effects that certain combustion modifications have on pollutant emissions. These include the change in atomization conditions and the combustion of oil/water emulsions.

Sprays are characterised by a mean drop size and the cone angle. The variation of these parameters resulted in important changes in solid and NOx emissions, that displayed an inverse evolution for most of the cases. However, a decrease in mean drop size with a nearly constant spray angle led to a significant reduction in unburnt carbon with a similar NOx level. On the contrary, if spray angle is also wider, NOx emissions increase. Some detailed in-flame measurements demonstrated that a wide spray is characterized by faster mixing rates, that enhance fuel nitrogen conversion in the flame core.

Oil/water emulsions with water content between 4 and 10 % by weight were tested. Particle emissions were reduced by about 30 % with a 10 % water concentration. The same emulsion lowered NOx level by almost 25 % with respect to the neat oil. These effects increase with water content, but differences are lower at higher concentration. This combustion technique seems adequate to achieve acceptable levels of solid and NOx emissions when burning highly viscous fuels.

ACKNOWLEDGEMENTS

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REFERENCES


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Figure 1 - Experimental furnace.

Figure 2 - Measurements of Sauter Mean Diameter (SMD) and spray angle.

Figure 3 - NOx and solid emissions under different atomization conditions.

Figure 4 - General structure of the flame.
Figure 5 - Spatial distribution of fuel vapor concentration for run 5.

Figure 6 - Spatial distribution of fuel vapor concentration for run 3.

Figure 7 - Effect of water concentration and fuel temperature on particulates.

Figure 8 - Effect of water concentration and fuel temperature on NOx.